Green Energy and Technology

Atul Sharma
Sanjay Kumar Kar *Editors*

# Energy Sustainability Through Green Energy

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# Foreword

The debate about climate changes due to industrial activity post mid-nineteenth century is no more a subject of academic discussions and modelling various scenarios. The after-effects of greenhouse gas emissions due to human activity is there for all of us to see manifesting in the form of extreme climatic conditions. In November 2014, it was widely reported in newspapers that all the 50 states of the United States recorded sub-zero temperatures, a never heard before phenomenon. Coupled with such facts another challenge that the world is likely to face by 2030, according to some UN estimates, is the *stress nexus* of rising demands for water, food and energy.

The growing population of the planet, which according to estimates is likely to be around 9 billion by 2050 as against 2 billion during the mid-nineteenth century and aspirations of people leading a reasonably decent lifestyle is putting more and more pressure on the existing *congealed* resources of our planet. And at the same time, it is also being realized that the days of *easy oil* are over. Oil (and its equivalents like gas) as a major source of primary energy is gradually to be explored in inhospitable, difficult and deeper terrains. Thus, the Energy Returned On Energy Invested (EROEI) has also gradually been reducing from the levels of 100:1 in the 1860s to somewhere around 17–18:1 in 2010 and is projected to fall further. This ratio, below the levels of 5–9:1, according to some estimates, will make oil production unviable with the available technology.

Thus, energy being the quintessential requirement for human progress, two fundamental questions need to be considered in right earnest. The *first* being the ability to produce enough primary energy to meet demand and the *second*, not damaging the climate further with human activity leading to greenhouse gas (GHGs) emissions beyond the IPCC (Intergovernmental Panel on Climate Change) recommended limits of 450 ppm.

IPCC, in its latest deliberations, has brought out the following facts:

1. Average surface temperature has already increased by 0.85 °C over the period from 1880 to 2012.
2. Existing levels of three key GHGs—carbon dioxide, methane and nitrous oxide—are the highest in at least 800,000 years.

3. Global mean sea level rose by 19 cm from 1901 to 2010.
4. Period from 1983 to 2012 was the warmest 30-year period in the last 1,400 years.

IPCC has further said that the world will have to totally phase out fossil fuels in power generation by the end of the century.

These developments have, obviously, led to the search for commercially exploitable *other sources* of energy that while meeting human needs do not cause further damage to the environment for the sustenance of our planet. It is expected that *energy mix* of the planet will change substantially in the years to come.

Green Energy or Renewable Energy is an area that will form a substantial portion of the energy mix in the country and will occupy centre stage in providing the much needed fillip to the void likely to be experienced by us in the near foreseeable future. There is enough promise for various green energy initiatives like solar, solar thermal, wind, bio-mass, hydro, hydrogen and nuclear power.

It is, indeed, a very timely effort by Dr. Atul Sharma and Dr. Sanjay Kumar Kar, known to me for over five years now, from Rajiv Gandhi Institute of Petroleum Technology (RGIPT), an institute of national importance, to have come out with a book that discusses myriad ways in which the natural resources of our well-endowed country can be made use of for meeting the energy needs of our millions of citizens without causing further damage to the environment.

In course of my interactions with both the professors of RGIPT, which is co-promoted by various organizations from the petroleum industry, we have often discussed about the likely energy scenarios in the days ahead. During such discussions, the need to publish a book on energy sustainability was felt. I congratulate both the editors for having come out with the book which will be of immense help to students, practising managers and policy makers alike.

Biswajit Roy
Executive Director (HRD)
Indian Oil Corporation Limited
New Delhi

# Preface

A few decades ago, energy sustainability was just thought in terms of accessibility relative to the rate of use. Today, in the context of the decent agenda of sustainable growth, including concerns about global warming, greenhouse gas emissions, climate change and so on are very important issues. These include environmental effects and the question of the energy generation process as well as emissions, which are the primary reasons for damage to the earth environment during energy production, distribution and consumption. Sustainable energy development criteria have been promoted in several years into the front line of energy policy, which also showed how we address our energy needs on a sustainable basis.

Energy demand is likely to increase in the entire world, the ratio supplied by electricity is likely to rise rapidly, however, more energy demand is for continuous, and this qualitative consideration will continue to dominate in the energy sector. Meeting the needs of the present energy demand without compromising the needs of the future, the whole world has to pay attention to the energy sustainability, so that environmental protection remains equally important at the same time. Energy sustainability could drive environment friendly technological innovations with viable techno-commercial applications for social upliftment.

Renewable resources such as solar energy, wind energy, biomass, bio-gas and bio-fuels, hydro energy provide a source of sustainable energy. Worldwide, renewable energy resources are available to supply the expanding energy needs without environmental damage. However, the current renewable energy share is less in the worldwide energy production. It is an acknowledged fact that it should have been much higher as much as in favour of the environment, which is the most essential issue globally. Almost everywhere in the globe, clean energy production is given much attention due to the current environmental issues, which can only be solved by the renewables. Many countries are making significant efforts to move up the renewable energy ratio and overall approximated 19 % of global energy consumption produced by renewable energy in 2012 which continued to grow in 2013.

The aim of this book is to share the latest developments and advances in materials and processes involved in green energy generation, transmission-distribution, storage, etc., with chapters written by professors and researchers in the energy and materials field, using original research materials. This book may be used as a reference book in college/university/training institute/professionals all over the world. This book can also be referred in all the green energy-related laboratories, industries and academic libraries and as a refereed book for “Alternative Energy Sources, Renewable Energy Resources, Climate Change, Energy Sustainability, Energy Policies etc.” for undergraduate and graduate students. The book presents a perfect blend of research and practice explained in a very simplistic manner. It also covers the sustainable provision of energy that meets the needs of the present without compromising on the ability of future generations to meet their needs.

Rae Bareli, India Atul Sharma
Noida, India Sanjay Kumar Kar

# Overview of the Book

The increasing level of greenhouse gas emissions and the rise in fuel prices are the main reason for efforts to more effectively use various sources of renewable energy. Scientists all over the world are in search of sustainable energy options, which demands sustainable planning of sustainable energy developments. This confirms that the urgency of meeting the present needs without compromising the ability of future generations to satisfy their needs.

Increasing the share of green energy sources can trim down greenhouse gas emissions, which is a major factor in global warming as well as climate change worldwide. The operating cost of technologies to capture green energy, which is speedily declining and becoming economically competitive with fossil fuels, while also reducing the risk of climate change is what is actually needed worldwide. Investing in green energy creates a bunch of jobs, quick economic growth, and improves energy security, which is highly required worldwide because of shortage of fossil fuel resources.

The book explores the latest developments and advances in materials and processes involved in energy generation, transmission-distribution and storage, etc., and chapters written by several scientists, researchers and academicians in the field of energy. The results and recommendations are essential reading for policymakers, professionals, researchers and anyone concerned with energy sustainability through green energy. The book with 19 chapters is divided into six parts, which include relevant topics presented in detail below:

- Solar energy
- Wind energy
- Green buildings
- Thermal energy Storage
- Bio-mass, Bio-fuels, Bio-gas
- Other Green Energy

# Part I: Solar Energy

### Solar Photovoltaic Technology and Its Sustainability

In this chapter, Anil Kumar, Geetam Richhariya and Atul Sharma have discussed the application of solar photovoltaic technology for sustainable growth. The renewable energy sources are the clean green technology, which motivates the healthy environment but also encourages using them in rural areas where grid supply is not applicable. The fundamentals of solar photovoltaic technologies and their sustainability on the earth are discussed. The various internal phenomena that occur inside the sun and the solar spectrum is also discussed. The various applications of photovoltaic and modelling of the solar cell are presented in this chapter.

### Solar Drying—A Sustainable Way of Food Processing

Co-authors of this chapter, M.A. Aravindh and A. Sreekumar explore deployment of Solar Drying as a sustainable way of food processing. In a developing country like India, having the second largest population and with agriculture as a source of income to nearly 60 % of the total population, post harvest and storage loss is a major quandary which needs to be addressed in due diligence. There are many food preservation techniques such as cold storage, drying, etc., that have evolved over the years to tackle the above losses. The major constraint is that almost all the technologies utilize fossil fuel resources, which are depleting very fast and wise use of these precious resources are preferred for long-term energy sustainability. Therefore, sustainable methods for food preservation are the need of the hour. Solar drying is one of the best choices in this context. There are many models of solar dryers developed and a good quantum of research is progressing in many parts of the world to propagate the solar drying technology for value addition of agriculture products. The solar drying technology is a classic example to showcase how the sun's free energy could be effectively utilized for the benefit of mankind. This chapter explains the different types of dryers, aspects of solar drying, parameters involved in the drying process and the economic analysis to analyse the feasibility of the solar drying system. Case studies of some of the successful installations are also included to propagate the solar drying technology in the country.

### Jawaharlal Nehru National Solar Mission in India

In this chapter, co-authors Atul Sharma, K. Srivastava and Sanjay K. Kar discuss the importance, objectives and achievements of the Jawaharlal Nehru National Solar Mission in India. The global environmental scene has changed fiercely over the last century. The changing scenario demands greater concern and an action-oriented enabling policy framework for use of sustainable and renewable energy. The Government of India has taken necessary cognizance of the global developments and initiated several green environment policy measures under the National Action Plan on Climate Change. One of the initiatives is the Jawaharlal Nehru National Solar Mission (JNNSM). This chapter discusses the objectives of JNNSM and the developments made so far to improve the share of solar energy and reduce energy poverty in India.

## Part II: Wind Energy

### Insights into Wind Energy Market Developments in India

In this chapter, co-authors Sanjay K. Kar and Atul Sharma discuss wind market developments in India. According to the authors wind power is gaining a stronger position in the Indian electricity market, mainly caused by preferential feed-in tariff and other incentives given by the central and state governments. Through the chapter, the authors assess the growth of the Indian wind market compared to other leading markets across the globe. Then, state level progress is discussed in detail. The authors review wind-specific policy measures and incentive schemes devised by the central government, state government and regulatory bodies to achieve the desired objectives. The authors discuss the challenges of increasing wind penetration in India. They conclude that to achieve greater wind penetration the Central government, the State government and the regulatory bodies need to work cohesively and collaboratively to iron out implementation failures and take appropriate measures for successful implementation of various rules, regulations and policies.

### Wind Energy Technology and Environment Sustainability

The author of this chapter Vilas Warudkar emphasizes that wind power plays an important role in the development of a country's economy as it reduces the country's dependency on fossil fuels. Wind energy is generally categorized as a clean, environment friendly and renewable source of energy. India is blessed with an immense amount of renewable energy resources and wind energy is one of the promising sources for energy supply option. The demand for electricity has grown significantly in the recent years and India depends widely on coal and oil to meet its energy demands. In the recent past, there has been intense research activity carried out in the development, production and distribution of energy in India, which results in the development of the need for new sustainable energy due to limited fossil fuel resources and problems associated with the environment (smog, acid rain and greenhouse gass emissions).

Development and promotion of non-conventional sources of energy such as solar, wind, geothermal and bio-energy are also getting increasing attention. Wind energy is a non-polluting source of energy and its mature technology and comparatively low cost makes it a promising and primary non-conventional energy source in India. The gross wind power capacity in the country is estimated at about 49,000 MW; a capacity of 21,264 MW upto May 2014 has been added so far through wind.

Continued research and development to increase the value of forecasting power performance, reducing the uncertainties related to engineering integrity, enabling large-scale use and minimizing environmental impact are some of the areas needing concerted efforts in wind energy. These efforts are also expected to make wind power more reliable and cost competitive with conventional technologies in the future for environmental sustainability.

## Part III: Green Buildings

### Achieving Energy Sustainability Through Green Building Approach

In this chapter, co-authors Ashish Shukla, Renu Singh and Poonam Shukla throw light on green building approaches for sustainability. There are three urgencies in the UK climate and energy policies (i) reducing greenhouse gas emissions, specifically $CO_2$ by 80 %, by 2050 (ii) decreasing fossil fuel consumption especially built environment sector; and (iii) reducing dependence on imported energy. Buildings account for 40 % of the total non-transport energy consumption both in the UK and EU, therefore reduction of energy consumption in the built environment will make a significant contribution in meeting these targets. On average, UK residents spend between 2.7 and 8.4 % on gas and electricity bills. Water bills also account for 0.5–3 % of their income. These scenarios make it important to consider green building design and reduce the social, environmental and economic impacts building are creating on us. Sustainability through green building design should encompass "cradle-to-grave analysis". Building Research Establishment Environmental Assessment Methodology (BREAM) is the world's foremost environmental assessment method and rating system for buildings. BREAM was launched in 1990 and sets the standard best practice in sustainable building design, construction and operation. The assessment uses measures of performance against established benchmarks. This chapter highlights interesting features for achieving sustainable development through green building design.

### Aerogel-Based Materials for Improving the Building Envelope's Thermal Behavior: A Brief Review with a Focus on a New Aerogel-Based Rendering

In this chapter, co-authors M. Ibrahim, Pascal Henry Biwole, Patrick Achard and Etienne Wurtz recommend aerogel-based materials for improving the building envelope's thermal behaviour. Most developed countries have set the objective to reduce their energy consumption and greenhouse gas emissions. In most countries, the building sector is the largest energy consumer. This sector offers a significant potential for improved energy efficiency through the use of high-performance insulation and energy-efficient systems. For existing buildings, renovation has high priority in many countries, because these buildings represent a high proportion of energy consumption and they will be present for decades to come. Several studies have shown that the best way to reduce the energy consumption in buildings remain the reduction of heat losses through the envelope. Nowadays, there is a growing interest in the highly insulating materials such as Aerogels. Due to their highly insulating characteristics, aerogels are becoming one of the most promising materials for building insulation. Although the cost of aerogel-based materials remain high for cost sensitive industries such as buildings, this cost is expected to decrease in the following years as a result of the advancement in the aerogel production technologies as well as the large-scale material production leading to lower unit costs. In this study, a brief review of aerogel applications in buildings is presented. Some examples of opaque aerogel-based materials and translucent aerogel-based systems are illustrated. Then, a new insulating rendering based on silica aerogels is presented. Its impact on energy performance for different houses is examined.

### An Overview of Phase Change Materials for Building Applications

In this chapter Helia Taheri and Atul Sharma offer an overview of phase change material for building applications. The increasing level of greenhouse gas emissions and the rise in fuel prices are the main reasons for efforts to more effectively use various sources of renewable energy. One of the effective ways to reduce the economic consumption of fuel is by using thermal energy storages. The use of a latent heat storage system using phase change materials (PCMs) is an effective way of storing thermal energy and has advantages of high-energy storage density and isothermal nature of the storage process. Nowadays, by using lightweight materials in buildings, architects need lightweight thermal storages, therefore the use of PCMs has started. In this chapter, the authors discuss the benefits of using PCMs as thermal mass instead of the common thermal mass. Next, the characteristics of PCMs, their categories and building applications that can use PCMs as thermal mass are discussed. Finally, PCMs can be of benefit for lightweight buildings as thermal mass for reducing building loads and fuel consumption.

## Part IV: Thermal Energy Storage

### Phase Change Materials—A Sustainable Way of Solar Thermal Energy Storage

G. Raam Dheep and A. Sreekumar emphasize the use of phase change material for sustainable solar thermal storage. Renewable energy sources are time-dependent in nature and the effective utilization of devices based on renewable energy requires appropriate energy storage medium to commensurate the mismatch between energy supply and demand. Solar energy is the primary source of energy among renewable energy sources which can be used for a wide variety of electrical and thermal applications. The intermittent and unpredictable nature of solar energy generally necessitates a storage medium in-between that stores energy whenever it is available in excess and discharges energy whenever it is inadequate. Therefore, the storage of thermal energy becomes necessary to meet the larger energy demand and to achieve high efficiency. Thermal energy storage using latent heat-based Phase Change Materials (PCM) tends to be the most effective form of thermal energy storage that can be operated for a wide range of low, medium and high temperature applications. This chapter explains the need, desired characteristics, principle and classification of thermal energy storage. It also summarizes the selection criteria, potential research areas, testing procedures, possible application and case studies of PCM-based thermal energy storage system.

### Latent Heat Thermal Storage (LHTS) for Energy Sustainability

Latent Heat Thermal Storage (LHTS) has been an interesting topic for researchers, readers and producing companies across the globe. In this chapter, co-authors M.A. Rahman, M.A. Kibria, M.M. Hossain, S. Rahman and H. Metselaar describe application of LHTS in solar power production and green buildings. In order to restrain the trend in present fossil fuel consumption, Latent Heat Thermal Storage (LHTS) using Phase Change Material (PCM) has received a common interest among scientists as it has high energy storage capacity. In this chapter, LHTS System and their applications for solar thermal power generation and building application have been discussed. The prospect of LHTS in reducing present fossil fuel consumption has also been demonstrated. Moreover, the recent development of PCM has been reported for practical LHTS application.

## Part V: Bio-mass, Bio-fuels, Bio-gas

### Energy Sustainability by Biomass

Energy generation from biomass has been a subject of discussion for quite some time, especially in the emerging and developing countries. Co-authors of this chapter, Manjari Shukla, Sanjay Singh, Sarfaraj Ahmad Siddiqui and A. Shukla look into sustainable energy production from biomass. With rapidly growing energy demand and concerns over energy security and environment, researchers worldwide are exploring deeply to deploy renewable energy sources. Development of economical biofuel at sufficiently large scale may provide a major breakthrough in this direction, with strong impact on sustainability. More importantly, environmental benefits may also be achieved by the utilization of renewable biomass resources, which could help the biosphere for a longer time. In this chapter, the authors review the availability and bioenergy potential of the current biomass feedstock. These include (i) food crops such as sugarcane, corn and vegetable oils, classified as first generation feedstocks, and environmental and socio-economic barriers limiting its use. (ii) Second generation feedstocks involving lignocellulosic biomass derived from agricultural and forestry residues and municipal waste followed by constraints for their full commercial deployment. Key technical challenges and opportunities of the lignocellulosic biomass-to-bioenergy production are discussed in comparison with first generation technologies. (iii) The potential of the emerging third generation biofuel from algal biomass is also reviewed.

### Biofuels as Alternate Fuel from Biomass—The Indian Scenario

The co-authors of this chapter, Renu Singh, Sapna Tiwari and Monika Srivastava discuss the role of bio-mass as an alternative to fossil fuel. Biofuels are produced from living organisms or from metabolic byproducts (organic or food waste products). Fuel must contain over 80 % of renewable materials in order to be considered as biofuel. Biomass is carbon dioxide neutral and its sustainable use minimizes the seasonal variation and pollutants' emission into the air, rivers and oceans. This energy plays an important role in the replacement of renewable energy resources for fossil fuels over the next several decades. Enormous range of biomass is processed to produce bioenergy biologically, thermochemically and biochemically. In developing countries such as India, biomass is the primary source of bioenergy. Global climate change policies would overcome many barriers to secure the future of biomass and, indirectly, biofuels. Due to social and economic benefits, biomass is considered as a deserving alternative for sustainable development.

**Technology Development and Innovation for Production of Next-Generation Biofuel from Lignocellulosic Wastes**

The author of this chapter, Vinod Kumar Sharma, highlights the evolution of biofuels while giving priority attention to next generation biofuel from lignocellulosic waste. Both biochemical (chemicals, enzymes and fermentative microorganisms) and thermochemical (heat and chemical) processes are addressed. For biochemical processes, topics related to the pre-treatment, hydrolysis and fermentation steps as well as process integration, are also discussed. For thermochemical processes, research topics such as process development and process analysis are dealt with. Important R&D technical aspects, economic assessment of available technologies, limitations of certain technological approaches, etc., are also discussed.

**Advancement in Biogas Digester**

In this chapter, co-authors Anil Kumar, B. Mandal and Atul Sharma discuss the advancements in biogas digester for green energy production and consumption. Biogas is a renewable energy source with different production pathways and various excellent opportunities to use. Biogas usually refers to a gas produced by anaerobic digestion or fermentation of organic matter including manure, sewage sludge, municipal solid waste, biodegradable waste, energy crops or any other biodegradable feedstock. Biogas primarily comprises of methane and carbon dioxide. In this review, is discussed the worldwide status of biogas production, history of the biogas digester in the world, classification of biogas digester and its advantages and disadvantages. Government policies concerning the use of kitchen waste-based digesters and the social and environmental effects of the digesters have also been covered. More subsidies need to be given and more initiative needs to be taken by the government. The government has many policies for biogas digester plants, however, there is a lack of awareness among people inhibiting the adaptation of technology.

## Part VI: Other Green Energy

**Natural Gas to Drive Green and Sustainable Developments in India**

The author of this chapter, Sanjay K. Kar, offers detailed insights into natural gas market developments in India. The author points out that the per capita primary energy consumption in India has been increasing and there is great scope for growth to reach somewhere closer to leading economies like the United States, Russia and China. India's primary energy consumption is still dominated by coal with 54.5 % followed by oil (29.5 %), natural gas (7.8 %), hydro (5 %), renewables (2 %) and nuclear (1.2 %). India being one of the leading emerging economies requires plenty of energy to maintain the pace of its economic growth. India's economic development should be driven by green energy, with desirable levels of environment protection and ecological preservation. Along with the renewable sources of energy, natural gas is considered to be the fuel for green and sustainable developments in India. The author discusses the outcomes of green economy as green production, green marketing, green transport, green housing, green electricity and green consumption. The current scenario suggests that natural gas could be the one of the most preferred green fuels by 2030 in India. Some of the enabling factors likely to drive gas-based sustainable economy in India are: higher domestic production, import of equity gas, import of relatively cheaper shale gas (in the form of LNG) from the US, and import of dry gas through pipeline from central Asia, development of regasification infrastructure in India, and development of a fully functional national gas grid.

**Scope for Small Hydro Projects in India**

The author of this chapter, A.K. Chaturvedi has discussed the Scope for Small Hydro Projects in India. Energy is essential for the sustenance of life. Also energy and the economic growth of a nation are interlinked. Energy security of a country entails optimum utilization of indigenous and those sources of energy to which a nation can have access. Hydropower is an important and an economically competitive source of electricity. In India, hydro projects up to 25 MW capacities have been categorized as small hydro power projects (SHPs) and the Ministry of New and Renewable Energy (MNRE) is responsible for their construction. The technology for the SHP is fully indigenized. SHPs though economical and less environmentally degrading, suffer from cascading due to a number of plants in tandem, may result into poorer quality of water and may have hydrology impacted at the sub-basin level. India has a potential of about 20,000 MW through SHP, and as such, it has been declared as one of the thrust areas. The Ministry is encouraging the development of small hydro projects both in the public and in private sector. There are about 25 equipment manufacturers of SHP turbine in the country with an estimated capacity of about 400 MW per year.

**Hydrogen and Fuel Cells**

In this chapter, Bahman Shabani and John Andrews focus on the new generation future fuel, hydrogen. Considering social (e.g. energy security), economic and environmental issues associated with the reliance on finite fossil fuel resources for energy generation, hydrogen (based on renewable energy and energy efficiency) is seen by many scientists and economists as a sustainable solution that can help the end users of energy meet their future supply requirements as well as greenhouse gas and other emission reduction targets. While diversity of renewable energy resources is the key advantage of these alternatives, their intermittency and unpredictability have to be addressed by complementing them with proper energy storage options such that these resources can be reliably employed to power stationary and mobile applications uninterruptedly as required. Hydrogen energy systems as reviewed in this chapter can play a strong energy storage role in conjunction with renewable energy resources, particularly in applications with long-term (e.g. in standalone stationary applications with highly variable seasonal input of renewables, central grids, or microgrids) and/or long-range (i.e. in automotive applications) energy storage requirements. The main components of a hydrogen energy system include hydrogen generation arrangement; hydrogen storage; distribution and delivery systems (long or short distance); and the means of converting the chemical energy of hydrogen into a desirable form of energy (e.g. electricity) for end consumers. The latest research and development related to these elements are discussed in this chapter.

**Combined Cooling, Heating, and Power (CCHP) or Trigeneration Technology: An Approach Toward Higher Energy Efficiency, Emission Reduction Potential and Policy**

The author of this chapter, Anant Shukla, points out that the energy demand in India is growing at a very fast rate; the present energy generation cannot keep pace with this increasing demand with energy shortage of 6.2 % and peak shortage of 2.3 %. To address the increasing gap between demand and supply there is an urgent need to bridge the gap through energy efficiency and integration of renewable energy in the energy mix of the country. This chapter presents a new concept in the Indian building sector which addresses energy efficiency through the Trigeneration technology. A gas engine with natural gas is used to produce power and waste heat from the engine for cooling and heating through Vapour Absorption Machine (VAM) and hot water recovery from Low Temperature (LT) jacket water. This increases the efficiency upto 85 % or more compared to the conventional methods of power production. The author discusses one such case study on a pilot project implemented under the Indo-German Energy Programme. The Indo-German Trigen project is the first project successfully implemented under the International Climate Initiative in India. The pilot project is funded by the German Federal Ministry of Environment, Nature Conservation Building and Nuclear Safety (BMUB) and is the first project completed successfully under International Climate Initiative (IKI) of BMUB in India. This chapter presents information on the techno-economics of the pilot project at New Delhi.

**Energy Sustainability Through Nuclear Energy**

In this chapter, A. Shukla reiterates that energy sustainability is one of the most vital factors for the growth of any nation as well as for global mankind. With exponentially increasing energy demand and concerns for carbon emission/climate change, it is inevitable to pave a pathway for energy production, which takes care of the ever-increasing energy requirements as well as provides clean energy resources. Though there are concerns related to the safety of nuclear reactors and safe treatment of nuclear waste, nuclear energy is still one of the most clean energy sources in terms of carbon emissions with large availability of fuels to run nuclear power plants. Thus, nuclear energy has strong potential to fill the present gap between need and supply and to provide energy sustainability. This chapter explores the possibility of achieving energy sustainability through nuclear energy along with the possible challenges in this direction.

# Acknowledgments

Before the start of this project in late 2013, we were not fully aware of the investment in time and effort that would go into editing a book. We thought of bringing out an edited book to share knowledge, development and scientific advancement in the field of green energy for a large group of interested readers. So we felt we could simply get connected with researchers around the world and request them to share their work in the form of book chapters for an edited volume. To us this sounded quite simple at the beginning. But to our surprise, we were proven wrong on many occasions. Now we understand better...! Since the authors who have contributed to this book are from the scientific and academic community with prior commitments, our deadlines for submitting book chapter proposals, first drafts of the chapters, peer reviews of all manuscripts, and submission of final revisions of the contributions received frequent challenges. Throughout, however, we received remarkable encouragement and enthusiasm from our contributors and reviewers. We are really honoured to have contributions from all the contributors who have been very supportive, dedicated and responsive throughout our interaction. We are extremely thankful to all our passionate contributors and reviewers!

This book never would have taken off without the generous support of Dr. J.P. Gupta, Director RGIPT and our colleagues at RGIPT. It would never have been completed without the cooperation, administrative and editorial assistance of Ms. Swati Meherishi and Ms. Aparajita Singh of Springer. Our heartfelt thanks to all these dedicated and cooperative individuals!

Finally, this project consumed quite some of our leisure time that should have been dedicated to our families. There is no doubt that we are very excited, enthusiastic and proud about the final output of our work, we also feel sorry about unwittingly neglecting them on many occasions, especially weekends. For all their patience and moral support, we dedicate this book to Iti, Druv, Yash, Tapaswini and Kashyapi.

Atul Sharma
Sanjay Kumar Kar

# Contents

# About the Editors

**Dr. Atul Sharma** completed his M. Phil. Energy and Environment (August 1998) and Ph.D. on the topic *Effect on Thermophysical Properties of PCMs due to Thermal Cycles and Their Utilization for Solar Thermal Energy Storage Systems* (June 2003) from School of Energy and Environmental Studies, Devi Ahilya University, Indore (M.P.), India.

He has worked as a Scientific Officer at Regional Testing Centre Cum Technical Backup Unit for Solar Thermal Devices, at the School of Energy and Environmental Studies, Devi Ahilya University, Indore funded by the Ministry of Non-Conventional Energy Sources of the Government of India. He also worked as a Research Assistant at Solar Thermal Research Center, New and Renewable Energy Research Department at Korea Institute of Energy Research, Daejon, South Korea (1 April 2004–31 May 2005) and as a Visiting Professor at Department of Mechanical Engineering, Kun Shan University, Tainan, Taiwan, R.O.C (1 August 2005–30 June 2009).

Dr. Sharma is currently Assistant Professor at Rajiv Gandhi Institute of Petroleum Technology (RGIPT) which has been set up by the Ministry of Petroleum and Natural Gas, Government of India through an Act of Parliament (RGIPT Act 54/2007) along the lines of the IITs with an "Institute of National Importance" tag. The institute is co-promoted as an energy domain-specific institute by six leading PSUs—ONGC Ltd., IOCL, OIL, GAIL, BPCL and HPCL in association with OIDB. The mission of the institute is to work towards promoting energy self-sufficiency in the country through its teaching and R&D efforts.

Dr. Sharma has published several research papers in various international journals and conferences. He also published several patents related to the PCM technology in the Taiwan region. He is working on the development and applications of phase change materials, green building, solar water heating system, solar air heating system, solar drying systems, etc. Dr. Sharma is conducting research at the Non-Conventional Energy Laboratory (NCEL), RGIPT and is currently engaged with the Department of Science and Technology (DST), New Delhi sponsored projects at his lab. Further, he served as an editorial board member and was reviewer for many national and international journals, project reports and book chapters.

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Prior to joining RGIPT, Sanjay worked at Pandit Deendayal Petroleum University, Gandhinagar and Indian Institute of Management, Ahmedabad, India. As a visiting faculty he has been associated with the Chonnal National University, South Korea, National Institute of Fashion Technology, India and other national level management institutes.

He regularly contributes articles to refereed journals like Renewable and Sustainable Energy Reviews, Emerging Markets Case Studies, Oil, Gas and Energy Law Intelligence, Asian Case Research Journal, Vikalpa: The Journal of Decision Makers, Indian Retail Review, Business Perspective, and Pranjana. To his credit he has several case studies, research papers, book chapters, conference papers and presentations.

His current research focus areas include green energy, green economy, distribution and pricing of natural gas, branding, retail format mix, retailing of petroleum products, energy policy, energy security, marketing of renewables, etc.

Sanjay conducts training and development programmes for corporate executives, especially in the energy sector. He has been training executives from some of the fortune 500 companies. In his leisure time, he enjoys cricket, music and old Hindi movies.

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# Part I
# Solar Energy

# Solar Photovoltaic Technology and Its Sustainability

**Anil Kumar, Geetam Richhariya and Atul Sharma**

**Abstract** The renewable energy sources include the clean green technology, which motivates a healthy environment but also encourages using them in rural areas where grid supply is not available. The fundamentals of solar photovoltaic technologies and their sustainability on the earth are discussed in this chapter. The various internal phenomena that occur in the sun and the solar spectrum are discussed. The various applications of photovoltaics and modeling of the solar cell are also discussed.

**Keywords** Renewable energy · Solar energy · Photovoltaic

## 1 Introduction

Fossil fuels are the main sources worldwide for producing efficient electricity for users. However, the continuous use of these sources causes their depletion. Their use for production of electricity and in other applications pollutes the environment, increases emission of carbon dioxide in nature, causes global warming, and many more direct or indirect problems for nature and for living organisms (Shan et al. 2014). An alternative is the use of renewable energy sources, which result in very less emission of carbon dioxide. The main nonconventional sources of energy are solar, wind, and hydro. Solar energy is the best and most attractive energy source due to its less harmful impacts on the environment (Kumari and Babu 2012). Among the renewable energy sources, photovoltaic (PV) energy is widely used in low-power applications. Photovoltaic generators convert solar radiation directly into electricity.

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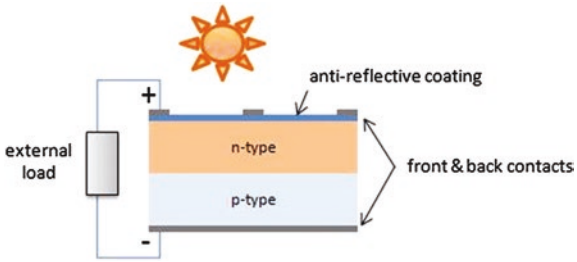


**Fig. 1** Photovoltaic cell

Being inexhaustible, pollution-free, silent, and having no rotating parts makes it the best attractive alternative. The photovoltaic effect was first observed in 1839, by a French physicist. This effect was studied in solids such as selenium. The efficiency using selenium was very less, i.e., only 1–2 % (AIA Research Corporation 1976). The French physicist observed that under illumination, a voltage appeared across the two identical electrodes in a weak conducting solution.

In the 1950s, a new development in photovoltaics that occurred was silicon-based photovoltaic cells (AIA Research Corporation 1976). Silicon has been the main choice of material for photovoltaics and will continue to be so in the near future. A P–N junction-based photovoltaic cell circuit is shown in Fig. 1. The share of silicon solar cells and modules is about 90 % of the total PV market.

## *1.1 The Sun*

The survival of animals and plants depends on the energy coming from the sun; the survival of microbes also depends on sunlight. In photovoltaics, sunlight is used for the production of electricity, which has become a basic human need.

The diameter of the sun is around 1,400,000 km. At the core of the sun, millions of tons of hydrogen is converted into helium through nuclear fusion to create the sun's energy; thus, its surface temperature is about 6,000 °C. The mean distance between the earth and the sun is 149,597,890 km. The solar mass is about 332,946 times the mass of the earth (Pavlovic et al. 2006), while the luminosity of the sun is about 3.86 × 1026 W.[1]

## *1.2 Solar Radiation*

The electromagnetic radiation from the sun (i.e., visible light, infrared light, and ultraviolet radiation) spreads out in space in all directions. On earth, only a small fraction of the total radiation is reached. Solar radiation is composed of direct and diffuse radiations. Direct solar radiation, also called beam radiation, directly

[1] http://www.ips.gov.au/Educational/2/1/12.

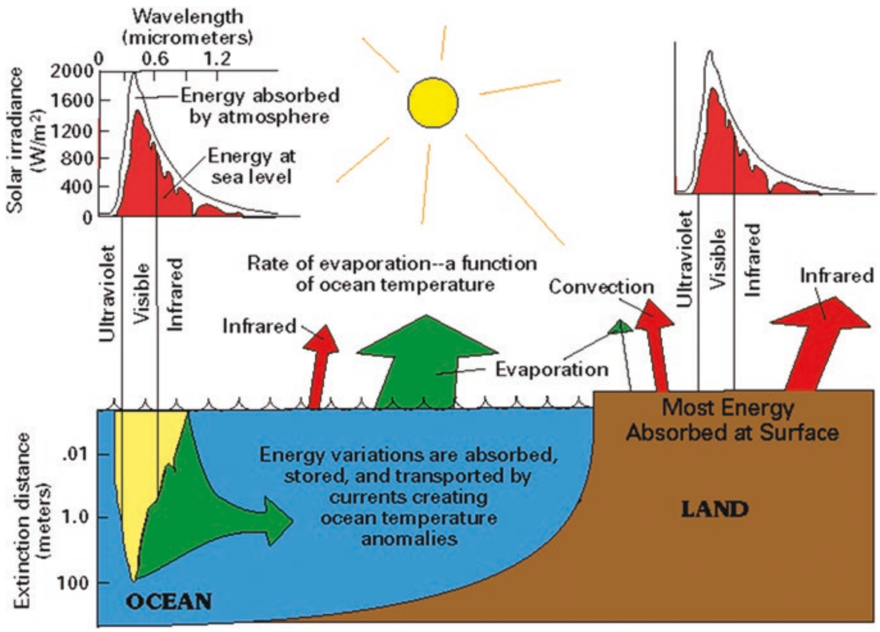


**Fig. 2** Penetration of the solar radiation spectrum in water

reaches the surface of the earth. It has a definite direction. By contrast, diffuse solar radiation is scattered by molecules and particles available in the atmosphere before reaching the surface of the earth.

Solar radiations reach the surface of the earth at different proportions due to the varying atmospheric conditions. Some solar radiations coming from the sun are absorbed and reflected back to the environment, while some are scattered by the components of the atmosphere (Fig. 2).

The wavelength of ultraviolet, visible, and infrared solar radiation is 0.20–0.39, 0.39–0.76, and 0.76–100.00 μm, respectively (see Footnote 1). The ultraviolet radiations are absorbed by oxygen and nitrogen available in the atmosphere and converted into heat energy.

The visible light consists of orange, blue, red, yellow, and green as shown in Fig. 3. Visible and infrared solar radiations are emitted in 44 and 49 %, respectively, by the sun. Infrared solar radiation is absorbed by carbon dioxide, water present, and ozone in the atmosphere.

## *1.3 Advantages of Solar Energy*

**No Pollution/Clean System:** A solar power system is a clean and nonpolluting power plant. During the operation of a solar power plant, no fuel such as carbon is

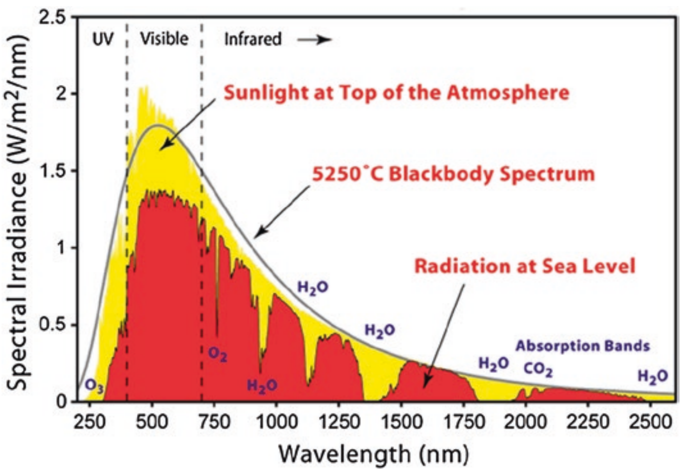


**Fig. 3** Spectrum of solar radiation

required, thus there are no emissions of carbon dioxide, sulfur oxide, and nitrogen oxide, which pollute the environment.[2]

**Less Maintenance/Noiseless Operation:** The solar power system does not have any rotating part; it is a solid-state device, and thus, less maintenance is required.

**Renewable Source of Energy:** As long as the sun exists, solar energy will also exist. The input of the solar power system comes through the sun, which is a constant source of power and thus cannot be exploited in the future.

**Stand-alone System:** Solar power systems can be installed on the roofs of buildings or homes for electric supply. It does not require a large land area compared to conventional power plants.

## *1.4 Disadvantages of Solar Energy*

Discontinuous source of energy: The solar energy coming from the sun is not constant, therefore, it cannot be utilized during nighttime. Solar energy also depends on the weather condition; it can be fully utilized in sunny weather, but less on cloudy days.

Costly: The solar energy is harnessed from solar panels, which is very costly.

Large land area: A solar power plant requires a large land area to meet the requirements.

[2] http://www.conserveenergyfuture.com/advantages_SolarEnergyphp#sthash.56FdYsIm.dpuf.

Replacement of batteries: The electricity produced from the solar cell/panel is direct current, which is used to charge the batteries; thus it requires replacement of batteries from time to time.

## 2 Classification of Solar Energy

Solar energy can be classified depending on its application: first, as a thermal system where thermal energy is utilized to heat the system and second, as a photovoltaic system where solar energy is utilized in the form of electrical energy.

1. **Solar thermal**—conversion of sunlight into heat
2. **Photovoltaic**—sunlight converted into electricity

In this chapter, our focus is on basic photovoltaic technologies and their applications. In a photovoltaic system, solar energy from the sun is utilized to produce electrical energy through solar panels. The solar cells are connected together to form a solar module, and solar modules are joined together to build a solar panel. The solar panels produce direct current. To connect the solar system to grid, DC power is required to be converted into AC power. The inverter is used to convert direct current into alternating current and batteries are required to store DC power for supplying power at night.

## 3 Semiconductors: Building Blocks of Photovoltaic

Solar photovoltaics is made of a semiconductor material. A semiconductor is not a good conductor of electricity and is a material whose resistivity lies between the conductor and the insulator (i.e., $10^{-4}$–0.5 ohmmeter), for e.g., silicon, germanium, selenium. However, the resistance of the semiconductor decreases with increase in temperature, which shows that a semiconductor has a negative temperature coefficient. The valence band of the semiconductor is almost filled by electrons; whereas the conduction band is nearly empty. The forbidden energy gap is very less, about 1 eV, therefore, a small amount of energy is required for valence electrons to move toward conduction band.

### *3.1 Classification of Semiconductors*

Semiconductors can be classified as: (1) intrinsic (pure semiconductor) and (2) extrinsic (impure semiconductor)

(a) **Intrinsic semiconductor**:

Intrinsic semiconductor can also be known as a pure semiconductor. At room temperature, electron–hole pairs are created. When a potential is applied across it,

**Table 1** Difference between intrinsic and extrinsic semiconductor

| Factors | Intrinsic semiconductor | Extrinsic semiconductor |
|---|---|---|
| Purity of semiconductor | Pure semiconductor | Impure semiconductor |
| Density of electrons | Density of electrons is equal to the density of holes | Density of electrons is not equal to the density of holes |
| Electrical conductivity | Electrical conductivity is low | Electrical conductivity is high |
| Temperature effect | Dependence on temperature only | Dependence on temperature as well as on the amount of impurity only |
| Impurities | No impurities | Trivalent impurity, pentavalent impurity |

conduction commences through free electrons and holes caused due to the breaking of covalent bonds through thermal energy. Therefore, the current flow in the intrinsic semiconductor is a combination of electron and hole.

(b) **Extrinsic semiconductor**:

At room temperature, the intrinsic semiconductor has very less conduction. Therefore, for improving the conductivity of the intrinsic semiconductor, a small amount of impurity is added. This semiconductor is now called an extrinsic semiconductor. The process of the addition of impurities to the intrinsic semiconductor is called doping. In this process, either the number of electrons increases or the number of holes increases depending on the type of impurity added. Two types of impurities are added: (1) pentavalent and (2) trivalent. Addition of pentavalent impurity produces free electrons, while in case of trivalent impurity, additional holes are generated. Further differences between intrinsic and extrinsic semiconductor are given in Table 1.

## *3.2 Types of Extrinsic Semiconductors*

- **P-type semiconductor**:

P-type semiconductor is formed by the addition of a small quantity of trivalent-type impurity to an intrinsic semiconductor. The trivalent impurities result in additional holes, which accept the electrons in the semiconductor; therefore, these impurities are also called acceptor impurities (Fig. 4).

- **N-type semiconductor**:

N-type semiconductor is formed by the addition of a small quantity of pentavalent type impurity to an intrinsic semiconductor. The addition of pentavalent impurities in pure semiconductor causes additional electrons in the semiconductor. The pentavalent impurities are also known as donor impurities as they donate free electrons to the semiconductor (Fig. 5).

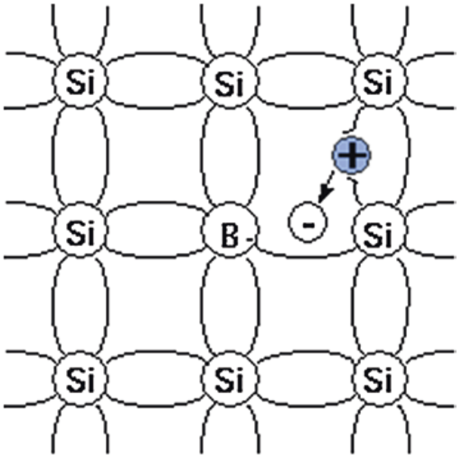


**Fig. 4** Structure of p-type semiconductor

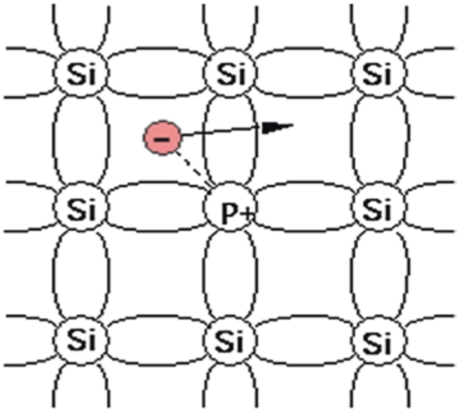


**Fig. 5** Structure of n-type semiconductor

## *3.3 Formation of Photovoltaics*

To develop a photovoltaic cell, two kinds of semiconductors are sandwiched together. When p-type and n-type semiconductors are joined together, they form a p–n junction or a solar cell. The p–n junction is the control element for a solar cell; thus, electrons will only flow in one direction but not in the other. In forward biased direction, current flows from p to n semiconductor or behaves like a short circuit, while in reverse direction, current does not flow and thus behaves like an open circuit. Structure of p–n photovoltaic cell is shown in Fig. 6. When the photovoltaic cell is exposed to sunlight, it reduces the width of the deletion layer and the current flows into the connected electrical load.

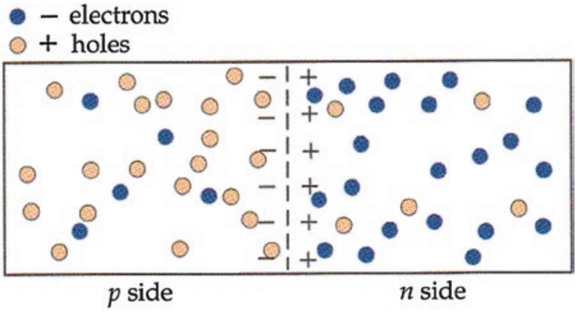


**Fig. 6** Structure of photovoltaic

## *3.4 Working Principle of Photovoltaic Cell*

When sunlight strikes on the solar panels, it absorbs photons that produce electrons and holes in the semiconductor material, and thus, electric current flows (Messenger and Ventre 2000). The constructional view of a photovoltaic system is shown in Fig. 7. The efficiency of the panel depends on the amount of solar energy absorbed by the semiconductor material. When light falls on the cell, photons are absorbed by the panel and the semiconductor generates electron–hole pairs. Then the electron–hole pairs are separated in the semiconductor. The electrons move toward negative terminal, while the holes move toward positive terminals. Thus, electrical energy is generated.

A photovoltaic cell behaves like an ordinary p–n junction under no illumination. When it is forward biased the excess electrons are moved from p to n semiconductor.

## *3.5 Modeling of Photovoltaic Cell*

A single diode model of solar cell consists of a current source which represents a light-generated current in parallel with a diode. The photon current is directly

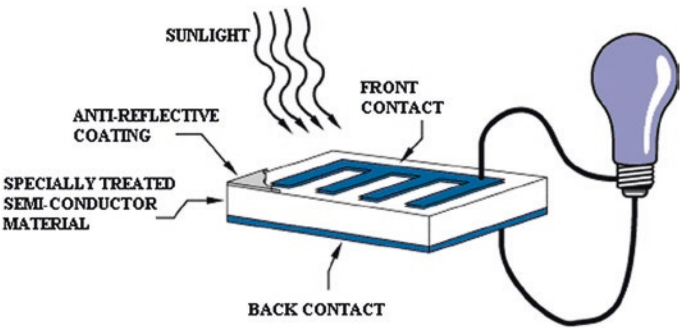


**Fig. 7** Constructional view of photovoltaic system

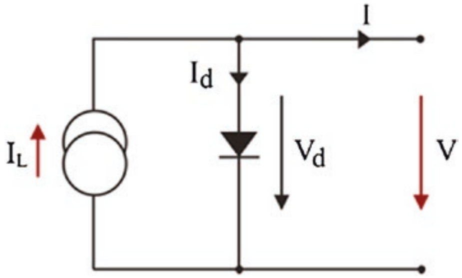


**Fig. 8** Single diode model of photovoltaic

proportional to the solar radiations. When the light is not illuminated, a dark current is flown into the circuit similar to the diode (Fig. 8).

The typical equation for single diode model of solar photovoltaic is as follows (Bonkoungou et al. 2013):

$$I = I_L - I_R \left[ e^{\{qV/mkT\}} - 1 \right] \quad (1)$$

where

$I$ is the cell output current,
$I_L$ is the light-generated current or photocurrent,
$I_R$ is the reverse bias saturation current of diode,
$Q$ is the electron charge,
$V$ is the terminal voltage,
$M$ is the diode ideality factor, and
$T$ is the cell temperature.

A photovoltaic cell can also be characterized in terms of the short-circuit current, $I_{SC}$, and the open-circuit voltage, $V_{OC}$. At the constant junction temperature, when the terminal of solar cell is short-circuited, the short-circuit current $I$sc is given as follows:

For $V = 0$,

$$I_{SC} = I = I_L \quad (2)$$

At the constant junction temperature, when the terminal of solar cell is open-circuited, the open-circuit voltage $V$oc is given as follows:

For $I = 0$,

$$V = V_{oc} \quad (3)$$

Thus, the cell output voltage is given as

$$P = V\,[I_{sc} - I_R e^{\{qV/mkT\}} - 1] \quad (4)$$

Following are the basic terms related to modeling of the solar cell.

(a) **Short-circuit current ($I_{SC}$):**

Short-circuit current is calculated at short-circuiting terminals of the solar cell. It increases slightly with increasing temperature and is directly proportional to the incident optical power. Under the short-circuit condition of the solar cell, the voltage across the terminal is zero and the impedance offered is very low. The short-circuit current can be expressed by the following equation (Zhou et al. 2007):

$$I_{SC} = I + I_O\{\exp(V/V_T) - 1 \tag{5}$$

(b) **Open-circuit voltage ($V_{OC}$)**:

The open-circuit voltage is expressed at the open terminals of the solar cell. It decreases with increases in temperature. The open-circuit voltage is logarithmically dependent on the solar irradiance. The open-circuit voltage can be expressed by the following equation (Zhou et al. 2007):

$$V_{OC} = V_T In\,\{(I_{sc}/I_O)\; + 1\} \tag{6}$$

(c) **Fill factor (FF)**:

The fill factor is defined as the ratio of the product of maximum value of voltage and current (i.e., actual power) to the product of open-circuit voltage and the short-circuit current (i.e., dummy power). It is a figure of merit for the solar cell performance (Zhou et al. 2007; Bowden and Rohatgi 2001).

$$\mathrm{FF} = V_m I_m / V_{oc} I_{sc} \tag{7}$$

(d) **Maximum output power ($P_{max}$)**:

The maximum power may be defined as the power that can be delivered by the modules/array to the load. It can be utilized to evaluate the performance of a PV system. It is a function of the fill factor, open-circuit voltage, and short-circuit current.

(e) **Efficiency ($\eta$)**:

It is the ratio of electrical power that the solar cell delivers to the load to the optical power incident on it. Incident optical power is normally specified as the solar power on the surface of the earth, which is 1 mW/mm$^2$. The efficiency can be expressed by the following equation (Zhou et al. 2007; Bowden and Rohatgi 2001):

$$\eta = \mathrm{FF} V_{oc} I_{sc} / \text{solar power} \tag{8}$$

where

$I_{sc}$ is the short-circuit current,
$V_{oc}$ is the open-circuit voltage,
$V_m$ is the maximum value of voltage,
$I_m$ is the maximum value of current, and
$V_T$ is the terminal voltage

# 4 Generations of Photovoltaic

## *4.1 First Generation*

First generation solar cells refer to single-junction devices with large surface area, good quality, highly efficient, and high cost. These cells are usually fabricated using a silicon wafer. Structural view of crystalline solar cell is shown in Fig. 9. This generation of solar cell consists of monocrystalline and polycrystalline silicon solar cells. The monocrystalline silicon solar cell is the oldest solar cell technology. It is drawn from the Czochralski (CZ) method. A silicon ingot is made from a molten vat. Then, it is sliced into a number of ingots forming the substrate of the solar cell. The monocrystalline panels have shown the highest laboratory efficiency at about 24 % (Pavlovic et al. 2011). The main drawback of the monocrystalline solar cell is its high cost due to the expensive fabrication process. Another drawback is its decrease in efficiency as temperature decreases to about 25 °C. Proper maintenance is required for installing the panel such that air circulation is provided over the panel. Polycrystalline silicon solar cells are cheaper than monocrystalline solar cells, but suffer from less efficiency due to nonuniform lattices. Instead of a single large ingot, it has a number of ingots drawn from molten vat. The polycrystalline silicon solar cell has shown efficiency of only 12–14 %

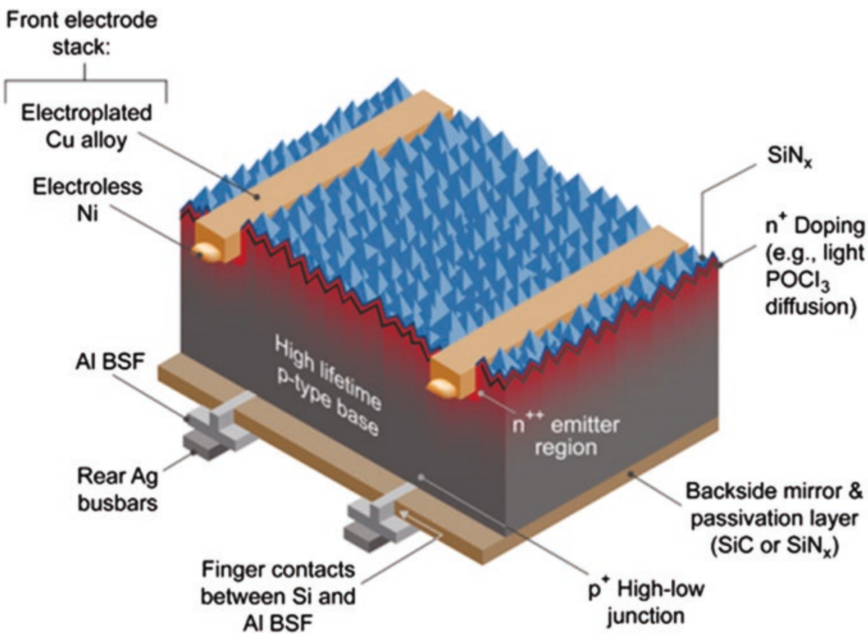


**Fig. 9** Structural view of crystalline solar cell

(Pavlovic et al. 2011). The first generation solar cell is more attractive due to its high efficiency. However, they are very uneconomical.

## 4.2 Second Generation

The second generation includes thin-film solar cell. A structural view of thin-film solar cell is shown in Fig. 10. They are more economical than silicon crystalline solar cell, but lack efficiency. The development of dye-sensitized solar cells (DSSCs) belongs to the third generation in the era of solar cells, reflecting low-cost and high-efficiency features. However, the efficiency of DSSC is not greater than crystalline solar cell, but much greater than thin-film solar cell. These have more attractive features due to their environmental friendliness.

In a thin-film PV cell, a thin layer of semiconductor PV materials is deposited on glass, metal, or plastic foil. Due to their non-single-crystal structure, thin films suffer from poor efficiency and also require larger array areas, and thus, area-related costs such as mountings also increase. Cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and amorphous silicon (a-Si) are examples of thin-film technologies used as outdoor applications for photovoltaic solar power production.

A CdTe solar cell is fabricated by using a thin film of CdTe. This semiconductor layer absorbs photons and converts it into electricity. The main advantages of CdTe thin-film solar cells include low fabrication cost and increasing efficiency (Pavlovic et al. 2011). The CdTe material has a high optical absorption coefficient for visible portion of the thin film of CuInSe2 (CIS)-based photovoltaic (PV) modules and comprises low-cost substrates. CIS solar cell technology has high absorption coefficient of the solar cell absorber layer. Gallium arsenide-based thin-film solar cells have been manufactured and investigated to determine their suitability for future solar power systems. The vapor of gallium arsenide is deposited onto substrates of aluminum foil. Gallium arsenide (GaAs) is a compound of the

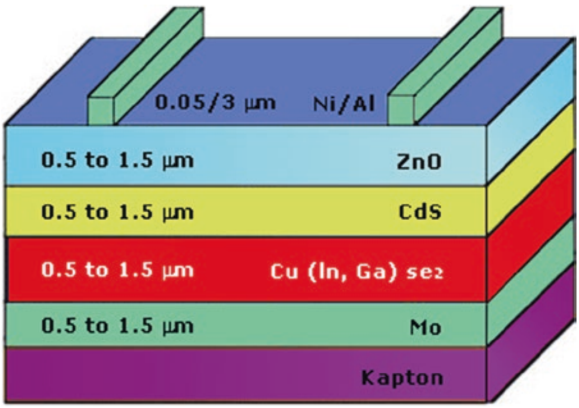


**Fig. 10** Structural view of thin-film solar cell

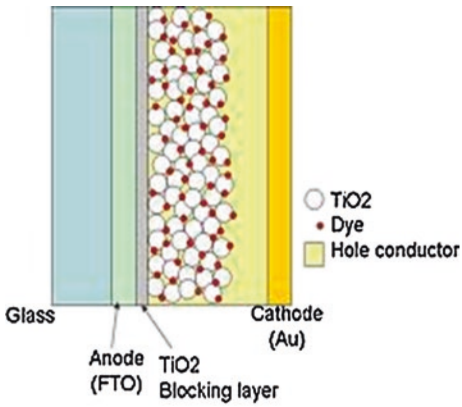


**Fig. 11** Structural view of dye solar cell

elements gallium and arsenic. It can be used for manufacturing infrared light-emitting diodes, solar cells, etc. Recently, the efficiency of GaAs has been registered as 28.8 % (Pavlovic et al. 2011). A demerit of CdTe is that cadmium is a deadly poison, and hence not very eco-friendly.

### *4.3 Third Generation*

The third generation refers to organic/dye-sensitized solar cell; structural view of a dye solar cell can be seen in Fig. 11. A DSSC consists of a titanium dioxide photo-anode electrode, a counter electrode as a cathode, an absorbed dye, and an electrolyte. Dye-sensitized solar cell (DSSC) is a semiconductor photovoltaic device that converts solar radiation from the sun into electric current. The natural dye sensitizer is excited when the DSSC is exposed to sunlight, and thus causes the formation of electrons from the titanium dioxide photoanode. Then, the electrons move to the counter cathode through the electrolyte and complete the circuit. Conducting glass is used as a substrate for improving the electrical conductivity of the DSSC. Mainly, indium-doped tin oxide and fluorine-doped tin oxide are used as substrates. The most attractive features of DSSC include low cost, simple fabrication, and low density. These can be employed for rooftop solar applications being lightweight.

## 5 Types of PV Cell Materials

PV cells are made of semiconductor materials. The major types of materials are crystalline and thin film, which vary from each other in terms of light absorption efficiency, energy conversion efficiency, manufacturing technology, and cost of production.

### 5.1 Single-Crystal Silicon Solar Cell

Single-crystal silicon cells are the oldest in the field of solar cells. The crystalline solar cell is fabricated from the CZ method (Li et al. 1992). In this method, high-purity silicon is melted in a crucible. Some doping is added to improve the conductivity of the semiconductor. Generally, boron or phosphorous is used as a dopant. A seed crystal is dipped into the molten silicon and pulled upward and rotates continuously. After some time, single silicon ingot is formed from the melting silicon. Single-crystal silicon has a uniform molecular structure.

The silicon crystal panels are more suitable for outdoor applications. The higher penetration of sunlight into the solar cell results in high efficiency. The conversion efficiency of single-crystalline solar module is about 15–20 % (Li et al. 1992). However, the fabrication of single solar cell is a time-consuming process, complex, and expensive. The performance of monocrystalline solar cells is most affected as the temperature increases. However, the life span of these solar cells is large compared to other solar cells.

### 5.2 Gallium Arsenide Solar Cell

GaAs is formed by a mixture of gallium and arsenic that possess characteristics similar to silicon (Fig. 12). The conversion efficiency of GaAs is greater than that of crystalline silicon solar cells; also, GaAs solar cells are thinner but more expensive than crystalline solar cell. The GaAs solar cell accounts about 30 % efficiency (Aleksic et al. 2002; Yablonovitch et al. 2012). An advantage of GaAs is that it has high light absorption of sunlight. GaAs solar cells are more suitable for solar collector systems because they offer high resistance to temperature (AbuShama et al. 2004; Kim et al. 2007).

However, they are uneconomical because GaAs is grown onto a single-crystal substrate and thus is more applicable for concentrator-type systems. As the efficiency of these solar cells is high, they can be beneficial for space applications.

### 5.3 Thin-Film Solar Cell

Multiple thin-film layers of semiconductor materials are deposited on a substrate, i.e., glass, plastic foil, or metal to form thin-film solar cells. The thickness of the film is very less or less than a micrometer compared to traditional solar cells. This results in more lightweight and flexible solar cells. However, the efficiency of thin-film solar cells is very less compared to crystalline solar cell.

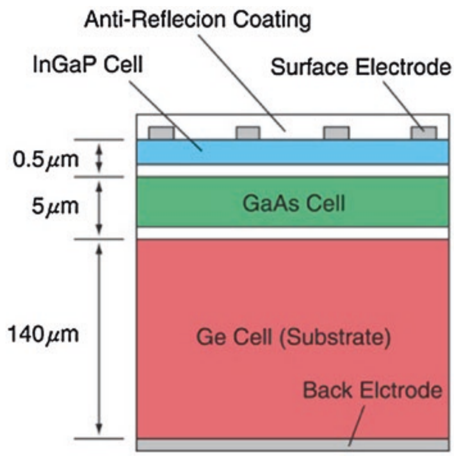


**Fig. 12** Gallium arsenide solar cell

**Advantages**:

- High radiation tolerance;
- Flexible appearance makes it attractive for applications;
- Mass production of solar cells makes them cheaper than other solar cells.

**Disadvantages**:

- Poor efficiency;
- Large space area is required, which increases additional cost of mountings;
- Degrade faster than crystalline solar cells;
- Special handling is required.

**Applications**:

- Electronic powering circuits;
- Domestic lighting applications;
- In solar fields.

## *5.4 Amorphous Silicon Solar Cell*

An a-Si solar cell is fabricated by using a noncrystalline form of silicon, i.e., a-Si solar cell. These can be used in small-scale applications as the thickness is about 1 μm, which is very less as compared to monocrystalline solar cell. A noncrystalline form of silicon has higher light absorptive capacity than single silicon crystalline structure, since the thin-film structure makes it more flexible and of less weight.

**Disadvantages**:

- Less efficiency, i.e., 5–9 % only
- Degrades fast

### 5.5 Cadmium Telluride Solar Cell (CdTe)

A CdTe solar cell is a compound made of cadmium and tellurium. CdTe solar cells are grown in substrate. Polyimide, metal foils, and glass are commonly used as the substrates. Their high efficiency, low cost, stability, and potential for low-cost production make them suitable for large-area applications. The CdTe solar cell has high absorption coefficience and has shown laboratory efficiency as high as 16.5 % (Lynn 2010; Fthenakis 2004). The commercial module efficiency is the same as an a-Si solar cell, i.e., 7–9 % (Tiwari and Agrawal 2011).

**Advantages**:

- High absorptive capacity.
- Economical manufacturing process.

**Disadvantages**:

- Toxicity: Cadmium is a toxic heavy element. It is the waste product of zinc refining.
- Less efficiency: Currently achieved efficiency of CdTe solar panels is 10.6 %, which is lower than the typical efficiencies of crystalline silicon solar cells.
- Abundance: The telluride has its limited natural reserves.

### 5.6 Organic Solar Cells

The main obstacles in front of inorganic solar cells are high material and manufacturing cost. Organic solar cells are light-weight, low-cost, and can be employed for energy generators for large areas. The organic materials have high optical absorption coefficients. The organic solar cells are made in thin film structure which offers a light weighted and flexible solar cell. These are made from organic semiconductors i.e polyphenylene vinylene, copper phthalocyanine and carbon fullerenes. However, the conversion efficiency of organic solar cells is less as compared to crystalline solar. The highest reported efficiency is about 11% (Su et al. 2012).

## 6 Photovoltaic Applications

### 6.1 Hybrid Solar Power System

Solar energy cannot be harnessed during night hours due to unavailability of sun radiations. Therefore, there is a need for a hybrid solar system, which consists of two or more power generation systems. A solar power system can be connected to a turbine to fulfill the electricity requirement during night hours. More than

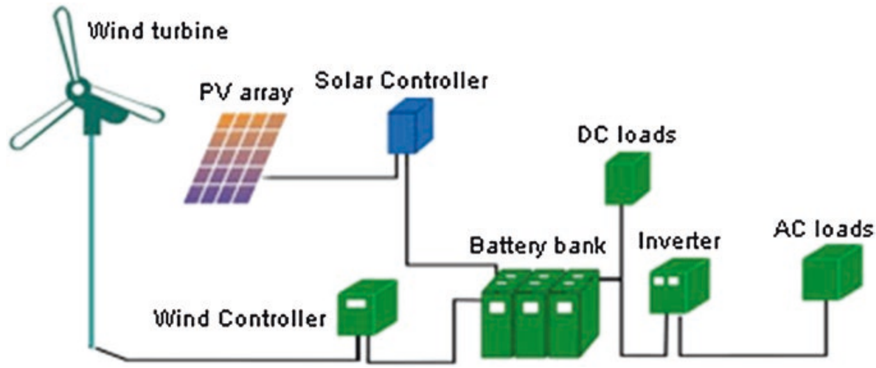


**Fig. 13** Hybrid solar power system

one renewable energy source can be used, such as a wind power plant, which can be connected to the solar power plant and a turbine with a battery for backup. A hybrid solar power system is shown in Fig. 13. Direct current generated through a solar power plant is converted into alternating current using an inverter. The inverter feeds electrical energy to the house. Wind generators generate alternating current and so do not require any conversion terminal. A battery is used to meet secondary requirements.

## *6.2 Solar Lighting System*

Suresh et al. developed a solar lighting system. They found variations in the theoretical and practical values used in the construction of the circuit in the laboratory. due to tolerances of the components and the intensity of sunlight (Suresh et al. 2011). Electrical circuit of solar lighting system is given in Fig. 14.

The conventional applications of lighting, heating, and pumping cause global warming and deplete these sources from the earth. On the other hand, the implementation of solar lighting systems reduces air pollution and as they are renewable sources, they cannot deplete.

## *6.3 Solar Lantern*

In remote and rural areas, people use oil lamps which are expensive, unhealthy, not sufficient source, and dangerous, cause environmental problems, and produce greenhouse gases. Another alternative for oil lamps is the solar lantern. A solar lantern consists of a solar panel situated on the rooftop and a battery and a lamp as

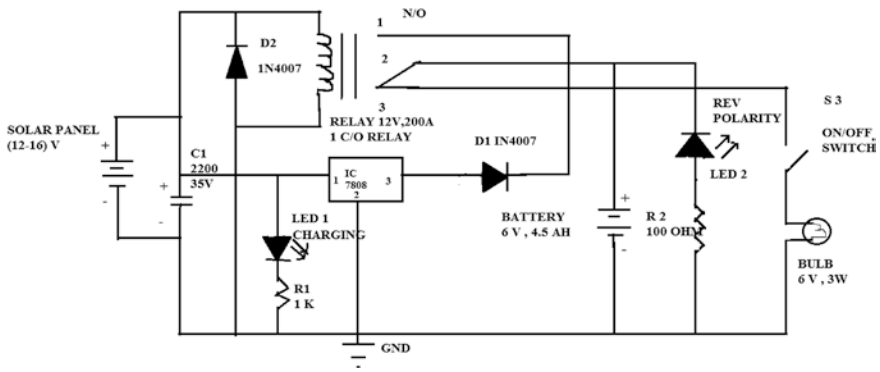


**Fig. 14** Solar lighting system

load (Fig. 15). The solar lantern is the most beneficial device for the poor . During the day, it can be charged and thus provide light at night. It is a portable device and hence is easy to carry anywhere.

### *6.4 Organic Light-emitting Diode (OLED)*

Zmija et al. performed various experiments to observe the performance of organic light devices. They also observed the basic difference between organic and inorganic devices. An organic LED is a monolithic, thin-film solid-state device that emits light after energizing (Fig. 16). Low power consumption, lightweight, high brightness, and high emission efficiency are the merits of organic LEDs. Being lightweight makes it a portable device (Mija and Maachowski 2009).

**Fig. 15** Solar lantern

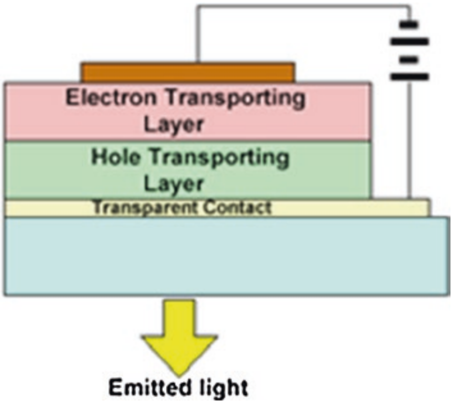


**Fig. 16** Organic light-emitting diode

The cell structure of the OLED consists of a thin film of organic material sandwiched between two anode and cathode electrodes. One of the electrodes is required to be transparent to allow light into the thin layer of organic material and application in displays (Mija and Maachowski 2009).

**Applications of OLED**:

a. Digital versatile disk players;
b. Cellular phones;
c. Televisions;
d. Notebooks, etc.

**Obstacles**:

a. Limited lifetime: The lifetime of OLED is limited due to degradation of organic materials. Some displays are sensitive to moisture, resulting in limited life span.
b. Degradation of blue light: Organic materials degrade more rapidly than inorganic materials, resulting in poor performance of OLED, especially, the blue light output decreases more than the others.
c. Water impacts on OLED: Organic materials used for making OLED may be damaged in the presence of the water, especially in the rainy season.

## 7 Solar Power Projects

The burning of fossil fuel through conventional power plants pollutes the environment, causing global warming. Electricity produced by nonconventional sources such as solar, wind, and biomass causes no carbon emission and thus no global warming, resulting in less environmental problems. In India, nonconventional power plants accounted for about 31.15 GW of capacity as on January 31, 2014

(Power Generation from Various Renewable Energy Sources 2014; Ministry of New and Renewable Energy 2014).

The major contribution in the enhancement of solar energy is from Gujarat and Rajasthan. Gujarat accounts 858 MW capacity of solar energy, while Rajasthan contributes about 553 MW. Maharashtra and Madhya Pradesh account for 100 and 37 MW, respectively, of the total installed capacity of solar energy. A small contribution of 23 MW is by Andhra Pradesh. The capacity of solar power projects in various states of India is given in Fig. 17.

## 8 Comparison of Power Plants in India

The comparison of thermal, hydro, nuclear, and nonconventional power plants with regard to carbon emission, total installed capacity, and requirement of fuel is shown below. Carbon emission while using nonconventional sources is zero, while there is heavy carbon emission through thermal power plants. The primary source for nonconventional power plants is sun, water, wind, and biomass which cannot degrade in the future. Thus, renewable power plants are more beneficial for the safe environment and human healths. A comparison of the power plants in India is given in Table 2.

## 9 Sustainability of Photovoltaics

Vokas et al. designed a hybrid photovoltaic–thermal collector that can be used for heating and cooling applications for domestic purposes. It has thermal efficiency of about 9 %. However, the efficiency of photovoltaic–thermal collector is lower than the conventional solar collector.

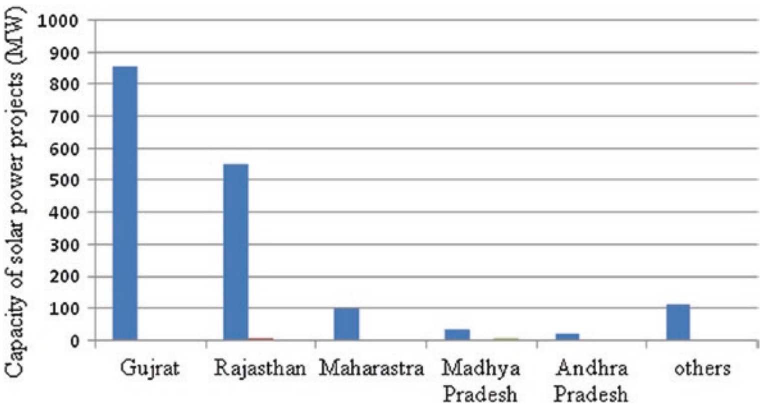


**Fig. 17** Solar power projects in India

**Table 2** Comparison of power plants in India (Ministry of New and Renewable Energy 2014)

| Sources | $CO_2$ emission | Required fuel/primary source | Total installed capacity in India (in MW) |
|---|---|---|---|
| Thermal | 164.39 kt $CO_2$ | Coal/lignite | 148,478 |
| Hydro | 0.0 | Water | 40,730 |
| Nuclear | 0.0 | Uranium, thorium | 4780 |
| Non-conventional sources | 0.0 | Sun radiations, wind, biomass | 31,692 |

The authors compared solar thermal energy produced through the photovoltaic–thermal system and conventional solar system for domestic heating and cooling loads and concluded that there is a difference 6.65 % between the two systems, and thus, the photovoltaic thermal system is more efficient and is a convenient choice (Vokas et al. 2006). Results of a survey of photovoltaic–thermal system in domestic heating and cooling loads in the region of Athens is given in Table 3.

Assoa and Menezo developed a solar photovoltaic/thermal (PV/T) hybrid air collector designed for natural ventilation. Electrical efficiency can be improved by heat extraction for cooling of PV modules. They designed a dynamic two-dimensional mathematical model of solar PV/T hybrid air collector to determine the impact of air gap ventilation on the preheated air thermal production and electrical production. They concluded that for cooling of integrated PV modules, natural ventilation is adequate (Assoa and Menezo 2014).

An-Seop Choi et al. proposed an integrated PV blind system with a daylight responsive dimming system. This integrated system produces and stores electrical lighting energy simultaneously. In buildings' photovoltaic system, very little research has been done in the field of integration with other energy saving systems. Electrical lighting through LED also increases the dimming efficiency. In the reference room, the power generation was about 68 % compared to those in the test room, while in the test room, the electrical lighting energy savings was about 65 % compared to those in the reference room. LED lighting resulted in greater dimming efficiency compared to conventional fluorescent lighting (Kim et al. 2014).

Mahapatra et al. compared $CO_2$ emissions via kerosene-based lamps with modern bioenergy systems and solar photovoltaics (Table 4). To determine $CO_2$ emissions, fuel consumption rates are required. In rural areas, compared to kerosene-based

**Table 3** The average study of photovoltaic–thermal system in domestic heating and cooling loads in the region of Athens (Vokas et al. 2006)

| Domestic load | Photovoltaic–thermal system (%) | Conventional solar system (%) |
|---|---|---|
| Domestic heating (for surface area, 30 $m^2$) | 47.79 | 54.26 |
| Domestic cooling (for surface area, 30 $m^2$) | 25.03 | 31.87 |

**Table 4** $CO_2$ emissions from different lighting systems (Mahapatra et al. 2009)

| Type of system | Fuel consumption | Luminous flux (lumen) | Gross $CO_2$ emission | Net $CO_2$ emission |
|---|---|---|---|---|
| Kerosene wick lamp | 21.6 (ml/h) | 76 | 0.055a (kg/h) | 0.055 (kg/h) |
| Noorie | 50 (ml/h) | 1250 | 0.128 (kg/h) | 0.128 (kg/h) |
| Petromax | 80 (ml/h) | 1300 | 0.205 (kg/h) | 0.205 (kg/h) |
| Biogas mantle lighting systems | 0.125 $m^3$/h | 600 | 0.246 (kg/h) | Nil |
| Biogas-based electricity | 1 $m^3$ biogas and 80 ml diesel/kWh | 81,900 | 2.185 (kg/kWh) | 0.00537 (kg/kWh) |
| Biomass gasifier | 1.4 kg wood/kWh | 81,900 | 2.684 (kg/kWh) | 0.00537 (kg/kWh) |

lighting, solar photovoltaic and modern bioenergy systems are of great significance, providing reliable lighting with reduced $CO_2$ emissions. (Mahapatra et al. 2009).

Kumar and Rosen studied integrated photovoltaic–thermal solar collectors. The efficiency of an integrated system is greater compared to individual solar systems. Moreover, it encourages the utilization of solar energy and increases the useful energy per unit collector area. The overall efficiency of a solar photovoltaic thermal collector is higher than the addition of the efficiencies of individual solar photovoltaic and solar thermal systems. This combined system is more applicable for space heating and drying applications (Kumar and Rosen 2011).

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# Solar Drying—A Sustainable Way of Food Processing

**M.A. Aravindh and A. Sreekumar**

**Abstract** In a developing country like India, having the second largest population and agriculture as the source of income to nearly 60 % of the total population, post-harvest and storage loss is a major quandary, which needs to be addressed in due diligence. Many food preservation techniques like cold storage, drying, etc., have been evolved out over the years to tackle the above losses. The major constraint is that almost all the technologies are utilizing fossil fuel resources, which are depleting very fast and wise use of these precious resources are preferred for long-term energy sustainability. Therefore, sustainable methods for food preservation are the need of the hour. Solar drying is one of the best choices in this context. Different models of solar dryers have been developed and good quantum of research is progressing in most of the countries to propagate the solar drying technology for value addition of agriculture products. The solar drying technology is a classical example to showcase how sun's free energy could be effectively utilized for the benefit of mankind. This chapter explains the different types of dryers, different aspects of solar drying, parameters involved in the drying process and the economic analysis to analyse the feasibility of the solar drying system. Case studies of a few of the successful installations are also included.

**Keywords** Food processing · Open sun drying · Solar drying · Economic analysis

## 1 Indian Agriculture and Its Economics

India has one of the oldest civilizations in the world with diverse culture, climate, food habits, etc. We mastered the art of agriculture in our infantry itself, and it has taken a speedy growth since its independence. As of now, India holds the second

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Green Energy and Technology, DOI 10.1007/978-81-322-2337-5_2

largest agricultural land amounting to 179.9 million hectares [Agriculture (2013), Detailed Project Report of the National Agricultural Education Project (NAEP) (2012)]. Green Revolution has elevated India to the second largest exporter and consumer of food grains in the world. With nearly 60 % of the Indian population still depends on agriculture for livelihood, it plays a major role in GDP with a share of 13.9 % in the financial year 2012–13. In April 2013 to February 2014, the export value of agricultural products from India has reached US$44.59 billion with an expected growth of 4 % in the present financial year.

### *1.1 Post-Harvest Losses*

Even with these positive statistics worries come up when looking into the annual post-harvest loss, which is estimated to be as high as INR 2.5 lakh crores in 2013–2014 (ASSOCHAM 2014). Leading the list is West Bengal with an annual loss of INR 13,657 Crores, followed by Gujarat, Bihar and Uttar Pradesh with individual annual losses of more than INR 10,000 Crores. This is because of the shortage of food storage facilities and under utilization of advanced technologies for food processing. Currently, India has a food storage capacity of roughly 74.6 million tonnes owned by Food Corporation of India (FCI) and state agencies with an annual production of 250 million tonnes of rice and wheat alone. Hence, the storage facilities need to be enormously expanded. With the passing of Food Security Bill, the need for food storage has come to limelight. Increase in population and reduction in worldwide food production has given us less options either to produce more food or to reduce the losses by preserving or storing.

## 2 Preservation Methods

Agricultural crop is perishable and it will get damaged as time passes by the attack of bacteria, fungi, etc. (Simth 2011). Preserving fruits, vegetables, grains, meat, marine products, spices, etc., has been practiced for thousands of years. Some of the food preservation methods are given below.

- Fermentation

Fermentation is the method of controlled spoilage of food stuff with micro-organisms like yeast; say milk to curd or ghee, which helps in extending the usage time. This method cannot be used for all products, but there are products which are better when fermented such as rice, chocolate and coffee.

- Curing or salting

Curing or salting is the preserving method using salt which will absorb moisture from the food materials thereby making the bacteria inhospitable. Though the bacterial activity is restricted, we need to find ways to prevent moulds. Bacon, salt pork, smoked fish, olives, pickles preserved lemons, etc., are examples of salt preserved foods.

- Drying or dehydrating

Drying or dehydration is one of the oldest methods of food preservation by removing the moisture from the food materials by open drying in the sun or by passing hot air over the products. Open drying is associated with disadvantages such as contamination, insect infestation and spoilage due to rains. Other types of drying using conventional energy sources require high capital and running cost to build and operate the facilities.

- Freezing

Freezing is the method of keeping the products in cold storage. This method helps to store the products for months or even for years. Cold storage is not a feasible method particularly in developing countries as it is expensive.

- Canning

Canning is by heating and storing in containers for prolonged usage. It is expensive and also associated with risk of botulism poisoning. Botulism is a rare and potentially fatal paralytic illness caused by a toxin produced by the bacteria Clostridium botulinum.

- Irradiation

Irradiation is one of the latest technologies used for food preservation using controlled radiation to kill micro-organisms which can cause food spoilage. Thereby storage time can be extended provided the chemical make-up of the food is also unaltered.

## 3 Methods of Drying

In the food chain handling, drying is considered as one of the critical operations. The principle objective of drying is to supply the required thermal energy in an optimum manner yielding high-quality products. Drying is broadly classified into three types based on the temperature requirement such as low temperature, high temperature and freeze-drying. Osmovac and desiccant methods are also employed in certain situations (Garg and Prakash 1997; Suhas et al. and Nayak 2009).

### *3.1 Low-Temperature Drying*

It is used for places where the average ambient temperature is around 10 °C. The temperature range used for this type of drying ranges from 15 to 50 °C. It uses natural or heated air with low temperature to dry the product in very longer time. Even though it is a relatively slower process and is dependent on favourable weather conditions, it has some advantages such as lesser spoilage, good quality product, less labour and capital investment.

### 3.2 High-Temperature Drying

High-temperature drying uses temperature starting from 50 °C, and this is the most common method in developed countries. It is used for drying high moisture content products such as fruits and vegetables. A hot air recirculation system may be employed with a dehumidification unit to increase the effectiveness of the system with less wastage of energy.

### 3.3 Freeze-Drying

Freeze-drying helps in removing water from fluids, say fruit juices. The operating temperature for this type of drying ranges from −10 to −40 °C. The product is first frozen and kept in low-temperature condenser or chemical desiccant. The water will get condensed or absorbed by the desiccant. It is used for drying heat-sensitive materials, but it is a slow and expensive process.

### 3.4 Osmovac Drying

It is a two-step process, which involves osmosis and vacuum vaporization, and is employed for drying fruit juices. Initially, the product is heated up to a temperature higher than the ambient temperature for better dehydration and then is made to undergo osmosis process. It is then carried to a chamber where vacuum drying happens.

### 3.5 Desiccant Drying

It is one of the best methods for dehydrating the exhaust air for recirculation, if the exhaust air is still hot. Hence, the efficiency of the system can be improved. The desiccant can be regenerated using solar heat.

## 4 Food Drying

Drying is one of the most prevailing methods of food preservation, where the moisture is removed preventing the growth of micro-organisms that causes food damage. This method helps in reducing the weight and volume of the product which reduces the transportation and storage load and also helps in storing the food in ambient temperature.

Drying is a process which involves a combined heat and mass transfer, where the surface moisture is removed first and the moisture from the interior is forced to move to the surface which is removed later. Hence, to enhance drying process, products are made to smaller pieces or sliced to increase the surface area. Increased surface area helps in better moisture removal. There are other parameters which also can affect the drying process such as temperature gradient, air flow rate and air humidity.

### *4.1 Objectives of Drying*

The major objectives of the drying process are as follows:

- To reduce the food spoilage caused by larger production and limited usage. There will be huge production during some particular season but the consumption will be very less, and hence, the food will be unused leading to less income to the farmers.
- Prolonged usage of the product preventing them from spoiling due to microbial attacks.
- Drying will reduce the weight dramatically and makes transportation easy.
- High-quality dried product will have good market value and hence will bring high profit to the producers.

### *4.2 Classification and Selection of Dryers*

Dryers are classified into five types based on the techniques in which the food is dehydrated. In open sun drying, the food is dehydrated when it is exposed directly to solar radiation. The moisture is carried away by wind as it blows above the product. Here the food products are placed in polythene sheet, mud or cement floor or on racks. In direct sun driers the food material are kept inside the drier. The air inside the drying chamber is heated up due to greenhouse effect and also product absorbs direct solar radiation. Vent holes are provided for passage of fresh air and removal of moist air from the drying cabinet. The food materials are completely protected from solar radiation in indirect dryers, which uses solar air heater to raise the air temperature. The hot air is allowed to pass through the drier, where the product is loaded. Indirect driers are essential for food which loose nutritional value on exposure to solar radiation. Hybrid dryers make use of fossil fuel or biomass fuel like rice husk to ensure a constant drying process. Fuelled dryers are driven by either conventional fuels or utility supplied electricity. (Sodha et al. 1987).

## 5 Solar Drying

Solar drying has been considered as one of the most promising areas for the utilization of solar energy, especially in the field of food preservation. Open sun drying is the most common method employed in tropical countries for the drying of agricultural products, food stuffs, etc. The method is simple, as it does not involve any costly equipment. The product to be dried is spread under sun, and the moisture evaporates from it over a course of time. Even though the process is simple, it suffers from disadvantages such as dust contamination, insect infestation, microbial contamination and spoilage due to rains. Product dried in this way is unhygienic and sometimes unfit for human consumption (Garg and Prakash 1997).

Solar drying can be most successfully employed as a cost-effective drying technique. It has got several attractive features. For example, energy is available free of cost and can be harnessed in the site itself. Controlled drying is also possible by this method, and it enhances the quality of dried product. Solar drying systems must be properly designed in order to meet particular drying requirements of specific crops and to give satisfactory performance with respect to energy requirements. A wide variety of solar dryers have been designed by many researchers. Drying conditions for different products will be different, and hence, the solar dryer should be designed for their particular requirement. A good design can help in producing high-quality products and hence bring good returns to the farmers.

India receives good amount of solar radiation in the range of 4–7 kWh/m$^2$-day around 300–330 days in a year. Thus, it is one of the most promising sources of energy. Unlike fossil fuels and nuclear energy, it is an environmentally clean source of energy. Secondly, it is free and available in adequate quantities in almost all parts of the world where people live in. Solar energy is always in an advantageous position compared with depleting fossil fuels. In a tropical country like India, most of the energy demands can be met by simple systems that can convert solar energy into appropriate forms. By proper application of technologies, excellent thermodynamic match between the solar energy resources and many end-uses can be achieved (Sreekumar 2011a, b).

## 5.1 Comparing Solar Drying with Other Options

When one considers solar drying, it has to be compared with other options available. In some situations open-air drying or fuelled dryers may be preferable to solar. Solar drying will only be successful if it has a clear advantage over the current practice. Table 1 lists the merits and demerits of solar drying when compared with traditional open-air drying, and then with the use of fuelled dryers (Sreekumar 2011a, b; Garg and Prakash 1997).

The comparison will assist in deciding among solar, open-air and fuelled dryers. The local site conditions will also play an important role in this decision. Some indicators that solar dryers may be useful in a specific location include

1. Conventional energy is unavailable or unreliable
2. Plenty of sunshine
3. Quality of open-air dried products needs improvement
4. Land is extremely scarce (making open sun drying unattractive)
5. Introducing solar drying technology will not have harmful socio-economic effects.

**Table 1** Solar dryers compared with open-air and fuel drying

| Type of drying | Merits (+) and Demerits (−) of Solar Dryers |
|---|---|
| Solar versus Open-air | + Superior quality dried products |
| | + Minimizes losses and contamination |
| | + Less drying area |
| | + Better preservation of nutrition and colour |
| | + Less labour intensive |
| | + Reduced drying duration and less chance of spoilage |
| | + Bring down to safe moisture level, which allows longer storage |
| | + Controlled drying |
| | − Comparatively more expensive |
| | − In some cases, food quality is not significantly improved |
| | − In some cases, market value of food will not be increased |
| Solar versus Fuelled | + Prevents fuel dependence |
| | + Operating cost is almost zero |
| | + Often less expensive |
| | + Reduced environmental impact |
| | − Requires adequate solar radiation |
| | − Hot & dry climates preferred |

## *5.2 Design Consideration*

As far as design of a solar drier is concerned, there is no uniform design standards applied to all the models. This is mainly because of all the drying parameters are variable from one product to another. Knowledge of heat and mass transfer combined with material properties is essential to design a solar drier as all the processes involved are highly nonlinear. Due to this, scaling of a solar drier is generally complicated. Design experience of pilot scale and field-level familiarity will be helpful for the development of a new solar dryer. An advanced design will lead to hygienic production of high-quality product with a considerable reduction in drying duration. Temperature required for a particular product to be considered an important aspects for the design of a solar dryer. During the course of time, many commercial designs are evolved out even though market penetration of solar dryer is very poor. Non-awareness about the technicalities and lack of good design to perform a suitable requirement can be considered as a barrier to large-scale deployment of solar driers. Most of the commercial models available are poorly designed without much parametric optimization. This necessitates an urgent measure of designing highly efficient, cost-effective and adaptable solar drying system. Various calculations must be performed to determine the parameters such as quantity of air required, mass of moisture removed from the produce, rise and fall of air temperature and amount of energy required, which will be useful for techno-economic feasibility analysis. The mechanical design consideration concentrates on fixing the mechanical details of the drying chamber and collector. Mechanical design studies are regarding materials for solar air heater fabrication, cabinet size, tray volume, number of trays, size of ducting and cladding, etc. The other design parameters that should be taken into account are geographical location, local climatic conditions, types of materials to be dried, available solar flux, etc. The design consideration for the drying system, i.e. the solar air heater used to supply hot air, drying chamber and ducting is discussed here separately (Sreekumar 2011a, b).

### 5.2.1 Design Aspects of Drying Chamber

In a commercial solar drying system for bulk product drying, the solar air heater is integrated with a drying chamber. The following are the major design parameters of a drying chamber (Garg and Prakash 1997).

(a) quantity of product to be dried per batch or day and size of the drying cabinet to hold the material
(b) capacity of the dryer (kg/batch)
(c) system for loading and unloading the material
(d) materials for dryer cabinet and tray construction
(e) arrangement to pass hot air through the material to be dried
(f) effective circulation and recirculation of hot air through the dryer
(g) a vent through which the warm moist air to remove from the drying chamber.

### 5.2.2 Thermodynamical Aspects

Based on the thermodynamical aspects, the quantity of air needed for drying a specified mass of the product to be evaluated. Two different methods are employed here for these calculations. They are listed below:

(i) The psychrometric chart

The capacity of air for moisture removal depends on its humidity and temperature. The study of relationship between air and its associated water is called psychrometry. On the psychrometric chart, various thermodynamic properties of moist air such as vapour pressure, relative humidity, humidity ratio, dry bulb temperature, wet bulb temperature, dew point temperature, enthalpy and specific volume can be estimated. When any two of the three temperatures are known, i.e. dry bulb, wet bulb or dew point, all other properties can be determined from the psychrometric chart.

In the psychrometric chart (Fig. 1), humidity ratio is the ordinate and dry bulb temperature is the abscissa. The upper curve of the chart is labelled wet bulb and dew point temperatures. The other curves on the psychrometric chart that are similar in shape to the wet bulb lines are lines of constant relative humidity (%). The straight lines sloping gently downward to the right are lines of constant wet bulb temperature. The interaction of a dry bulb and a wet bulb line gives the state of the air for a given moisture content and relative humidity. The amount of air needed for drying a particular quantity of product can be calculated using psychrometric chart.

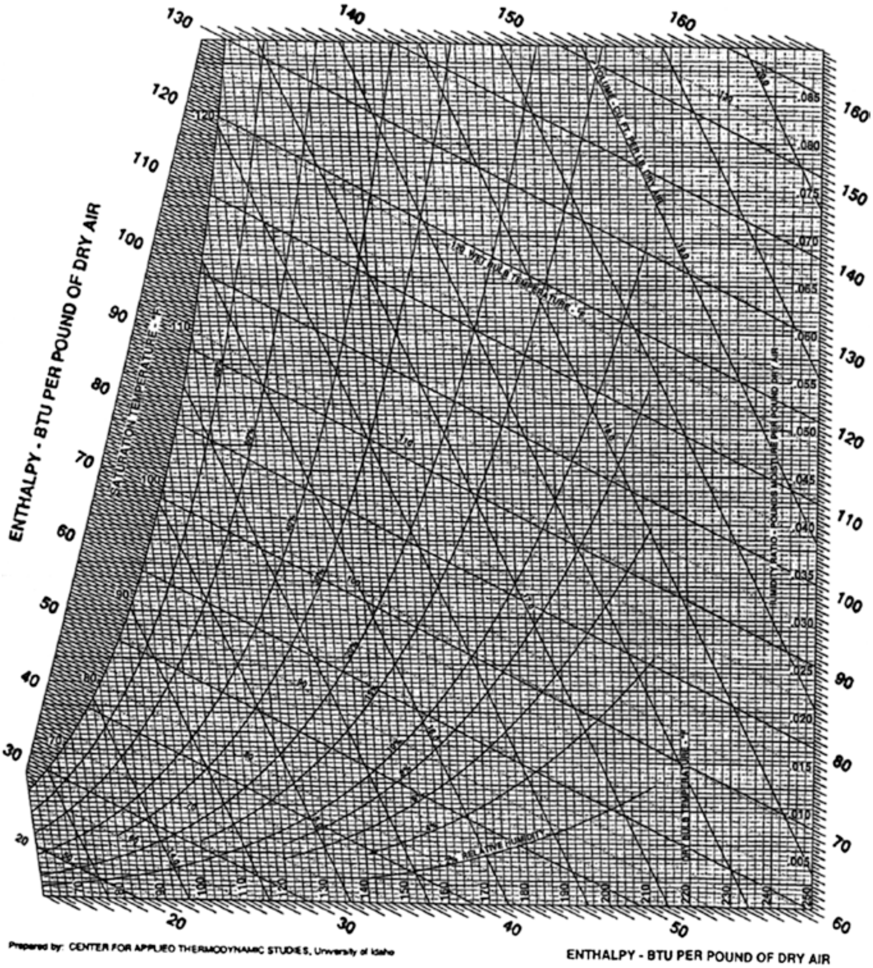


**Fig. 1** Psychrometric chart (*Source* ASHRAE)

(ii) The energy balance equation for drying

The energy balance is an equation that expresses the following idea mathematically: The energy available from the air going through the food inside the dryer should be equal to the energy needed to evaporate the amount of water to be removed from the crop. The removal of water from a surface by evaporation requires an amount of heat equal to the latent heat of evaporation of water plus a current of air moving over the surface to carry away the water vapour produced. Hence, the task in solar dryer is to calculate and then achieve optimum temperature, $T_f$ and air flow, $m_a$ to remove the specified amount of water, $m_w$. So we have

$$m_w L = (T_f - T_i)\, m_a C_p$$

where $m_w$ = mass of water evaporated; $L$ = latent heat of evaporation; $m_a$ = mass of air circulated; $C_p$ = specific heat of air; $T_f$, $T_i$ = final and initial temperatures.

After these, the volume of air can be determined by using the gas laws

$$\frac{V_{air}}{m_v} = \left(\frac{m_a}{m_v}\right)\left(\frac{RT}{P}\right)$$

i.e.,

$$V_{air} = \frac{m_a RT}{P}$$

where $m_w$, the amount of water evaporated can be read from moisture ratio scale or can be calculated from the energy balance equation.

Because the vapour pressure of bound water in hygroscopic material is less than saturation, the effect of bound water is also to be taken into account. Again, the latent heat value should be chosen to correspond to a very low vapour pressure.

The equations can be employed for evaluating various parameters as mentioned above. Here, these are made use of in calculating the quantity of air needed for drying ($m_a$) for various materials to be dried (Tiwari 2002).

## 6 Effect of Parameters on Drying

The most important parameters which determine the quality of the dried product are the mass flow rate and the temperature of the working fluid, i.e. air. Other parameters are air velocity, humidity and the required final moisture content. Effects of different parameters are discussed below (Ratti and Mujumdar 1997).

### *6.1 Temperature*

Drying temperature is a major deciding factor, which mainly determines the quality of the dried product. High drying temperature may impair the germination capacity of seeds and also can damage the product either changing the chemical combination or smoulder the product. Lower drying temperature may lead to longer drying time which may lead microbial contamination. Recommended drying temperature with the initial and permissible moisture content for different products are shown in Table 2 (Garg and Prakash 1997). The temperature should be maintained to the permissible level so that the drying will not damage the product.

### *6.2 Mass Flow Rate*

Mass flow rate also plays an important role in drying process. Optimum mass flow rate is designed using the temperature requirement and also the maximum air velocity which can be maintained inside the drying chamber.

**Table 2** Initial and final moisture content and the maximum recommended drying temperature for different food products

| Product | Moisture content (%) | | Maximum drying temperature ($^{o}$C) |
|---|---|---|---|
| | Initial | Final (permissible) | |
| Paddy | 22–24 | 11 | 50 |
| Maize | 35 | 15 | 60 |
| Wheat | 20 | 16 | – |
| Carrots | 70 | 5 | 75 |
| Green beans | 70 | 5 | 75 |
| Onions | 80 | 4 | 55 |
| Garlic | 80 | 4 | 55 |
| Potato | 75 | 13 | 75 |
| Chilly | 80 | 5 | 65 |
| Fish | 75 | 15 | 50 |
| Apples | 80 | 24 | 70 |
| Grapes | 80 | 15–20 | 70 |
| Banana | 80 | 15 | 70 |
| Pineapple | 80 | 15 | 65 |
| Coffee | 50 | 11 | – |
| Cotton | 50 | 7 | 75 |
| Copra | 30 | 5 | – |
| Groundnut | 40 | 9 | 50 |
| Leather | 50 | 18 | 35 |
| Fabrics | 50 | 8 | 75 |

### *6.3 Relative Humidity of Air*

The relative humidity of air is an important factor same as that of temperature because humidity gradient between air and the product will be a major driving force in a natural convection system. Lower relative humidity of the air can increase the drying rate and will help in reducing the drying time.

### *6.4 Moisture Content of the Drying Product*

The moisture content of the product to be dried is an important factor for determining the quality of the product and thereby the market value. Products with higher moisture content are found to have lesser drying time than those having very lesser moisture content. It is because the higher moisture content product may have better mass flow of the moisture from the interior of the product to the surface so that it is removed where the one with lower moisture content may have a thick outer skin.

# 7 Effect of Drying on Nutritional Value

Dried products are very good source of nutrients but the dehydration process may alter the quality of the products. This can be limited by having proper pre-treatment of the materials and also by controlling the drying process. Some of the quality parameters considered are colour, visual appeal, flavour, retention of nutrients, free from contaminant, etc. These factors will decide on the market value of the product. Pre-treatments, novel drying techniques and optimized drying methods can help in producing good quality products (Shyam 2005).

## *7.1 Pre-treatment and its Influence on Nutrition Loss*

Blanching and dipping in solution like sulphites are the most commonly used pre-treatment methods. Steam blanching is done by direct injection of steam into the blanching chamber followed by rapid cooling. In some cases, concentrated sugar solution is used. Such pre-treatments are found to be a serious reason for nutrient loss. Reports show that there is around 80 % loss of carotene content when blanching is done. Loss of vitamins and other nutrients are also occurring due to blanching. Osmotic treatments found to have better results in retaining vitamins than other methods.

## *7.2 Effect of Drying on Nutrients*

Drying temperature has got a significant role in vitamin loss. Temperature has to be maintained at the desired level to preserve nutrients in the product. Retention of nutrients was higher in shade drying and freeze-drying than other methods like oven or sun drying.

# 8 Solar Driers in the Field

Some of the successful installations of solar driers in India are given below.

## *8.1 SPRERI Forced Circulation Solar Dryer*

Sardar Patel Renewable Energy Research Institute (SPRERI) developed a forced circulation solar dryer that uses modular air heaters of standard 2 $m^2$ surface area.

**Fig. 2** Forced circulation solar air heater-based dryer developed by SPRERI

One such system is shown in Fig. 2. The outlet temperature from the air heater was 70 °C on clear sunny days and that inside the dryer varied from 50 to 60 °C depending on the state of drying. The system could dry two batches of 100 kg fresh onion flakes in a day. Besides onion, the system was found to be useful for drying many other farm and industrial products (Chavda and Kumar 2008).

### *8.2 Solar Tunnel Dryer at Udaipur*

A solar tunnel dryer was developed for drying of dibasic calcium phosphate (DCP) for industrial use at M/S Phosphate India Limited, Udaipur. The loading capacity of the semi-cylindrical shaped tunnel dryer was of 1.5 tonne per batch. Two such tunnels were installed in series to accommodate 3.0 tonne of material. The maximum temperature recorded inside the solar tunnel dryer was 62 and 50 °C on a summer and winter day, respectively, which is about 15 °C higher than ambient temperature. Drying duration was 16 h for DCP up to the safe moisture content during winter seasons while total 12 h was needed during summer seasons for reducing moisture content from 37.3 to 9.4 %. The solar tunnel dryer reduced moisture content to around 10 %. The developed dryer is reported to be use in a chemical Industry near Udaipur (Singh et al. 2007).

### *8.3 Solar Cabinet Drier: CUSAT*

A cabinet drier of area 1.27 $m^2$ for drying of farm products such as spices and fruits was developed by Cochin University of Science and Technology (CUSAT), India. Figure 3 shows the photograph of the dryer. It has a collector at the top and

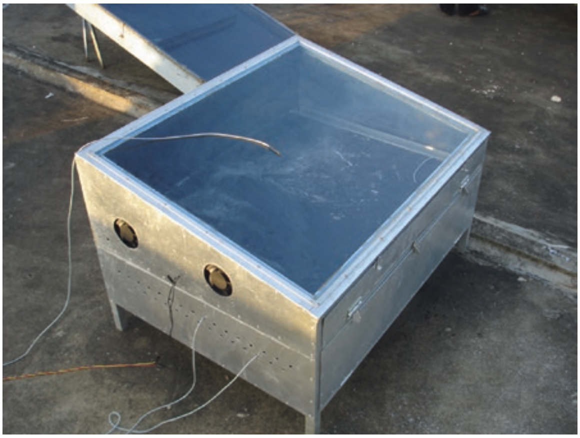

**Fig. 3** Solar Cabinet Drier—CUSAT, India

a drying chamber at the bottom. This arrangement limits direct exposure of the sunlight on the product, which helps in retaining the natural colour. The loading capacity is 4 kg per batch and has two axial fans of 20 W, provided for air circulation. Bitter gourd was dried to 5 % moisture content from an initial moisture content of 95 % in 6 h (Sreekumar 2010).

## *8.4 Tunnel Drier for Copra Drying: Pollachi*

A tunnel drier for copra drying was developed by Ayyappan and Mayilsamy in Pollachi, India (Ayyappan and Mayilsamy 2010). It was a community model greenhouse dryer with a 10 m length 4 m width. The greenhouse effect is created by having a semicircular portion on the top with a height of 3 m at the centre. UV-stabilized polyethylene film of 200 μ thickness is used as glazing material for the dryer. It has a loading capacity of 5000 coconuts per batch. Two exhaust fans of diameter 30 cm each and three air vents with butterfly valves were used for air circulation. Experimental results show that the average moisture content of the coconuts was reduced from 52 to 8 % in 57 h in full load conditions. High-quality copra was produced using the tunnel drier developed.

## *8.5 Drier Integrated with Solar Air Heater—CUSAT*

An advanced type of solar drier having a drying cabinet and a solar air heater was developed in CUSAT, India (Sreekumar 2010). Figure 4 shows the photograph of the dryer. The collector area is 46 $m^2$ with a loading capacity of 200–250 kg in the drying chamber. It is used for drying fruits and vegetables with good quality. It took only 8 h to dry 200 kg of apple.

**Fig. 4** Drier integrated with solar air heater—CUSAT

### *8.6 An Indirect Solar Dryer for Paddy Drying: Planters Energy Network*

An indirect-type solar dryer for drying of paddy was installed in Theni district, Tamilnadu, India by Planters Energy Network, India, under the project for developing solar air heaters for using it in agro-based industries. The total collector area of the dryer is 212 $m^2$ divided into three partitions with 3000 $m^3$/h mass flow rate each. The loading capacity of the dryer is 12 tonnes, which is dried at a temperature of 60 °C for 6–8 h. Similar systems were also developed for drying of tea leaves, marine products, farm produce and so on (Palaniappan and Haridasan 2000).

### *8.7 Solar Dryer with Wire Mesh Air Heater: Pondicherry University*

A solar drier integrated with a wire mesh air heater (Fig. 5) was developed in the Centre for Green Energy Technology, Pondicherry University, India (Aravindh and Sreekumar 2014a, b). As advancement in the solar air heater design, wire

**Fig. 5** Solar Dryer with wire mesh air heater—Pondicherry University

mesh made of GI with wire diameter of 1 mm and pitch of 3.175 mm was used as absorber. The collector area is 6 $m^2$ and having a loading capacity of 30 kg in the drying chamber. It is powered with a 0.5 HP blower with a mass flow rate of 500 $m^3$/h. The system was developed for drying of food stuffs such as fruits, vegetables and marine products. Experiments with different products such as bitter gourd, pineapple and ivy gourd showed better results when comparing to open sun drying.

## *8.8 Solar Tunnel Dryer: Pondicherry University*

In this drier, a DC fan is used to push hot air through the drying material. Selective coated Aluminium was used as absorber plate and consists of perforated trays to load the material. The salient feature of this drier is that the fan is operated by a solar cell. Hence, this system is completely independent from the electricity grid and is suitable to far flung areas where electricity grid is not available. Another advantage is that the speed of the fan is controlled by the solar radiation availability. It will run fast peak solar hours and helps to remove the excess heat from the drier. The maximum hot air temperature recorded on a clear sunny day was 71 °C. Figure 6 shows the photograph of the solar PV operated cabinet drier. The system was used for drying of fruits, vegetables and fish.

## *8.9 SEED Dryer*

Society for Energy, Environment and Development at Hyderabad, India developed a solar-powered air dryer for processing curry leaf, mushrooms, mango, tomato, etc. A photograph of the dryer is shown in Fig. 7. Ambient air enters from the bottom of the cabinet and gets heated by solar radiation, which penetrates through the upper glass cover. Hot air passes through the trays and carries moisture from the

**Fig. 6** Solar tunnel dryer developed at Pondicherry University

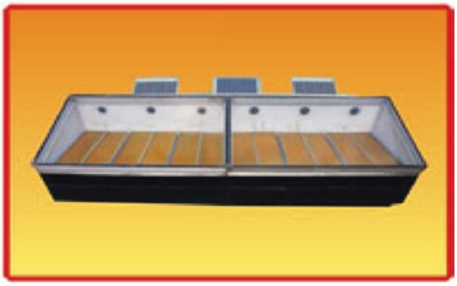

**Fig. 7** SEED dryer

product to the space below the glass, from which it is removed with solar-powered exhaust fans. To meet the load requirement during non-solar hours, electric heating provision was also provided. Cabinet temperature recorded was in the range from 40 to 65 °C, about 15–30 °C higher than ambient temperature.

### *8.10 Portable Farm Dryer by Punjab Agricultural University*

A low-cost natural convection solar dryer for drying different farm products was developed by Punjab Agricultural University, India. In order to facilitate loading of product, cover may be removed from the multirack dryer along with the shading devices placed over each tray. If the product is less than the total capacity of the dryer, only the top trays are used. Photograph of the dryer is shown in Fig. 8. Maximum temperature reported in the farm dryer was about 75 °C when a maximum solar radiation of 750 $W/m^2$ and ambient temperature of 30 °C (Singh et al. 2006).

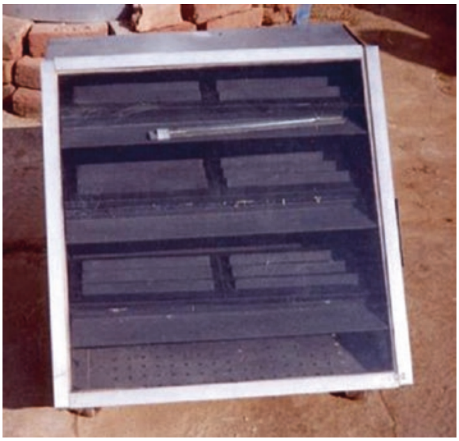

**Fig. 8** Punjab agricultural dryer

# 9 Economic Analysis for Solar Drying

Economic analysis for drying can be performed using three methods such as annualized cost, life cycle savings and payback period (Sreekumar 2010; Aravindh and Sreekumar 2014a, b). Annualized cost method helps in finding out the cost of drying for unit weight of the product by different drying techniques such as solar and electric heater. The drying cost of solar dryer remains almost constant over the entire life of the system, but the cost is variable in the case of electric and fossil fuel-based dryer due to the fluctuating price of electricity and petroleum products. Even though the annualized cost gives a comparative study, it is not precise due to volatile fossil fuel prices. Hence, to make a clearer understanding on the economics of the dryer, life cycle savings method is used, which determines the savings made in the future years and also to make the present worth of annual savings over the life of the system. Payback period will give the investment's return period, and hence, this determines the acceptability of the technology. For further understanding, a sample economic analysis is given below for the dryer developed by Centre for Green Energy Technology, Pondicherry University. The product used for drying is pineapple having an initial moisture content of 83 %. The parameters considered are listed in the Table 3.

## 9.1 Annualized Cost

Using the data from the above Table, for every 30 kg of fresh product being loaded, 7.8 kg of dried product is retrieved. With an average 250 sunny days per year with 1 batch per 2 days, it comes 125 batches per year. The cost of drying using solar drying was calculated as 30 INR per kg. While in the case of electric dryer, the cost goes up to 41.6 INR per kg.

**Table 3** Parameters considered for economic analysis

| | |
|---|---|
| 1. Capital investment for solar dryer | 120,000 INR |
| 2. Capital investment for electric dryer | 100,000 INR |
| 3. Interest rate | 12 % |
| 4. Inflation rate | 8 % |
| 5. Cost of fresh pineapple | 50 INR |
| 6. Cost of dried pineapple | 500 INR |
| 7. Electricity cost | 5 INR/kWh |
| 8. Quantity of fresh pineapple loaded per batch | 30 kg |
| 9. Lifespan | 15 years |
| 10. Efficiency of the electric heater | 75 % |

**Table 4** Life cycle savings

| Year | Annual savings (INR) | Present worth of annual savings (INR) | Present worth of cumulative saving (INR) |
|---|---|---|---|
| 1 | 270,250 | 245,682 | 245,682 |
| 2 | 291,870 | 241,215 | 486,897 |
| 3 | 315,220 | 236,829 | 723,726 |
| 4 | 340,437 | 232,523 | 956,249 |
| 5 | 367,672 | 228,295 | 1,184,544 |
| 6 | 397,086 | 224,145 | 1,408,689 |
| 7 | 428,853 | 220,069 | 1,628,758 |
| 8 | 463,161 | 216,068 | 1,844,826 |
| 9 | 500,214 | 212,140 | 2,056,966 |
| 10 | 540,231 | 208,282 | 2,265,248 |
| 11 | 583,449 | 204,495 | 2,469,744 |
| 12 | 630,125 | 200,777 | 2,670,521 |
| 13 | 680,535 | 197,127 | 2,867,648 |
| 14 | 734,978 | 193,543 | 3,061,191 |
| 15 | 793,777 | 190,024 | 3,251,215 |

### *9.2 Life Cycle Savings*

With a selling cost of 500 INR for the dried product and the savings per batch of the dried product comes roughly to 1080 INR. For a saving of 1080 INR per batch, the life cycle savings is given in the Table 4. For an initial investment of 120,000 INR, the present value of the savings after 15 years of operation of the dryer was worked out nearly 3,251,215 INR.

### *9.3 Payback Period*

The savings in the very first year is 245,682 INR for an initial investment of 120,000 INR. Hence, the investment can be recovered back in the first year itself. Calculation shows that the payback period is roughly 0.54 years which comes to around 130 drying days.

## 10 Conclusion

Solar drying is a promising technology for drying of food products for developing country like India, where solar energy is abundant. This can dramatically reduce the post-harvest food spoilage which is a major concern for the second largest populated country. Even though the drying conditions for every product are different, a dryer can be modelled in such a way that it can dry any product with good control parameters such as temperature and the mass flow rate. Case studies show some of many successful installations. From the case studies, it is very much evident that it is a proven technology and should be given wider publicity.

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# Jawaharlal Nehru National Solar Mission in India

**Atul Sharma, Kriti Srivastava and Sanjay Kumar Kar**

**Abstract** The global environmental scene has changed fiercely over the last century. The changing scenario demands a greater concern and action-oriented enabling policy framework for the use of sustainable and renewable energy. The Government of India has taken necessary cognizance of the global developments and has initiated several green and environment friendly policy measures under the National Action Plan on Climate Change. One of the initiatives taken by the government is the Jawaharlal Nehru National Solar Mission (JNNSM). This chapter discusses the objectives of JNNSM and the developments made so far to improve the share of solar energy, ensure supply security, and reduce energy poverty in India.

**Keywords** Solar energy · JNNSM · India

## 1 Introduction

### *1.1 The Global Environmental Scene*

The global environmental scene has changed fiercely over the last century. As energy is an indispensable part of all earthly processes the main development of a country is majorly focused on its energy production and consumption. To fulfill this energy requirement in the past economy; fossil fuels, oil, and natural gas were the main sources. In 2012 the global use of fossil energies was about 450 Exajoules ($450 \times 10^{18}$ J), 20 times greater than during the 1890s (IEA 2013a).

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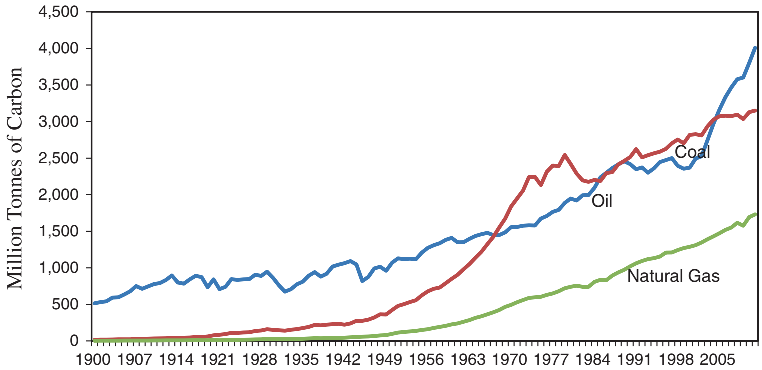



**Fig. 1** Global carbon dioxide emissions from fossil fuel burning by fuel type, 1900–2011

This excessive exhaustion of fossil fuels is causing large emissions of greenhouse gases like carbon dioxide, oxides of sulfur and nitrogen, and many others. The power generated from fossil fuels globally releases more than 1000 grams of $CO_2$ per kilowatt-hour ($gCO_2/kWh$) (Scientific American and January 2014) and the atmospheric level in 2004 was 368 ppm, which has risen from the stable 280 ppm because of use of fossil fuels (Sims 2004). Figure 1 shows the global carbon dioxide emissions caused due to burning of fossil fuels as in 2011 (EPI 2013).

Such harmful gases lead to serious environmental pollution in air, water, as well as land causing health ailments, inconsistent weather changes, global warming, and an increase in sea levels. It also augments fuel insecurity among countries. All this requires a serious check, which otherwise can cause loss of big landmasses and species. In order to become resilient in the future, all nations are trying to move toward sustainable ways of energy production in order to keep the environment clean along with the required energy production. These methods involve renewable resources, i.e., wind, solar, hydro, geothermal, and biomass that are inexhaustible and produce far less pollution than conventional resources.

## *1.2 Energy Supply Options for Mitigation of Harmful Gases*

A major portion of energy production can be obtained from renewable resources like solar and wind energy because these are inexhaustible and available in plenty. Solar energy is the creator of all the different energies available to us like wind, hydro, biomass, etc. With about 300 clear, sunny days in a year, India is equipped with vast solar energy potential. About 5000 trillion kWh per year energy is incident over India's land area with most parts receiving 4–7 $kWh/m^2/day$[1]; Muneer et al. 2005). Solar energy can be harnessed through solar thermal and solar

[1]MNRE: Government of India. Renewable energy is clean, green and sustainable. Available at: http://www.mnre.gov.in/.

**Table 1** World solar photovoltaics installations, 2007–2013

| Year | Solar photovoltaic installations | |
|---|---|---|
| | Cumulative installations (MW) | Net annual additions (MW) |
| 2007 | 9291 | 2672 |
| 2008 | 16,063 | 6772 |
| 2009 | 24,265 | 8202 |
| 2010 | 41,330 | 17,065 |
| 2011 | 71,218 | 29,888 |
| 2012 | 102,076 | 30,858 |
| 2013 | 139,637 | 37,561 |

photovoltaic (SPV) methods for various applications. While solar thermal technologies utilize the heat energy from the sun for several purposes, this sunlight can be converted into electricity using photovoltaic (PV) systems. The PV generation technique is a technique of converting solar radiation or quantum of light into direct current generation using a semiconductor material like silicon, germanium, or compounds of gallium that exhibit the photovoltaic effect. While in case of solar thermal technologies, a selective absorber like salt hydrates or eutectic compounds (Cuevas et al. 2014) efficiently store solar energy in the visible and the near infrared spectral regions though exhibiting poor infrared radiating properties. This energy is used to generate thermal energy or electrical energy for use in industries, and in the commercial and residential sectors.

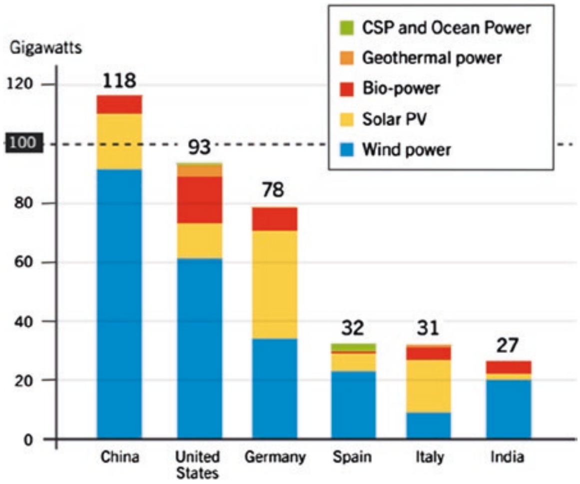
Solar being a sustainable form of energy and available in plenty, has been attracting plenty of investments globally. Table 1 represents the share of total investment in power plants, which shows that solar PV grew from 14 % in 2000 to over 60 % in 2012 (IEA 2013b).

### *1.3 Renewable Energy Market—India*

The petroleum shortage in major industrial countries of the world in the 1970s guided the foundation of the Commission for Additional Sources of Energy (CASE) in the Department of Science and Technology (India) in March 1981. This was charged with the responsibility of contriving policies and their implementation, programs for efficient use of new and renewable energy resources apart from conspiring and escalating R&D in the sector. In 1982, the Department of Non-conventional Energy Sources (DNES) integrated with CASE created at that point in the “Ministry of Energy”. In 1992, DNES became the Ministry of Non-conventional Energy Sources (MNES) and later in October 2006, again the Ministry was re-christened as Ministry of New and Renewable Energy (MNRE) with the aim to ensure energy security, increase the share of clean power, energy availability and access, energy affordability, and energy equity.[2]

[2]MNRE: GOI. Introduction to Solar Energy. Available at: http://www.mnre.gov.in/.

Fig. 2 Renewable energy in India in comparison with the top five countries




To create an empowering policy framework for the installation of 20,000 MW of solar power by 2022 and to upraise the capacity of grid-connected solar power generation, the Jawaharlal Nehru National Solar Mission (JNNSM) was launched by the Prime Minister of India on January 11, 2010. It is a major initiative of the Government of India and State Governments to promote ecologically sustainable growth while tackling India's energy security challenge.[3] The motive of this mission is to make India the world leader in solar energy and ramp up its development both at the centralized and decentralized levels. MNRE focuses on promoting the development and deployment of various technologies for increasing the installed capacity of grid interactive and off-grid systems. Power generation from renewable sources is upsurging in India, with the total share of renewable energy in India rising from 7.8 % in 2008 to 12.3 % in 2013. Figure 2 shows that India stands sixth globally along with 31.7 GW in renewable energy installations and of that 21.1 GW (67 %) was installed in the wind power sector as on March 2014 (REN 2014a).

## 1.4 World Status and Scenario

Renewable energy resources and significant prospects for energy efficiency are present over wide geographical regions in contrast to other exhaustible energy sources, which are concentrated in a restricted number of countries. Rapid setting up of renewable energy and energy efficiency, and technological expansion of energy resources, would result in substantial energy security and economic profits.

[3]MNRE: Jawaharlal Nehru National Solar Mission towards building solar India. Available at: http://www.mnre.gov.in/.

In the 1970s environmentalists stimulated the development of renewable energy both as a substitute for the subsequent depletion of oil, as well as a source to reduce the dependence from oil.[4] To achieve this, the first electricity generating wind turbines were invented. Solar was long being used for heating and cooling purposes, but solar PV systems were too expensive to build solar farms until 1980. Renewable energy contributed 19 % to the total energy consumption and continued to grow in 2013 (REN 2014c). Both modern renewable technologies like hydro energy, wind power, solar energy, and biofuels, as well as contemporary biomass contributed in almost equal amounts to the global energy output.

In 2013, renewables faced diminishing policy support and ambiguity in the United Kingdom and the United States. Electric grid-related limitations, disagreement in some countries for electric utilities relating to rising competition, and ongoing high global subsidies for fossil fuels were the major issues. Overall, other than the US and UK renewable energy developments were progressive in 2013. Many installations of small-scale, scattered renewable systems for distant locations along with grid-connected systems were installed, where consumers wished to generate at least a few percentage of their electricity demand at their location. The highest substantial growth happened in the power sector, with global capacity of more than 1560 Gigawatts (GW), more than 8 % in 2012. Hydropower augmented by 4 % to approximately 1000 GW, and other renewable resources together developed nearly 17 % to above 560 GW (REN 2014c).

Technology costs were a major reason for the fall in investment during 2013–2014. Although PV module prices reduced in early 2013 as the market's severe overloading improved, steadiness of plant costs of photovoltaic systems continued to drop. Moreover, there was a shift in the global blend of PV installations in 2013, with a lesser share of relatively high cost per megawatt installed in residential systems and a higher share of relatively low cost per megawatt installed in utility scale systems, particularly in China. The outcome was that although PV capacity installed increased from 31 GW in 2012 to a record of 39 GW in 2013, the dollar investment in solar capacity reduced by 23 % at $104 billion (Bloomberg new energy finance 2014).

## 2 Global Solar Energy Status

### *2.1 Direct Solar Irradiation and Solar Technologies*

Figure 3 shows the annual global irradiance, which differs in intensity depending on the geographic location of various regions.[5]

[4]Encyclopedia of Alternative energy. The World of David Darling. Available at: http://www.daviddarling.info/.

[5]Solar GIS. Direct solar irradiance (DNI). Available at: http://solargis.info/.

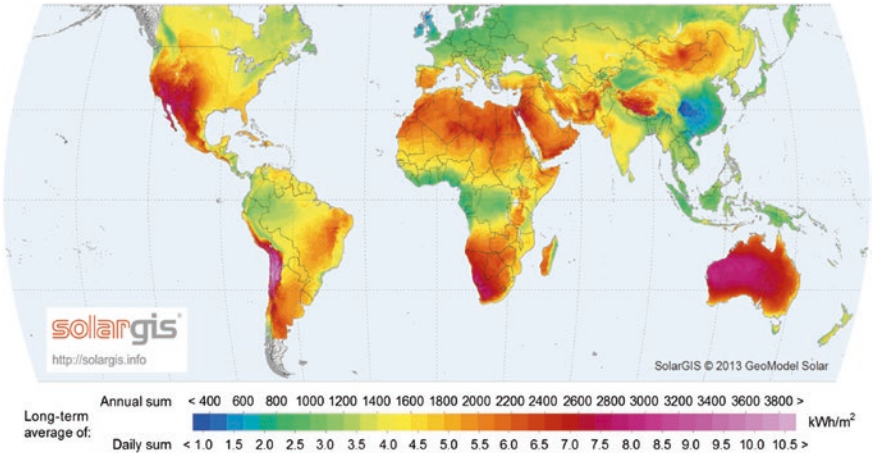



**Fig. 3** World map of direct normal irradiation (DNI)

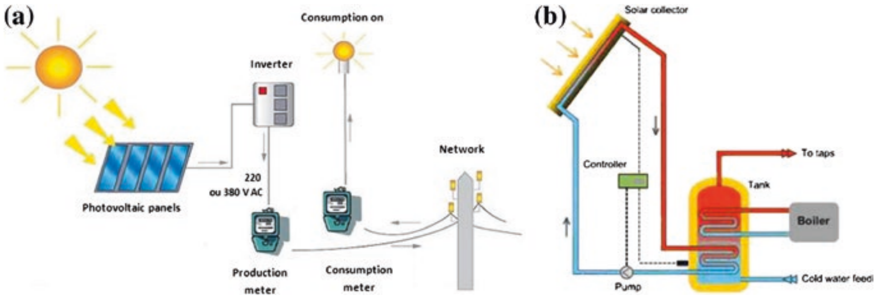



**Fig. 4** **a** Solar PV system and **b** solar thermal collectors

The irradiation values are between 500 and 2500 kWh/m$^2$ (IEA 2013b). Solar energy can be harnessed at different regions around the world, mostly depending on the distance from the equator. Regions receiving high irradiance throughout the year can utilize the solar energy for meeting its daily needs as well as in producing most of its energy requirement from solar energy. The solar technologies used to harness this energy by active and passive systems (Fig. 4) are mainly categorized on the basis of their capturing, converting, and distributing solar energy.

PV solar panels convert sunlight directly into electricity. These are often used to power calculators and watches. They are made of semiconductor materials like silicon and germanium, analogous to those used in computer chips. When these materials absorb solar radiation, the solar energy liberates electrons from the material atoms resulting in electron flow through the material to produce electricity. The process of converting light hν (photons) into energy is called the photovoltaic (PV) effect. In case of solar thermal systems, solar radiation is used to produce thermal energy instead of using conventional energy sources. This thermal energy is generally used to heat water or other working fluids, and can be used to power

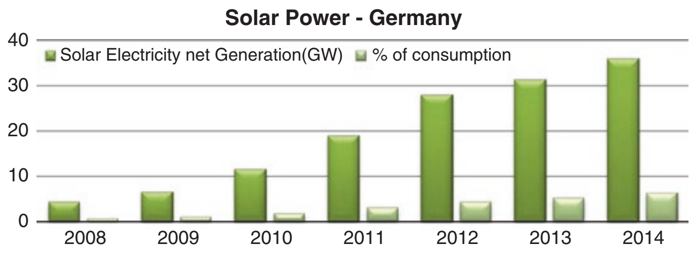



**Fig. 5** Solar electricity net generation and consumption 2008–2014

solar cooling systems. Solar thermal systems are different from solar photovoltaic (PV) systems, which generate electricity rather than heat. Passive solar techniques include positioning a building from the sun, deciding materials with favorable thermal mass and light dispersing attributes, and planning spaces that naturally circulate the air. This method is effectively useful in regions that receive less sunlight in order to keep the buildings warm and naturally habitable.

## *2.2 Countries with Maximum Solar Energy Installations*

### 2.2.1 Germany

Germany's renewable energy sector is among the most innovative and successful worldwide. In July, Germany's Ministry for the Environment, Nature Conservation, and Nuclear Safety released a report on the country's Renewable Energy Sources Act,[6] which was designed to push price reduction based on enhanced energy efficiency from the economy point of view. The Act came into force in 2000 and was the preliminary flash of a tremendous boost of renewable energies in the country. The Act was significant in promoting the expansion of renewable energies in the electricity sector and consequently the share of electricity produced from renewable energy in Germany increased from 6.3 to 30 % from 2000 to 2014 (Fraunhofer institute for solar energy systems ISE 2014). Germany had the biggest European market, but it fell from the first to the fourth position globally, adding only 3.3 GW after three consecutive years of averaging around 7.6 GW. With its total PV installations approaching 36 GW, Germany now has the most installed capacity compared to any other country so far Fig. 5; (REN 2014b).

Continued development in solar power has been vital for the accomplishment of the energy systems transformation in Germany. The share of solar energy in the German electricity production could rise by 70 % in the next four to five years, from around 4 % currently to approximately 7 % by 2016. The market support price for new solar energy systems has reduced to half since 2008 due to the the feed-in tariffs for renewable

[6] https://www.clearingstelle-eeg.de/files/private/active/0/5-EEG_2000_BGBl-I-305.pdf. Accessed on 11th December, 2014.

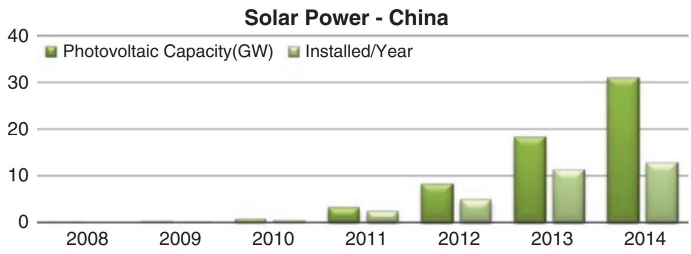



**Fig. 6** Solar electricity net generation and consumption 2008–2014

energy, which were announced by the German Renewable Energy Act (see Footnote 6). A feed-in tariff allows stakeholders a guaranteed return on their investment, which is a necessity for development. In 2012, support for solar energy fell by 27 %, which was two times the rate in 2011. At the end of 2012, Germany had 36 GW of installed solar capacity, which produced 28.3 TWh of electricity.[7] The country's largest photovoltaic power plants are Senftenberg Solar park (capacity 148 MW), Lieberose Photovoltaic Park (70.8 MW), Strasskirchen Solar Park (54 MW), Waldpolenz Solar Park (thin filmed PV power plant with a capacity of 40 MW), and Köthen Solar Park (45 MW).[8] Solar water and air collector capacity exceeded 283 GWth in 2012 and reached an estimated 330 GWth by the end of 2013. As in past years, China has been the main demand driver, accounting for more than 80 % of the global market (REN 2014d).

### 2.2.2 China

The solar PV market had a record year, adding more than 39 GW in 2013 for a total exceeding 139 GW. China showed impressive growth, accounting for nearly one-third of the worldwide capacity, followed by Japan and the United States (REN 2014d). In comparison to the cumulative global installation, China's manufacturing industry has achieved the unexpected. Since 2004, the growth rate of China's solar cell manufacture surpassed 100 % in the period from 2008 to 2013 as shown in Fig. 6 (IEA 2013c). Overall, 400 PV companies are currently doing business in China and hence, China is the world's leading installer of solar PV, adding a record 11.3 GW of capacity to a cumulated 18.3 GW in 2013 (A Snapshot of Global PV 1992), which is more than twice as much as in 2012 when China installed about 5.0 GW of solar panel capacity (China National Photovoltaics Status Report 2012). In 2013, more than 50 % of China's new photovoltaic was installed in the western provinces of Gansu, Xinjiang, and Qinghai, being distant from population hubs. The world's largest 320 MW solar cell project was accomplished at the end of 2013 near to the Longyangxia hydropower dam situated in Qinghai (IEA 2013c). Intense

[7] http://theenergycollective.com/robertwilson190/456961/reality-check-germany-does-not-get-half-its-energy-solar. Accessed on 11th December, 2014

[8] German Solar Industry Association: The network of solar industry. Available at: http://www.solarwirtschaft.de/.

development work is being carried out in China with large projects in remote areas to increase the installation of small systems that do not require electricity transmission from remote places. China has also targeted to instal more than 8000 megawatts of rooftop photovoltaics by 2014 (BP 2014). It is evident that China can soon become the world leader in solar power being already so in wind power. In May 2014, the government of China announced a solar cell target of 70 GW by 2017.[9]

As in past years, China was the main demand driver, accounting for more than 80 % of the global market and maintaining its lead in the production of solar thermal collectors. Demand in key worldwide markets continued to be slow, but markets expanded in a few countries such as Brazil, India, Greece, etc., where solar thermal water heating is cost competitive. The trend toward deploying large domestic systems continued, as did growing interest in the use of solar thermal technologies for district heating, cooling, and industrial applications (see Footnote 7). Concentrated solar power (CSP) is also expanding rapidly in China. The production capacity in China is expected to cross 1 GW by 2020. Companies that have successfully operated CSP prototype systems in pilot locations globally are progressing toward multi-megawatt CSP projects.[10]

### 2.2.3 Italy

Solar power installation in Italy has grown rapidly in recent years with the country ranking among the world's largest producers of electricity through solar energy. In line with the European renewable energy directives, Italy has to obtain 17 % of its ultimate energy intake from renewable energy sources by 2020. According to Italy's National Renewable Energy Action Plan (NREAP), the country has a target of sharing 26.4 % of electricity from renewable energy (Sahu 2015). To encourage the development of electricity generation from renewable resources, Italy is using a range of incentive policies such as green certificates, market premiums, feed-in tariffs, and reverse auctions. In accordance with the liberal solar PV feed-in tariffs (FiTs), decreasing PV equipment prices, and good quality solar assets, almost 7900 MW of solar PV capacity was installed in 2011 (REN 2014c). Italy was the largest solar market in the world in 2011. At the end of 2012, with regard to the total PV capacity installed, Italy ranked third worldwide with nearly 17,600 MW just behind the leader, Germany.[11] During 2013, overall 7 % of the electricity generated was through solar power, while it is expected to double by 2030.[12]

[9] http://www.earth-policy.org/indicators/C47/solar_power_2014. Accessed on 2th December, 2014.

[10] http://www.helioscsp.com/noticia.php?id_not=2337. Accessed on 2th December, 2014.

[11] http://www.earth-policy.org/datacenter/xls/indicator12_2014_2.xlsx. Accessed on 3rd December, 2014.

[12] http://www.pv-tech.org/news/italys_pv_generated_electricity_increased_by_19_in_2013. Accessed on 4th December, 2014.

Italy introduced its quota and green certificate program in 1990 in order to stimulate the electricity generation from nonconventional sources. However, solar electricity generation is reinforced only by a solar-specific feed-in tariff method. In 2005 and 2006, the Italian Ministry of Economic Development allotted decrees that generated a premium incentive for solar PV. The policy provided an incentive background with tiered tariffs and premiums for solar PV projects of different sizes and at different sites like buildings, land, etc. The existing form of Italy's solar PV incentive policy, the Conto Energia V, came into force in August 2012 and provided definite feed-in tariffs and premiums for 20 years. Conto Energia V announced average incentive reductions of 43 % for surface attached installations and 39 % for rooftop PV panels compared to the incentive levels available before 2012 (Sahu 2015).

### 2.2.4 Japan

Japan is the world's fourth largest energy consumer, making solar power an important national project. Since the late 1990s, Japan started its energy program with solar energy and is presently a leading manufacturer of solar panels. Due to these efforts, Japan ranks fourth in the world for cumulative solar PV installed capacity, which is mostly grid connected (see Footnote 12). By the end of 2013, Japan had installed 13,600 MW of PV, which is enough to generate 13,600 GWh (1.4 % of 2013s national electricity consumption).[13] In 2014, Japan will emerge as the largest solar power in the world as China is losing its solar capacity target of 14 GW in 2014. Japan is also expected to add 10.3 GW to 11.9 GW of solar power in 2014.[14]

Though the present renewable energy usage is low, Japan is planning to speed-up added renewable energy development. Among these sources, solar energy is considered as one of the most encouraging energy alternatives. Japan is the fastest rising nation that is encouraging PV and is now leading the world Photovoltaic market. Indeed, 45 % of photovoltaic cells in the world are manufactured in Japan. Japan installed 6.9 GW of PV in 2013 and ranked second in terms of installations.

### 2.2.5 The United States

In 2013, renewables faced declining policy support and uncertainty in many European countries and in the US. Electric grid-related constraints, opposition in some countries from electric utilities concerned about rising competition, and

[13] http://www.iea-pvps.org/index.php?id=93&eID=dam_frontend_push&docID=2099. Accessed on 4th December, 2014.

[14] http://www.greentechlead.com/2014/11/28/japan-displace-china-largest-solar-market-2014-19922. Accessed on 4th December, 2014.

continuing high global subsidies for fossil fuels were the main concerns. However overall, with some exceptions in Europe and the United States, renewable energy developments were positive in 2013. The USA conducted much early research in PV and CSP, and due to these efforts it was among the top countries in the world to generate enough electricity through solar energy. The oldest solar power plant in the world is the 354 MW SEGS thermal power plant in California (Sharma 2011). The Ivanpah Solar Electric Generating System is a solar thermal power project in the California Mojave Desert, with a gross capacity of 392 megawatts (MW).[15] The 280 MW Solana Generating Station is a solar power plant near Gila Bend, Arizona, completed in 2013. Present trends specify that a huge number of photovoltaic power plants are being constructed in the south and southwest regions, where there is sufficient land in the sunshiny deserts of California and Arizona.

## 3 Solar Energy Status—India

India is bestowed with an abundance of solar energy, which can produce up to 5000 trillion kilowatts of clean green energy. The country has almost 300 sunny days every year and 4–7 kWh/$m^2$ of solar insolation every day (see Footnote 3). If this energy is harnessed proficiently, it can easily decrease our energy deficit situation with zero carbon emission. Several states in India have already recognized their solar energy potential and other states are geared to meet their rising energy needs with clean and abundant solar energy. Figure 7 shows a pictorial view of global horizontal irradiation on different regions in India (see Footnote 5).

### *3.1 Institutional Framework*

Till date, there are several organizations in India involved in renewable energy development and research. Their policies, aim, and objectives are as below:

#### 3.1.1 Ministry of New and Renewable Energy (MNRE)

India was the first country to set up a ministry for new and renewable resources in order to accelerate research and development in this field. The MNRE is the nodal Ministry of the Indian Government for all matters involving new and renewable energy. The main objective of MNRE is to develop and instal renewable source technologies in order to meet the energy necessities of the country (see Footnote 2).

[15] http://www.nrel.gov/csp/solarpaces/project_detail.cfm/projectID=62. Accessed on 5th December, 2014.

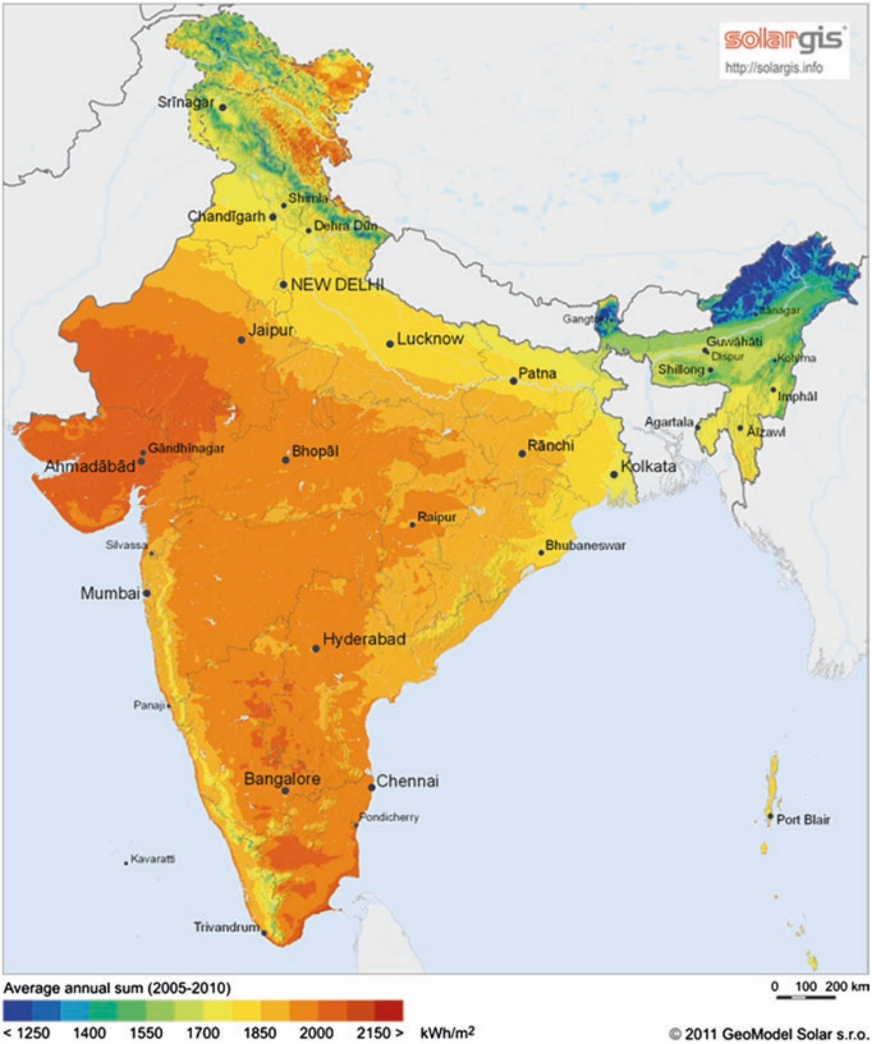



**Fig. 7** Global horizontal irradiation (GHI) in India

This ministry deals with the formulation of policies and their implementation. It is subdivided into different divisions that deal with the respective renewable resource, its development, and technologies related to it. The additional policies of the ministry are executed by State Nodal Agencies. All the big States have introduced energy agencies solely for nonconventional energy sources. These agencies, consecutively, organize contributions from nongovernmental organizations, local institutions, and village-level groups for implementation of policies. Simultaneously, the R&D

platform is supported by the MNRE, chiefly in educational establishments, national test centers, and to a certain degree, in public and private sector industries.

Under the Allocation of Business Rules, being a scientific ministry the following specific duties are allotted to MNRE:

- Research and advancement of biogas and promotion of programs involving biogas elements;
- Programs regarding upgraded chulhas (cooking system) and their improvement;
- Indian Renewable Energy Development Agency (IREDA);
- Integrated Rural Energy Program (IREP);
- Wind energy;
- Everything related to hydro power projects irrespective of their size;
- Study and expansion of other renewable sources of energy, and program involving their development;
- Geothermal Energy.

### 3.1.2 State Nodal Agencies

For advertising and commercialization of nonconventional energy sources and increasing energy security in the country, state nodal agencies have been arranged in different states of India. These agencies function under the (MNRE) Ministry of New and Renewable Energy and they promote renewable sources and energy proficiency in the corresponding states.

The main objectives of these state nodal agencies are as follows:

- Promote, synchronize, and encourage research projects for archetype (demo projects) and trial examinations in a specific area for renewable energy sources.
- Deliver technical and monetary aids for the creation of programs, policies, and schemes for addition of renewable energy development in respective states.
- Carry out by itself or in association with other agencies, programs of research and advancement, applications, and addition as related to different renewable energy sources.
- Commence or promote techno-economic viability studies for cost–benefit examination.
- Frame and implement broad-based programs for conservation of energy at different stages of operation, in different sections of the economy.
- Investigate the environmental effects of all energy-related procedures.
- Form an Energy Resources Center, which will gather and compare energy and interconnected information.
- Develop and sustain documentation facilities in the field of energy and renewable energy above all.
- Develop communication and teaching projects for prevalent broadcasting of energy and environmental concerns.

### 3.1.3 Indian Renewable Energy Development Agency (IREDA)

The IREDA was founded on March 11, 1987 as a government company under the Companies Act, 1956.[16] It was formed to sponsor, develop, and outspread monetary aid for renewable energy and energy proficiency. The main objectives of IREDA include:

- To offer economic support for projects and schemes dealing with generation of electricity through conventional methods and through renewable sources and also to sustain energy via energy efficiency.
- To keep up its place as a leading organization to deliver proficient financing in renewable energy and conservation projects.
- To escalate its share in the renewable energy sector by advanced financing.
- Develop productivity of services given to customers through frequent development of systems, procedures, and resources.
- To struggle to be a competitive institution for maintaining customer satisfaction.

## 4 Jawaharlal Nehru National Solar Energy Mission (JNNSM)

The JNNSM was launched on January 11, 2010 by the Prime Minister under the banner of renewable energy.[17] It is part of India's National Action Planon Climate Change, which focuses on India's response to climate change, and addresses diverse policy issues such as energy security and the creation of new competencies (PMI 2010). The main aim of this mission is to make India a global leader in terms of solar energy, by forming policies for its bigger scale distribution throughout the country as fast as possible.

The mission has set the ambitious target of deploying 20,000 MW of grid-connected solar power by 2022 and is aimed at reducing the cost of solar power generation in the country through (i) long-term policy; (ii) large-scale deployment goals; (iii) aggressive R&D; and (iv) domestic production of critical raw materials, components, and products, in order to achieve grid tariff parity by 2022 (PMI 2010). The mission will create an enabling policy framework to achieve this objective and make India a global leader in solar energy. The Mission was set up with a three-phase method, traversing from the period 2011–2022. The period from 2010–2013 is known as Phase I, the 12$^{th}$ Plan, i.e., 2013–2017 as Phase II, and 2017–2022 the 13$^{th}$ Plan as Phase III(see Footnote 19).

In the midterm of each plan, and all through till the end of the 12th and 13th Plans, assessment will be carried out for advancement and evaluation of capacity and goals for the following phases, based on emerging cost and technology trends,

[16] http://www.ireda.gov.in/. Accessed on 5th December, 2014.

[17] http://www.mnre.gov.in/file-manager/UserFiles/mission_document_JNNSM.pdf. Accessed on 5th December, 2014.

**Table 2** JNNSM target of Capacity additions (see Footnote 19)

| S. no | Phase | Segments | | |
|---|---|---|---|---|
| | | Utility grid together with rooftop installations (MW) | Off- grid solar applications (MW) | Solar collectors |
| 1 | Target for Phase I | 1000 | 200 | 7 million square meters |
| 2 | Cumulative target for Phase II | 10,000 | 1000 | 15 million square meters |
| 3 | Cumulative target for Phase III | 20,000 | 2000 | 20 million square meters |

both domestic and global. The objective of this mission is to defend the government from subsidy exposure in case the predicted cost decline does not materialize or it is quicker than the expectations. The immediate aim of the Mission was to focus on developing a facilitating environment for solar technology dissemination in the country at the centralized and decentralized levels. The first phase focused on the development of small hanging alternatives in solar energy, encouraging off-grid systems to provide energy to the population that did not have access to main grid energy production. The other goal is the addition of a modest capacity in grid-based systems. In the second phase, as per the achievements made in the previous plan, capacity will be aggressively scaled-up to create an environment of accelerating and competitive solar energy dispersion in the country.

### 4.1 Mission Targets for the Three Phases

The mission, also called Solar India, has set a determined objective of totalling 20 GW of grid-connected solar energy and 2 GW of off-grid capacity by 2022 in three phases. The target of the mission under each phase is given in Table 2.

### 4.2 Capacity Additions in Phase I

Regardless of having vast solar resources, India's solar power capacity was virtually imaginary till lately. Relentless development in this industry came with the commencement of the Mission in 2010. Before this India's solar power capacity was only 17.8 MW.[18] Phase I of the Mission was focused on grid-connected solar

[18]ceew.in/pdf/Roundtable-Issue-Brief.pdf. Accessed on 5th December, 2014.

**Table 3** State wise installed capacity of solar PV projects under various schemes as of January 31, 2014 and September 30, 2014

| S. no. | State/UT | Total commissioned capacity till January 31, 2014 (MW) | Total commissioned capacity till September 30, 2014 (MW) |
|---|---|---|---|
| 1 | Andhra Pradesh | 92.9 | 169.66 |
| 2 | Arunachal Pradesh | – | 0.025 |
| 3 | Chhattisgarh | 5.1 | 7.1 |
| 4 | Gujarat | 860.4 | 919.05 |
| 5 | Haryana | 7.8 | 12.8 |
| 6 | Jharkhand | 16 | 16 |
| 7 | Karnataka | 31 | 54 |
| 8 | Kerala | – | 0.025 |
| 9 | Madhya Pradesh | 195.315 | 355.08 |
| 10 | Maharashtra | 237.25 | 283.9 |
| 11 | Orissa | 15.5 | 29.5 |
| 12 | Punjab | 9.325 | 35.77 |
| 13 | Rajasthan | 666.75 | 727.55 |
| 14 | Tamil Nadu | 31.8217 | 99.5 |
| 15 | Uttar Pradesh | 17.375 | 29.51 |
| 16 | Uttarakhand | 5.05 | 5 |
| 17 | West Bengal | 7.05 | 7.21 |
| 18 | Andaman and Nicobar | 5.1 | 5.1 |
| 19 | Delhi | 3.0138 | 5.465 |
| 20 | Lakshadweep | – | 0.75 |
| 21 | Puducherry | – | 0.025 |
| 22 | Chandigarh | – | 2 |
| 23 | Others | 1.615 | 0.79 |
| | Total | 2208.3655 | 2765.81 |

energy projects. In order to obtain 500 MW of photovoltaics and 500 MW of solar thermal energy, the central government directed two batches of reverse sales. These bidding practices offered feed-in tariffs and long-term PPAs to the particular least cost designers. The feed-in tariffs were accompanied by support to energy benefits through the bundling of solar power with conventionally created electricity, decreasing the average per-unit cost of solar electricity. Table 3 shows the cumulative capacity of installations made in different States in India during Phase I of JNNSM (http://mnre.gov.in/file-manager/UserFiles/grid-connected-solar-power-project-installed-capacity.pdf assessed on 6th December, 2014).

With the purpose to expedite grid-connected solar power production in Phase I, short of direct funding by the Government of India, it has permitted NTPC Vidyut Vyapar Nigam (NVVN) as the central organization to buy 1000 MW of solar power from different project creators, bundle it with the unassigned power

**Table 4** Indian cumulative power production

| Fuel | MW | Share (%) |
|---|---|---|
| *Total thermal* | | |
| Coal | 1,52,971 | 60.2 |
| Gas | 22,608 | 8.9 |
| Oil | 1200 | 0.5 |
| Hydro (Renewable) | 40,799 | 16.1 |
| Nuclear | 4700 | 1.9 |
| RES (MNRE) | 31,692 | 12.5 |
| Total | 2,54,049 | |

obtainable from the NTPC coal-based centers, and sell this power to the delivery services. The bundling concept was presented to keep the cost at nearly Rs. 5/kWh. It was decided to choose projects of a capacity of 500 MW each centered on solar thermal and solar photovoltaic technologies. Due to a comparatively lengthier gestation period of solar thermal energy, which is of about two years or more, the setup of projects for 500 MW was accomplished in the 2010–2011 five-year plan. The size of solar thermal projects was between 20 and 100 MW per project designer.[19]

## 5 Grid-Connected Solar Power in India

The electricity sector in India had an installed capacity of around 254.04 GW as on September 2014. Eliminating captive production the electricity production in India was 911.6 TWh in the financial year 2013. There was a 4 % growth over the previous year 2012. During 2014, electricity production was at 967 TWh. Over the financial year 2007–2014, electricity production increased at a CAGR compound annual growth rate of 5.6 % (Ministry of Power Central Electricity Authority, New Delhi: GOI. Executive Summary Power Sector: Sept 2014). Table 4 shows the Indian cumulative power production as on September 30, 2014.[20]

Table 5 also gives the status of the grid-connected renewable as on September 30, 2014 as per the data shown on the MNRE website.[21] Wind power played a major role in the renewable energy sector, while the solar energy share also improved due to the JNNSM in the past few years. The same progress will be maintained in the near future up to 2022.

[19] mnre.gov.in/file-manager/UserFiles/draft-jnnsmpd-2.pdf. Accessed on 6th December, 2014.

[20] http://www.powermin.nic.in/indian_electricity_scenario/introduction.htm. Accessed on 7th December, 2014

[21] http://www.mnre.gov.in/mission-and-vision-2/achievements/. Accessed on 7th December, 2014.

**Table 5** Status of the renewable energy in India

| Renewable energy program/systems | Cumulative achievement up to 30 September 2014 | Share (%) |
|---|---|---|
| Wind power | 21,996.78 | 67.10 |
| Small hydro power | 3856.68 | 11.77 |
| Biomass power and gasification | 1365.20 | 4.16 |
| Bagasse cogeneration | 2689.35 | 8.20 |
| Waste to power | 106.58 | 0.33 |
| Solar power | 2765.81 | 8.44 |
| Total | 32,780.40 | 100.00 |

## 6 Challenges for Grid-Connected Solar Power

Solar energy continues to be expensive compared to other sources of renewable energy. It has heavy investments along with established and directed policy measures to incentives for various stakeholders. The challenge is to bring down the cost of raw material and other allied activities for installing solar power systems. Reducing the installation cost may enhance return on investment (ROI) of the investors, thereby attracting investors. Solar energy is of intermittent nature, thereby making it difficult to integrate in the grid. This is true in most renewable sources. Intermittent supply can disturb the grid system by creating an imbalance. The efficiency of solar cells which was relatively low (15–22 %) compared to other sources of energy production has been found to be increasing and currently is about 47 %. However, such a high efficiency level is just at the experiment level and commercially unavailable.

Solar tariff determination is a challenging area for the State Electricity Regulatory Commission (SERCs). To minimize large variance across states the Central Electricity Regulatory Commission (CERC) issues guidelines for tariff determination, which states that tariff of solar power can be around Rs. 7.72 per KWh for PV-based power plants and Rs. 11.88 per KWh for solar thermal-based power plants.

On January 27, 2012, while deciding levelized tariff for solar photovoltaic power, the Gujarat Electricity Regulatory Commission (GERC) considered a capital cost of Rs.100 million/MW or 1–2 lakh/kW, operations and maintenance cost (0.75 % of the capital cost with 5.72 % annual escalation), capacity utilization (18 %), performance degradation (1 %), auxiliary consumption (0.25 % of energy generation), and rate of return (14 %). Based on the above-mentioned technical and financial parameters, the levelized tariff including return on equity for megawatt-scale solar photovoltaic power projects availing accelerated depreciation is calculated to be Rs. 9.28 per kWh, while the tariff for similar projects not availing accelerated depreciation is calculated to be Rs. 10.37 per kWh.[22]

[22]www.ireeed.gov.in/policyfiles/147-224_GJ0305270112.pdf. Accessed on 7th December, 2014.

**Table 6** Tariff rates for solar photovoltaic's power plants commissioned in Gujarat from January 29 to March 2015 (2012)

| Photovoltaic systems | Tariffs | January 29, 2012–March 31, 2013 | April 1, 2013–March 31, 2014 | April 1, 2014–March 31, 2015 |
|---|---|---|---|---|
| For megawatt-scale photovoltaic projects availing accelerated depreciation | Levelized tariff for 25 years | Rs. 9.28 | Rs. 8.63 | Rs. 8.03 |
| | For first 12 years | Rs. 9.98 | Rs. 9.13 | Rs. 8.35 |
| | For subsequent 13 years | Rs. 7.0 | Rs. 7.0 | Rs. 7.0 |
| For megawatt-scale photovoltaic projects not availing accelerated depreciation | Levelized tariff for 25 years | Rs. 10.37 | Rs. 9.64 | Rs. 8.97 |
| | For first 12 years | Rs. 11.25 | Rs. 10.30 | Rs. 9.42 |
| | For subsequent 13 years | Rs. 7.50 | Rs. 7.50 | Rs. 7.50 |
| For kilowatt-scale photovoltaic projects availing accelerated depreciation | Levelized tariff for 25 years | Rs. 11.14 | Rs. 10.36 | Rs. 9.63 |
| For kilowatt-scale photovoltaic projects not availing accelerated depreciation | Levelized tariff for 25 years | Rs. 12.14 | Rs. 11.57 | Rs. 10.76 |

GERC determined the tariff for two sub-periods. For megawatt-scale photovoltaic projects availing accelerated depreciation, the tariff for the first 12 years shall be Rs. 9.98 per kWh and for the subsequent 13 years it shall be Rs. 7 per kWh. Similarly, for megawatt-scale photovoltaic projects not availing accelerated depreciation, the tariff for the first 12 years shall be Rs. 11.25 per kWh and for the subsequent 13 years it shall be Rs. 7.50 per kWh as given in Table 6.

Similarly, the levelized tariff including return on equity in kilowatt-scale solar photovoltaic power projects availing accelerated depreciation is calculated and finalized at Rs. 11.14 per kWh, while the tariff for similar projects not availing accelerated depreciation is calculated and finalized at Rs. 12.44 per kWh. The Commission has decided that there shall be a flat levelized tariff for 25 years for the kilowatt-scale photovoltaic power projects. The GERC determined levelized tariff for solar thermal power projects availing accelerated depreciation to be Rs. 11.55 per kWh, while the tariff for similar projects not availing accelerated depreciation was to be Rs. 12.91 per kWh.

## 7 Conclusion

JNNSM is one of the key initiatives launched by the Government of India to bring about solar energy revolution in India. The solar energy revolution is on its way to impact the livelihood of the rural Indian household. The intended initiative is directed to change the energy consumption style of urban and industrial consumers. JNNSM is expected to build awareness, elicit interest, ignite desire, and stimulate use of solar energy in the country. The program is well designed and directed to bring renewable orientation among the stakeholders. It is expected that the program can bring a change in energy consumption orientation, which can lead toward green production, transport, and above all a greener environment.

Under the off-grid and decentralized solar applications scheme of the JNNSM, the MNRE provides a 30 % capital subsidy, which ranges from Rs.27/-per Wp to Rs.135/- per Wp for installation of solar PV systems and power plants. In order to promote extensive adoption of solar applications the Ministry provides additional incentives to special category States, viz., the Northeastern States, Sikkim, Jammu & Kashmir, Himachal Pradesh, and Uttarakhand, Lakshadweep and A&N Islands, a capital subsidy 90 %, which ranges from Rs.81/- Wp to Rs. 405/-per Wp for Government organizations (Not for commercial organizations and corporations).

JNNSM set a target of achieving installation solar heaters of about cumulative 42 million sq. m by 2022. At the end of the first phase, 2010-2013 the mission achieved the target of 7 million sq. m installation (see Footnote 21). According to the recent statistics of MNRE, by the end of August 2014, projects with a total capacity of 28,778 kWp were to be sanctioned under off-grid solar applications.

It is observed that the government initiatives under the JNNSM were found to have a positive impact on:

- the growth solar energy production and consumption;
- growth of solar equipment manufacturing industry;
- employment generation;
- rural electrification;
- solar lighting;
- solar water heating system installation.

It is noticed that the solar equipment manufacturing industry is rapidly growing in India and JNNSM seems to be the driving force behind the growth story. Currently, there are many manufacturers empanelled with the MNRE or its agencies for:

- solar pump manufacturers (19+),
- solar light manufacturers (32),
- solar tube collectors (55+),
- solar water heater systems (158+).

It is clearly visible that the JNNSM seems to galvanize the growth and development of the solar energy market in India. The market is steadily striving for higher efficiency and effectiveness. There is no second thought in our mind that JNNSM is going to improve our share of renewable energy supply at affordable price and establish a sense of supply security in the country.

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# Part II
# Wind Energy

# Insights into Wind Energy Market Developments in India

**Sanjay Kumar Kar and Atul Sharma**

**Abstract** Wind power is gaining a stronger position in the Indian electricity market, mainly due to preferential feed-in tariff and other incentives given by the Central and State governments. This chapter assesses the growth of the Indian wind market compared to other leading markets in the globe. Then, State-level progress is discussed in detail. The chapter reviews policy measures and incentive schemes devised by the Central government, State government, and regulatory bodies to achieve the desired objectives. The authors discuss the challenges of increasing wind penetration in India and conclude with steps to achieve greater wind penetration through active participation of the Central and State governments and the regulatory bodies by working cohesively and collaboratively to iron out implementation failures and take appropriate measures for successful implementation of various rules, regulations, and policies.

**Keywords** Wind energy · India · Policy · Indian Electricity Act 2003

## 1 Introduction

The electricity sector accounts for a significant portion of greenhouse gas (GHG) emissions in the world. In India, this sector contributes approximately 40 % of GHG (PGCIL 2013) as close to 69 % power generation is based on fossil fuel.

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Considering depleting fossil fuel reserves, environmental degradation, and high level environmental externalities, there is an increasing need for harnessing renewable energy. One of the renewable sources with proven technology, commercial viability, and greater acceptability is wind energy. Globally, wind power deployment has been steadily increasing since 2003 and extended to 318 GW in 2013. Cumulative capacity deployment has been led by China, the United States, Germany, Spain, and India. Wind power installation now constitutes about 4.9 % of the total global electricity installed capacity of 6500 GW (GWEC 2013) and about 8.5 % in India. European state heads set an ambitious target of achieving wind contribution of 20, 33, and 50 % by 2020, 2030, and 2050 respectively. Wind technology roadmap by the International Energy Agency (IEA 2013) targets 15–18 % share of global electricity from wind power by 2050. Achieving such targets at various levels demands adequate grid infrastructure with efficient integration and development of active and efficient international power exchange.

## 2 Renewable Energy

Renewable energy (RE) is growing steadily and is most likely to become the backbone of many developed and developing countries (Kar et al. 2015). RE has been given necessary support across the globe. For example, the cost of support mechanisms for renewable energy was over €30 billion in 2010 across the European Union (EU), of which €2.2 billion was for wind energy. According to IEA (2014) global renewable generation is seen to rise by 45 % and make up nearly 26 % of global electricity generation by 2020. The share of RE in India is increasing and the figure stood at 12.4 % by the end of February 2014. The southern region has the highest share of renewable power with 22.5 % while the eastern region has only a 1.4 % share (Table 1).

### *2.1 Rationale for Renewables*

Rising fossil fuel prices, energy security concerns, and environmental considerations are expected to drive RE sources like wind in many parts of the world. Reduced subsidy on fossil fuel, imposition of carbon tax, and increasing support for RE through fiscal, monetary, and other incentives will allow renewable fuels to compete economically with existing alternatives. In this section various factors pushing for RE are discussed.

#### 2.1.1 Fossil Fuel Prices

Price of fossil fuels is highly volatile. Historical data suggests that fossil fuel, especially crude price has been exposed to numerous shocks in the past and such shocks cannot be ruled out in the future. Numerous reasons ranging from

**Table 1** All India installed electricity generation capacity (MW) as of February 28, 2014

| Region | Thermal | | | Thermal total | Nuclear | Hydro | RES | Grand total | Share (%) of RES |
|---|---|---|---|---|---|---|---|---|---|
| | Coal | Gas | Diesel | | | | | | |
| Northern | 35,283.5 | 5281.26 | 12.99 | 40,577.75 | 1620 | 15,994.75 | 5729.62 | 63,922.12 | 9.0 |
| Western | 54,069.51 | 9739.31 | 17.48 | 63,826.3 | 1840 | 7447.5 | 9925.19 | 83,038.99 | 12.0 |
| Southern | 26,582.5 | 4962.78 | 939.32 | 32,484.6 | 1320 | 11,398.03 | 13,127.33 | 58,329.96 | 22.5 |
| Eastern | 24,727.88 | 190 | 17.2 | 24,935.08 | 0 | 4113.12 | 417.41 | 29,465.61 | 1.4 |
| North-east | 60 | 1208 | 142.74 | 1410.74 | 0 | 1242 | 252.65 | 2905.39 | 8.7 |
| Islands | 0 | 0 | 70.02 | 70.02 | 0 | 0 | 10.35 | 80.37 | 12.9 |
| All India | 140,723.4 | 21,381.35 | 1199.75 | 163,304.5 | 4780 | 40,195.4 | 29,462.55 | 237,742.44 | 12.4 |
| Share (%) | 59.2 | 9.0 | 0.5 | 68.7 | 2.0 | 16.9 | 12.4 | 100.0 | |

*Source* Author's analysis based on GoI, CEA, 2014 geopolitical to man-made disasters have been responsible for oil shocks and high price fluctuations. Such fluctuations often lead to speculation and economic instability. Unexpected price rise of fossil fuel results in financial disorder in fossil fuel import driven countries. For instance, the Asian Coal Marker price per ton increased from $84.57 in 2007 to $148 in 2008. Such stiff price impacted many importing countries. During the same period Liquefied Natural Gas (LNG) import price registered a rise of 62 %, from $7.73/MMBtu to $12.55/MMBtu. During 2000–2013, the price of benchmark spot crude like Brent, Dubai, and Nigerian Farcados grew at a compounded annual growth rate exceeding double digits and the Western Texas Intermediary (WTI) was not far behind (Table 2). The historical data suggests the prices of all the fossil fuels have been increasing, with few reductions. To minimize the impact of fossil fuel price fluctuations on the energy expenditure, renewable sources have been identified as the thrust area for future energy demand and supply.

### 2.1.2 Environmental Concerns

Increasing concerns over the continued use of fossil fuel-based power generation is leading to environmental pollution and threat to existence of mother earth, including humans. The extraction, processing, and combustion of fossil fuels cause significant adverse impacts on water and air quality, human health and mortality, bio-diversity, and global temperature.

Greenhouse gases (GHG) released by burning of fossil fuels like carbon monoxide (CO), sulfur dioxide ($SO_2$), oxides of nitrogen, and particulate matter and heavy metals such as mercury create several environmental disturbances and can also be fatal to humans. For example, $SO_2$ contributes to acid rain formation which is detrimental to buildings and monuments. The World Health Organization (WHO) reports that in 2012 around 7 million people died—one in eight of total global deaths—as a result of exposure to air pollution. Diseases like ischemic heart disease, stroke, chronic obstructive pulmonary disease (COPD), lung cancer; and acute lower respiratory infections in children are the outcome of pollution. It should be noted that “Excessive air pollution is often a by-product of unsustainable policies in sectors such as transport, energy, waste management and industry. In most cases, healthier strategies will also be more economical in the long term due to health care cost savings as well as climate gains” (WHO 2014).

Globally, fossil-fuel-fired power plants are the single largest source of anthropogenic $CO_2$ emissions. Existing power plants around the world will pump out more than 300 billion tons of carbon dioxide over their expected lifetimes and the power plants constructed globally in 2012 alone will produce about 19 billion tons of $CO_2$ during their existence (Davis and Socolow 2014). Fossil power is expanding globally, and the already substantial committed emissions from the power sector are increasing. For example, fossil-based power generation contributed about 38 % carbon dioxide emissions and 31 % of the total US greenhouse gas emissions in the US in 2012 (USEPA 2014).

**Table 2** Global fossil fuel price fluctuations during 2000–13

| | Coal price ($/tonne) | | | LNG price ($/MMBtu) | | | | Spot crude price ($/bbl) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Asian marker | Northwest Europe marker | US Central | Japan (cif) | German (cif) | NBP index, UK | Henry Hub, US | Brent | WTI | Dubai | Nigerian Farcados |
| 2000 | 31.76 | 35.99 | 29.90 | 4.72 | 2.89 | 2.71 | 4.23 | 28.50 | 30.37 | 26.20 | 28.42 |
| 2001 | 36.89 | 39.03 | 50.15 | 4.64 | 3.66 | 3.17 | 4.07 | 24.44 | 25.93 | 22.81 | 24.23 |
| 2002 | 30.41 | 31.65 | 33.20 | 4.27 | 3.23 | 2.37 | 3.33 | 25.02 | 26.16 | 23.74 | 25.04 |
| 2003 | 36.53 | 43.60 | 38.52 | 4.77 | 4.06 | 3.33 | 5.63 | 28.83 | 31.07 | 26.78 | 28.66 |
| 2004 | 72.42 | 72.08 | 64.90 | 5.18 | 4.32 | 4.46 | 5.85 | 38.27 | 41.49 | 33.64 | 38.13 |
| 2005 | 61.84 | 60.54 | 70.12 | 6.05 | 5.88 | 7.38 | 8.79 | 54.52 | 56.59 | 49.35 | 55.69 |
| 2006 | 56.47 | 64.11 | 62.96 | 7.14 | 7.85 | 7.87 | 6.76 | 65.14 | 66.02 | 61.50 | 67.07 |
| 2007 | 84.57 | 88.79 | 51.16 | 7.73 | 8.03 | 6.01 | 6.95 | 72.39 | 72.20 | 68.19 | 74.48 |
| 2008 | 148.06 | 147.67 | 118.79 | 12.55 | 11.56 | 10.79 | 8.85 | 97.26 | 100.06 | 94.34 | 101.43 |
| 2009 | 78.81 | 70.66 | 68.08 | 9.06 | 8.52 | 4.85 | 3.89 | 61.67 | 61.92 | 61.39 | 63.35 |
| 2010 | 105.43 | 92.50 | 71.63 | 10.91 | 8.01 | 6.56 | 4.39 | 79.50 | 79.45 | 78.06 | 81.05 |
| 2011 | 125.74 | 121.52 | 87.38 | 14.73 | 10.48 | 9.04 | 4.01 | 111.26 | 95.04 | 106.18 | 113.65 |
| 2012 | 105.50 | 92.50 | 72.06 | 16.75 | 11.03 | 9.46 | 2.76 | 111.67 | 94.13 | 109.08 | 114.21 |
| 2013 | 90.90 | 81.69 | 71.39 | 16.17 | 10.72 | 10.63 | 3.71 | 108.66 | 97.99 | 105.47 | 111.95 |
| CAGR (%) | 8 | 7 | 7 | 10 | 11 | 11 | −1 | 11 | 9 | 11 | 11 |

*Source* Authors analysis based on the data compiled from BP Statistical Review 2014

According to the Centre for Science and Environment (Centre for Science and Environment 2013) air pollution is the fifth leading cause of death in India, with 620,000 premature deaths in 2010. This is up from 100,000 in 2000—a sixfold increase.

In the recent past the drive for environmental protection and climate change through reduced $CO_2$ and other harmful gas emissions has been the top priority for global bodies like WHO, United Nations (UN), International Monetary Fund (IMF), and World Bank. To meet the twin objectives of additional power production and $CO_2$ emission reduction, it is required to shutdown already built fossil-based power plants, restrict new fossil-based capacity addition, and promote renewable power production.

### 2.1.3 Energy Security

In the recent years the academic literature started expanding the scope of energy security from just supply security to many other dimensions (Winzer 2012; Mansson et al. 2014). Energy security has been critically analyzed based on supply of primary energy, resource availability (Hallock et al. 2004), production cost and cost fluctuations (Buen 2006), upstream markets and imports (Mansson et al. 2014; Kar and Sinha 2014), energy mix diversification, and lack of storage infrastructure (Kar and Sinha 2014). Other important factors that have been reviewed with respect to energy security include infrastructure, vulnerability and robustness, infrastructure resilience, economic vulnerability, high or volatile prices, and cost of power interruptions. The supply-based energy security discussion primarily focuses on high demand and supply vulnerability. Even the current energy security scholars are widening the scope of energy security by exploring interrelated areas and trying to establish linkage between food, water, and energy security.

The academic literature on India's energy security brings to light a rich mix of energy security concerns (Bambawale and Sovacool 2011) including supply, affordability, availability, and accessibility (Kar and Sinha 2014). In the Indian context, the energy security more or less synonymous with the supply security of fossil fuel as the country's import dependence has been constantly increasing. By March 31, 2013, the total crude oil and petroleum product import reached \$156,799 million from \$6413 million in March 1999. During this period, the petroleum product export increased from a meager \$86 million to \$60,664 million. Despite the strong export value growth, the net import was quite alarming with a value of \$94,553 million in 2013–2014 (PPAC 2014) and likely to have a severe dent in the trade deficit of the country in the future. India also imports LNG to the tune of \$4000–5000 million per annum. Besides that coal import increased from 17.9 % to 171 million tons in the financial year (FY) 2013–2014 amid a widening demand–supply gap in India. Considering the Asian Coal Marker Price of about \$91/ton prevalent in 2013, the import cost would translate to about \$15,540 million.

Globally as well as in India, energy security concern is one of the major drivers of renewable power development, especially wind power.

#### 2.1.4 Sustainable and Inclusive Growth

Sustainable development and the interdependence of the economy and environment are becoming increasingly important to global policy makers (John 1992). Even the sustainable development model is linked to inclusive growth in the developing and least developed countries. Sustainable development has been an important topic for policy makers and research scholars since 1970. Sustainable development has been defined as the development that meets the need of the future generations without compromising the ability of the future generation to meet their needs (WCED 1987; Pearce 1987). Many researchers such as John (John 1992) argue that sustainability is linked to less depletion of natural resources and conservation of nonrenewable sources. The World Bank (World Bank 1987) quoted that promoting growth, alleviating poverty, and protecting the environment are mutually supportive objectives in the long run.

Sustainable development should include inclusive growth, especially in the context of the developing and least developed world. CAPE for India (ADB 2007a) emphasized to increase support for inclusive development alongside infrastructure networks, energy efficiency, clean environment, regional cooperation, capacity development, and policy advice, among others (Rauniyar and Kanbur 2010). The Asian Development Bank, in its report (ADB 2007b), suggests for inclusive and environmentally sustainable growth.

## 3 Leading Wind Markets in the World

Currently, China leads in wind power installation, followed by the US, Germany, Spain, India, UK, Italy, France, Canada, and Denmark (Fig. 1). On the other hand the US leads in wind consumption followed by China, Germany, Spain, India, France, Italy, Portugal, and Canada. This section discusses in detail about the top ten countries in terms of wind installation.

### *3.1 China*

Currently, China is leading the wind capacity addition and cumulative wind capacity installation (91.4 GW) in the world. China had only 568 MW of installed capacity in 2003 and reached 91,424 MW by the end of 2013 (Table 3). In 2013, wind power generated 134.9 billion kWh of electricity compared to 100.4 billion kWh in 2012, contributing 2.6 % of the country's total electricity generation (GWEC 2013). Cai et al. (2011) indicate that the rapid development of RE, especially wind power has made a great contribution to emission reduction and job growth in China.

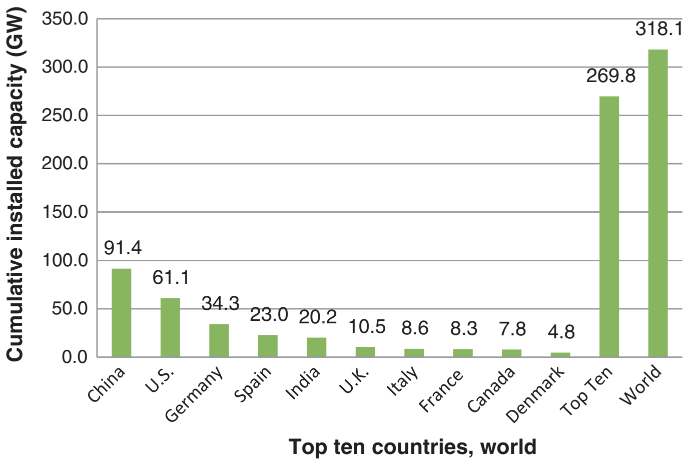



**Fig. 1** Cumulative wind installed capacity at the end of 2013

The phenomenal growth in terms of capacity addition has been achieved through a sustained focus on wind energy and well-developed wind policy framework leading to suitable investment climate for green energy. Wind power development in China could be divided into various phases: Phase-I (Demonstration Phase, 1986–2000), Phase-II (Early Commercialization and Tariff Setting, 2001–05), Phase-III (Renewable Energy Law and Targets, 2005–07), and Phase-IV [Wind Base Program, introduction of feed-in-tariff (FIT), offshore projects, and amendment of the Renewable Energy Law (2008–11)].

The demonstration stage was crucial for a kick-start and was gathering momentum. In the initial demonstration period (1986–1993), the main activity was building small-scale demonstration wind farms using grants from foreign donor countries and loans. By the end of the demonstration stage about 400 MW of wind power was installed in China.

During the second phase the market transformation through tariff setting and local manufacturing of wind turbines happened. By the end of 2004, the market share of locally made wind turbines had reached 18 % (Pengfei 2005). By the end of this phase, China achieved more than 2,000 MW installations.

The rapid growth of the wind energy industry in China has been driven primarily by national renewable energy policies developed during the third phase. The Renewable Energy Law introduced in 2006 and the first implementation rules of the law were issued in 2007. During this phase critical initiatives like mandatory market share renewable (excluding hydro) were set at 1 % by 2010 and the Chinese government continued to maintain 70 % content requirement. China surpassed competitors in Denmark, Germany, Spain, and the US in 2009 to become the largest producer of wind turbines (Bradsher 2010).

During the fourth phase, the Chinese government introduced the Wind Base Program in 2008 and identified seven key wind power bases like Heibei, Inner

**Table 3** Cumulative installed wind power capacity in top ten countries in the world (2003–13)

| Year | China | US | Germany | Spain | India | U.K. | Italy | France | Canada | Denmark | Top ten | World | Share of top ten (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2003 | 568 | 6372 | 14,609 | 6203 | 2125 | 648 | 913 | 253 | 322 | 3115 | 35,128 | 39,431 | 89.1 |
| 2004 | 765 | 6725 | 16,629 | 8263 | 3000 | 888 | 1255 | 390 | 444 | 3123 | 41,482 | 47,620 | 87.1 |
| 2005 | 1272 | 9149 | 18,415 | 10,027 | 4430 | 1353 | 1718 | 757 | 684 | 3127 | 50,932 | 59,091 | 86.2 |
| 2006 | 2599 | 11,575 | 20,578 | 11,623 | 6270 | 1968 | 2123 | 1711 | 1460 | 3136 | 63,043 | 73,938 | 85.3 |
| 2007 | 5910 | 16,824 | 22,194 | 15,145 | 7845 | 2428 | 2726 | 2495 | 1846 | 3136 | 80,549 | 93,889 | 85.8 |
| 2008 | 12,020 | 25,076 | 23,826 | 16,689 | 9655 | 3161 | 3736 | 3577 | 2369 | 3158 | 103,267 | 120,624 | 85.6 |
| 2009 | 25,805 | 35,086 | 25,673 | 19,160 | 10,926 | 4257 | 4849 | 4713 | 3319 | 3468 | 137,256 | 158,975 | 86.3 |
| 2010 | 44,733 | 40,298 | 27,097 | 20,623 | 13,065 | 5259 | 5797 | 5977 | 4008 | 3801 | 170,658 | 198,001 | 86.2 |
| 2011 | 62,364 | 46,929 | 29,071 | 21,674 | 16,084 | 6593 | 6878 | 6809 | 5265 | 3956 | 205,623 | 238,126 | 86.4 |
| 2012 | 75,324 | 60,007 | 31,270 | 22,784 | 18,421 | 8649 | 8118 | 7623 | 6204 | 4162 | 242,562 | 283,194 | 85.7 |
| 2013 | 91,424 | 61,091 | 34,250 | 22,959 | 20,150 | 10,531 | 8552 | 8254 | 7803 | 4772 | 269,786 | 318,117 | 84.8 |
| CAGR (%) | 66.2 | 25.4 | 8.9 | 14.0 | 25.2 | 32.2 | 25.1 | 41.7 | 37.5 | 4.4 | 22.6 | 23.2 | |

*Source* Authors analyzed using data available at http://www.earth-policy.org/data_center/C23, and other published sources

Mongolia East, Inner Mongolia West, Jilin, Jiangsu, Gansu Jiuquan, and Xinjiang for capacity addition of 69,076 MW by 2015 and 138,086 MW by 2020. In 2009, China introduced a feed-in tariff (FIT) for wind power generation, which applies for the entire operational period (usually 20 years) of a wind farm. China has four different tariff categories ranging from CNY 0.51/kWh (USD 0.08/kWh) to CNY 0.61/kWh (USD 0.10/kWh), depending on the region's wind resources. The introduction of FIT is considered to be one of the important indicators of long-term price stability.

Despite the exceptional growth over the last decade, by the end of 2013, China had just exploited 13 % of the total exploitable potential of 700 GW onshore and 1200 GW offshore wind energy (Junfeng et al. 2010). Despite its rapid expansion, the Chinese wind power sector continues to face significant challenges, including issues surrounding grid access and integration, reliability of turbines, and the development of offshore wind projects (IRENA-GWEC 2012).

Over the last decade, China has been aggressive in terms of capacity addition but capacity utilization seems to be low. Therefore, China is lagging behind the US in terms of wind power consumption. China was placed in the second position in 2013 and consumed more than the combined wind power consumption of Germany and Spain but 37.5 TWh lower than the US. Due to a lack of incentives, the Chinese grid operators were initially reluctant to absorb large amounts of wind energy, resulting in lower evacuation, transmission, and consumption. The Chinese government is committed to connecting 100 GW of wind power by 2015 and 150 GW by 2020 (IRENA-GWEC 2012, p. 49). This would enable China to overtake US as the leading wind power consuming country in the world.

## 3.2 USA

The US has been the leading wind power consumer in the world (Table 4) and has been constantly challenged by China. However, compounded annual growth rate is 27.9 %, which is lower than China (55.9 %). Wind energy continues to improve its standing in the US energy footprint, generating over 167 million MWh in 2013, with more than 4 % of electricity generation. In 2013, nine states in the USA achieved wind electricity generation of more than 12 % of their total electricity. Iowa was leading the table with 27.4 %, followed by South Dakota (26 %), Kansas (19.4 %), Idaho (16.2 %), Minnesota (15.7 %), North Dakota (15.6 %), Oklahoma (14.8 %), Colorado (13.8 %), and Oregon (12.4 %) (Mongomery 2014).

## 3.3 Germany

The German wind energy market continued to be the European leader with a capacity addition of 3238 MW in 2013 to bring Germany's total installed capacity

**Table 4** Wind power consumption (TWh)

| | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | CAGR (%) | Share in 2013 (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| United States | 11.3 | 14.3 | 18.0 | 26.9 | 34.8 | 55.9 | 74.6 | 95.6 | 121.4 | 142.2 | 169.4 | 27.9 | 27.0 |
| China | 1.0 | 1.3 | 1.9 | 3.7 | 5.5 | 13.1 | 27.6 | 44.6 | 70.3 | 96.0 | 131.9 | 55.9 | 21.0 |
| Germany | 18.7 | 25.5 | 27.2 | 30.7 | 39.7 | 40.6 | 38.6 | 37.8 | 48.9 | 50.7 | 53.4 | 10.0 | 8.5 |
| Spain | 12.5 | 16.2 | 21.3 | 23.3 | 27.8 | 32.5 | 37.9 | 44.2 | 42.4 | 49.5 | 55.8 | 14.6 | 8.9 |
| India | 2.6 | 5.2 | 6.0 | 9.5 | 11.4 | 13.3 | 18.2 | 21.7 | 26.4 | 31.2 | 34.8 | 26.6 | 5.5 |
| United Kingdom | 1.3 | 1.9 | 2.9 | 4.2 | 5.3 | 7.1 | 9.3 | 10.2 | 15.5 | 19.6 | 27.4 | 32.0 | 4.4 |
| France | 0.4 | 0.6 | 1.0 | 2.2 | 4.1 | 5.7 | 7.6 | 9.4 | 11.6 | 14.3 | 15.2 | 39.5 | 2.4 |
| Italy | 1.5 | 1.8 | 2.3 | 3.0 | 4.0 | 4.9 | 6.5 | 9.1 | 9.9 | 13.4 | 15.0 | 23.6 | 2.4 |
| Portugal | 0.5 | 0.8 | 1.7 | 2.9 | 4.0 | 5.7 | 7.5 | 9.1 | 9.0 | 10.0 | 11.8 | 34.1 | 1.9 |
| Canada | 0.7 | 0.9 | 1.6 | 2.4 | 3.0 | 3.8 | 6.6 | 8.6 | 10.1 | 11.2 | 11.5 | 29.2 | 1.8 |
| Total (top ten) | 50.4 | 68.6 | 83.9 | 108.8 | 139.5 | 182.6 | 234.5 | 290.4 | 365.5 | 438.1 | 526.1 | 23.8 | 83.7 |
| Total world | 63.4 | 85.6 | 104.3 | 133.1 | 170.6 | 219.1 | 277.8 | 343.2 | 435.9 | 522.1 | 628.2 | 23.2 | 100.0 |

*Source* Compiled and analyzed using data available in BP Statistical Review, 2014 up to 34.25 GW. During 2013, Germany contributed 27 % of wind capacity added in Europe (12,031 MW) and 29 % of the EU (11,159 MW).

During January 1–June 30, 2014, 30 offshore wind turbines with a combined capacity of 108 MW were connected to the grid (EWEA 2014) compared to 48 turbines with a combined capacity of 240 MW connected in 2013 (EWEA 2013).

In 2012, the average FIT was 8.8 c/kWh for wind power (onshore) with one of the lowest external cost of 0.3 c/kWh in Germany (Greenpeace Energy 2012). Development of the renewable market has been one of the biggest factors in reduced wholesale electricity price in Germany. Wholesale electricity prices have fallen from over €80/MWh at peak hours in Germany in 2008 to just €38/MWh in 2013 (Economist 2013).

## *3.4 Spain*

Spain had the second largest market with a cumulative capacity of 22.9 GW in the EU. But a meager 175 MW new capacity addition in 2013 put them in a very challenging position to retain their position. In Spain, wind power is the second best technology in terms of capacity installed with just over 21 % behind the combined cycle power plants with a share of about 25 %.

The Spanish wind power sector is now in jeopardy because of reduced profitability after the government passed, in February 2013, the Royal Decree-Law 2/2013. This measure forced all wind producers who did not opt to sell power directly on the pool market to operate under the fixed FIT alternative. Such a step is considered to be regressive by producers as remuneration under the FIT option by modifying the inflation indexing parameters applicable to it (AEE 2013). Such retroactive policy measures prevent investors to put their money in wind projects. This is clearly evident from the fact that during January–June 2014, Spain only installed a wind turbine of 0.08 MW in Galicia, bringing the total installed wind power to 22,970.58 MW.

Lack of new investment directly impacts the wind power industry: (1) lack of a new domestic order for the component manufacturers forced them to rethink about their operations in Spain. In Spain, wind energy covers the electricity consumption of 10 million households. The industry generates employment for over 27,000 people and exports are worth over €1.8 billion. It avoids the emission of around 22 million tons of $CO_2$ per year. According to the Spanish Wind Energy Association, the Spanish government penalizes the wind industry with so-called Energy Reforms, which practically harms the prospects of new employment generation, additional green electricity, and GHG reduction.

There are serious problems in the power systems of Spain. Despite a diversified mix of electricity generation technologies, in 2012, Spanish households and industrial customers paid 30 and 18 % higher price before tax, respectively, above the European average (Gobierno De Espana 2013). For a similar average market price of electricity, regulated costs in Spain are 40 % above comparable countries, but the system does not cover its cost-creating tariff deficit. Initially, Spain encouraged huge investments in the renewable sector, which led to a strong capacity addition leading to a large excess capacity in international comparison. Consequently, yearly tariff deficits accumulated; despite having paid €10 billion off, the outstanding debt reached €26 billion by May 2013.

Spain's bet for renewable technologies at a very early stage, at high investment costs, and not fully profiting from their learning curve proved counterproductive. For instance, Spain installed 2708 MW, 76 % of PV capacity in 2008 above 6 M€/MW, with a 450 €/MWh tariff. But Germany installed 64 % of its PV capacity between 2010 and 2011, at 3–4 M€/MW, with a 250 €/MWh tariff (Gobierno De Espana 2013). It is evident that the Spanish power system has been far from the desired level of efficient operations. Therefore, with dual objectives of bringing market efficiency and reducing the debt burden the Spanish government took reform measures. On the other hand the current Spanish wind industry looks very gloomy. It needs impetus from the government and necessary investments from the investors to come out of a self-created mess. Early action would certainly bring wind growth back on track.

### *3.5 India*

The Ministry of New and Renewable Energy (MNRE) set a target of capacity addition of 29.8 GW from various RE sources during the 12th Plan period of which about 15 GW is expected to come through wind. As of July 31, 2014, cumulative installed wind capacity reached 21.7 GW, contributing close to 8.7 % of the total installed power capacity in India. Wind power generation has been constantly increasing from just 6 billion units in 2005–2006 to 31.26 billion units in 2013–2014.

An aggregate demonstration wind power capacity of 71 MW (Fig. 2) has been established at 33 locations in nine States viz., Andhra Pradesh, Gujarat, Karnataka, Kerala, Madhya Pradesh, Maharashtra, Rajasthan, Tamil Nadu, and West Bengal. Demonstration projects are concentrated in Tamil Nadu and Gujarat, amounting to 52 % of the total demonstration capacity.

The government has given various fiscal and financial incentives, such as capital/interest subsidy, generation-based incentive (GBI), accelerated depreciation (AD), concessional excise, and custom duties for the promotion of RE sources in the country. The government actively promotes foreign technology transfer in the RE sector. Foreign Direct Investment (FDI) up to 100 % under the automatic route is permitted in the RE, subject to the provisions of the Electricity Act, 2003.

The FDI in the RE sector including wind energy has increased during 2010–2013. As reported by (PIB 2013a) FDI during 2010–2011, 2011–2012 and 2012–2013 has been US$214.40 million, US$452.17 million, and US$1106.52 million respectively. Indian wind component manufacturing industry is becoming increasingly competitive. Recently, Inox Wind Limited (IWL)—an Indian wind

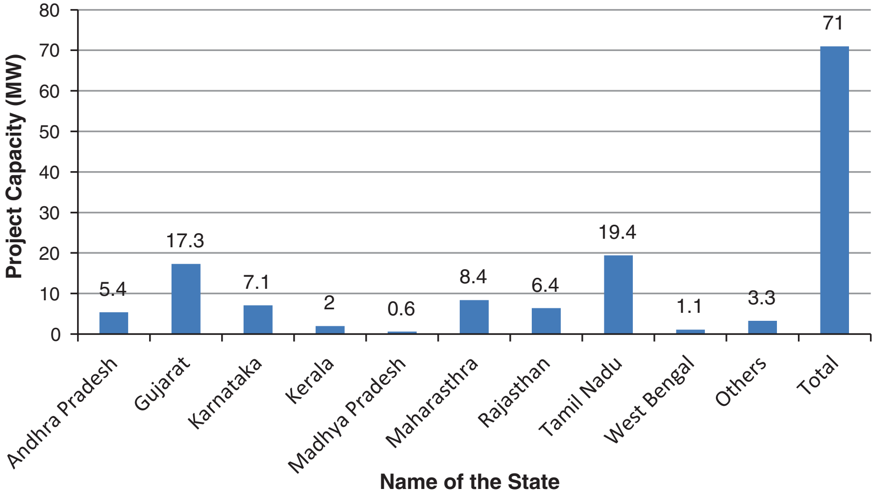



**Fig. 2** Demonstration projects (MW)

component manufacturer was awarded a 170 MW order from Continuum Wind Energy, a Singapore-based company. The order, valued in excess of Rs. 900 crore ($148.5 million), is one of the largest wind turbine orders in the country for a single project.

There are 19 manufacturers of wind turbines, making about 45 models in India. About 11 of them have international collaborations with foreign manufacturers. India has an annual wind turbine production capacity of around 4000 MW, which can be expanded up to 8000 MW. India is exporting wind mills, turbine/engines to countries like, US, Australia, Brazil, China, Europe, etc. The value of export increased to $314,405.30 million in 2013–2014 compared to $251,136.19 million in 2010–2011 and the value of export for April–June 2014 reached $76,032.65 million (DoC 2014).

### *3.6 United Kingdom*

A recent report by the Royal Academy of Engineering (2014) indicates that the cumulative installed capacity in the United Kingdom (UK) to reach 26 GW and provide around 20 % of electrical energy consumed by 2020. At the end of 2013, with a cumulative capacity 10,531 MW, UK was placed as the sixth largest wind market in the world in 2013. After, Germany, UK was the second largest market for wind in Europe, adding 1883 MW in 2013 of which 1150 MW was onshore and 733 MW was offshore. The UK is the largest offshore wind market in the world with total installations of almost 3681 MW, accounting for over half of the European (and global) offshore market. According to the latest data released in February 2014, 5,244 wind turbines were operational and 948 were under construction in the UK (Royal Academy of Engineering 2014). During January 1–June 30, 2014, 147 offshore wind turbines with a capacity of 532 MW were connected to the grid (EWEA 2014) compared to 212 turbines with a combined capacity of 733 MW connected in 2013 (EWEA 2013).

Offshore wind is one of the youngest and pioneering industries with the potential to generate employment, reduce fossil fuel imports, and offer huge expansion and export opportunities in the UK. Yet, offshore wind loses out on the ground of high cost and lack of grid connectivity. Compared to other conventional sources like coal, nuclear, and other fossil fuel-based power production offshore wind is costly. Often the standard levelized cost of electricity (LCOE) ignores the total societal cost of electricity (SCoE) associated with fossil or nuclear power production. An internal estimation conducted by Siemens indicates that the total cost of electricity (LCOE + SCoE) for offshore and onshore wind would be €60/MWh and €59, respectively, by 2025, in the UK. The wind offshore and onshore would be the most cost competitive compared to coal (€100/MWh), nuclear (€106/MWh), natural gas (€106/MWh), and photovoltaic (€106/MWh). Lack of grid connectivity, especially for offshore wind seems to be a major bottleneck. To remove such a bottleneck the concept of an offshore transmission owner (OFTO) was introduced in 2010. But the regulation on OFTO restricts wind farms as well as National Grid to be OFTO. So, not much investment is coming for offshore wind production. In order to remove investment risk and the bottleneck, the Green Investment Bank (GIB), backed by the government of the UK, launched a new fund for offshore wind energy projects in the country. GIB will raise £1 billion (€1.25 billion) for funding already-operational offshore wind projects in the UK.

According to the latest Offshore Wind Industrial Strategy Report, published by the UK government and industry, the offshore sector has the potential to create 30,000 jobs and contribute more than €8 billion to the economy in the UK alone by 2020 (GWEC 2013).

### *3.7 Italy*

Italy installed only 444 MW for a total of 8552 MW (Fig. 3), 65 % below its installations for 2012. I added 7639 MW of wind capacity during 2003–2013 which helped to enhance the consumption level from 1.5 to 15 TWh (Fig. 4). Italy only contributed 4 % of total European wind installation in 2013. It launched its first competitive auction for a new FIT. Tariffs awarded were at an average discount of 7.81 % to the base auction price of EUR 127/MWh, or about EUR 117/MWh. This new price level is lower than the earlier price of about EUR 155/MWh.

### *3.8 France*

France is determined to reduce overdependence on nuclear energy and the target has been set to reduce nuclear dependency from 75 to 50 % by 2025. By the end of 2013, France reached a cumulative capacity of 8254 MW from just 253 MW

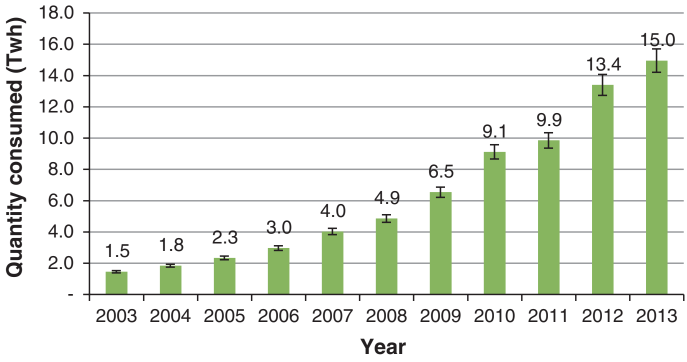



**Fig. 3** Wind power consumption (TWh) in Italy

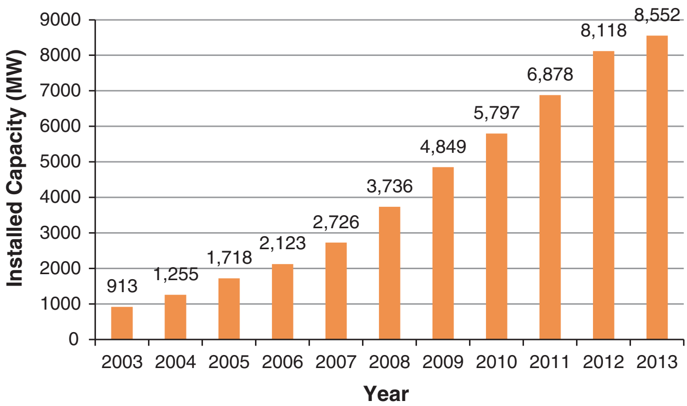



**Fig. 4** Cumulative installed wind capacity (MW) in Italy

in 2003. France is very close to Italy in terms of cumulative capacity and it added 631 MW compared to just 434 MW by Italy in 2013. France is well placed to overtake Italy as the seventh largest wind market in the world. France has set a goal of reaching 19 GW of wind energy by 2020, up from its current level of 8.2 GW.

France encourages wind power production by offering incentives to onshore wind power plants: EUR 0.082/kWh for 10 years and between EUR 0.028/kWh and EUR 0.082/kWh for the next 5 years, depending on the location of the wind farms and the hours of electricity produced. Similarly, the offshore wind firms EUR 0.13/kWh for 10 years and between EUR 0.03 and EUR 0.13/kWh for the next 10 years, depending on the location of the wind farms and the hours of electricity produced (KPMG 2013).

### 3.9 Canada

Canada added 1,600 MW of wind installation through 23 new projects in 2013 and the total installed capacity reached 7803 MW. Wind energy is now positioned to supply approximately 3 % of Canada's electricity demand; enough power to meet the annual needs of over 2 million Canadian homes.

### 3.10 Denmark

Denmark took its cumulative installed capacity up to 4772 MW with a capacity addition of 657 MW in 2013. Wind power accounted for over 33 % of Denmark's total electricity consumption in 2013. The Danish policies and measures to support wind power—and wind industry—development were initiated at a much earlier stage of market development (Buen 2006). Denmark's achievement is built on several key factors such as fast-mover in wind power, progressive energy policy, and strategic intent to achieve 50 % wind power in the electricity system by 2020. The Danish government is committed to developing a green economy through green growth making serious efforts to promote green technologies and green consumption habits among its consumers. Wind is a major industry in Denmark employing around 25,000 people and the wind component manufacturing industry is very well developed. According to the Danish Wind Industry Association, the Danish market accounted for approximately 1 % of sales for Vestas and 3 % of sales for Siemens Wind Power in 2012 (MFAD 2014). It is observed that the price per kWh paid for wind-power production has decreased since the implementation of the electricity reform from average c€7.9 in 2000 to c€6.1 in 2006 (Munksgaard and Morthorst 2008).

## 4 Wind Energy Potential in India

India has an estimated wind potential of about 480 GW, which includes onshore (102 GW), desert (29 GW), and offshore (350 GW). More details on the wind potential are discussed below.

### 4.1 Onshore Wind Potential

The Center for Wind Energy Technology (C-WET) estimates the wind energy potential of 49.10 GW at 50 m height and about 102.8 GW (Table 5) at 80 m height.

**Table 5** Estimated wind potential in India

| States/UTs | Estimated potential (MW) | |
|---|---|---|
| | At 50 m | At 80 m |
| Andaman and Nicobar | 2 | 365 |
| Andhra Pradesh | 5394 | 14,497 |
| Arunachal Pradesh[a] | 201 | 236 |
| Assam[a] | 53 | 112 |
| Bihar | – | 144 |
| Chhattisgarh[a] | 23 | 314 |
| Daman and Diu | – | 4 |
| Gujarat | 10,609 | 35,071 |
| Haryana | – | 93 |
| Himachal Pradesh[a] | 20 | 64 |
| Jharkhand | – | 91 |
| Jammu and Kashmir[a] | 5311 | 5685 |
| Karnataka | 8591 | 13,593 |
| Kerala | 790 | 837 |
| Lakshadweep | 16 | 16 |
| Madhya Pradesh | 920 | 2931 |
| Maharashtra | 5439 | 5961 |
| Manipur[a] | 7 | 56 |
| Meghalaya[a] | 44 | 82 |
| Nagaland[a] | 3 | 16 |
| Orissa | 910 | 1384 |
| Pondicherry | – | 120 |
| Rajasthan | 5005 | 5050 |
| Sikkim[a] | 98 | 98 |
| Tamil Nadu | 5374 | 14,152 |
| Uttarakhand[a] | 161 | 534 |
| Uttar Pradesh[a] | 137 | 1260 |
| West Bengal[a] | 22 | 22 |
| Total | 49,130 | 102,788 |

[a]Wind potential has yet to be validated with actual measurements
*Source* CWET

## *4.2 Desert Wind Capacity*

A recent study conducted by PGCIL (2013) estimates that India has the potential to generate 8–10 MW/km$^2$ of desert areas, which will increase in view of technological advancements in wind turbine rating, hub height, rotor diameter, etc. Considering the above potential it is estimated that deserts like the Thar (Rajasthan), Rann of Kutch (Gujarat), and Ladakh (Jammu and Kashmir) have a combined installed wind power capacity of 29 GW.

### 4.3 Offshore Wind Capacity

In a recent study conducted by WISE, the offshore wind potential of Tamil Nadu has been estimated at 127 GW at 80 m height, which will need further validation. Another study by the Scottish Development International in January 2012 estimated the potential to establish around one GW capacity wind farm each along the coastline of Rameshwaram and Kanyakumari in Tamil Nadu. According to MNRE estimates India has a potential of 350 GW offshore wind energy capacity (PIB 2013b).

## 5 Wind Energy Progress in India

Wind energy capacity installation is steadily growing in India. As of May 2014, India had more than 21.2 GW of installed capacity compared to just 1.7 GW in 2002 (Fig. 1). Tamil Nadu is the leader in terms of installed capacity with 7276 MW (Table 6) followed by Maharashtra (4098 MW), Gujarat (3414 MW), Rajasthan (2820 MW), and Karnataka (2409 MW). Gujarat has the potential to surpass Maharashtra and Tamil Nadu in the future, because 90 % of the potential yet to be exploited compared to 31 % in Maharashtra and 49 % in Tamil Nadu.

### 5.1 State-wise Progress in India

Wind energy progress across the State is not uniform owing to various factors like wind speed, policy measures, and financial and nonfinancial offers at the State level. In this section we analyze the State-wise wind market developments.

#### 5.1.1 Tamil Nadu

Tamil Nadu with more than 7252.61 MW of installed wind capacity is the leading wind producing State in India with a contribution of 34 % total installed capacity. Figure 5 presents the year wise installed capacity addition in the State. Tamil Nadu's wind energy feed to the grid system has been increasing. During 2011–2012 the State fed wind energy to a magnitude of 12.6 % of the total electricity fed to the grid, compared to 11.65 in 2010–2011 (MNRE 2012). Tamil Nadu Generation and Distribution Company (TANGEDCO) and private wind mill operators have been able to install more than 11,000 wind generators in various potential locations across the State.

Tamil Nadu is estimated to have offshore wind potential of 127,428 MW (MNRE 2012). The coast along Tamil Nadu is the best in the country with very high potential areas having net capacity utilization factor (CUF) of over 40 % and

**Table 6** Wind power installed capacity (MW) in India

| State | Andhra Pradesh | Gujarat | Karnataka | Kerala | Madhya Pradesh | Maharashtra | Rajasthan | Tamil Nadu | West Bengal | Others | Total | Cumulative |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Up to March 2002 | 93.2 | 181.4 | 69.3 | 2 | 23.2 | 400.3 | 16.1 | 877 | 1.1 | 3.2 | 1666.8 | |
| 2002–03 | 0 | 6.2 | 55.6 | 0 | 0 | 2 | 44.6 | 133.6 | 0 | 0 | 242 | 1908.8 |
| 2003–04 | 6.2 | 28.9 | 84.9 | 0 | 0 | 6.2 | 117.8 | 371.2 | 0 | 0 | 615.2 | 2524 |
| 2004–05 | 21.8 | 51.5 | 201.5 | 0 | 6.3 | 48.8 | 106.3 | 675.5 | 0 | 0 | 1111.7 | 3635.7 |
| 2005–06 | 0.45 | 84.6 | 143.8 | 0 | 11.4 | 545.1 | 73.27 | 857.55 | 0 | 0 | 1716.17 | 5351.87 |
| 2006–07 | 0.8 | 283.95 | 265.95 | 0 | 16.4 | 485.3 | 111.9 | 577.9 | 0 | 0 | 1742.2 | 7094.07 |
| 2007–08 | 0 | 616.36 | 190.3 | 8.5 | 130.39 | 268.15 | 68.95 | 380.67 | 0 | 0 | 1663.32 | 8757.39 |
| 2008–09 | 0 | 313.6 | 316 | 16.5 | 25.1 | 183 | 199.6 | 431.1 | 0 | 0 | 1484.9 | 10,420.71 |
| 2009–10 | 13.6 | 197.1 | 145.4 | 0.8 | 16.6 | 138.9 | 350 | 602.2 | 0 | 0 | 1464.6 | 11,905.61 |
| 2010–11 | 55.4 | 312.8 | 254.1 | 7.4 | 46.5 | 239.1 | 436.7 | 997.4 | 0 | 0 | 2349.4 | 14,255.01 |
| 2011–12 | 54.1 | 789.9 | 206.7 | 0 | 100.5 | 416.5 | 545.7 | 1083.5 | 0 | 0 | 3196.9 | 17,451.91 |
| 2012–13 | 202.1 | 208.3 | 201.7 | 0 | 9.6 | 288.5 | 614 | 174.6 | 0 | 0 | 1698.8 | 19,150.71 |
| May 31, 14* | 753 | 3414 | 2409 | 55 | 439 | 4098 | 2820 | 7276 | 1.1 | 3.2 | | 21,268.3 |
| Potential | 14,497 | 35,071 | 13,593 | 837 | 2931 | 5961 | 5050 | 14,152 | 22 | 10,674 | 102,788 | |
| Actual developments (%) | 5 | 10 | 18 | 7 | 15 | 69 | 56 | 51 | 5 | 0.03 | 21 | |

*Source* Compiled from various published sources
*Note* As the data collected from different sources and period of reference may differ and data presented in this table may not match with the earlier tables

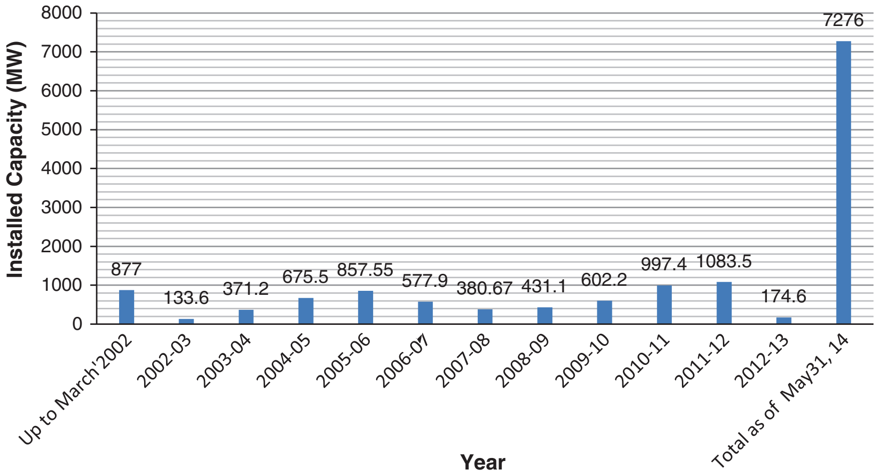



**Fig. 5** Wind installed capacity growth in Tamil Nadu

wind power density of over 700 W/m$^2$ at several locations. Therefore, the offshore wind deployment in Tamil Nadu could be commercially viable despite high costs.

### 5.1.2 Maharashtra

Maharashtra is the second largest wind market with an installed capacity of 4098 MW. But the State is leading in terms of actual wind power development, 69 % exploitation of estimated potential of 5961 MW. The State has been one of the pioneers of wind market developments in India. Success of wind power growth in Maharashtra could be ascribed to commitment, plan, and execution and timely regulatory interventions.

To promote green energy generation in the State the Maharashtra Electricity Regulatory Commission (MERC) started setting Renewable Portfolio Standards (RPS) since August 2006. MERC fixed the target of 3, 4, and 5 % of total power purchase renewable purchase for 2006–2007, 2007–2008, and 2008–2009 respectively. For evacuation arrangements of wind energy project, there is a provision for giving 50 % subsidy through Green Energy Fund.[1]

### 5.1.3 Gujarat

The State of Gujarat has the highest onshore wind power potential of 35,071 MW in the country. In order to harness this potential, the State Government introduced policies for offering incentives to the sector in 1993, 2002, 2007, 2009, and 2013.

[1] http://www.mahaurja.com/PDF/InformationBookletforWind.pdf, accessed on August 30, 2014.

So far, the State has installed 3414 MW wind power, with a low conversion rate of 10 and 90 % of the potential yet to be fully exploited. To improve wind developments in the State, Wind Energy Policy-2013, shall remain in force till March 31, 2016. Gujarat Energy Transmission Corporation Limited (GETCO) has the responsibility of building transmission infrastructure beyond the terminal point of evacuation infrastructure. To ensure the necessary commitment of the wind project developers, the GERC has provision regarding furnishing of Bank Guarantee of Rs. 5 lakh/MW by the project developers to GETCO (GERC 2012).

### 5.1.4 Rajasthan

Rajasthan has a potential of 5050 MW installed capacity and actual installation of about 2820 MW, with a conversion rate of 56 %. In recent times the State has been very active in terms of developing renewable power, more specifically wind power. Attractive wind tariff has been set by the RERC to promote wind power developments. Levelized wind tariff for power plants commissioned in Jaisalmer, Jodhpur, and Barmer districts is fixed at INR 5.64/kWh [without higher depreciation (HD) benefit] and INR 5.31/kWh (with HD benefit). Whereas wind tariff other than the above three districts in Rajasthan is fixed at INR 5.93/kWh (without HD benefit) and INR 5.57/kWh (with HD benefit). It is to be noted that in districts Jaisalmer, Jodhpur, and Barmer wind capacity utilization factor and HD benefits are 20 % and INR 0.35/kWh, respectively, so a slightly higher price is admissible. Table 7 gives the factors considered by the RERC for wind tariff determination in Jaisalmer, Barmer, and Jodhpur districts. To reduce burden on the developers, the tariff order dated May 18, 2012 of Rajasthan specifies that the responsibility of building evacuation infrastructure from pooling substation to interconnection point of the utility is that of the transmission utility and not of the developer.

### 5.1.5 Karnataka

The Renewable Energy Policy (2009–2014) by the Karnataka government set a target of enhancing the contribution of RE in the total installed capacity of the State from 2400 MW to about 6600 MW by 2014, out of which wind power contribution was earmarked at 2969 MW. Karnataka has a potential of 13,593 MW wind power installed capacity, but only 2409 MW capacity was installed till end of May 2014, with only 18 % actual development against the potential. It is clearly visible (Fig. 6) that the Karnataka government has not been able to achieve the year-wise target set for wind energy under the Renewable Energy Policy.

Karnataka Electricity Regulatory commission (KERC) considers Rs. 56 million per MW toward capital cost as reasonable, which is inclusive of the evacuation cost of Rs. 1 million per MW.

C-WET data suggests that 40 % of the State's areas are capable of yielding a CUF ranging between 22 and 32 %, even at 50 m hub height. Considering the

**Table 7** Parameters used for determining wind tariff for plants located in Jaisalmer, Barmer and Jodhpur districts, Rajasthan

| Assumption head | | Unit | Base case |
|---|---|---|---|
| *Power generation* | | | |
| Capacity | Installed power generation capacity | MW | 1 |
| | Capacity utilization factor (CUF) | % | 21 |
| | Deration factor | % | 1.25 |
| | Life of transmission System | Years | 35 |
| | Life of power plant | Years | 25 |
| *Project cost* | | | |
| Capital cost per MW | | Rs. lakh/year | 565 |
| Project cost | | Rs. lakh/year | 540 |
| Transmission line | | Rs. lakh/year | 25 |
| *Sources of fund* | | | |
| Debt:Equity | Debt | % | 70 |
| | Equity | % | 30 |
| | Total debt amount | Rs. lakh/year | 395.5 |
| | Total equity amount | Rs. lakh/year | 169.5 |
| Funding options-1 (domestic loan) | Loan amount | Rs. lakh | 395.5 |
| | Moratorium period | Years | 0 |
| | Interest rate | % | 12.71 |
| | Loan repayment per annum | Rs. lakh | 32.96 |
| Funding options-2 (equity finance) | Equity amount | Rs. lakh | 169.5 |
| | Return on equity | % | 16.00 |
| | Discount rate | % | 13.10 |
| *Financial assumptions* | | | |
| Fiscal assumptions | Income tax (for year-11 to year-25) | % | 30.90 |
| | Min. alternate tax (MAT) rate (for year-1) | % | 20.01 |
| | MAT rate (for year-2 to year-10) | % | 19.06 |
| | 80 IA benefits | Yes/No | Yes |
| | Higher depreciation (HD) benefit | Rs. /kWh | 0.34 |
| Depreciation | Depreciation rate (power plant) | % | 5.83 |
| | Depreciation rate (transmission) | % | 5.83 |
| | Years for 5.83 % rate | | 12 |
| *Working capital requirement* | | | |
| O&M charges | | Months | 1 |
| Maintenance spare | % O&M expenses | % | 15.00 |
| Receivables for debtors | | Months | 1.5 |
| Interest on working capital | | % | 12.21 |
| *Operation and maintenance expenses (2014–15)* | | | |
| Power plant | | Rs. lakh/MW | 7.09 |
| Transmission lines | | Rs. lakh/MW | 0.78 |

(continued)

**Table 7** (continued)

| Assumption head | | Unit | Base case |
|---|---|---|---|
| Total O&M expenses | | Rs. lakh/MW | 7.87 |
| Total O&M expenses escalation | | % | 5.85 |
| Months of operations | | MU | 12 |
| Working hours/day | | h | 24 |
| No. of days | | days | 365 |
| Total no. of hours | | h | 8760 |
| Tariff (with HD benefit) | | Rs. /kWh | Rs. 5.31 |
| Tariff (without HD benefit) | | Rs. /kWh | Rs. 5.64 |

*Source* RERC, Order Dt. 16 July 2014

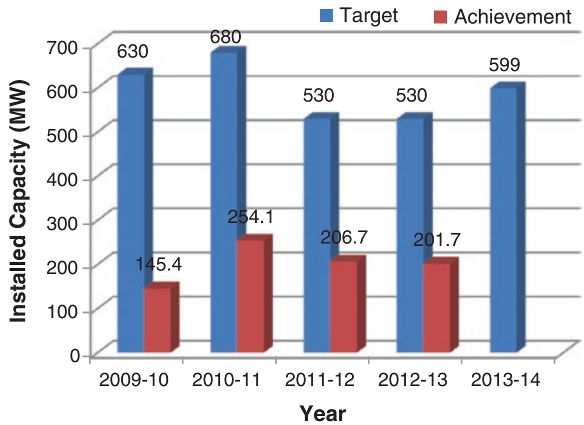



**Fig. 6** Wind capacity target and achievements in Karnataka. *Source* Karnataka Renewable Energy Policy (2009–14) and authors' analysis

good yield range and advancement in wind turbine manufacture, KERC rejected a petition of the Indian Wind Energy Association's demand to revise the CUF downward from a normative CUF of 26.5 to 25 %. However, the Commission revised the interest rate at the base lending rate plus 250 basis points to absorb risk of investments and allowed an interest rate of 12.3 % (KERC 2013). The Commission adopted 5.83 % depreciation instead of 7 % allowed in the 2009 order for the first 12 years of wind energy projects. The Commission retained RoE at 16 % (post tax); the O&M cost at the same percentage of 1.25 % of the capital cost with 5 % escalation annually, and fixed the interest on working capital at 13 % compared to 13.25 % allowed in the tariff order passed in 2009.

### 5.1.6 Madhya Pradesh

A capacity utilization factor of 20 % without de-rating as reasonable for new projects has been adopted by MPERC. The commission allows 1 % of the capital cost of the project as O&M expenses in the first year with an escalation of 5.72 % for each year thereafter. MPERC considers a plant life as 25 years for wind power generation units for tariff determination purposes. Depreciation at 7 % per annum for the first 10 years and balance 20 % for the next 15 years of the project life is considered by the Commission. Keeping in view the requirements of the tariff policy for preferential tariff for renewable sources of energy, the Commission allows an attractive pre-tax return on equity (RoE) at 20 %. The Commission considers the annual interest rate on debt at 12.75 and 13.25 % on the working capital for tariff determination purposes. The Commission allows a discount rate of 10.2 % levelized tariff setting. Based on the above considerations the Commission sets the levelized tariff for wind at INR 5.92 per unit for plants commissioned after March 2013. The distribution company in whose area the energy is consumed (irrespective of the point of injection) shall deduct 2 % of the energy injected towards wheeling charges in terms of units.

## *5.2 Challenges*

Wind power in India faces challenges of lower capacity utilization, high cost, evacuation and grid infrastructure, grid and power system. Most of the challenges are similar to global wind markets. However, considering our economy, size of population, income distribution, and level of energy poverty these challenges are proving impediments to growth, development, and penetration of wind energy. Some of these challenges are discussed in detail below:

### 5.2.1 Low Performance of Wind Power Plants

The capacity utilization factor (CUF) for wind is very low compared to power plants operating on conventional fuel. As the CUF depends on quality of wind speed, type, and size of the wind turbine, so the CUF varies from location to location.

Considering the new wind machines are technically advanced, more efficient, can run even at low speed, and are with higher hub heights the Tamil Nadu SERC considers a capacity utilization factor (CUF) of 27.15 % for tariff determination. Historical data from the UK suggests that the load factor for onshore wind has stabilized at around 26 %, and for offshore wind they are increasing to around 35 % (Royal Academy of Engineering 2014).

### 5.2.2 Wind Power Economics

The wind power economics is highly dependent on costs and revenue. Therefore, the tariff structure is the key to economic viability of wind production.

Considering the relatively young industry, wind needs preferential treatment before competitive tariff bidding. In many of the countries in the world wind power has been given preferential treatment at the early stages of market development. Similarly, in India, electricity regulators allow preferential tariff treatment within an acceptable range for making wind power economically viable for the developers. Wind power is moving faster toward achieving grid parity in India. However, conventional fuel like coal is still a comparatively cheaper option.

### 5.2.3 Lack of Evacuation Infrastructure

Lack of evacuation infrastructure is one of the biggest challenges for wind power in India. Often the points of wind power production and the State electricity grids are distantly located (Ayodele et al. 2012), causing a serious challenge to evacuate wind power. To overcome this pricing of wind power has an inbuilt component for developing evacuation infrastructure. However, this may not be sufficient enough to build adequate evacuation infrastructure. The Gujarat Electricity Regulatory Commission (GERC) allows Rs. 3.8 million/MW for developing evacuation infrastructure. A study conducted by the Power Grid Corporation Limited (PGCIL 2012) estimates that the cost of the transmission system strengthening both at the intra-State and inter-State level would be around Rs. 40,000 crores during the 12th Plan period.

Integration of electricity generated from RE resources to the grid is the focus area of PGCIL. As a part of this initiative, PGCIL is working on a mechanism to set up a system to feed electricity generated from offshore wind energy projects to the national grid (DNA 2014).

### 5.2.4 Minimizing Grid Imbalance

Most designed capacity of the grid is based on the conventional and stable power supply. However, wind power is intermittent and may fluctuate depending on the weather, wind speed, and wind zone. Under favorable weather conditions, power produced from the wind source and feed-into the grid is found to be higher than usual feed causing imbalance in the grid system (Weisser and Garcia 2005; Georgilakis 2008). Such imbalances happen quite often in well-developed wind markets in Germany, Spain, and Italy. Even in India, most of the RE rich States have observed aggravated high voltage grid conditions in the case of renewable injections in other than the peak hours. By contrast, Tamil Nadu faces a low voltage situation in case of heavy wind injection. As suggested by PGCIL (2012) voltage variations can be managed by installing bus reactors and controlled reactors (TCR) at RE polling stations. Also, dynamic VAR compensators like STATCOM should be installed in pockets of RE farms at an estimated cost of Rs. 704 million.

Wind power output fluctuates with weather conditions, creating two challenges for the electrical system: added variability and uncertainty for grid operators and planners. Intermittent wind power can negatively impact the security of the power system, power quality, and the power system stability (Ayodele et al. 2012; PGCIL 2012). Some of the mitigating strategies are: use of wider geographical location to smoothen out the oscillations in the output of intermittent energy sources, smart and intelligent grid development, improved forecasting techniques, availability of flexible generation, robust transmission interconnection between various balancing areas, demand side management (PGCIL 2012), better regulatory, and grid reinforcement.

## 6 Electricity Regulatory Developments

Regulatory developments are mostly incremental in nature, which comes from past learning experience. Regulations are framed to protect the interests of all stakeholders. This section describes the relevant electricity regulatory developments in India.

### *6.1 Evolution of Electricity Regulations*

Electricity requires a significant level of regulation, but not necessarily government control. India's electricity sector has a regulatory history of more than 100 years. *The Indian Electricity Act, 1910 provided* the basic framework for the electric supply industry in India but the growth was mostly controlled through licenses issued by the State Government. The Act provided provision for licence for the supply of electricity in a specified area and legal framework for laying down of wires and other works. Also, provisions laying down relationship between licensee and consumer were mandated by the Act.

The Electricity (Supply) Act, 1948 moves toward control of regulation-based system through creation of State Electricity Boards (SEBs). One of the objectives of creating SEBs was to expand the electricity penetration from just cities to towns and villages.

Main amendments to the Indian Electricity Supply Act 1948 were brought in 1975—to enable generation in the Central sector, 1985—to bring in commercial viability in the functioning of SEBs—Sect. 59 amended to make the earning of a minimum return of 3 % on fixed assets a statutory requirement (w.e.f 1 April 1985), 1991—to open generation to private sector and establishment of Regional Load Despatch Centres (RLDCs), and 1998—to provide for private sector participation in transmission, and also provision relating to Transmission Utilities.

The next big regulatory development happened through the Electricity Regulatory Commission Act, 1998. This Act created a provision for setting up a Central/State Electricity Regulatory Commission (C/SERCs) with powers to determine tariffs. However, the constitution of SERC was optional for the States.

The best part of this Act was regulated tariff determination rather than controlled tariff fixing by the government.

The transformational Electricity Act, 2003 was enacted in 2003 and this Act repealed the above three Acts, namely (i) The Indian Electricity Act, 1910 (ii) The Electricity (Supply) Act, 1948, and (iii) The Electricity Regulatory Commission Act, 1998. The Electricity Act 2003 has been the driving force behind electricity reforms in India. The salient features of the Electricity Act 2003 are as follows:

- The Act under Sect. 61(h) has a provision for the promotion of co-generation and generation of electricity from renewable sources of energy.
- Free generation has been permitted, a major improvement from the License system. Hydro projects exceeding the capital cost notified by Central Government, however, need concurrence of the Central Electricity Authority. So the wind power producers do not require any license.
- As per the Act, transmission, distribution, and trading license from the Appropriate Commission is required. The Appropriate Commission can exercise the power exempt under certain categories.
- No license is required for generation and distribution in notified rural areas.
- Provision for setting National Load Despatch Centre (NLRC) and RLDCs for optimal scheduling and despatch. NLRC and RLDCs will not engage in the business of trading in electricity.
- Transmission Utility at the Central as well as State level to be a Government company—with responsibility for planned and coordinated development of the transmission network. Provision for private licensees is in transmission.
- Trading, a distinct activity recognized with the safeguard of the Regulatory Commissions being authorized to fix ceilings on trading margins, if necessary.
- Open access in distribution with provision for surcharge for taking care of the current level of cross subsidy with the surcharge being gradually phased out.
- Distribution of licensees would be free generation and trading.
- Setting up of the SERCs made mandatory for the States, which means more accountability at the State level.
- An Appellate Tribunal to hear appeals against the decision of the CERC and SERCs.
- Metering of all electricity supplied made mandatory.

## *6.2 Functions of CERC*

The CERC is empowered to deliver many functional activities and some of them are presented here:

- to regulate the tariff of generating companies owned or controlled by the Central Government or other companies having a composite scheme for generation and sale of electricity in more than one State;
- to regulate the inter-State transmission of electricity;

- to determine tariff for inter-State transmission of electricity;
- to issue licenses to persons to function as transmission licensee and electricity trader with respect to their inter-State operations;
- to specify Grid Code having regard to Grid Standards;
- to discharge such other functions as may be assigned under The Electricity Act, 2003.

## 6.3 Functions of SERCs

The formation of SERCs is an important step in the direction of setting up strong regulatory measures and reinforcement mechanism at the State level. The State Commission shall discharge the following functions, namely:

- determine the tariff for generation, supply, transmission and wheeling of electricity, wholesale, bulk or retail, as the case may be, within the State;
- regulate electricity procurement and purchase process;
- facilitate the intra-State transmission and wheeling of electricity;
- issue licenses to persons seeking to act as transmission licensees, distribution licensees, and electricity traders with respect to their operations within the State;
- promote the cogeneration and generation of electricity from renewable sources providing suitable measures for grid connectivity and renewable power purchase;
- fix trading margins in the intra-State trading of electricity, if considered, necessary; and
- discharge such other functions as may be assigned to it under The Electricity Act 2003.

The SERCs through the Act have been empowered to bring in necessary regulation related to production, distribution, transmission, and sale of electricity at the State level. The SRECs have the mandate to determine tariff in line with the CERC guidelines and can revise the tariff maximum once a year upon receiving the application of the stakeholders.

The above Electricity Act, 2003 empowers the SERCs to advise their respective State Governments in areas such as promotion of competition, efficiency, and economy in the activities of the electricity industry; promotion of investment in electricity industry, reorganizing and restructuring of the electricity industry of the State.

## 6.4 Regulating Grid Infrastructure

Till date operators of the grid infrastructure enjoy a kind of natural monopoly in India. Considering the magnitude of investment needed for fully integrated smart grid for optimal utilization of conventional and renewable power, it is highly desirable to bring in competition through innovative market-driven mechanism to attract financial stakeholders willing to invest in the grid infrastructure.

## 7 Wind Energy Policy and Programs

MNRE is responsible for central level renewable policy formulation. Other central level independent bodies such as Central Electricity Authority (CEA) and Central Electricity Regulatory Commission (CERC) are the custodians of policies and regulations. Other bodies like Indian Renewable Energy Development Agency (IREDA) are important policy implementation partners. For example, IREDA has a mission to be a pioneering, participant friendly, and competitive institution for financing and promoting self-sustaining investment in energy generation from renewable sources such as wind, energy efficiency, and environmental technologies for sustainable development.

### *7.1 Need for Incentives*

The wind sector needs incentives to build confidence in technology, compensate for low Plant Load Factors (PLFs) as compared to conventional sector, complement the low FIT, encourage better grid connectivity by building infrastructure, and improve the net present value (NPV) of the project (MNRE 2014). We discuss details of fiscal and monetary incentives offered by the Central and State Governments in India.

#### 7.1.1 Fiscal Incentives by the Centre

AD for the wind industry was introduced in 2003 and withdrawn in 2013 before being reinforced 2014. Tax holidays granted for wind power projects. Exemptions/reductions in Central Sales Tax and General Sales Tax are available on sales of the RE equipment in various States.

Green technology (including wind energy) is listed as a focused group scheme. Under this scheme, export of RE product to all countries is entitled for an additional duty credit equivalent to 2–5 % of freight on board (FOB) value of exports. To boost the wind equipment manufacturing sector the following concessions were made in the Union Budget 2014 (MoF 2014):

- Basic customs duty reduced from 10 to 5 % on forged steel rings used in the manufacture of bearings of wind operated electricity generators. Lower custom rates applicable to other products related to wind power generation are shown in Table 8.

**Table 8** Incentives for wind industry in India

| Indirect tax based incentives | | |
|---|---|---|
| Description of goods | | Custom rates (%) |
| I | Wind operated electricity generators up to 30 kW and wind operated battery chargers up to 30 kW | 5 |
| II | Parts of wind operated electricity generators for manufacturer of wind operated electricity generators, namely | |
| | (a) Special bearing | 5 |
| | (b) Gear box | 5 |
| | (c) Yaw components | 5 |
| | (d) Wind turbine controllers | 5 |
| | (e) Parts of the goods specified at (a)–(d) above | 5 |
| | (f) Sensor | 25 |
| | (g) Brake hydraulics | 25 |
| | (h) Flexible coupling | 25 |
| | (i) Brake calipers | 25 |
| III | Blades for rotor of wind operated electricity generators for the manufacturers or the manufacturers of wind operated electricity generators | 5 |
| IV | Blades for rotor of wind operated electricity generators for the manufacturers or the manufacturers of wind operated electricity generators | 5 |
| V | Raw materials for manufacturer of blades for rotor of wind operated electricity generators conditions | 5 |
| | A. If the importer at the time of importation furnishes in all cases, a certificate to the Dy. Commissioner of Customs or Assistant Commissioner of Customs as the case may be, from an officer not below the rank of Deputy Secretary to the Government of India in the Ministry of Non-Conventional Energy Sources recommending the grant of this exemption and in the case of the goods at (ii) to (v) the said officer certifies that the goods are required for the specified purposes; and<br>B. Furnishes an undertaking to the said Dy. Commissioner of Customs Assistant Commissioner to the effect that:<br>(i) in the case of wind operated electricity generators up to 30 kW, or wind operated battery chargers up to 30 kW, he shall not sell or otherwise dispose off, in any manner, such generators or chargers for a period of two years from the date of importation. In the case of wind operated electricity generators up to 30 kW, or wind operated battery chargers up to 30 kW, he shall not sell or otherwise dispose off, in any manner, such generators or chargers for a period of two years from the date of importation<br>(ii) in case of other goods specified at (ii)–(v), he shall use them for the specified purpose, and<br>(iii) in case he fails to comply with sub-conditions (i) or (ii), or both conditions, as the case may be, he shall pay an amount equal to the difference between the duty leviable on the imported goods but for the exemption under this notification and that already paid at the time of importation | |

*Source* http://www.ireda.gov.in/forms/contentpage.aspx?lid=1357, accessed on Sept. 18, 2014

- Full exemption from Special Additional Duty provided on parts and raw materials required for use in the manufacture of wind operated electricity generators.
- Excise duty reduced from 12 % to Nil on forged steel rings used in the manufacture of bearings of wind operated electricity generators.
- Wind operated electricity generator, its components and parts thereof, water pumping windmills, wind aero-generators, and battery chargers exempted from excise duty.

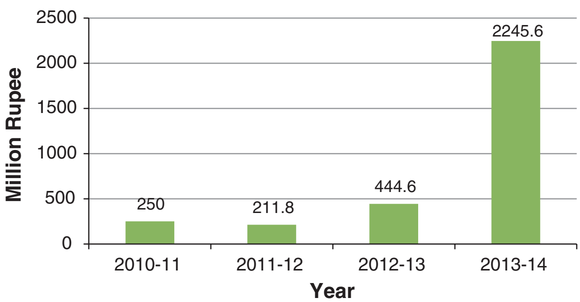
### 7.1.2 Monetary Incentives

The Government of India extends the 'GBI' for the project developers for 5 years. This would amount to a total expenditure of Rs. 18,000 crore. Budgetary allocation for GBI in the current fiscal is Rs. 800 crore. GBI was introduced in 2011 and withdrawn in 2012 and again reintroduced in 2013. The Government of India spent over Rs. 315 million during 2010–2014; Fig. 7 shows the year-wise distribution (PIB 2014).

GBI can be claimed irrespective of the rate of depreciation opted by the Wind Power Producers (i.e., 15 + 20 % (additional) on written down value method basis or 7.69 % on the straight line method basis) as provided under Income Tax Act 1961. This is applicable only for projects commissioned on or after April 1, 2012 and are eligible under the Extension Wind GBI Scheme. Under the GBI scheme a registered wind producer will be eligible for a reward of Rs. 0.50 per unit of electricity fed into the grid with a cap of Rs. 6.2million/MW. The GBI is over and above the tariff approved by the State Electricity Regulatory Commission. The incentive will be for a minimum period of 4 years and a maximum of 10 years. The total disbursement in a year will not exceed one-fourth of the maximum limit of the incentive, i.e., Rs. 15.50 lakh per MW during the first 4 years. There is no floor or ceiling for a developer in terms of the MW capacity that can be considered for availing the incentive.

The incentive would be available for grid connected wind power projects set up for sale of electricity to the grid, at a tariff notified by SERC and/or State Government and also for captive wind power projects, including group captive to the extent of sale of electricity to the grid. The GBI would not be available to any wind power project selling power to third party (viz., merchant power plants).

**Fig. 7** Expenditure (Rs. million) under wind GBI scheme



The Central government encourages wind-solar hybrid systems with specific financial incentives. Government/public/charitable/academic/other nonprofit making institutions can get subsidy of Rs. 0.15 million and others not covered under the above category will be given subsidy of Rs. 0.1 million against a benchmark cost of Rs. 0.25 million per KW for Aerogenerators/Wind-Solar Hybrid Systems.

#### 7.1.3 State-Level Incentives

At the State level, the government provides various incentives to promote RE like wind. RE projects are exempted from electricity duty by many State Governments. Reduced or no VAT on RE components in some States. Tamil Nadu has reduced VAT from 14.5 to 5 %, Karnataka offers 5.5 % VAT for all the RE components, and Gujarat, Tamil Nadu, and Maharashtra offer 5 % VAT for all renewable components. Maharashtra has the provision for capital subsidy to the extent of 11 % for wind energy projects set up by the cooperative sector. Maharashtra allows 100 % refund of octroi/entry tax for renewable plants. The Rajasthan Government offers soft loans up to 1/3rd of capital cost at low interest rate.

### *7.2 State-Level Policy and Tariff Fixation*

Various State governments are well within their rights to frame macro level policy for wind power development. States such as Maharashtra, Tamil Nadu, Gujarat, Madhya Pradesh, Karnataka, and Kerala have dedicated wind policies for development of wind power. These States have made special provisions for rapid wind market development.

Under the Electricity Act 2003, SERCs are empowered to set policy related to wind power production, distribution, tariff fixation, and consumption. Tariff fixation based on competitive bidding is found to be the most critical driver of wind production, evacuation, and purchase. A comparative tariff policy at the State level for leading wind markets in India is given in Table 9.

It is found that most SERCs acknowledge that the following parameters are important for right and attractive tariff determination:

- Capital investment, including auxiliary costs for foundation, grid-connection, and so on
- Capacity utilization factor
- De-rating factor
- Debt-equity ratio
- Term of the loan
- Interest rate
- Return on equity
- Life of plant and machinery

**Table 9** Tariff/incentives for wind power generation in various states in India

| | Interest Rate on Debt (IRD)/ Working Capital (IRWC), Discount Rate (DR), Depreciation (D), Return on Equity (RoE) | Tariff Period (TP), Capex, O&M, CUF, Evacuation Cost (EC), Tenure Loan (TL), Debt:Equity Ratio (DER) | Tariff (T)/Third Party Sales (TPS) | Other Incentives (OI), Reactive Power (RP), Banking (B), Wheeling (W) |
|---|---|---|---|---|
| Andhra Pradesh | IRD: 12.30 %<br>IRWC: 12.8 %<br>DR: 10.62 %<br>D: 4.5 % for 1st 10 years and 3 % from 11th year onwards on straight line basis<br>ROE: 20 % pre-tax for first 10 years and 24 % pre-tax from 11th year onwards | TP: 25 years<br>Capex: Rs. 57.5 million/MW (including evacuation cost)<br>O&M: Rs. 7.4 lakh/MW with escalation of 5 % per annum<br>CUF (80 M, Z1–Z5): 20, 22, 25, 30, 32 %<br>CUF (50 M, Z2–Z5):20, 23, 27, 30 %<br>CUF: Normative 23 %<br>TL: 10 years<br>DER: 70:30 | T: Rs. 3.50/per kWh w.e.f. 9 September 2008 (frozen for 10 years). But tariff has been revised on 15 Nov. 2012 to Rs. 4.7/kWh-will applicable till March 31, 2015<br>TPS: Allowed under Electricity Act 2003 | OI: Given industry status<br>RP: RP: 10 paise per kVARh up to 10 % and 25 paise per kVARh above 10 %<br>W: 5 % of energy wheeled<br>B: Wind power projects are not eligible for banking of energy |
| Tamil Nadu | IRD: 12.25 %<br>IRWC: NA<br>DR:NA<br>D: 4.5 % the depreciation shall be calculated on 85 % of the capital<br>investment<br>ROE: 19.85 % pre-tax | TP: 20 years<br>Capex: Rs. 57.5 million/MW<br>O&M: 1.1 % on 85 % of the capital investment and 0.22 % on 15 % of the capital investment and escalation factor of 5 % from second year onwards<br>CUF: 27.15 %<br>De-rating: 1 % per annum after the first 10 years<br>TL: 10 years<br>DER: 70:30 | T: Wind mills commissioned between July 31, 2012–July31, 2014: Rs. 3.51/kWh<br>Wind mills commissioned before May 15, 2006: Rs. 2.75/kWh<br>Wind mills commissioned between May 15, 2006 and Sept. 18, 2008: Rs. 2.90/KWh<br>Wind mills commissioned between Sept. 19, 2008 and July 31, 2012: Rs. 3.39/kWh<br>TPS: Allowed by SERC since March 20 2009 | RP: 25 paise per kVARh will be levied on wind energy generators, who draw reactive power up to 10 % of the net active energy generated. Anyone drawing in excess of 10 % of the net active energy generated will be liable to pay double the charge<br>W: Fixed 40 % of the transmission charges and 40 % of the wheeling charges as applicable to the conventional power to the Wind power<br>B: 5 % (12 months in a financial year (April–March) |

(continued)

**Table 9** (continued)

| | Interest Rate on Debt (IRD)/ Working Capital (IRWC), Discount Rate (DR), Depreciation (D), Return on Equity (RoE) | Tariff Period (TP), Capex, O&M, CUF, Evacuation Cost (EC), Tenure Loan (TL), Debt:Equity Ratio (DER) | Tariff (T)/Third Party Sales (TPS) | Other Incentives (OI), Reactive Power (RP), Banking (B), Wheeling (W) |
|---|---|---|---|---|
| Karnataka | IRD: 12.3 %<br>IRWC: 13 %<br>DR:<br>D: 5.83 % depreciation for the first twelve years and 1.54 % from 13th year onwards<br>ROE: 16 post-tax | TP: 25 years<br>Capex: Rs. 56.0 million/MW including Rs. 10 lakh/MW evacuation cost<br>O&M: 1.25 % of capital cost with 5 % escalation annually<br>CUF: 26.5 %<br>TL: 10 years<br>DER: 70:30 | T: Fixed on 11 December 2009 at Rs. 3.40/per KWh without any escalation for 10 years of commercial operation but revised on October 10, 2013 to Rs. 4.20/kWh-will be applicable till 10 Oct. 2018<br>TPS: Allowed under Electricity Act 2003 | OI: No electricity duty for 5 years<br>RP: 40 paise per KVARh<br>W: 5 % of energy<br>B: subject to payment of difference of UI charges between the time of injection and time of drawl and also on payment of banking charges @ 2 % of input energy |
| Kerala | IRD: 12.30 %<br>IRWC: 12.80 %<br>DR: 12 %<br>D: 5.72 %<br>Depreciation: 5.83 % p.a. for the first 12 years and remaining spread over useful life<br>ROE: 20 % pre-tax for first 10 years and 24 % pre-tax thereafter | TP: 20 years<br>Capex: Rs. 57.5 lakh/MW<br>O&M: Rs. 9.0 lakh/MW escalated at 5.72 %<br>CUF: 25 %<br>TL: 10 years<br>DER: 70:30 | T: Fixed in 2008 at Rs. 3.14/kWh for 20 years but recently revised on January 1, 2013 to Rs. 4.77/kWh<br>TPS: Allowed under Electricity Act 2003 | |
| Gujarat | IRD: 13 %<br>IRWC: 12 %<br>DR:11.08 %<br>D: 6 % per for first 10 years and 2 % 11th year onwards<br>ROE: 14 % and the tax payment of MAT at the rate of 20.008 % per annum for first 10 years and corporate tax at the rate of 32.445 % per annum for the next 15 years | TP: 25 years<br>Capex: Rs. 56.8 million/MW (excluding the power evacuation cost from wind farm substation to STU substation)<br>O&M: Rs. 8 lakh/MW for the first year and 5.72 % escalation from the second year onwards<br>CUF: 24 %<br>EC: Rs. 3.8 million/MW towards constructing the evacuation line up to 100 km length<br>TL: 10 years<br>DER: 70:30 | T: Rs. 3.50/kWh for 20 years but revised in 2012 to Rs. 4.61 per kWh (without depreciation benefit) and Rs. 4.23/kWh (depreciation benefit)<br>TPS: Allowed by the GERC | OI: Electricity duty exempted<br>RP: 10 paise/kVARh: for drawl of = <10 % of net energy exported 20 paise/kVARh: for drawl of >10 % of net active energy exported<br>W: 7–10 % of energy fed to the grid Wheeling of wind energy for the third party sale and captive use shall be exempted from cross subsidy charge<br>B: Allowed. Settlement to be done month to month and surplus energy at the end of month shall be deemed as sold to the utility as per the tariff rate. Banking is not available for the third party sale |

(continued)

**Table 9** (continued)

| | Interest Rate on Debt (IRD)/ Working Capital (IRWC), Discount Rate (DR), Depreciation (D), Return on Equity (RoE) | Tariff Period (TP), Capex, O&M, CUF, Evacuation Cost (EC), Tenure Loan (TL), Debt:Equity Ratio (DER) | Tariff (T)/Third Party Sales (TPS) | Other Incentives (OI), Reactive Power (RP), Banking (B), Wheeling (W) |
|---|---|---|---|---|
| Madhya Pradesh | IRD: 12.75 % (SBI base rate + 300 basis point)<br>IRWC: 13.25 %<br>DR: 10.20 %<br>D: 7 % per annum for the first 10 years<br>ROE: 20 % pre-tax | TP: 25 years<br>Capex: Rs. 59.6 million/MW (including evacuation cost)<br>O&M: 1 % of the capital cost in first year with an escalation of 5.72 % for each year thereafter<br>CUF: 20 %<br>TL: 10 years<br>DER: 70:30 | T: Year wise rates (Rs./kWh) from 1st–20th year<br>1st year—4.03<br>2nd year—3.86<br>3rd year—3. 69<br>4th year—3.52<br>5th–20th year—3.36. Revised tariff in March 2013: Rs. 5.92/kWh<br>TPS: Allowed by the MERC but within state | OI: Electricity duty exempted for 10 years from the date of commissioning. VAT/entry tax exemption for wind plants<br>RP: 27 paise/unit<br>W: 2 % of Energy injected<br>B: Allowed, but proposal for this invited from DISCOM |
| Maharashtra | IRD: 12.83 % (SBI base rate + 300 basis point)<br>IRWC: 13.23 %<br>DR: 15.58 %<br>D: 7 % per annum for first 10 years and 1.33 % from 11th year onwards<br>ROE: 19 % pre-tax per annum for the first ten years and after 10 years 24 % pre-tax per annum | TP: 25 years<br>Capex: Rs. 58.5 million/MW<br>O&M: Rs. 8.58 lakh per MW for FY 2014–15<br>CUF (Z1–Z4): 22, 25, 30, 32 %<br>Tariff fixed for: 13 years<br>TL: 10 years<br>DER: 70:30 | T (2014–15):<br>Z1: Rs. 5.70/kWh (without tax and HD benefits) and Rs. 5.33 (with tax and HD benefits)<br>Z2: Rs. 5.01/kWh (without tax and HD benefits) and Rs. 4.69 (with tax and HD benefits)<br>Z3: Rs. 4.18/KWh (without tax and HD benefits) and Rs. 3.91 (with tax and HD benefits)<br>Z4: Rs. 3.92/kWh (without tax and HD benefits) and Rs. 3.67 (with tax and HD benefits)<br>TPS: Allowed a maximum up to 50 % only within the state | OI: Power evacuation arrangement, approach road, electricity duty exemption for 10 years from the date of commissioning, 100 % octro/entry tax refund and loan to cooperative societies<br>W: 2 % of energy + 5 % as T&D loss<br>B: Allowed any time of the day and night subject to the condition that surplus energy<br>Settlement to be done within a year |

(continued)

**Table 9** (continued)

| | Interest Rate on Debt (IRD)/ Working Capital (IRWC), Discount Rate (DR), Depreciation (D), Return on Equity (RoE) | Tariff Period (TP), Capex, O&M, CUF, Evacuation Cost (EC), Tenure Loan (TL), Debt:Equity Ratio (DER) | Tariff (T)/Third Party Sales (TPS) | Other Incentives (OI), Reactive Power (RP), Banking (B), Wheeling (W) |
|---|---|---|---|---|
| Rajasthan | IRD: 12.71 % (SBI base rate + 300 basis point)<br>IRWC: 12.21 % (SBI rate + 250 basis point)<br>DR:13.10 %<br>D: 5.83 % per annum for the first 12 years and the balance spread over the useful life<br>ROE: 16 % pre-tax and tax payment for MAT rate: 1st year 20.01 %, 2nd–9th year: 19.06 %, 11th–25th year: 30.90 % | TP: 25 years<br>Capex: Rs. 56.5 million/MW (including inclusive of Rs. 25 lakh/MW towards the cost of transmission system including pooling station up to the interconnection point, and this includes Rs. 2 lakh/MW for grid connectivity charges payable to Transmission licensee)<br>O&M: Rs. 7.87 lakh/MW with 5.85 % escalation<br>CUF: 21 % for Jaisalmer, Jodhpur and Barmer districts and 20 % for other districts<br>TL: 10 years<br>DER: 70:30 | T: Rs. 5.31/KWh (with HD benefit) and Rs. 5.64/kWh (without HD) for Jaisalmer, Barmer and Jodhpur. Rs. 5.93/kWh (without HD benefit) and Rs. 5.57/kWh (with HD) for all other districts<br>TPS: Allowed under Electricity Act 2003 | OI: Exemption from electricity duty @50 % for 7 years<br>RP: 5.75 paise per kVArh w.e.f. 1 April 2009 with escalation of 0.25 paise per year<br>Land is given on lease at a minimal cost to the developers<br>W: 50 % of normal charge as applicable for 33 kV, in addition to the transmission charges of 3.6 % & surcharge<br>B: Six Months (Apr.–Sept. and Oct.–March. Utilization of banking energy not permitted in Dec.–Feb.) |

*Source* Compiled from Order No. 6 of 2012, Tamil Nadu Electricity Regulatory Commission, Order Suo-moto, July 7, 2014, MERC; Order No. 2 of 2012, August 8, 2012, GERC; OP No. 19/2012, October 10, 2013, KERC, O P No. 13 of 2012, November, 15, 2012, APERC; RE Tariff Regulations, 24 February 24, 2014, RERC; Madhya Pradesh Wind Power Policy 2012

- Depreciation of plant and machinery
- Operation and maintenance expenditure include insurance, regular maintenance, repair, spare parts, and administration.

Capital investment

The wind-power plant capital (installed) cost in India has been increasing steadily (TERI and ORG 1997). Recently the 12th five-year plan document by the Planning Commission (Planning Commission 2013) reports that the cost per MW of wind power has increased from Rs. 43 million/MW in the FY 2003–04 to Rs. 57 million/MW in FY 2010–2011. Recently, most SERCs are considerate and allow higher capital cost/MW. In 2012, the Tamil Nadu Electricity Regulatory Commission (TNREC 2012) allowed Rs. 57.5 million/MW and Madhya Pradesh ERC permitted Rs. 59.6 million/MW, including cost of power evacuation system for the control period without indexation (MPERC 2013). Tamil Nadu SERC considers 85 % of the capital cost attributable to machinery cost, 10 % to civil works, and 5 % to land cost.

Capacity utilization factor

In India the capacity utilization factor is lower compared to the US and European countries.

De-rating of machines: The TNSERC has fixed the de-rating of machines at 1 % per annum after the first 10 years.

Debt Equity Ratio: The Tariff Policy lays down a debt equity ratio of 70: 30 for power projects and all SERCs follow the same.

Term Loans: It is a challenging task to get term loans for wind projects in India. The Government through IREDA helps wind power developers for financing and refinancing.

Interest Rate: IREDA suggests an interest rate applicable to the wind sector is between 11.75 % and 12.50 %. Many of the ERCs are following IREDA's suggestions while considering the interest rate for tariff determination. Uttar Pradesh (UP), Karnataka, and Tamil Nadu ERCs consider the interest rate at 10.25 %, 11 %, and 12.25 % respectively (TNREC 2012).

Return on Equity (ROE): Return on equity SERCs are Madhya Pradesh (16 % pretax), Karnataka (16 %) and Andhra Pradesh (AP) (15.5 % pre-tax), Tamil Nadu (19.85 % pre-tax) (TNREC 2012).

Plant life: Many of the SERCs consider a plant life of 20/25 years for tariff determination. TNERC considers a plant life of 20 years for wind machines.

Depreciation: The Commission proposes to retain the rate of 4.5 % per annum and the depreciation calculated at 85 % of the capital investment, which represents the cost of plant and machinery.

O&M expenses: TNSERC permits O&M expenses of 1.1 % on 85 % of the capital investment and 0.22 % of the 15 % of the capital investment and an escalation factor of 5 % from the second year onwards. 85 % of the capital cost refers to the plant and machinery cost and 15 % refers to the land and civil works.

### 7.3 Renewable Purchase Obligations (RPO)

As of now, 26 SERCs specified the mandatory purchase obligation under Sect. 86, 1(e) of the Electricity Act, 2003 for purchase of fixed percentage of energy generated from RE sources (The Electricity Act 2003). The RPO percentage varies from 0.5 to 10.25 %, depending on the local renewable resources and the electricity distributed in those States (MNRE 2014). The RPO targets set by the various SERCs during 2010–2015 is shown in Table 10. The RPO can be fulfilled through direct

**Table 10** State-wise RPO targets in India

| | | 2012–13 (%) | | | 2013–14 (%) | | | 2014–15 (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Total | Solar | Non-solar | Total | Solar | Non-solar | Total | Solar | Non-solar |
| 1 | Arunachal Pradesh | 4.20 | 0.10 | 4.10 | 5.60 | 0.15 | 5.45 | 7.00 | 0.20 | 6.80 |
| 2 | Andhra Pradesh | 5.00 | | | 5.00 | | | 5.00 | | |
| 3 | Assam | 4.20 | 0.15 | 4.05 | 5.60 | 0.20 | 5.40 | 7.00 | 0.25 | 6.75 |
| 4 | Bihar | 4.00 | 0.75 | 3.25 | 4.50 | 1.00 | 3.50 | 5.00 | 1.25 | 3.75 |
| 5 | Chhattisgarh | 5.75 | 0.50 | 5.25 | 5.75 | 0.50 | 5.25 | 5.75 | 0.50 | 5.25 |
| 6 | Delhi | 3.40 | 0.15 | 3.25 | 4.80 | 0.20 | 4.60 | 6.20 | 0.25 | 5.95 |
| 7 | Goa | 3.00 | 0.40 | 2.60 | 3.00 | 0.40 | 2.60 | 3.00 | 0.40 | 2.60 |
| 8 | Gujarat | 7.00 | 1.00 | 6.00 | 7.00 | 1.00 | 6.00 | 7.00 | 1.00 | 6.00 |
| 9 | Haryana | 2.00 | 0.00 | 2.00 | 3.00 | 0.05 | 2.95 | | 0.25 | |
| 10 | Himachal Pradesh | 10.25 | 0.25 | 10.00 | 10.25 | 0.25 | 10.00 | 10.25 | 0.25 | 10.00 |
| 11 | Jammu and Kashmir | 5.00 | 0.25 | 4.75 | | | | | | |
| 12 | Jharkhand | 4.00 | 1.00 | 3.00 | | | | | | |
| 13 | Karnataka | 5.00 | 0.25 | 4.75 | | | | | | |
| 14 | Kerala | 5.00 | 0.25 | 4.75 | 5.00 | 0.25 | 4.75 | 5.00 | 0.25 | 4.75 |
| 15 | Madhya Pradesh | 4.00 | 0.60 | 3.40 | 5.50 | 0.80 | 4.70 | 7.00 | 1.00 | 6.00 |
| 16 | Maharashtra | 8.00 | 0.25 | 7.75 | 9.00 | 0.50 | 8.50 | 9.00 | 0.50 | 8.50 |
| 17 | Manipur | 5.00 | 0.25 | 4.75 | 5.00 | 0.25 | 4.75 | 5.00 | 0.25 | 4.75 |
| 18 | Meghalaya | 1.00 | 0.40 | 0.60 | 1.00 | 0.40 | 0.60 | 1.00 | 0.40 | 0.60 |
| 19 | Mizoram | 7.00 | 0.25 | 6.75 | 7.00 | 0.25 | 6.75 | 7.00 | 0.25 | 6.75 |
| 20 | Nagaland | 8.00 | 0.25 | 7.75 | | | | | | |
| 21 | Odisha | 5.50 | 0.15 | 5.35 | 6.00 | 0.20 | 5.80 | 6.50 | 0.25 | 6.25 |
| 22 | Tamil Nadu | | | | 11.00 | 2.00 | 9.00 | 11.00 | 2.00 | 9.00 |
| 23 | Tripura | 1.00 | 0.10 | 0.90 | 1.00 | 0.10 | 0.90 | 2.00 | | |
| 24 | Uttar Pradesh | 6.00 | 1.00 | 5.00 | 6.00 | 1.00 | 5.00 | 6.00 | 1.00 | 5.00 |
| 25 | Uttarakhand | 5.05 | 5.00 | 0.05 | 6.05 | 0.05 | 6.00 | 7.08 | 0.075 | 7.00 |
| 26 | West Bengal | | | | 4.00 | 0.10 | 3.90 | 4.50 | 0.15 | 4.35 |

purchase via bilateral contracts and a tradable REC mechanism which can further generate revenue for RE projects.

Several State electricity regulatory commissions have announced RPOs to promote generation, distribution, and consumption of RE across India. In case the generation-based RPOs are not met, the shortfall can be met through Renewable Energy Certificate (REC)—a market-based incentive.

### 7.3.1 Generation-Based Renewable Purchase Obligation

Generation-based RPOs ensure the minimum percentage offtake by the electricity distribution companies and some large power consumers from the renewable producers. The RPO creates a minimum market for renewable irrespective of market dynamics. Generation-based RPO have been divided into two categories: solar and nonsolar. Wind RPO falls under the nonsolar category and unlike solar it is not given mandatory purchase requirement. As some of the States do not have adequate wind resources, so production and purchase becomes a challenge.

### 7.3.2 Renewable Energy Certificates

Renewable certificate (REC) launched in 2010 is a tradable certificate where one wind REC (nonsolar) certificate is equal to 1 MWh of wind energy generated. Wind REC can be purchased by distribution companies, open access, and captive consumer to meet the RPO. If any entity is not able to meet the generation-based RPO, the same may be met through purchasing REC certificates in the same category. Obligation to purchase electricity from generation based on solar as an RE source can be fulfilled by the purchase of solar certificates only, and the obligation to purchase electricity from generation other than solar can be fulfilled by the purchase of nonsolar certificates. The floor and forbearance price of one nonsolar REC is Rs. 1500.00 and Rs. 3300.00 respectively (MNRE 2014).

### 7.3.3 Compliances and Failure

Noncompliance of RPO has a direct bearing on the REC mechanism. If the obligated entity does not fulfill the RPO as provided in the regulations during any year and also does not purchase the certificates, the SERC may direct the obligated entity to deposit into a separate fund, to be created and maintained by such obligated entities, such amount as the Commission may determine on the basis of the shortfall in units of RPO and the forbearance price decided by the Central Commission. There is a provision of empowering officers from a State agency to operate the account and if desired the fund can be utilized to purchase RECs from the power exchange to meet the shortfall. In case of genuine difficulty or nonavailability of the obliged entity may approach the Commission for consideration.

## 8 Conclusion

It is estimated that India's wind power capacity installation would exceed 164GW by 2030 and with an average CUF of 20 % would translate to 32.8 GW of actual production. Current wind installation penetration level is about 8.5 % in India compared to 4.9 % globally. However, wind market development is not uniform across the country owing to factors such as wind potential, availability of wind at desired speed and height, evacuation infrastructure, grid infrastructure, investment climate and policy, tariff structure, wind power buy-back or third party sales policy, wheeling, banking, capacity utilization, government support, financial and nonfinancial incentives, wind-specific policy, and proactive/reactive SERCs, and reinforcement of mandatory RPOs. It is observed that States like Tamil Nadu, Maharashtra, and Gujarat have been able achieve a certain level of competitive advantage over the other States. Other States like Karnataka, Madhya Pradesh, and Kerala are making steady progress. These States are able to draw upon the learning experience of the early movers for faster market developments and wind penetration. The early movers face unique challenge of repowering the old mills whereas the late movers have the advantage of setting up next-generation power plants.

Higher feed of renewables into the grid creates serious challenges in terms of managing grid imbalance and power system disturbances. Modernization of existing wind turbines with advanced technology and new features like fault ride through (FRT) and frequency capabilities could enhance grid balance. Repowering would certainly improve capacity utilization factor and increase renewable power production. To facilitate the high wind penetration, regulations/connectivity standards are to be introduced to ensure that their large-scale integration does not affect the power system security and reliability.

To achieve greater wind penetration the Central government, State government, and the regulatory bodies need to work cohesively and collaboratively and iron out implementation failure, especially in the areas of renewable purchase obligation. The States having high/moderate wind potential should have a mandatory wind RPO, with compulsory generation-based obligations. Any failure in RPO compliances should be seriously dealt with. The SERCs should judiciously exercise their power to make renewable, the fuel of this century in India. The CERC and the SERCs should push for formation of a Wind Energy Mission at the earliest; this would provide the much needed impetus for the growth of wind power, especially offshore wind in India.

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# Wind Energy Technology and Environment Sustainability

**Vilas Warudkar**

**Abstract** Wind power plays an important role in the development of country's economy as it reduces country's dependency on fossil fuels. Wind energy generally categorized as a clean, environmentally friendly, and renewable source of energy. India is blessed with an immense amount of renewable energy resources, and wind energy is one of the promising sources for energy supply option. The demand of electricity has grown significantly in recent past years, and India depends widely in coal and oil to meet energy demands. In recent past years, there has been intense research activities carried out in the development, production, and distribution of energy in India, which results in the development of the need for new sustainable energy due to limited fossil fuel resources and problem associated with the environment (smog, acid rain, and greenhouse gasses emission). Development and promotion of non-conventional sources of energy such as solar, wind, geothermal, and bio-energy are also getting continuous attention. Wind energy is non-polluting source of energy, and its mature technology and comparatively low cost make it promising and primary non-conventional energy source in India. The gross wind power capacity in the country is estimated about 49,000 MW, and a capacity of 21,264 MW up to May 2014 has been added so far through wind. Continued research and development to increase the value of forecasting power performance, reducing the uncertainties related to engineering integrity, enabling large-scale use, and minimizing environmental impact are some of the areas needing concerted efforts in wind energy. These efforts are also expected to make wind power more reliable and cost competitive with conventional technologies in the future for an environmental sustainability.

**Keywords** Wind energy · Renewable energy · Wind power · Potential · Installed capacity · Generation · Environment · Sustainability

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# 1 Energy Scenario

Energy availability is a direct measure of the state of development of a country. Per capita availability of energy indicates the relative affluence of the people. For example, per capita electricity consumption of OECD nations is of the order of 12,000 kWh per person per year as compared to the world average of 2400 kWh/year. In the case of India, it is only about 631.41 kWh/year indicating relatively very poor level of development. About 55 % of the population in the country does not have electricity in their homes. About 70 % of India's energy generation capacity is from fossil fuels, with coal accounting for 40 % of India's total energy consumption followed by crude oil and natural gas at 24 and 6 %, respectively. India is largely dependent on fossil fuel imports to meet its energy demands. By 2030, India's dependence on energy imports is expected to exceed 53 % of the country's total energy consumption. India has an installed generation capacity of 211,766.22 MW which mainly comprises of thermal and hydroelectric installations. The share of different sources of energy in India is shown in Table 1.

Due to rapid economic expansion, India has one of the world's fastest growing energy markets and is expected to be the second largest contributor to the increase in global energy demand by 2035, accounting for 18 % of the rise in global energy consumption. Given India's growing energy demands and domestic fossil fuel reserves, the country has ambitious plans to expand its renewable and nuclear power industries. India has the world's fifth largest wind power market and plans to add about 20 GW of solar power capacity by 2022. India also envisages to increase the contribution of nuclear power to overall electricity generation capacity from 4.2 to 9 % within 25 years. The country has five nuclear reactors under construction and plans to construct 18 additional nuclear reactors by 2025.

# 2 Renewable Energy

Renewable energy is the term used to describe energy flows that occur naturally and continuously in the environment, such as energy from the wind, waves, or tides. The origin of the majority of these sources can be traced back to either the

**Table 1** All India installed capacity and sources of energy

| Source/technology | MW | % |
|---|---|---|
| Total thermal | 14,0976.18 | 66.7 |
| Coal | 120,873.38 | 57.2 |
| Gas | 18,903.05 | 9.0 |
| Oil | 1199.75 | 0.6 |
| Hydro (renewable) | 39,339.40 | 18.5 |
| Nuclear | 4780.00 | 2.25 |
| RES (MNRE) | 26,677.1 | 12.55 |
| Total | 210,951.72 | |

sun (energy from the sun helps to drive the earth's weather patterns) or the gravitational effects of the sun and the moon. This means that these sources are essentially inexhaustible.

The key issue is how to extract this energy as effectively as possible and convert it into more useful forms of energy. This can range from directly using the energy from the sun to heat water to using mechanical devices, such as wind turbines, to convert the kinetic energy in the wind into electrical energy.

## *2.1 Renewable Energy Utilization*

Energy underpins virtually every aspect of our economy and day-to-day lives. However, the use of fossil fuels, which currently provide the bulk of our energy, releases greenhouse gases (such as carbon dioxide) into the atmosphere. Due to factors such as population growth and changes in lifestyle, the demand for energy has increased to levels where the burning of fossil fuels is releasing enough greenhouse gases into the atmosphere to begin to directly affect our climate system.

To help lessen the effects of climate change, we must reduce the level of greenhouse gases emitted. This can be achieved by generating our energy from sources that emit low or even zero levels of greenhouse gases, such as renewable energy. We can also make sure that we use energy as efficiently as possible. However, these are not either/or options.

The potential in India for generation of power from renewable sources is indeed quite sustainable as it is endowed with large sunny and windy areas; besides significant quantities of biomass material, urban and industrial wastes and small hydroresources special emphasis have therefore been laid on generation of grid quality power from these renewable, as it is called because of its eco-friendly nature.

In fact, generation of grid quality power from renewable is very much an established fact in our country. The total installed capacity of power based on renewable sources has also reached 26,677.1 MW, and the total installed capacity of power generated from all sources as shown in Table 2.

**Table 2** Total installed capacity of power generated from all renewable energy sources in India

| S. No. | Technology | Installed capacity in MW |
|---|---|---|
| 1. | Biomass power (Agro-residues) | 1248.60 |
| 2. | Wind power | 18,420.40 |
| 3. | Small hydropower (up to 25 MW) | 3496.14 |
| 4. | Cogeneration biogases | 2239.63 |
| 5. | Waste to energy | 96.08 |
| 6. | Solar power | 1176.25 |
| | Total | 26,677.1 |

As on December 31, 2012

There are various sources of power and there are very few that are renewable but then, the use of energy has increased manifold and consequently the demand. Therefore, we need some such sources of energy that are renewable so that we can cope with the imminent energy crisis that is coming. Wind energy, solar energy, and hydropower are examples of renewable energy, which can be recycled and reused again and again. These power sources do not create pollution neither is there a scope of these energy sources of being exhausted.

Wind energy is plentiful, renewable, widely distributed, and clean and reduces greenhouse gas emissions when it displaces fossil fuel-derived electricity. The intermittency of wind seldom creates insurmountable problems when using wind power to supply a low proportion of total demand, but it presents extra costs when wind is to be used for a large fraction of demand.

## 3 Wind

Wind is simply air in motion. It is caused by the uneven heating of the earth's surface by the sun. Since the earth's surface is made up of land, desert, water, and forest areas, the surface absorbs the sun's radiation differently.

During the day, air above the land heats more quickly than air above water. The hot air over the land expands and rises, and the heavier, cooler air over a body of water rushes into take its place, creating local winds. At night, the winds are reversed because air cools more rapidly over land than over water.

Similarly, the large atmospheric winds that circle the earth are created because land near the equator is heated more by the sun than land near the North and South Poles.

Today, people can use wind energy to produce electricity. Wind is called a renewable energy source because it is inexhaustible.

## 4 History of Wind Machines

Throughout the history, people have harnessed the wind. Over 5000 years ago, the ancient Egyptians used wind power to sail their ships on the Nile River. Later, people built windmills to grind their grain. The earliest known windmills were in Persia (the area now occupied by Iran). The early windmills looked like large paddle wheels.

Centuries later, the people in Holland improved the windmill. They gave it propeller-type blades and made it so it could be turned to face the wind. Windmills helped Holland become one of the world's most industrialized countries by the seventeenth century.

American colonists used windmills to grind wheat and corn, to pump water, and to cut wood at sawmills.

In this century, people used windmills to generate electricity in rural areas that did not have electric service. When power lines began to transport electricity to rural areas in the 1930s, the electric windmills were used less and less.

Then in the early 1970s, oil shortages created an environment eager for alternative energy sources, paving the way for the re-entry of the electric windmill on the American landscape.

## 5 Present Wind Machine

Today’s wind machine is very different from yesterday’s windmill. Along with the change in name have come changes in the use and technology of the windmill.

While yesterday’s machines were used primarily to convert the wind’s kinetic energy into mechanical power to grind grain or pump water, today’s wind machines are used primarily to generate electricity.

Like old-fashioned windmills, today’s wind machines still use blades to collect the wind’s kinetic energy. Windmills work because they slow down the speed of the wind. The wind flows over the airfoil-shaped blades causing lift, like the effect on airplane wings, causing them to turn. The blades are connected to a drive shaft that turns an electric generator to produce electricity.

Modern wind machines are still wrestling with the problem of what to do when the wind is not blowing. Large turbines are connected to the utility power network—some other type of generator picks up the load when there is no wind. Small turbines are often connected to diesel/electric generators or sometimes have a battery to store the extra energy they collect when the wind is blowing hard.

## 6 Types of Wind Machines

Two types of wind machines are commonly used today:

1. Horizontal-axis wind turbine
2. Vertical-axis wind turbine

### *6.1 Horizontal-Axis Wind Turbines*

Horizontal-axis machines have received the most developmental effort and have been the most successful commercially.

The horizontal-axis WECS with lifting elements [horizontal-axis wind turbines (HAWTs)] has a wide variety of applications, dating as far back as early Persia, and sizes (from a few watts to a few megawatts). The system has been used to provide energy for water pumping, electrical generation, grinding grain, and other

**Fig. 1** Doesburger windmill, Ede, The Netherlands. *Source* http://entcambodia.wordpress.com/

uses in many parts of the world. Horizontal-axis lifting element WECS designs are shown in Fig. 1.

Horizontal-axis wind turbines (HAWTs) have the main rotor shaft and electrical generator at the top of a tower and must be pointed into the wind. Small turbines are pointed by a simple wind vane, while large turbines generally use a wind sensor coupled with a servo motor Fig. 2. Most have a gearbox, which turns the slow rotation of the blades into a quicker rotation that is more suitable for generating electricity.

The HAWT has several essential features. It must have one or more lifting elements, or blades, attached to an axis that is aligned with the wind. The HAWT requires some mechanism to orient the axis so that it is aligned with the wind; it also requires a support structure to raise the active elements into a reasonable wind regime, and this support structure must have sufficient strength to resist the aerodynamic loads that may be applied. An energy conversion system and a control system are also required.

Rotors have been built with number of blades ranging from one to several. Machines with two or three blades are the most common. For the same total solidity, it is usually less expensive and more structurally sound to minimize the number of blades; but when fewer than three blades are used, the moment of

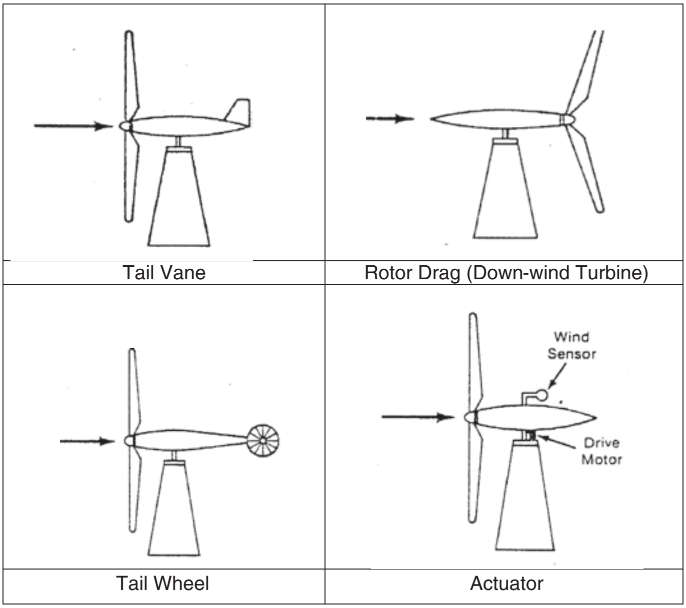


**Fig. 2** Typical orientation mechanism for HAWTs

inertia of the rotor is not the same about two mutually perpendicular axes in the plane of the rotor.

Since a tower produces turbulence behind it, the turbine is usually pointed upwind of the tower. Turbine blades are made stiff to prevent the blades from being pushed into the tower by high winds. Additionally, the blades are placed a considerable distance in front of the tower and are sometimes tilted up a small amount.

Downwind machines have been built, despite the problem of turbulence, because they do not need an additional mechanism for keeping them in line with the wind, and because in high winds, the blades can be allowed to bend which reduces their swept area and thus their wind resistance.

### 6.1.1 Parts of HAWTs

The simplest possible wind energy turbine consists of these crucial parts (Fig. 3):

- Rotor Blades
- Shaft
- Hub
- Gear box
- Nacelle
- Generator
- Brakes

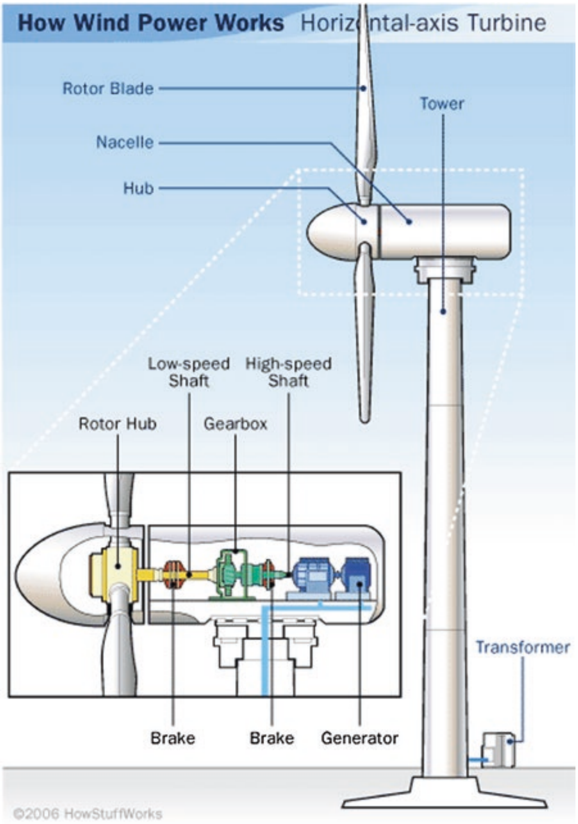


**Fig. 3** Parts of HAWTs

- Tower
- Foundation

### 6.1.2 Advantages of HAWTs

- Blades are to the side of the turbine's center of gravity, helping stability.
- Ability to wing warp, which gives the turbine blades the best angle of attack. Allowing the angle of attack to be remotely adjusted gives greater control, so the turbine collects the maximum amount of wind energy for the time of day and season.
- Ability to pitch the rotor blades in a storm, to minimize damage.
- Tall tower allows access to stronger wind in sites with wind shear. In some wind shear sites, every 10 m up, the wind speed can increase by 20 % and the power output by 34 %.
- Tall tower allows placement on uneven land or in offshore locations.
- Can be sited in forests above the tree line.
- Most are self-starting.

- Can be cheaper because of higher production volume, larger sizes, and, in general, higher capacity factors and efficiencies.

## *6.2 Vertical-Axis Wind Turbines*

In 1925, Darrieus patented a variety of vertical-axis WECS models that used aerodynamic lift. Figure 4 shows the concept submitted in the original patent. As with the UWT, the vertical-axis wind turbine (VAWT) uses one or more blades attached to an axis, it is shown in Fig. 4. However, in the case of the VAWT, the axis is aligned vertically across the wind.

Vertical-axis wind turbines (VAWTs) have the main rotor shaft running vertically. Key advantages of this arrangement are that the generator and/or gearbox can be placed at the bottom, near the ground, so the tower does not need to support it and that the turbine does not need to be pointed into the wind. Drawbacks are usually pulsating torque that can be produced during each revolution and drag created when the blade rotates into the wind. It is also difficult to mount vertical-axis turbines on towers, meaning they must operate in the often slower, more turbulent air flow near the ground, resulting in lower energy extraction efficiency.

**Fig. 4** Darrieus wind turbine. *Source* http://en.wikipedia.org/wiki/Darrieus_wind_turbine

There are three types of VAWT: the fixed-pitch curved-blade machine, the fixed-pitch straight-blade machine, and the variable-pitch straight-blade machine. All VAWTs are subject to cyclic aerodynamic loads, and the lift force reverses direction relative to the blades during each turn of the rotor so that nearly symmetrical air foils are required.

The straight-blade machines have the advantage of simple blade construction. However, the centrifugal bending moments on the blades limit the blade speed and the allowable unsupported blade length. The curved-blade machines have a blade shape that a flexible element would adopt under the centrifugal load, so the blades are subjected to low bending stresses.

### 6.2.1 Parts of VAWTs

The simplest possible wind energy turbine consists of these crucial parts (Fig. 5):

- Rotor Blades
- Shaft
- Upper Hub
- Lower Hub
- Gear Box
- Generator
- Brakes
- Guy Wires
- Foundation

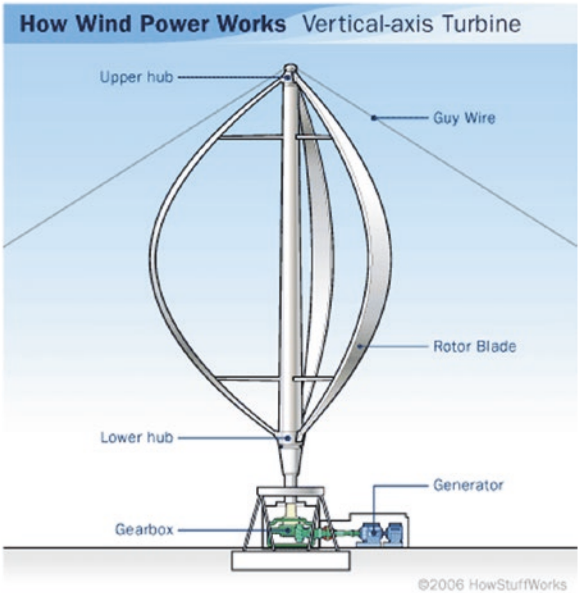


**Fig. 5** Parts of VAWTs

### 6.2.2 Advantages of VAWT

- Easier to maintain because most of their moving parts are located near the ground. This is due to the vertical wind turbine's shape. The airfoils or rotor blades are connected by arms to a shaft that sits on a bearing and drives a generator below, usually by first connecting to a gearbox.
- As the rotor blades are vertical, a yaw device is not needed, reducing the need for this bearing and its cost.
- Vertical wind turbines have a higher airfoil pitch angle, giving improved aerodynamics while decreasing drag at low and high pressures.
- Low height useful where laws do not permit structures to be placed high.
- Smaller VAWTs can be much easier to transport and install.
- Does not need a free-standing tower so is much less expensive and stronger in high winds that are close to the ground.
- Usually have a lower Tip speed ratio so less likely to break in high winds.
- Does not need to be pointed into the wind and can turn regardless of the direction of the wind.

## 7 Important Terms

**Lift** This force acts perpendicular to the direction of wind flow is shown in Fig. 6.

The reason why an airplane can fly is that the air sliding along the upper surface of the wing will move faster than on the lower surface.

**Drag** Resistance caused by friction in the direction opposite to that of the motion of components, such as wind turbine blades. This force acts parallel to the direction of wind flow is shown in Fig. 7.

**Cut-in Speed** The lowest wind speed at which a wind turbine begins producing usable power.

**Cut-out Speed** The highest wind speed at which a wind turbine stops producing power.

**Angle of Attack** Angle of attack is the angle between the wind direction and chord line of aerodynamic profile.

**Fig. 6** Lift phenomenon


**Fig. 7** Drag phenomenon

**Tip Speed Ratio** The tip speed ratio λ or **TSR** for wind turbines is the difference between the rotational speed of the tip of a blade and the actual velocity of the wind. If the velocity of the tip is exactly the same as the wind speed, the tip speed ratio is 1. A tip speed ratio above 1 means some amount of lift and below 1 usually indicates drag. A high tip speed ratio indicates mostly a better efficiency but is usually also related to a higher noise level and a heavier design.

$$\text{Tip Speed Ratio} = \frac{\text{Tip Speed of Blade}}{\text{Wind Speed}}$$

**Solidity** In reference to a wind energy conversion device, the ratio of rotor blade surface area to the frontal, swept area that the rotor passes through

$$\text{Solidity} = \frac{\text{Rotor blade surface area}}{\text{Rotor swept area}}$$

**Feather** As the wind speed increases, the power generated by the wind turbine also increases. Once the maximum rating of the power converter is reached, the pitch angle is increased (directed to feather) to shed the aerodynamic power. As the pitch angle is increased, the wind turbine operates at lower efficiency. The wind turbine can be controlled to pitch-to-feather or pitch-to-stall. It is more common that the wind turbine is pitched to feather to reduce the aerodynamic power of wind turbine blades.

**Furling** The process of forcing, either manually or automatically, the blades of a wind turbine out of the direction of the wind in order to stop the blades from turning is called furling. Furling works by decreasing the angle of attack, which reduces the induced drag from the lift of the rotor, as well as the cross section. One of the major problems in designing wind turbines is getting the blades to stall or furl quickly enough should a gust of wind cause sudden acceleration.
A fully furled turbine blade, when stopped, has the edge of the blade facing into the wind.

**Stalling** Wind turbine stalling works by increasing the angle at which the relative wind strikes the blades (angle of attack), and it reduces the induced drag (drag associated with lift). Stalling is simple because it can be made to happen passively (it increases automatically when the winds speed up), but it increases the cross section of the blade face-on to the wind and thus the ordinary drag.

A fully stalled turbine blade, when stopped, has the flat side of the blade facing directly into the wind.

**Fig. 8** Wake effect after turbine blade

**Wake Effect** A wind turbine will always cast a wind shade in the downwind direction. In fact, there will be a wake behind the turbine, i.e., a long trail of wind which is quite turbulent and slowed down.

We can actually see the wake trailing behind a wind turbine, if we add smoke to the air passing through the turbine (Fig. 8).

## 8 Betz' Law

Betz' law was first formulated by the German Physicist Albert Betz in 1919. Betz' law says that you can only convert less than 16/27 (or 59 %) of the kinetic energy in the wind to mechanical energy using a wind turbine.

We can therefore assume that there must be some way of breaking the wind which is in between these two extremes and is more efficient in converting the energy in the wind to useful mechanical energy. It turns out that there is a surprisingly simple answer to this: An ideal wind turbine would slow down the wind by 2/3 of its original speed. Here, V1 > V2. (Fig. 9)

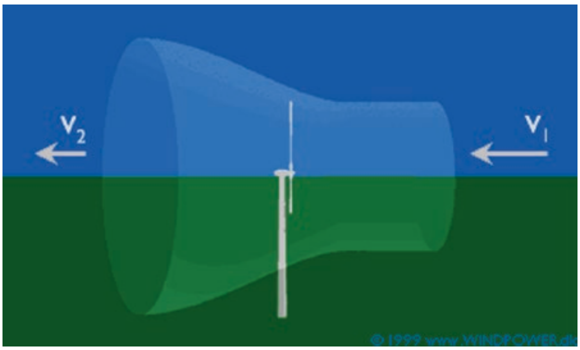


**Fig. 9** Betz' law

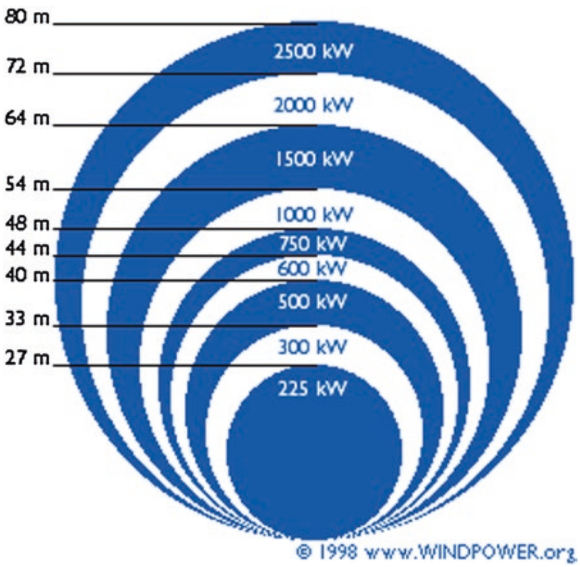


**Fig. 10** Effect of output w.r.t. rotor diameter

# 9 Factors Affecting Power

## *9.1 Rotor Swept Area*

Power output increases as the swept rotor area increases.

If we double the rotor diameter, we get an area which is four times larger (two squared). This means that we also get four times as much power output from the rotor (Fig. 10).

## *9.2 Tower Height*

Higher tower means more wind and greatly increased output. But higher tower increases the cost of manufacturing and maintenance (Fig. 11).

# 10 Wind Energy Production

How much energy can we get from the wind? We will use two terms to describe wind energy production: efficiency and capacity factor.

Efficiency refers to how much useful energy (electricity, for example) we can get from an energy source. A 100 % energy efficient machine would change all the energy put into the machine into useful energy. It would not waste any energy.

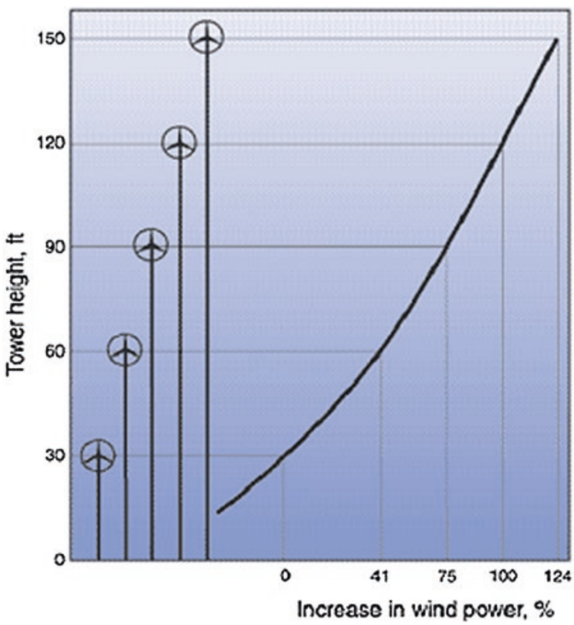


**Fig. 11** Effect of output w.r.t. tower height

It must be understood that there is no such thing as a 100 % energy efficient machine. Some energy is always "lost" or wasted when one form of energy is converted to another. The "lost" energy is usually in the form of heat.

Wind machines are just as efficient as coal plants. Wind plants convert 30 % of the wind's kinetic energy into electricity. A coal-fired power plant converts about 30–35 % of the heat energy in coal into electricity.

It is the capacity factor of wind plants that puts them a step behind other power plants. Capacity factor refers to the capability of a plant to produce energy. A plant with a hundred percent capacity rating would run all day, every day at full power. There would be no down time for repairs or refueling, an impossible dream for any plant.

Wind plants have about a 25 % capacity rating because wind machines only run when the wind is blowing around nine mph or more. In comparison, coal plants typically have a 75 % capacity rating since they can run day or night, during any season of the year. One wind machine can produce 275–500 thousand kilowatt-hours (kWh) of electricity a year. That is enough electricity for about 50 homes per year.

The USA is the world's leading wind energy producer. The USA produces about half of the world's wind power. Other countries that have invested heavily in wind power research are Denmark, Japan, Germany, Sweden, the Netherlands, UK, and Italy. The country-wise WEG Installation as of December 2012 is shown in Table 3. The yearly variation of wind power for the last three years in the world is shown in Fig. 12.

**Table 3** World country-wise WEG installation (as on December 2012)

| Position | Country | Total capacity 2012 (GW) | Total capacity 2011 (GW) | Total capacity 2010 (GW) | Total capacity 2009 (GW) |
|---|---|---|---|---|---|
| 1 | China | 75.564 | 62.364 | 44.733 | 25.81 |
| 2 | USA | 60.007 | 46.919 | 40.18 | 35.159 |
| 3 | Germany | 31.332 | 29.06 | 27.215 | 25.777 |
| 4 | Spain | 22.796 | 21.674 | 20.676 | 19.149 |
| 5 | India | 18.421 | 16.084 | 13.065 | 11.807 |
| 6 | Italy | 8.114 | 6.8 | 5.797 | 4.85 |
| 7 | France | 7.196 | 6.737 | 5.66 | 4.754 |
| 8 | UK | 8.445 | 6.54 | 5.203 | 4.092 |
| 9 | Canada | 6.200 | 5.265 | 4.008 | 3.319 |
| 10 | Portugal | 4.525 | 4.083 | 3.702 | 3.357 |
| | Rest of the world | 39.852 | 32.143 | 26.441 | 21.872 |
| | Total | 282.482 | 237.669 | 196.682 | 159.766 |

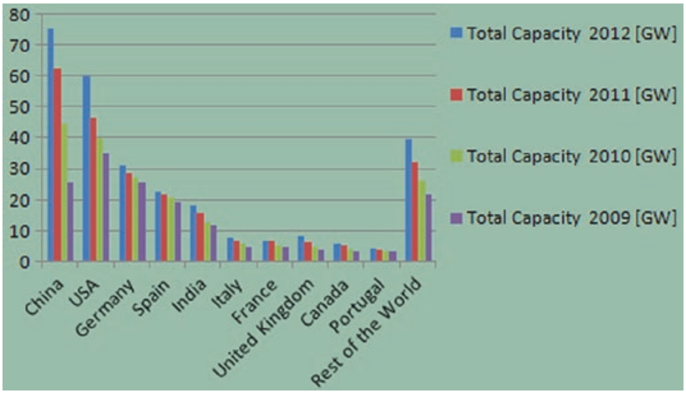


**Fig. 12** Yearly variation of wind power in the world. *Source* C-WET Chennai

Using a best-case scenario, the American Wind Energy Association (AWEA) estimates wind energy could produce more than 10 % of the nation's electricity within the next 30 years. So, wind energy may be an important alternative energy source in the future, but it will not be the sole answer to our energy problems. We will still need other energy sources to meet our growing demand for electricity.

The re-emergence of wind as a significant energy source is now encouraged by the need to meet increasing worldwide electricity demand and reduce the environmental impact caused by the conventional electricity generation technologies. Considerable progress in wind power technology during the last few decades has advanced it as an important supplier of grid connected electricity in the big world energy picture. Nowadays, wind power is the most rapidly growing and most widely utilized renewable energy technology, with a total of 159.2 GW installed worldwide at the end of 2009 producing 340 TWh per year, which is about 2 % of worldwide electricity generation as per WWEA, 2010.

During the last decade, the global installation of wind power capacity has accelerated. The wind industry mainly concentrates in Europe and the USA, but it is emerging in some developing countries such as China, India, and Brazil.

Using a best-case scenario, the AWEA estimates wind energy could produce more than 10 % of the nation's electricity within the next 30 years. So, wind energy may be an important alternative energy source in the future, but it will not be the sole answer to our energy problems. We will still need other energy sources to meet our growing demand for electricity.

## 11 Wind Power Potential in India

Among the different renewable energy sources, wind energy is currently making a significant contribution to the installed capacity of power generation and is emerging as a competitive option. The program covers research and development, survey and assessment of wind resources, implementation of demonstration and private sector projects and promotional policies.

Onshore wind power potential has been assessed at 45,130 MW assuming 1 % of land availability for wind power generation in the potential areas. However, technical potential is limited to only 13,000 MW assuming 20 % grid penetrations, which will go up with the augmentation of grid capacity in potential states. Statewise gross and present exploitable technical potential is given in Table 4.

In order to estimate the installable potential of the country, the Karlsruhe Atmospheric Mesoscale Model (KAMM) generated mesoscale wind power density map of 50 m level (Fig. 13) was integrated with the wind power density map generated with actual measurements (wherever data were available) and re-plotted the final wind power density maps by using GIS tool.

The installable wind power potential (name plate power) was calculated for each wind power density range by assuming 9 MW could be installed per square kilometer area. Finally, the potential in the country at 50 m level with clearly stated assumptions was estimated as 49 GW. Similar exercise without any validation had been carried out for 80 m level with the KAMM generated mesoscale map, and the results were calculated. The estimated installable potential at 80 m level was found to be 102,788 MW (Table 5). Wind power density map at 80 m level is given in Fig. 14.

Assessment on a GIS platform as described above shows that the outer limit (potential) of the extent to which wind farms can be set up in India with currently prevalent technologies, assuming as if the whole of the country (apart from the urban and the Himalayan areas) is covered with wind farms, is around 4250 GW. Potential in gigawatts at different levels of PLF is shown in Fig. 14, wind power density map at 80 m agl in Fig. 15, the wind speed map in Fig. 16, and the PLF map of the wind power potential is shown in Fig. 17.

**Table 4** States/Union Territories installable potential (MW) at 50 m level

| S. No. | State/UTs | Installable potential (MW) at 50 m level |
|---|---|---|
| 1. | Andaman and Nicobar | 2 |
| 2. | Andhra Pradesh | 5394 |
| 3. | Arunachal Pradesh[a] | 201 |
| 4. | Assam[a] | 53 |
| 5. | Chhattisgarh[a] | 23 |
| 6. | Gujarat | 10,609 |
| 7. | Himachal Pradesh[a] | 20 |
| 8. | Jammu and Kashmir[a] | 5311 |
| 9. | Karnataka | 8591 |
| 10. | Kerala | 790 |
| 11. | Lakshadweep | 16 |
| 12. | Madhya Pradesh | 920 |
| 13. | Maharashtra | 5439 |
| 14. | Manipur[a] | 7 |
| 15. | Meghalaya[a] | 44 |
| 16. | Nagaland[a] | 3 |
| 17. | Orissa | 910 |
| 18. | Rajasthan | 5005 |
| 19. | Sikkim[a] | 98 |
| 20. | Tamil Nadu | 5374 |
| 21. | Uttarakhand[a] | 161 |
| 22. | Uttar Pradesh[a] | 137 |
| 23. | West Bengal[a] | 22 |
| | Total | 49,130 |

[a]Wind potential is yet to be validated with measurements
*Source* C-WET Chennai

The country made a modest beginning in 1986 with the installation of wind turbine generator (WTG) having a total capacity of only 3 MW. Most of the WTGs installed during this period were imported from Denmark and Germany. The pace of development was gradual till the end of the millennium. Wind energy development gained momentum in the beginning of the current decade and rapid progress has been witnessed. The current installed capacity is 19,618 MW (Table 7), and the growth trend is shown in Table 6. The wind power installation in India grew from 3 MW during 1986 to 19,618 MW in 2013 (up to June).

Special study on wind resource assessment in North Eastern Region was initiated at 24 sites in six states, namely Arunachal Pradesh, Assam, Manipur, Tripura, Sikkim, and Mizoram of the region for long-term wind measurements with automated recording systems. In the Andaman and Nicobar Islands, wind resource assessment through 30 m tall masts with instrumentation at two levels

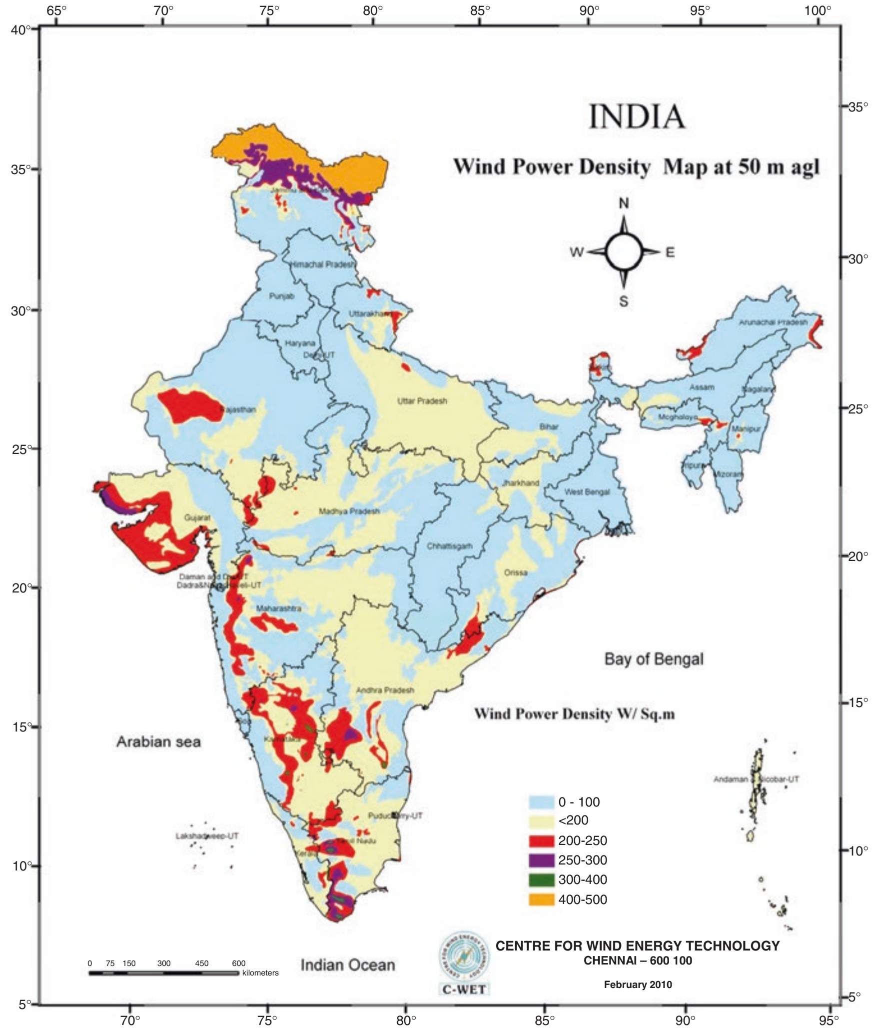


**Fig. 13** Wind power density map at 50 m level. *Source* C-WET Chennai

has been commissioned at Badmash Pahar, Corbins Pahar, Mt. Harriet (all in south Andamans), and Sabari (in middle Andamans). C-WET has carried out a pilot study to identify the wind potential locations to establish wind farms using the geographical information system in association with the National Remote Sensing Agency, Hyderabad. Table 8 shows the wind monitoring stations for which micro-survey has been completed.

**Table 5** States/Union Territories installable potential (MW) at 80 m

| S. No. | State/Union Territories | Installable potential MW |
|---|---|---|
| 1. | Andaman and Nicobar Islands | 365 |
| 2. | Andhra Pradesh | 14,497 |
| 3. | Arunachal Pradesh[a] | 236 |
| 4. | Assam[a] | 112 |
| 5. | Bihar | 144 |
| 6. | Chhattisgarh[a] | 314 |
| 7. | Gujarat | 35,071 |
| 8. | Jammu and Kashmir[a] | 5685 |
| 9. | Karnataka | 13,593 |
| 10. | Kerala | 837 |
| 11. | Madhya Pradesh | 2931 |
| 12. | Maharashtra | 5961 |
| 13. | Orissa | 1384 |
| 14. | Pondicherry | 120 |
| 15. | Rajasthan | 5050 |
| 16. | Tamil Nadu | 14,152 |
| 17. | Uttarakhand[a] | 534 |
| 18. | Uttar Pradesh[a] | 1260 |
| 19. | Other states[a] | 542 |
| | Total | 102,788 |

[a]Wind potential is yet to be validated with measurements
*Source* C-WET Chennai

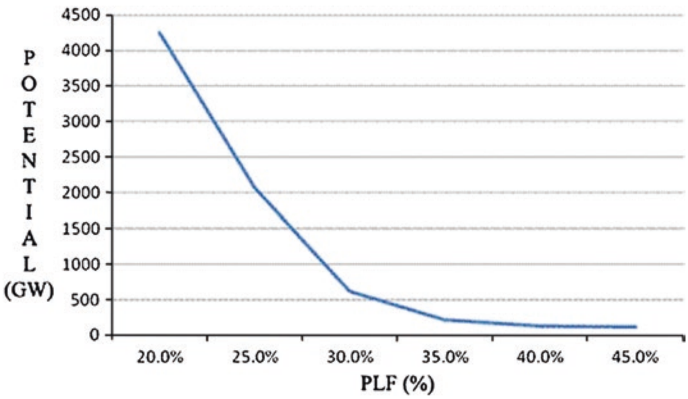


**Fig. 14** Wind farm potential for India exceeding various PLF levels

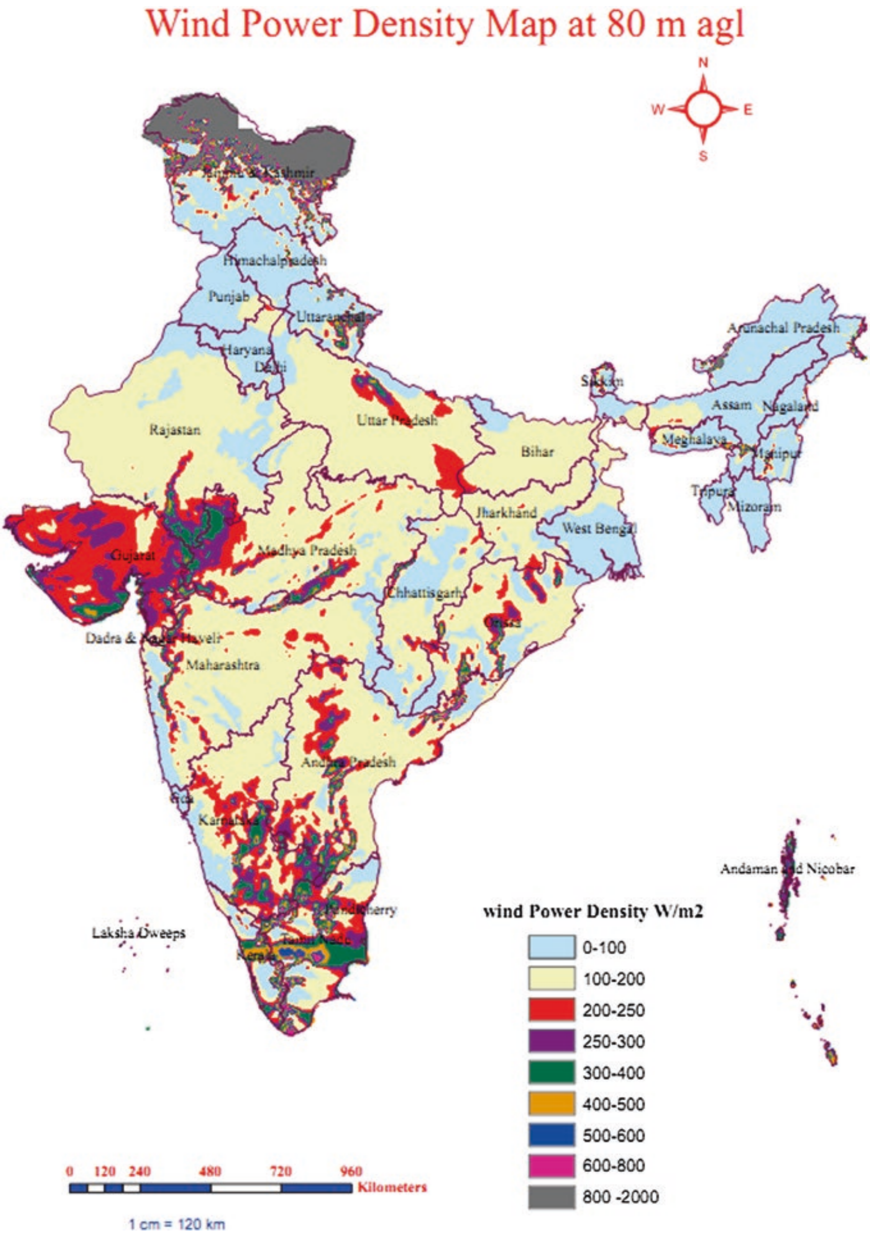


**Fig. 15** Wind power density map at 80 m agl. *Source* C-WET Chennai

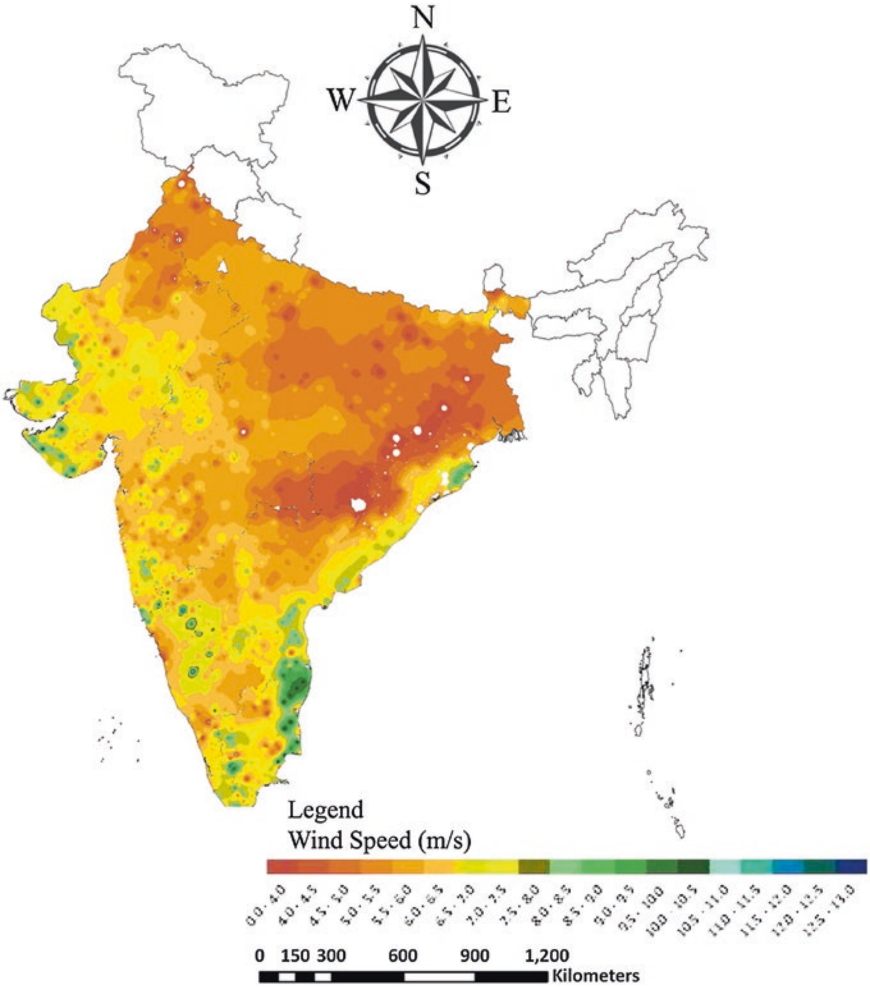


**Fig. 16** Wind speed map of India at 80 m agl (m/s). *Source* C-WET Chennai

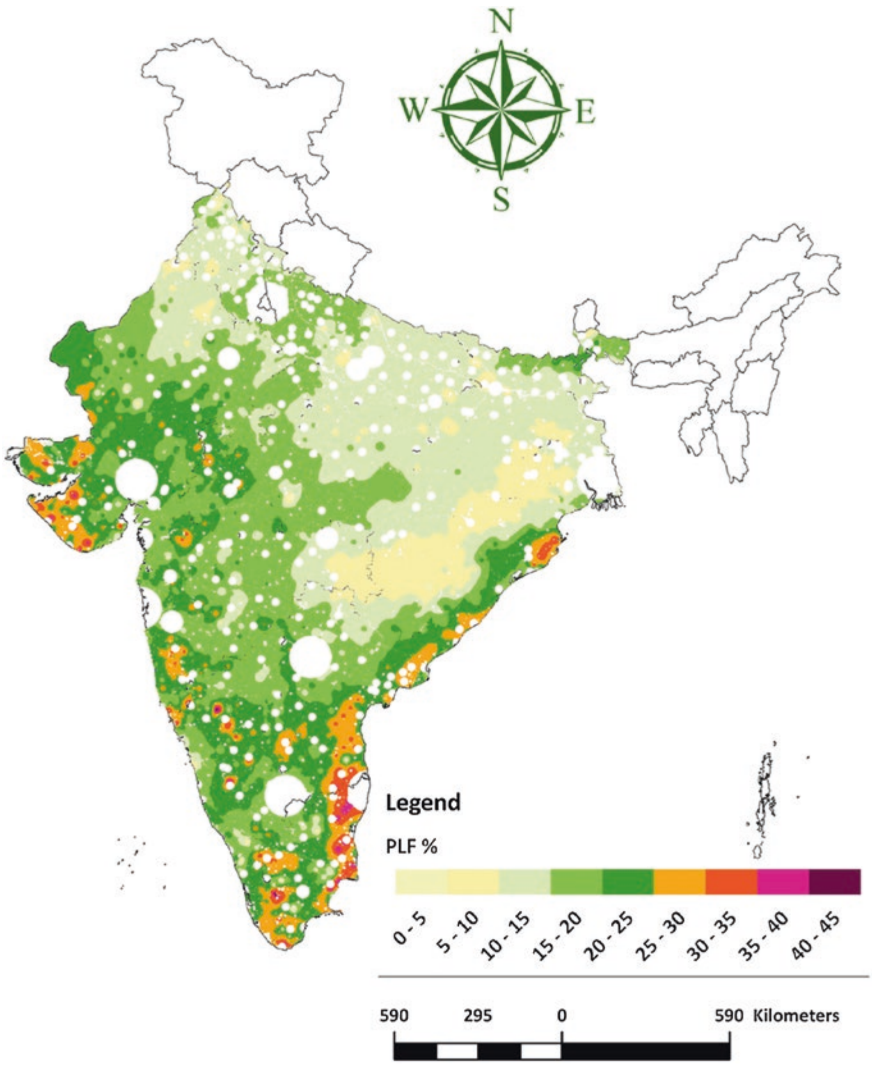


**Fig. 17** Wind power potential map of India by PLF (%). *Source* C-WET Chennai

**Table 6** Installed capacity of different states of India

| S. No. | State | Capacity in MW up to 31.06.2013 |
|---|---|---|
| 1 | Tamil Nadu | 7367 |
| 2 | Gujarat | 3283 |
| 3 | Maharashtra | 3142 |
| 4 | Rajasthan | 2497 |
| 5 | Karnataka | 2113 |
| 6 | Madhya Pradesh | 386 |
| 7 | Andhra Pradesh | 435 |
| 8 | Kerala | 35 |
| 9 | Others | 4 |
| | Total | 19,618 |

*Source* C-WET Chennai

**Table 7** Wind power developments in India since 1986

| Year | Installed capacity, MW |
|---|---|
| 1986 | 3 |
| 1987 | 5 |
| 1988 | 7 |
| 1989 | 10 |
| 1990 | 32 |
| 1991 | 37 |
| 1992 | 41 |
| 1993 | 54 |
| 1994 | 115 |
| 1995 | 351 |
| 1996 | 733 |
| 1997 | 902 |
| 1998 | 968 |
| 1999 | 1024 |
| 2000 | 1167 |
| 2001 | 1340 |
| 2002 | 1628 |
| 2003 | 1870 |
| 2004 | 2483 |
| 2005 | 3595 |
| 2006 | 5341 |
| 2007 | 7174 |
| 2008 | 8757 |
| 2009 | 11,587 |
| 2010 | 12,276 |
| 2011 | 16,084 |
| 2012 | 17,951 |
| 2013 (up to June 2013) | 19,618 |

*Source* C-WET Chennai

**Table 8** Wind monitoring stations with microsurvey completed

| S. No. | State | No. of stations |
|---|---|---|
| 1. | Andhra Pradesh | 11 |
| 2. | Gujarat | 21 |
| 3. | Karnataka | 15 |
| 4. | Kerala | 3 |
| 5. | Madhya Pradesh | 5 |
| 6. | Maharashtra | 17 |
| 7. | Orissa | 2 |
| 8. | Rajasthan | 3 |
| 9. | Tamil Nadu | 19 |
| 10. | West Bengal | 1 |
| | Total | 97 |

*Source* C-WET Chennai

## 12 Complex Terrain

Already, in some densely populated countries with a high level of installed wind capacity, the best sites, in terms of available wind resource, are being exploited. Space is limited also by the requirements of other activities (e.g., nature conservation, agriculture, military). In densely populated coastal countries, offshore sites are the "new" option, while in mountainous land-locked countries; sites are found in complex terrain, such as funnels, hills, and mountains. Other areas include those with cold and icing climates and, possibly, built-up areas. The definition of complexity here concerns not only terrain morphology but also its dynamic and thermal effects on the wind flow. It is then our aim to distinguish the different degree of modification imposed on the flow by topography. Moreover, a terrain classification will help to describe the types of circulation that can be managed by the different wind flow model classes.

### *12.1 Homogeneous and Flat Terrain*

The simplest kind of terrain is the one that can be described as flat and nearly homogenous regarding the surface characteristics that influence the boundary layer flow: soil type (e.g., clay, loam etc.), land use, roughness, albedo, moisture availability (e.g., Bowen ratio). In this situation, advection can be neglected, and the system can be considered in condition of local equilibrium.

### *12.2 Non-homogeneous Flat Terrain*

Some important local to mesoscale circulations are observed over flat terrain characterized by important horizontal non-uniformity. Differences in terrain features are reflected into horizontal variations of surface temperature and turbulent fluxes.

## 12.3 Single Hill

The wind flow over a hill of moderate slope is a complex terrain flow case that has been the object of many theoretical and experimental studies during the last 20 years. The major characteristics of the flow over a hill are determined not only by the hill shape but also by its size and atmospheric stability. In stable conditions, the vertical displacement of the air that takes place when the wind flows over a hill is opposed by a gravitational restoring force, and the flow is then affected by buoyancy.

## 12.4 Single Valley

The forced channeling produces winds flowing along the valley axis and generates sudden reversal of the wind direction when geostrophic wind moves across a line normal to the valley axis. The downward turbulent transport of horizontal momentum (that occurs over flat terrain too) produces wind directions within the valley that are similar to the geostrophic direction, with a slight turning near ground caused by friction.

## 12.5 Hilly Terrain

Hilly terrain can be defined as topography made by rows of hills and valleys or more generally the super positioning of single hills. Over this kind of terrain, many of the flow characteristics introduced in the previous paragraphs can be retained as still valid, and, if the slope steepness is limited, the linear theory can be considered applicable.

## 12.6 Complex Topography

Complex topography can be briefly defined as the landscape that is normally addressed as mountain. This kind of terrain, made by systems of crests and valleys that can be characterized by steep slopes, gives rise to thermally induced circulations, like mountain–valley breezes, generates mountain waves, and strongly modifies the characteristics of synoptic flow.

## 12.7 Very Complex Terrain

Complex terrain distinguish from those conditions where the features described in the previous section can be considered extreme, as in regions characterized by the presence of deep and narrow valleys (canyons) surrounded by tall mountains.

This kind of landscape is typical of the Alpine region, in southern Europe. Another example can be given by Mediterranean islands where steep topography adds its effect to coastal flow phenomena, in an area characterized by strong solar radiation. Complex topography can accentuate or counteract the sea breeze depending on the slope orientation.

## 13 Advantages of Wind Power

As mentioned earlier, wind power generation does not involve pollution and this power source is also renewable, but apart from these, there are some more advantages of wind Power, which are as follows:

- Wind is easily available in all parts of the world and can become a cheap source of power for developing countries that face the crisis of power on large scale.
- It is nature's endowment and therefore is available free of cost.
- Wind turbines do not consume additional power for power generation.
- The turbines do not take much space and therefore are very convenient to install. They are also available in various models and potentials. As their potentials differ, they are useful for all kinds of industries.

## 14 Disadvantages of Wind Power

The disadvantages of wind power are few in comparison to the advantages.

- The one disadvantage that makes it a less used and reliable source of energy is its varying strength. It is not same all the time, and therefore, the amount of power generated can vary.
- The turbines at times produce a lot of noise and there have been objections to the fact that the wind farms are being established in the countryside which is spoiling the scenic beauty.

## 15 Wind Power and Its Dual Sustainability

Wind energy is sustainable from an environmental point of view, where sustainable is defined as meeting society's current needs unharming our future generations. Wind energy is clean and renewable. Because of the fuel, the air is free and it provides the ultimate in energy independence. Wind energy has now emerged as a leading prospect, in part, because it is considered by us to be environmentally sustainable.

Wind energy technology advances have been dramatic, reducing costs from 30 cents per kWh in 1980 to the 3–5 cent range today. Power rating of the largest turbines has increased from 55 kW in 1980 to 4.5 MW in 2005. Although turbines larger than 2 MW are available, clustering 100 of them together for 200 MW is generally at the upper limit of what transmission interconnection to the grid can allow without costly upgrades. Consequently, the average new utility scale wind farm is typically in the 150 MW range.

Size matters when producing power with the wind. Some tall towers over 400 ft height can raise turbines to take advantage of stronger and less turbulent winds at higher elevations. New materials such as E-glass/polyester allow blade lengths of 150 ft compared to 15 ft in 1980. This is significant because a wind turbine's capability to generate electricity increases by the square of the blade length. Siting wind turbines in the right place is very important because the power produced by a wind turbine is proportional to the cube of the wind speed. For example, the potential of a wind turbine located at a site with an average wind speed of 15 mph versus one located at a site where the average wind speed is 10 mph can produce 238 % more electricity.

The percentage of time a turbine can be in use during the 8760 h (365_24) of the year (i.e., the turbine utilization rate) has increased from 36–38 to 40–43 % at the best sites. Modern turbines can operate at lower wind speeds more efficiently than older models. Furthermore, they can operate at wind speeds up to 50 mph, wind speeds that would have caused older models to be shut down or to fail. Improved technology has made wind energy more cost competitive by bringing its cost down, but dramatic increases in the cost of oil and natural gas have also made wind energy more competitive. Some experts argue that if environmental and health costs caused by electricity generation using fossil fuels such as coal are included, the cost of these sources of energy is 50–100 % higher than their nominal costs. Although wind energy is considered to be sustainable from an environmental point of view, it is not without its critics because of some environmental and social concerns. Locations with the best wind speeds sometimes coincide with migratory paths of birds. One counter by supporters of wind energy is that the statistics about many thousands of birds killed by oil spills. Visual pollution might effect from clear views or hinder tourism. But, the wind farm near Kanyakumari Tamil Nadu, India, has become a very famous tourist destination. The biggest problem the wind industry is facing in successfully funding wind energy projects is NIMBY (not-in-my backyard) opposition.

In some countries, the national security agencies are also of the concerns that wind farms might interfere with the operation of military radar systems.

The race to invest in wind farms suggests that an annual return of approximately 15 % is an attractive risk adjusted rate of return to compensate investors for the risks involved. Another potentially favorable factor for the financial economics of wind energy is that technology improvements can increase the utilization rate. This has been the historical trend in wind industry.

Beyond technology improvements, public policy that allows wind farms to locate at sites with the most steady and reliable wind conditions can enhance the utilization rate.

Furthermore, as the cost of sources of energy such as oil and natural gas becomes more expensive, wind energy becomes more competitive of return to compensate investors for the risks involved.

Clearly, the wind energy industry is on a short path to become financially self-sustaining. This is happening because of the convergence of improved technology, greater efficiency, and rising costs of competing sources such as oil and natural gas. Consequently, wind energy can soon provide the best of both worlds. It is already sustainable from an environmental perspective and it is becoming sustainable financially. In short, those investing in wind energy will be able to do well by doing well and achieve dual sustainability. Perhaps dual sustainability is true sustainability. Three decades ago private investment in wind energy was considered uneconomic, in part, because private investors could not capture social benefits that would be reaped by society from this clean and renewable energy source. It was a classic example where public policy was needed to foster development for the good of the society. This was achieved in several ways, including setting national goals for renewable energy, eliminating barriers to entry in an industry once dominated by large public utilities wedded to traditional technologies, and providing financial incentives.

# Part III
# Green Buildings

# Achieving Energy Sustainability Through Green Building Approach

**Ashish Shukla, Renu Singh and Poonam Shukla**

**Abstract** There are three urgencies in the UK climate and energy policies: (i) reducing greenhouse gas emissions, specifically $CO_2$ by 80 %, by 2050, (ii) decreasing fossil fuel consumption especially built environment sector and (iii) reducing dependence on imported energy. Buildings account for 40 % of the total non-transport energy consumption both in UK and EU; therefore, reduction of energy consumption in the built environment will make a significant contribution in meeting these targets. On average, UK residents spend between 2.7 and 8.4 % on gas and electricity bills. Water bills also account for 0.5–3 % of their income. These scenarios make it important to consider green building design and reduce the social, environmental and economic impacts building are creating on us. Sustainability through green building design should encompass "cradle-to-grave analysis". Building Research Establishment Environmental Assessment Methodology (BREEAM) is the world's foremost environmental assessment method and rating system for buildings. BREEAM was launched in 1990 and sets the standard best practice in sustainable building design, construction and operation. The assessment uses measures of performance against established benchmarks. This chapter will highlight interesting features of achieving sustainable development through green building design.

**Keywords** Green building · Climate and energy policy · Energy efficiency

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## 1 Introduction

A famous quote from Winston Churchill "We shape our buildings; thereafter they shape us". It implies the importance of building sector not in our lives but also as national strategy and heritage. Europe's buildings remain a large energy consumer comprising 40 % of final energy use and $CO_2$ emissions (Balaras et al. 2005; Itard et al. 2008; ACE 2009). However, on average, water usages and space heating are responsible for more than 60 % of the final energy consumption in both domestic and non-domestic building stock (Itard and Meijer 2008). Most of the policies initiated to reduce energy consumption in buildings lie in the main three categories: economic incentives, informational programmes and regulatory requirements (Shukla and Bull 2012). Economic incentives include reduction in taxes on clean energy technologies, better feed in tariff; informal programmes include environmental campaigns, energy audits and promotion of low carbon technologies; regulatory requirements include building standards or codes.

Regulatory requirements are still not mandatory in many countries across the world and specific guidelines for green building design either do not exist in those countries or still in the process of having one. Though it is considered a very effective way to implement green building design standard, but it is more difficult to implement at level of construction with various stakeholders. A certified national body is further required to implement these standard codes and practices. For example, National House-Building Council (NHBC)[1] is the UK's leading independent standard-setting body and provider of warranty and insurance for new homes. On average, 80 % of new homes built in the UK each year have an NHBC 10-year warranty. It is the UK's largest single Approved Inspector for Building Regulations. NHBC also looks after general construction quality, energy ratings, health and safety, sustainability and training.

Though often policy studies look either in favour or in contradiction of regulatory and economic instruments in terms of detailed study of their effectiveness (Beerepoot and Sunikka 2005; Murakami et al. 2002). However, the instruments like NHBC have protected the rights of home owners to have a house of certified standards.

EU countries have to comply with legislation is being driven by EU laws though member states also have the same at the national level. Energy Performance of Buildings Directive (EPBD) legislation is being driven by EU laws and has freedom of local implementation of building codes. National regulations in member states have to follow the concept of the EPBD and need be harmonised as much as possible (Szalay 2007).

The "Green Building" design codes and standards are quite evolved in EU member states and many other developed countries. However, a lot need to be done around the world where standards are either voluntary or underway. Figure 1 gives an image of the current status of building standards in many countries

[1]http://www.nhbc.co.uk/.

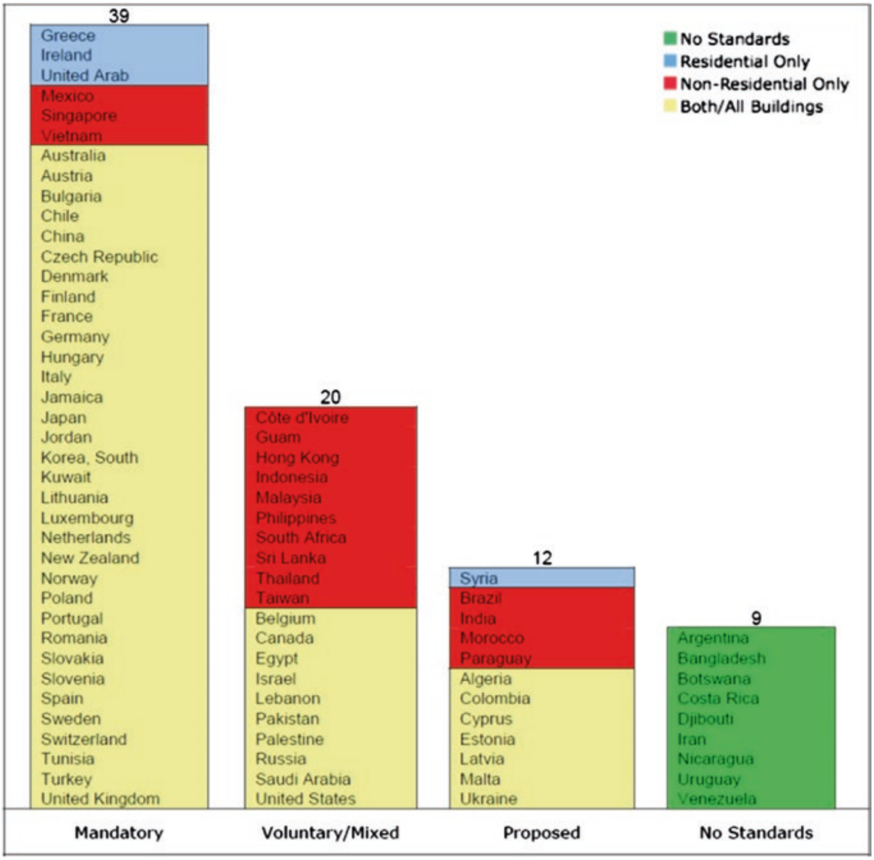


**Fig. 1** Worldwide status of energy standards for buildings (Shukla and Bull 2012)

around the globe. As clear in figure, most of EU member states have mandatory standards. In many countries, EPBD is supported by other parallel standards, e.g. MINERGIE in Switzerland and Building Research Establishment Environmental Assessment Methodology (BREEAM) in the UK. These national laws put forth more stringent standards to follow in the construction sector to regulate emissions and construction standards. In this chapter, we will talk in more detail about BREEAM and its relevance in UK green building design.

## 2 Defining Green Building Design Concept

In terms of performance, there are many definitions what a green building should do. These definition ranges from stating their performance in terms of energy and environmental impact with respect to average buildings and sustainable resource utilisation. In simple words, it can be said that building construction projects are no more only development projects but represent more a regenerative approach. It should improve and preserve the local habitat and surrounding environment. The perfect green building projects conserve and regenerate environment which is fundamental to sustainable development. A green building design also ensures the lowest possible environmental impact through its life cycle. It should also encompass maintaining natural features of development site and incorporate them into construction development. Use of low embodied energy/carbon materials in construction process is also very important element in green building design. It promoted the sustainable use of existing resources. While the definition for "green building design" is changing, its soul can be embedded into fundamental principles stated below.

(i) **Regeneration of Site**

Construction of green buildings starts with selection of proper site. It should include use of existing resource in the habitat and rehabilitation of existing buildings. It should also consist of regenerating the site rather than exploiting the local sources. While considering the site regeneration, most important thing is to keep in mind that locations, orientation of building plan, consideration of local eco systems, waste recycling, transportation methods, renewable energy generation, energy use and recycling. Furthermore, the plan of site design should also consider retrofitting existing buildings, flood consideration, flora and fauna of the region, access roads, and environmental friendly transport methods, e.g. means for cycling, parking, and most importantly sustainable resource utilisation.

(ii) **Energy efficiency**

Energy efficiency plays a vital role in reducing environmental impact building create during its life time. Highly efficient building can lead to lower the greenhouse gas emissions significantly. Energy efficiency in green building design consists of two major parts (i) related to construction and (ii) related to operation of the building. For a typical example of office building in total 60 % of losses, majority of them occurs because of ventilation and infiltration (Fig. 2). An airtight and well-designed ventilation unit may reduce the losses significantly.

Losses through building façade can significantly reduce through better insulation and improved window glazing. CIBSE Guide F: Energy Efficiency in Buildings NEW 2012 provides energy efficiency guideline in buildings. Recently published guidelines also include new section on "developing and energy strategy", and this new section reflects changes to planning policy, reflecting targets for reducing carbon dioxide emissions.

Another major area for improvement at system level in the buildings, e.g. lightings, boiler, refrigerator, other appliances and use of renewable heat/electricity. An efficient boiler will save significant amount of energy in comparison with old condensing boiler or refrigerator with high energy rating will provide better performance and save energy during its lifetime. EU energy label dictates the efficiency of appliances we use. A typical example of refrigerator is given in Fig. 3.

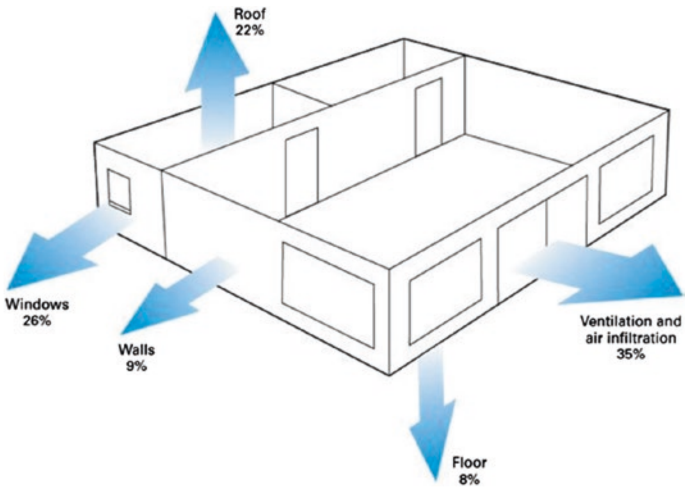


**Fig. 2** Building fabric losses. http://www.carbontrust.com/resources/guides/energy-efficiency/buildings-energy-efficiency

It becomes vital to find ways to reduce energy load, increase efficiency and maximise penetration of renewable energy sources.

(iii) **Conservation of resources and water**
In many parts of the world, water is a scarce resource. A green and sustainable building should use comply with measures to reduce water consumption and put in place efficient use of water. Also on site recycling of water, rain water harvesting is the only option to improve sustainability in green building design. Also delivery of drinking water and sewage treatment from buildings should be tackled efficiently as it has direct impact on building design.

(iv) **Building space and material use**
Building materials are important part in sustainable and green building design. Use of renewable material reduced the environmental impact and minimises the life cycle carbon foot print of the building development. Recently, use of eco-insulation and environmental friendly glazing materials is also getting momentum. Use of renewable materials also reduces the cost of de-construction and recycling at the end of building life.

(v) **Improved indoor air quality**
It is important that buildings provide safe and healthy environment to its occupants. Occupant's productivity and health depends on indoor environment of the building. While construction, precaution should be taken to build buildings free from moisture, toxic material exposure and VOC emissions. Also occupier should have proper control to regulate indoor air movement and ventilation into the building as per their requirement.

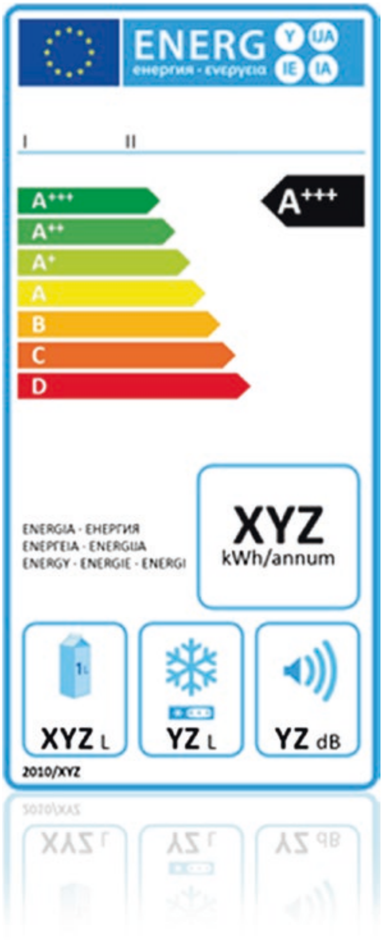


**Fig. 3** New EU energy label for refrigerators. http://www.newenergylabel.com/uk/labelcontent/refrigerators

(vi) **Operational, maintenance and waste recycling**

In the green building design, operational, maintenance and waste recycling should be envisaged at the earlier state of project. Building operation and maintenance issues help towards improved indoor environment, high productivity, reduced HVAC loads, reduction in energy consumption and reduction in system failures. It also ensures optimal resource utilisation and maintenance requirement. For example, water flow restrictor reduces the water consumption and cost effective to be used before building commissioning. Operation, maintenance and waste recycling methods also improved life cycle assessment and carbon foot print of the building.

(vii) **Renewable energy generation**
In recent year's advances in technologies and increasing depleting in fossil fuel resources, renewable energy is getting all the limelight. It is not only clean energy source but can also bring income generation through available feed in tariffs in many countries. In recent year, UK government launched many schemes to promote green building design and to increase renewable energy penetration into the built environment, e.g. renewable heat incentive (RHI) and Green Deal. Integrating renewable energy to buildings brings buildings to reduce their dependence on fossil fuels. It also helps designer to create low impact buildings.

## 3 Green Building Designs Vs Cost

Many times it is anticipated that green measures do cost more and affect the economics of the construction. However, with many government-backed schemes and user awareness for adopting green innovation, it has been proven that many green construction strategies cost more or less same during life time and can bring more benefits in several aspects ranging from energy savings, greenhouse gas mitigation, water conservation, etc. However, it is important at developer/builders end to blend right mix of green building techniques to provide cost effective building projects. Sustainability contains not only green building design method and operation but also building materials. And this should further contain people, waste and raw materials, carbon, water and biodiversity.

Also sustainability is equally important in retrofit projects. Re-use of building materials, utilisation of government policies and scheme, e.g. Green Deal in the UK, minimising waste, reducing water consumption, improving energy efficiency, and integrating renewable energy. Recently, C-Zero commissioned the construction of a £2.5 million housing development in Norfolk[2] (Fig. 4). The project aimed to prove that houses could be built from renewable materials at a competitive price in comparison with normal housing. In the first phase, Barnes Construction built total 29 houses. The project overcomes some remarkable challenges, e.g. proving commercial viability of the project and adopting and innovative form of low cost home ownership for rural communities.

The project code level 4 having construction *U* values of 0.19 for external walls, 0.08 for floor, 0.10 for roof and 1.2 for windows. In the buildings, airtightness of 2.5 and along with energy efficient lighting is achieved. Use of dual flush toilets, low water capacity baths and flow restrictors on all taps and showers help in controlling water consumption to 105 litres/person/day. In the building construction, all user materials were renewable with low levels of embodied carbon, i.e. Hemcrete. Also high proportion of recycled material is used in ground floor, roof tiles, ceramic wall tiles and flooring products. Energy monitoring and

[2] http://www.ukgbc.org/content/case-studies (Project Case Study Long Meadow).

**Fig. 4** Snapshot of long meadow project. http://www.ukgbc.org/content/case-studies (Project Case Study Long Meadow)

management also provided homeowner opportunity to reflect on their energy bills and reduce the consumption. In overall project achieved sustainability through three pillars of sustainability environmental, social and economic.

## 4 Sustainable Construction

In terms of historical emitters per capita, the UK stands among quite high in the Figure below. Much of the emitted carbon dioxide stays very longer in the environment. This also makes EU as well as the UK to take very stringent action towards mitigating greenhouse gas emissions (Fig. 5). Buildings account for almost half of energy consumptions and greenhouse gas emissions in European countries and energy demand in building will continue to grow worldwide. Only way to tackle the situation is through practising high design and operation standards for the buildings.

It is understood that in the twenty-first century, cities must be smarter and greener. It is only possibly by promoting sustainable design of building and cities. The concept of sustainability is a burning global issue encompassing various interrelated studies about people, the environment and society. As the buildings represent people, environment and society, it becomes more vital to consider sustainability how we construct and operate our buildings. The sustainability in the building characterises new approach that holds the concept of "Green Buildings". It should contain the design of whole process (Ding 2008) to embed environment, technology, economy, society and off course people (Fig. 6). Development objective should consider various options in the process (Ding 2008).

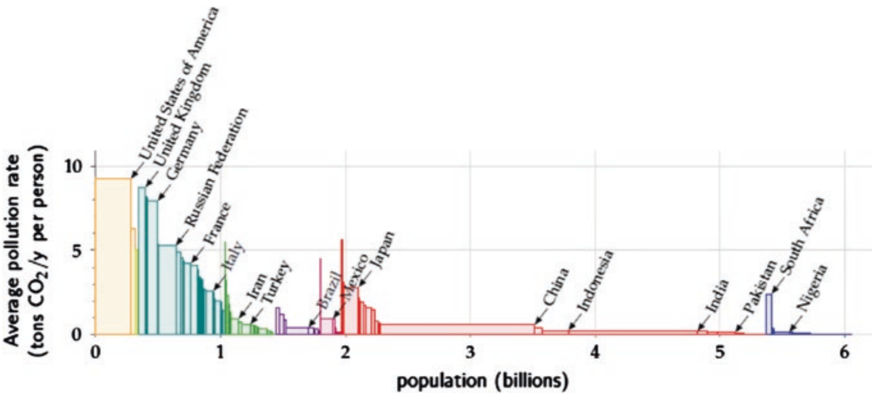


Fig. 5 Historical emitters per capita (1880–2004) (MacKay 2009)

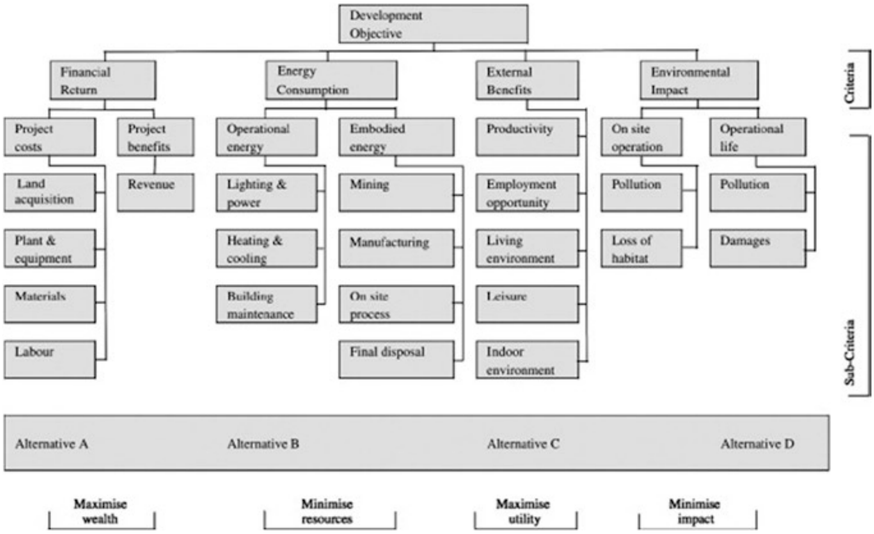


Fig. 6 Key elements in sustainable development (Ding 2008)

Kibert (2007) introduced the major criteria for sustainable construction as (i) reducing the resource intake (ii) reusing the resources (iii) recycling of materials (iv) conservation of environment (v) eradicating toxic materials in process (vi) economic viability and (vii) emphasising the quality. In order to summarise the key indicators for sustainable building design, one must consider mitigating environmental impacts, decreasing use of resources, increasing the efficacy and exploiting the economic benefits. It is also important to increase awareness among end-user towards sustainability issues to reduce the operational environmental impact from buildings occurring during consumption. Sustainable construction should be reflected through (Fig. 7) and encompass its each element.

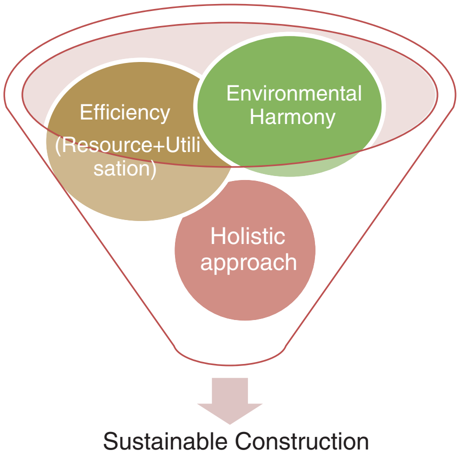


**Fig. 7** Fundamental of sustainable construction

## 5 An Overview of BREEAM Assessment

Nowadays, almost every simulation software is marketed as green building design tool; similarly, manufacturers of building materials also claim the same. However, these tools help in quantifying performance for the building design while taking care of various sustainability issues; still whole process needs to be more evolved and designer should understand the basics. In general, building codes, standards or regulations help to meet the required legislative requirements for building design, whereas concept of “Green Building design” or “Green Construction” is one step ahead. It helps in minimising the environmental impact; the new construction may incur in life time. BREEAM rating is one of the earliest building energy rating systems developed by Building Research Establishment (BRE) during 1990. It is considered as the first green buildings assessment method (Ding 2008; Mao et al. 2009). In the initial time of its development, it was checklist developed for designers to go through. However, in recent times, BREEAM is transformed to more comprehensive assessment tool.

### *5.1 BREEAM Certification Process*

It can be used in various stages of life cycle of building and widely accepted by UK building industry. BREEAM is also used as assessment toll in various countries, e.g. Canada and Australia. BREEAM third party verification can be summaried as shown in Fig. 8. The process starts with registration and goes through major six steps after which client received their ratings.

The BREEAM assessment certification requires a licensed assessor (Saunders 2008). The whole process starts with registration of the project through a form

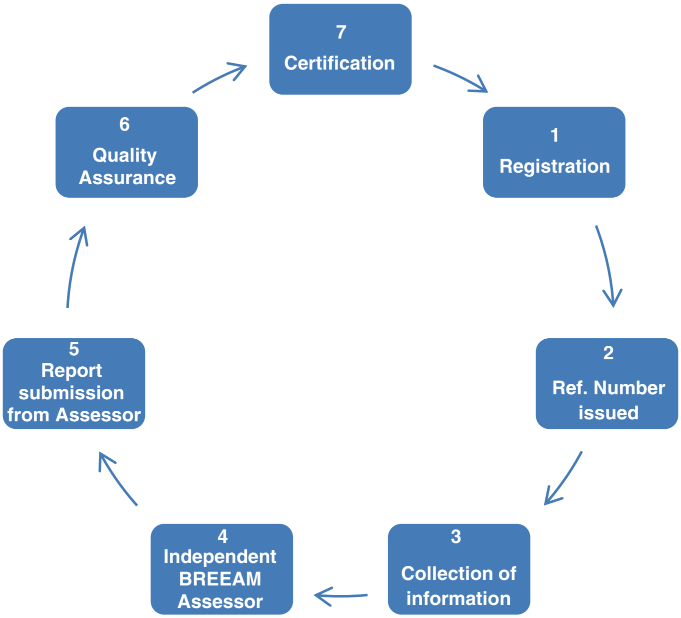


**Fig. 8** BREEAM certification process

which can be submitted online of by post. In the next step, a reference number is issued and information will be collected by the independent BREEAM assessor to establish compliance with BREEAM rating criteria. The report created by BREEAM assessor will be further submitted for quality assurance followed by final step of BREEAM rating certificate.

### *5.2 BREEAM Rating System and Weighting*

BREEAM assessment provides method on various to minimise the environmental impact from construction. It also helps creating healthy and comfortable indoor environment in the buildings. BREEAM rating system includes various types of buildings, e.g. offices, homes, retail units, school industrial. Also BREEAM versions for different regions such as BREEAM Canada, BREEAM Gulf, BREEAM Hong Kong and BREEAM International (BRE 2014).

The assessment of building takes place in a given time frame using the BREEAM assessment system. A final score is awarded through adding assessment of each criterion having its own weighting (Fig. 9).

BREEAM weighting for different section is shown in Fig. (9). The BREEAM assessment uses fixed weighting system to facilitate the relative impact of environmental issues of various parameters. Further 10 % weighting is allocated to

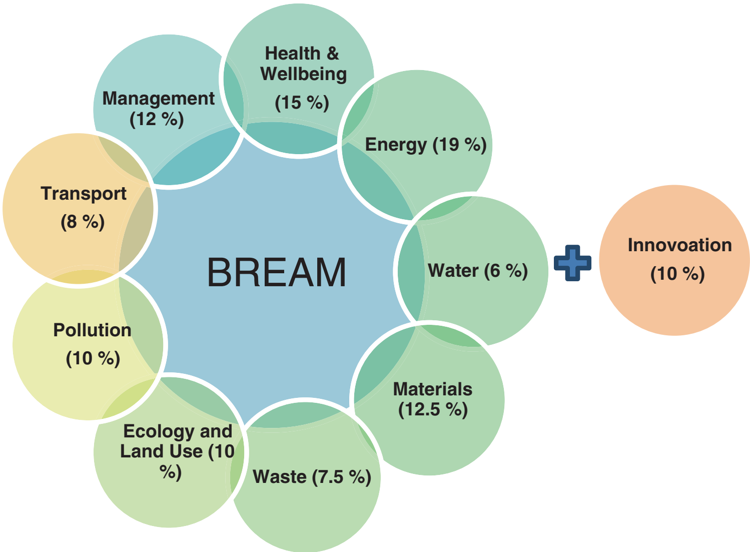


**Fig. 9** BREEAM rating system weighting

innovative approaches used in construction. The whole process gives a score to the assessment of building and this defines its rating, e.g. if scores (30–44 points) Pass; (45–54 points) Good; (55–69 points) Very Good; (70–84 points) Excellent; and (85+ points) Outstanding.

## 6 Renewable Energy Applications in Green Buildings

It has been internationally acknowledged to promote innovative approaches for mitigation of carbon dioxide ($CO_2$) emissions occurring from consumption associated with building construction and its operation. In this perspective, the energy performance of green buildings has massive effect on the sustainable development of the built environment. Kothari et al. (2010) stated that sustainable development is highly tangled with the deliberation of energy. Renewable energy sources, e.g. solar, winds and waves, play a substantial role for sustainable developments along with sustainable re-cycling, e.g. energy from the waste to heat.

Concept of smart homes (and smart grid) is also getting momentum (Fig. 10). The idea promotes onsite renewable generation, smart controls and smart metering and energy management. This also provides opportunity to end-user to interact with grid and use maximum benefits from available feed in tariffs.

Sustainable energy performance of green buildings also encompasses suitable integration of renewable energy. It also provides additional criteria in BREEAM assessment to bring innovation to construction. This also proves that solar

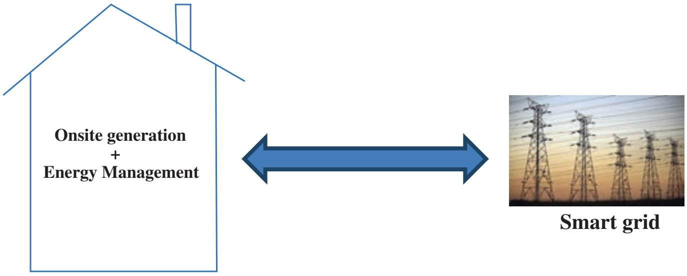


**Fig. 10** Smart buildings and smart grid

**Fig. 11** Sustainable building envelope centre, Shotton, Tata Steel, Deeside, United Kingdom

sustainability systems have always been a key feature towards development of green buildings.

Figure 11 shows refurbished industrial warehouse building to Sustainable Building Envelope Centre (SBEC) office. SBEC is based at Tata Steel Shotton site in North Wales and led by the Low Carbon Research Institute (LCRI), and SBEC operates out of a specially refurbished building designed to act as a test rig and proving ground for new technologies, demonstrating them in use. The building has provisionally been awarded a BREEAM Excellent rating.[3]

Figure 12 below shows top view of the Beddington Zero Energy Development, or BedZED; it is the UK's best-known eco-village. This multi-award winning development is one of the most coherent examples of sustainable living and sustainable construction in the UK.

The building project adopted the distinctive roofscape with solar panels and passive ventilation chimneys. Also on the site, renewable energy was to be generated using CHP sourcing locally woodchip to generate both heat and power. Also onsite photovoltaic deliver nearly 20 % of electricity demands of the residents.

Aforesaid examples show various ways to integrate renewable energy into the building fabric and transform it to sustainable envelope. Notably, in the buildings

[3] http://www.sbec.eu.com/en/.

**Fig. 12** UK's best-known eco-village (see Footnote 5)

for renewable energy generation, six main technologies are used: (i) solar panels (ii) wind turbines (iii) solar water heating, (iv) biomass, (v) combined heat and power (CHP) and (vi) heat pumps.

After maximising energy efficiency, utilisation of renewable energy offers further scope of carbon dioxide emission reduction. It also reduces buildings energy dependence on fossil fuel-based sources. Carbon Trust[4] in the UK provides low carbon building advice for building owners and occupiers on energy efficiency and effective use of renewable energy (Table 1).

As mentioned above, there are various ways to integrated renewable technology into the buildings. As per data published from carbon trust based on their 146 projects across the UK, it implies that photovoltaics have the highest installed costs. Though it is worth to note that in recent year, prices for photovoltaic installation have gone significantly low. The main conclusion from the above table is that selecting renewable energy technology is important factor and should vary depending on the site and case by case. For example, on a site which does not benefit with south facing, photovoltaic installation cannot be good option. Similarly, the areas with wind speed lower than threshold have no use of installation of wind turbine. Carbon trust suggests building users and occupiers to consider certain point while making key decision for selecting renewable energy technologies integration into their building. Figure 13 shows key consideration for green design of products and services. It consists of major four steps[5] (i) assessing feasibility (ii) buying a system (iii) installing a system and (iv) operating.

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[4]http://www.carbontrust.com/resources/guides/energy-efficiency/low-carbon-buildings-design-and-construction.

[5]http://www.bioregional.co.uk/files/publications/BedZED_seven_years_on.pdf

**Table 1** Installed cost per kW rated output and cost effectiveness of carbon (based on 146 projects 2006–2009)

| Technology | Installed cost per kW rated output | Cost per carbon savings (£/tonne $Co_2$) |
|---|---|---|
| Photovoltaics | £5944.66 | £12,410 |
| Solar hot water | £1476.42 | £8581 |
| Wind turbines | £4025.15 | £4520 |
| Hydro | £3867.19 | £2353 |
| Heat pump | £1193.90 | £7232 |
| Wood fuelled boiler | £462.81 | £752 |

http://www.carbontrust.com/media/81373/ctg050-power-play-renewable-energy-technologies-existing-buildings.pdf

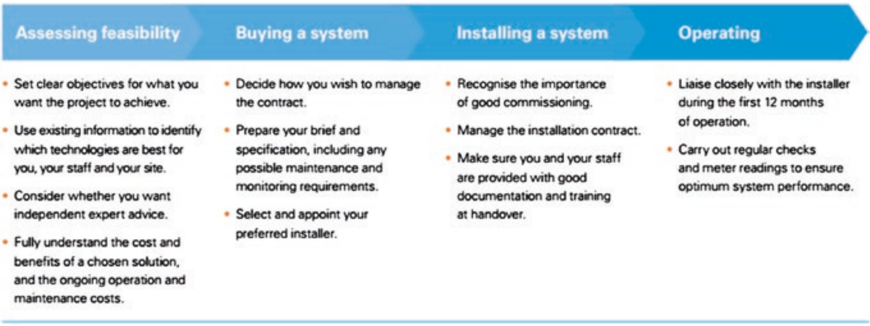


**Fig. 13** Key consideration for green design of products and services[6]

## 7 Conclusions

Designing buildings for sustainability has major challenge of green materials and sustainable resourcing. Though sustainable materials are gaining importance, but lack of knowledge and elongated time frames making it difficult to achieve. Building assessment ratings should cover building assessment across a broader range of environmental issues. The effect of BREEAM use in the British built environment from nearly 20 years along with other standards and regulations proved that UK construction industry is much further ahead in green building designs. Green Building design is getting more and more momentum in the United Kingdom and future for sustainable building design seems bright. Though sustainable building design have many challenges to face, however lack of skilled labours and environmental conscious construction firms/builder are main concerns for the British built environment.

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# Aerogel-Based Materials for Improving the Building Envelope's Thermal Behavior: A Brief Review with a Focus on a New Aerogel-Based Rendering

**Mohamad Ibrahim, Pascal Henry Biwole, Patrick Achard and Etienne Wurtz**

**Abstract** Most developed countries have set an objective to reduce their energy consumption and green house gas emissions. In most countries, the building sector is the largest energy consumer. This sector offers a significant potential for improved energy efficiency through the use of high-performance insulation and energy-efficient systems. For existing buildings, renovation has a high priority in many countries, because these buildings represent a high proportion of energy consumption and they will be present for decades to come. Several studies have shown that the best way to reduce the energy consumption in buildings remains the reduction of heat losses through the envelope. Nowadays, there is a growing interest in the highly insulating materials such as aerogels. Due to their highly insulating characteristics, aerogels are becoming one of the most promising materials for building insulation. Although the cost of aerogel-based materials remains high for cost-sensitive industries such as building industry, this cost is expected to decrease in the following years as a result of the advancement in the aerogel production technologies as well as the large-scale material production leading to lower unit costs. In this study, a brief review on aerogel applications in buildings is presented.

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Some examples of opaque aerogel-based materials and translucent aerogel-based systems are illustrated. Then, a new insulating rendering based on silica aerogels is presented. Its impact on energy performance for different houses is examined.

**Keywords** Energy efficient envelopes · Aerogel-based renderings · Thermal insulation · Building rehabilitation · Green building

## 1 Introduction

According to experts from intergovernmental panel on climate change (IPCC), it is almost certain that global warming observed over the past century is linked to greenhouse gas emissions produced by the human activities. To limit the aggravation of this phenomenon, the countries must reduce their greenhouse gas emissions. All business sectors are concerned, but the building sector requires a special attention because, according to a report on energy trends in buildings (Enerdata 2012), the building sector consumed about 41 % of total final energy requirements in Europe in 2010. It is the largest end-use sector, followed by transport (32 %), industry (24 %), and agriculture (2 %). The final energy consumption of buildings has increased by around 1 % per year since 1990 (Enerdata 2012).

The building sector offers significant potential for improved energy efficiency through the use of high-performance insulation and energy-efficient systems. For existing buildings, renovation has a high priority in many countries, including France, because these buildings represent a high proportion of energy consumption and they will be present for decades to come. Several studies (Verbeeck and Hens 2005; Enkvist 2007; EEW 2013) showed that the most efficient way to curb the energy consumption in the building sector (new and existing) remains the reduction of the heat losses by improving the insulation of the building envelope. For retrofitting and even for new buildings in cities, the thickness of internal or external insulation layers becomes a major issue of concern. Nowadays, there is a growing interest in the so-called super-insulating materials, such as aerogels. The unique properties of aerogels offer many new applications in buildings. Their extraordinary low thermal conductivity as well as their optical transparency allows their use for insulating building facades and insulating window panes.

Since their first discovery in the 1930s (Kistler 1931), aerogels have shown a great progress in the last decades. Due to their superior characteristic, they are used in different sectors including buildings, electronics, clothing, space applications, etc. However, lowering their production is still the most challenging issue for manufacturers, especially, when being used in the building sector. The cost of the aerogel-based insulation materials remain high compared to conventional insulation which hinders their entry to the market. Research is still continuing to develop more advanced technologies to lower the aerogel's production costs and enhance their performance.

## 2 Aerogel-Based Insulating Materials: Building Applications

Silica aerogels are silica-based dried gels having very low weight and excellent thermal insulation performance. Specifically, they have high porosity (80–99.8 %), low density (3 kg/m$^3$), and low thermal conductivity (0.014 W/m$^{-1}$ K$^{-1}$) (Dorcheh 2008). Silica aerogels are an innovative alternative to traditional insulation due to their high thermal performance, although the costs of the material remain high for cost-sensitive industries such as the building industry. Research is continuing to improve the insulation performance and to decrease the production costs of aerogels. The unique properties of aerogels offer many new applications in buildings (TAASIS 2011). The extraordinary low thermal conductivity of aerogels as well as its optical transparency allows its use for insulating building facades and insulating window panes. Two different types of silica aerogel-based insulating materials are being used in the building sector. The first type is the opaque silica aerogel-based materials, and the second one is the translucent materials.

### *2.1 Opaque Silica Aerogel-Based Materials*

Aerogel blankets/panels are used to insulate building walls, grounds, attics, etc. Aspen Aerogels Inc. (Northborough, MA, US) has developed an insulation blanket based on silica aerogels, Spaceloft® (Aspen Aerogels, Spaceloft® www.aerogel.com/products/pdf/Spaceloft_MSDS.pdf). It has a thermal conductivity of 0.0131 W/(m K). Spaceloft® was used to convert an old mill house in Switzerland into an energy-saving passive house (Fig. 1). A 9 mm thickness layer was used externally and internally on the walls and also internally on the floors. The *U*-value of the walls improved from 1 to 0.2 W/(m$^2$ K) (Aspen Aerogels, Case study, www.aerogel.com/markets/Case_Study_House_Renovation_web.pdf).


**Fig. 1** Aerogel blanket for retrofitting an old building

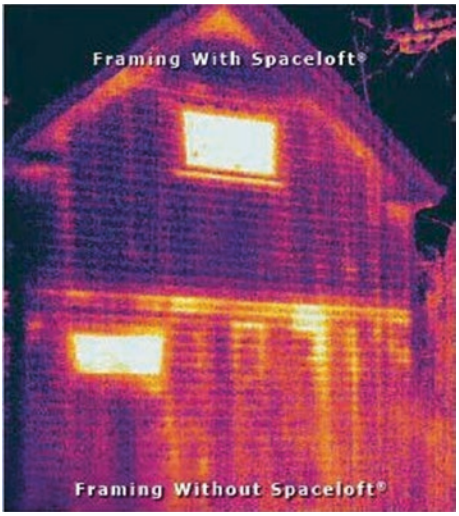


**Fig. 2** A thermographic image of a timber wall where the studs of the *top floor* are insulated with a thin layer of aerogel insulation whereas the *ground floor* is not

Due to its small thickness, Spaceloft® can be installed on interior walls of buildings preserving the area of the occupied spaces. A case study was done in the United Kingdom where a number of governmental housing units were retrofitted by adding Spaceloft® insulation layer at the interior wall surfaces (Aspen Aerogels, Case study, www.aerogel.com/markets/Case_Study_Interior_Wall_web.pdf). A 44 % reduction in the *U*-value, a 900 kWh/year energy reduction, and a 400 kg/year reduction in carbon emissions were obtained.

In a typical building, the framing is not insulated, resulting in heat losses through the studs. Spaceloft® insulation decreases heat loss through thermal bridges and improves thermal performance up to 40 % in steel studs and up to 15 % in wood studs. Figure 2 shows the reduction in the thermal bridges heat losses between the ground floor un-insulated frames and the top floor insulated frames (Aspen Aerogels, Case study, www.aerogel.com/markets/Case_Study_Framing_web.pdf). From this thermographic figure, it is illustrated that the aerogel blanket allows an almost uniform temperature distribution throughout the wall area (upper floor); however, we can see the variation in the ground floor's wall due to the increased heat losses through thermal bridges as a result of the absence of the aerogel blanket.

In another study, thermal performances and experimental tests were performed on walls and roofs using aerogel insulation (Kosny et al. 2007). Hot box measurements on wall assemblies containing aerogels showed that the *R*-value of wood-framed walls is improved by 9 % and that of a steel-framed wall by 29 %. Finite difference simulations performed on steel-framed wall assemblies using 0.6-cm-thick aerogel strips showed that aerogel can help in reducing the internal surface temperature differences between the center of the cavity and the stud location from 3.2 °C to only 0.4 °C. For roof structures, hot box measurements performed on the fastened metal roof insulated with aerogel strips showed an increase in the overall roof *R*-value by about 14 %.


**Fig. 3** Test bedroom and internal wall insulation of aerogel (*blue colored*) (Cuce et al. 2014b)

At the University of Nottingham, an experimental test house was built where a 2-cm layer of aerogel blanket was added at the internal surface of one of the bedroom's exterior walls. Co-heating test procedure was performed to the test bedroom before and after retrofitting, and thermal characteristics were determined both theoretically and experimentally. Also, heat losses through thermal bridges were analyzed with thermographic images. Figure 3 shows the test house, test bedroom, and the places insulated with aerogel. Initially, the wall had a *U*-value of 0.55 W/m$^2$ and was composed of a 1.3-cm layer of gypsum plaster (inner wall layer), a 10-cm layer of concrete block, a 5-cm cavity fill, and a 10-cm layer of brickwork. As a retrofit procedure, a 2-cm layer of aerogel blanket was applied. The *U*-value of the external wall after post-retrofit was determined to be 0.30 W/m$^2$ K resulting in heat losses reductions of around 46 %. In addition, a significant decrease in the thermal bridge heat losses was obtained in this study.

## *2.2 Translucent Silica Aerogel-Based Materials*

Another type of silica aerogel-based materials which are used in buildings is the translucent insulation materials. These materials have the advantage to combine a low thermal conductivity along with high transmittance of solar energy and

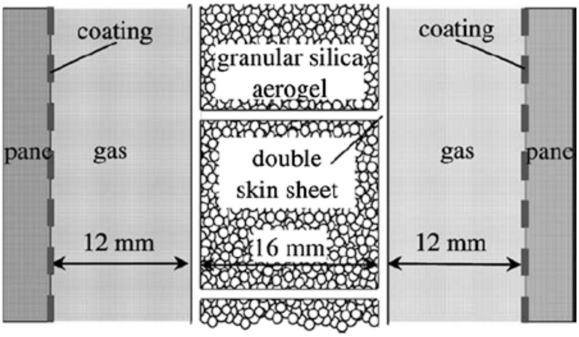


**Fig. 4** Cross-section through the granular aerogel-based glazing (Reim et al. 2002)

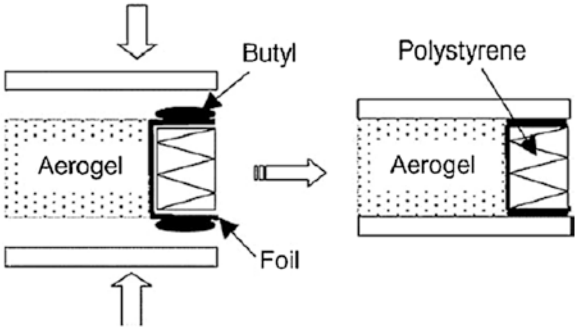


**Fig. 5** Cross-section of the monolithic aerogel-based evacuated glazing (Jensen et al. 2004)

daylighting. Research has been conducted in the last decade on the development of highly insulating windows based on granular aerogels and monolithic aerogels (Pajonk 1998). A new glazing element based on granular silica aerogel was developed at ZAE Bayern, Germany (Reim et al. 2002, 2005). The glazing consists of 16-mm double skin sheet made of polymethylmethacrylate filled with granular silica aerogels separated by two gaps filled with krypton or argon and installing glass panes at the ends (Fig. 4). Two types of granular silica aerogels are used: semi-transparent spheres and highly translucent granulates. Three window systems were developed. The first is a daylighting system by applying a low-e coating (emissivity = 0.08) on the panes. A total solar transmittance between 0.33 and 0.45 and a $U$-value having a range of 0.44–0.56 W/(m$^2$ K) were obtained. The second system is a sun protecting system developed by applying a lower emissivity (0.03) to the glass panes. A $U$-value of 0.37–0.47 W/(m$^2$ K), a visible transmittance of the range of 0.19–0.38, and a solar transmittance between 0.17 and 0.23 were achieved. The third is a solar collector by placing a heat exchanger between a layer of aerogels and two glass panes. When compared to a traditional flat-plate solar collector, the collector using aerogel granules has a reduction in heat losses of about 40 % and has a 3 cm smaller system thickness.

In a project supported by the European Union, a monolithic aerogel-based window was developed (Fig. 5) (Jensen et al. 2004). They obtained a total heat transfer coefficient for the window ($U$-value) of 0.66 W/(m$^2$ K) and a solar transmittance of 0.85 using a 13.5-mm-thick monolithic aerogel. Vacuum glazing technology

**Fig. 6** The two test rooms (Cotana et al. 2014)

was also used in developing this window. This *U*-value can be lowered when using more thickness of aerogel and at the same time keeping the solar transmittance more than 0.75. A case study was done for the Danish climate, where a triple-glazed window filled with argon was replaced by this aerogel-based window for a house built according to the passive house standards. Energy savings of about 19 and 34 % were achieved for 13.5 and 20 mm aerogel thickness, respectively.

In another study, the energy and lighting performance of a glazing system with silica aerogels is analyzed through in situ experiments (Cotana et al. 2014). Two identical test rooms (Fig. 6) were constructed in Perugia, Italy, one serves as the reference case and the other serves as the test case. Both test cells have a double-glazed south window; however, they differ in the filling layer between the window panes. The window of the reference case is filled with air while that of the test case is filled with aerogel granules. The obtained *U*-value is 1.5 W/($m^2$ K) for the reference window and 1 W/($m^2$ K) for the aerogel window. These test cells were highly instrumented, and continuous monitoring was performed during the heating season. Thermal energy monitoring showed the aerogel capability to keep the indoor thermal conditions more constant, i.e., total temperature decrease less than 3 °C, even several days after the heating system switching off. On the other hand, the classic air-filled double-glazing system immediately tended to lower indoor air temperature up to the outdoor temperature values in winter conditions. The heating energy consumption could be decreased up to 50 %. Concerning the lighting characteristics, the aerogel glazing could reduce the daily average illuminance up to 10 % during sunny days. This study showed that such aerogel systems could be a good solution to enhance the building's energy efficiency and indoor thermal comfort.

Buratti and Moretti (2012) investigated experimentally that different glazing systems having granular or monolithic aerogel. Different glazing systems were constructed. The monolithic aerogel was supplied by Airglass AB, Sweden, and the granular ones were supplied by Cabot Corporation, USA (Nanogel®). Thermal and light performance of the different systems was measured. They showed that the monolithic aerogel glazing systems has the best performance providing higher light transmittance (0.62) and lower heat transfer coefficient (0.6 W $m^{-2}$ $K^{-1}$) than the other systems. Also, the solar factor was 0.74. Furthermore, monolithic aerogel between two 4-mm glasses gave a 62 % reduction in heat losses, with a

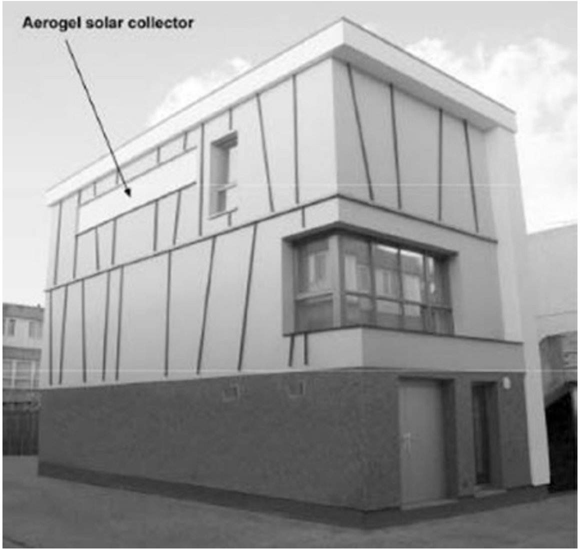


**Fig. 7** Solar thermal collector with aerogel glazing integrated to building facade (Dowson et al. 2012)

17 % reduction in light transmittance when compared to a conventional double glazing that is being used in buildings nowadays.

Another application of translucent silica aerogels is in solar thermal collectors. The idea is to replace the glass cover used in conventional solar collectors with a panel filled with aerogels. In situ performance of such collector integrated to a building's façade is investigated (Fig. 7) (Dowson et al. 2012). This study has shown higher performance than traditional single- or double-glazed solar thermal collectors. The useful energy gains were estimated to be in the range of 118–166 kWh/$m^2$/year for collectors with different aerogel cover thickness. Comparing conventional collectors, the useful energy gains are 110 and 140 kWh/$m^2$/year for a single-glazed collector and a double-glazed collector, respectively. The energy gains could be increased to 202 kWh/$m^2$/year when using high-performance monolithic aerogel.

## *2.3 Life Cycle Assessment*

Dowson et al. (2012) investigated the life cycle assessment of silica aerogels. The mass of raw materials and electricity used for the production of 1 $m^3$ of silica aerogel are determined to estimate the energy costs as well as the $CO_2$ burden during the manufacturing process. Then, this is compared to energy savings and $CO_2$ emission reduction when a single-glazed window is retrofitted by a translucent aerogel window over a 15 years product lifespan to see whether the resulting operational savings can payback the costs of aerogel production. Results showed that the payback period (PP) for the production cost and its $CO_2$ burden is within 0.3 and 1.9 years. However, the end of life processing impact, such as recycling, reusing, land filling, etc., and also transport costs were not taken into consideration in this study. Also, this study is limited to the production of only 1 $m^3$ of silica aerogel; thus, on a full scale (mass production), the results may not reflect accurately the energy cost and the $CO_2$ emission. Despite these factors, results have demonstrated that aerogel can provide a measurable benefit over its life cycle.

Huang (2012) has studied the feasibility of using silica aerogels in buildings. The energy-saving potential of silica aerogel used as building insulations is calculated by using the life cycle cost analysis. Results showed that silica aerogel can reduce the annual heat losses of a non-insulated building by around 51 %. Moreover, it can reduce about half of the annual heating costs when compared with other insulation materials. However, the cost of silica aerogel-based materials is higher than other traditional insulation materials. The payback time is estimated to be 3.54 years for aerogel materials which is longer than the other competitive solutions (0.22 years for expanded polystyrene, 0.07 years for extruded polystyrene).

Cuce et al. (2014a, b) compared the embodied energy of aerogel insulation with other conventional insulation materials for a simple case of retrofitting an exterior brick wall. Initially, the *U*-value of the wall is 2.3 W/($m^2$ K), and the target *U*-value is 0.3 W/($m^2$ K). Figure 8 shows the embodied energy and the insulation thickness needed to reach the objective using different insulating materials. It can be

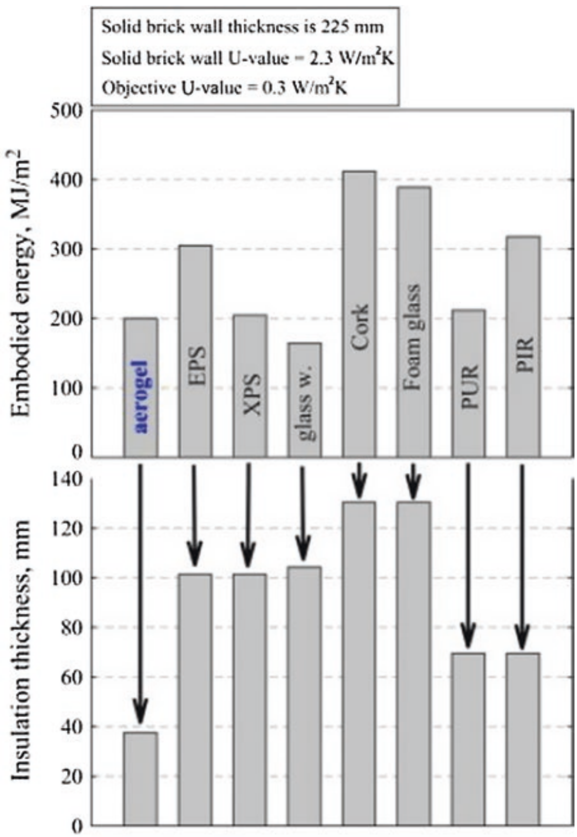


**Fig. 8** The embodied energy and insulation thickness for different materials used (Cuce et al. 2014a)

seen that aerogel in this regard performs favorably against the other conventional materials, with only glass wool having a lower value. However, the thickness of aerogel insulation is considerably lower meaning that more space savings could be achieved. Space savings is becoming an important factor especially in cities.

In another study, Cuce et al. (2014b) estimated the optimum thickness of aerogel blanket in exterior insulated and un-insulated cavity walls for the climate conditions of Nottingham, UK. They showed that the optimum thickness varies between 2 and 5 cm for already insulated walls and between 3.4 and 6 cm for un-insulated walls depending on the type of fuel being used. Aerogel insulation was found to be very appropriate for the non-insulated cavity walls (PP is around 2–3 years), whereas it is not a reasonable investment for the insulated cavity walls (PP is more than 10 years). Also, the impact of aerogel insulation on lowering the greenhouse concentrations is analyzed. Particularly, the annual reduction of $SO_2$ emissions for the UK's building stock is determined to be 326,000 and 512,400 tons for coal and fuel oil, respectively.

## 3 Aerogel-Based Rendering

A very limited number of studies exist on aerogel-based thermal insulating plasters. Barbero et al. (2014) provided an overall analysis of thermal insulating plasters in the European market. They concluded that innovative solutions for thermal insulating plasters based on materials with pore size in nanometer range, such as aerogel, could make a significant contribution to this field, reaching higher level of thermal performance and reducing the needed thickness. Additionally, successful approaches will have the ability to be used on both new and existing buildings, using techniques that are familiar to today's construction industry. According to the authors, thermal insulating plasters have the advantage of being applied on non-aligned, out of square, or, even, curved areas. They are flexible and can be suitable for any architectural and design solutions. Their easy application on the facades facilitates the rehabilitation of existing buildings. Researchers at EMPA building technologies laboratory (EMPA www.empa.ch) compared several insulating plasters found in the market today with the aerogel plaster (see Fig. 9) and concluded that the thermal conductivity of the aerogel plaster is significantly lower than that of the other plasters.

An innovative insulating coating or rendering (note that, in all what follows, the word "coating" is used to refer to an aerogel rendering or mortar having a certain thickness) based on the (super)-insulating materials silica aerogels has been developed (Fig. 10) possessing a low thermal conductivity (Achard et al. 2011 WIPO Patent WO/083174). The invention is a foam of mortar that can be applied to the external wall surfaces of a building to produce a thermally insulating rendering. It consists of water, a mineral and/or organic hydraulic binder, insulating filler comprising a powder or granules of hydrophobic silica xerogel, structuralizing filler (option), and additives (option).

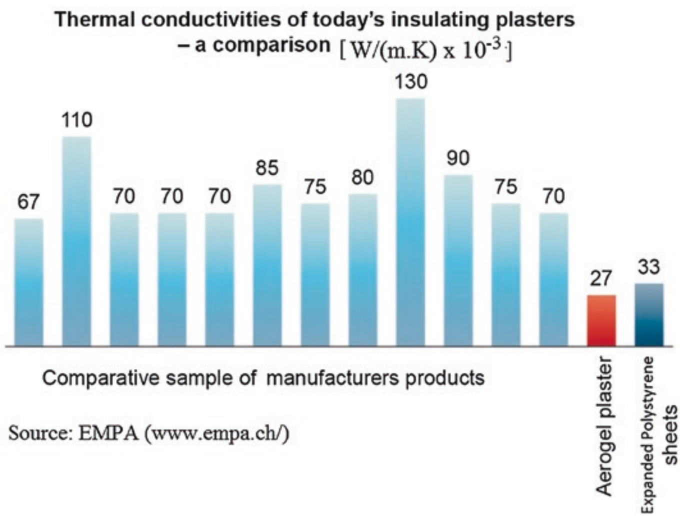


**Fig. 9** Thermal conductivity of today's insulating plasters and the aerogel plaster


**Fig. 10** The new aerogel-based insulating coating (*rendering*)

The aerogel granules are an industrial product manufactured separately in a specialized plant. Thus, the mortar is made from these aerogel grains that somehow replace the sand used in conventional mortar. The latter is prepared industrially as a dry composition by mixing all the above-mentioned components, and then, the mix is stored in bags and transported to the site for use. Then, on site, the product is mixed with water in order to obtain a paste with a viscosity suitable for the application, for example, by spraying, on the building's exterior surface.

This coating/rendering has been developed mainly for exterior wall surface applications. The coating thermo-physical characteristics are presented in Table 1. They are measured at the French scientific and technical center of buildings (CSTB). Its thermal conductivity is measured by means of guarded hot plate and heat flow meter according to the NF EN standard 12667. Its specific heat is measured by means of differential scanning calorimeter (DSC) according to NF EN 1159-3 standard. Its density is measured according to the NF EN 1602 standard. Its vapor diffusion resistance factor is measured using the Cup method according the NF EN ISO 12572 standard.

**Table 1** Thermo-physical properties of the new aerogel-based insulating coating

| | |
|---|---|
| Thermal conductivity (W/m K) | 0.0268 |
| Specific heat (J/kg K) | 990 |
| Density (kg/m$^3$) | 156 (dry) |
| Vapor diffusion resistance factor (−) | 4.25 (average) |
| Water absorption coefficient (kg/m$^2$ s$^{1/2}$) | 0.184 |

The thermal conductivity of this new aerogel-based coating (ABC) is 0.0268 W/(m K) which is better compared to that of traditional insulation (See Table 2). Moreover, the volumetric heat capacitance ($\rho * cp$) is much higher than that of traditional insulation.

The rendering's application on the building facades is rather easy. It is done through direct spraying onto the facade manually (using the ordinary techniques well known by builders, such as traditional plastering) or using a plastering machine. This has an advantage over traditional insulations especially for building retrofit cases. Traditional insulation needs a plane surface to be applied on. Furthermore, adjustment, gluing, and even fastening by means of dowels are also needed. Insulation materials are often manufactured in precise dimensions; this can lead to discontinuity in thermal insulation. In this sense, the new rendering takes advantage over traditional insulation: its application is simple, allows a continuous thermal insulation, and adheres directly to the masonry without leaving hollow gaps where moisture could form. This type of rendering can also be used to limit heat losses through thermal bridges. It can be easily applied to places where existing solutions of external insulation are technically difficult to apply especially for buildings. The new ABC can be used in new and existing buildings. For old buildings, it provides not only a better thermal performance but also a decoration for exterior deteriorated facades. Thanks to its mineral basis, the new rendering is very similar to the traditional building materials (e.g., masonry facades), and this makes it ideal for use on old buildings.

In contrary, since this rendering is based on silica aerogels, its production cost remains high relative to other existing insulation materials which will increase the PP as illustrated previously (Huang 2012). Furthermore, its mechanical properties are still not sufficient enough, so there is a need to add a reinforcing mesh.

In a recent research (Stahl et al. 2012), a new kind of rendering based on silica aerogels granulates, very similar to the one we are presenting, has been developed

**Table 2** Thermal conductivity of some traditional insulation products (Koebel et al. 2011 Aerogels for superinsulation: a synoptic view)

| Insulation product | Chemical composition | Thermal conductivity (W m$^{-1}$ K$^{-1}$) |
|---|---|---|
| Mineral wool | Inorganic oxides | 0.034–0.045 |
| Glass wool | Silicon dioxide | 0.031–0.043 |
| Foam glass | Silicon dioxide | 0.038–0.050 |
| Expanded polystyrene | Polymer foam | 0.029–0.055 |
| Extruded polystyrene | Polymer foam | 0.029–0.048 |

possessing a thermal conductivity of 0.025 W/(m K) and a density of around 200 kg/m$^3$. It contains a purely mineral- and cement-free binder. It can be applied to walls both manually or by the aid of a plastering machine.

## 3.1 Hygrothermal Performance

### 3.1.1 Introduction

An experimental test unit was constructed in 1984 (Krauss 1985) at PERSEE research center in Sophia Antipolis (latitude 43.616 N, longitude 7.055 E) in the southeast Mediterranean region of France (See Fig. 11). It is composed of two adjacent cells orientated to the south which are identical in dimensions but differ in the composition of the south wall. The first one, we will call it hereafter the test cell, has the south wall initially composed of heavy weight concrete with a layer of glass wool interior insulation. The second cell, the adjacent cell, has its south wall composed of a semi-transparent glazing system consisting of a composition of silica aerogel granules and phase change material (Berthou 2011; Johannes et al. 2011). A third cell (acquisition cell), adjacent to the other two, is also present and is oriented to the north

Initially, the south wall of the test cell was composed of a 25-cm layer of concrete (exterior layer), a 16-cm layer of glass wool, and a 1.3 cm of plaster board.

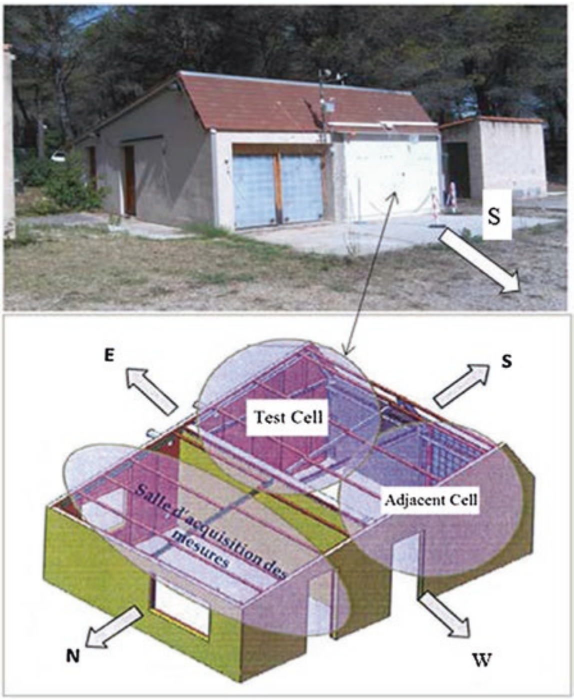


**Fig. 11** PERSEE experimental test cell

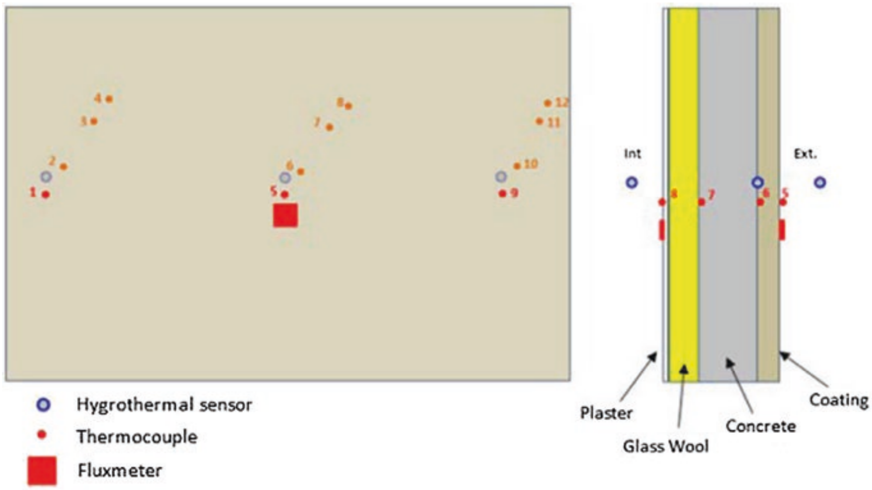


**Fig. 12** Measurement sensors within the south wall

A 4-cm layer of ABC was then added at the exterior surface of this wall. Trying to isolate the south wall from the thermal effects of the other walls enclosing the test cell, these elements—i.e., the east wall of the test cell, all the partition walls, the roof, and the ground—are very well insulated. Also, to avoid the effect of the direct solar gains, the test cell has no windows. For the south wall, temperature sensors are placed at the exterior surface of the coating, at the interface between the coating and the concrete, at the interface between concrete and internal insulation (glass wool), and at the interior surface of the plaster layer. For each of these positions, three sensors are present: near the east edge, near the west edge, and at the middle of the wall. The hygrothermal sensors are placed at the interface between the coating and the concrete (see Fig. 12). Also, outdoor weather conditions are monitored through temperature, humidity, wind, and solar irradiation sensors. The objective of this experiment was to validate a numerical model developed in the commercial software WUFI (Kunzel 1995). The latter is a specialized software in assessing the thermal and moisture performance of exterior walls. After that, we will use this model to carry out different simulations.

### 3.1.2 Model Validation

The measured and simulated temperatures and relative humidity at the interface between the ABC and concrete are plotted in Fig. 13 for a 2-week period. It can be seen from this figure that the numerical model is capable of generating temperatures and relative humidity close to those of measurements. The maximums and minimums of the simulated data are in phase with the measured ones. The temperatures are in good agreement between the two curves where the maximum

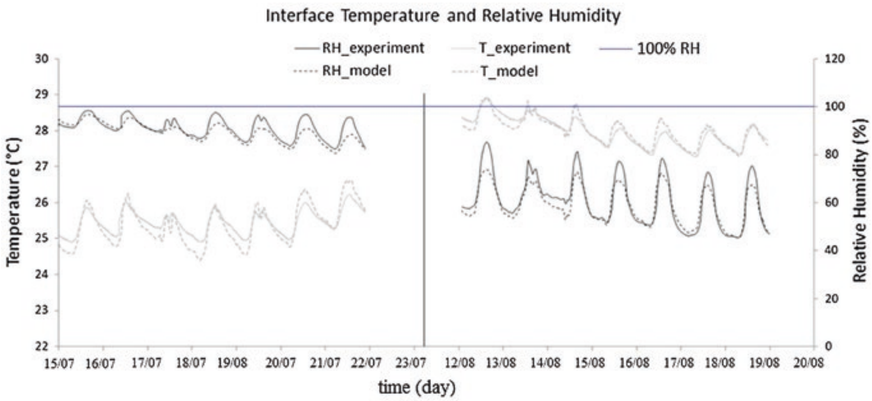


**Fig. 13** Measured and simulated temperature and relative humidity at the interface coating/concrete

discrepancy does not exceed 0.6 °C. Concerning relative humidity, a satisfactory agreement is observed between the measurements and the simulation results; however, the maximums of the simulation results are lower than those measured where the discrepancy between the two varies between 4 and 14 %.

### 3.1.3 Simulation Results

The simulations are carried out for Grenoble climate representative of a semi-continental French climate. The city of Grenoble was chosen as a simulation case because of its very specific climate: rain is more abundant, winter is colder, and summer is generally warmer than most other cities in France. Due to the mountainous environment that slows the winds and decreases their thermal regulation effect, the daily temperature range is much higher than any other place in France. The nights are generally cooler (except during heat wave periods), and the afternoon is warmer than those in other main cities. While in winter, the temperature can drop relatively low; in summer, the city undergoes heat among the highest in the country (more than 35 °C each year, usually for several days as in 2003, 2006, 2009, 2010, 2011, 2012, 2013). The surrounding Alps Mountain forms a barrier preventing rain-filled clouds to move out, while rainy westerly winds are trapped. Thus, rainfalls reach almost a meter per year over the city.

Results show that interior thermal insulation systems can cause several moisture problems: no capability to dry out over the years, condensation risk, etc (Fig. 14). The un-insulated walls have, in addition to these moisture risks, very high heat losses compared to the other insulated ones. Adding the aerogel-based rendering on the exterior surface of the un-insulated or the already internally insulated walls reduces significantly or removes the moisture risks. It also reduces significantly the wall heat losses. Compared to the un-insulated wall, the wall having the rendering on its exterior façade has a more potential to dry out by about 20 %.

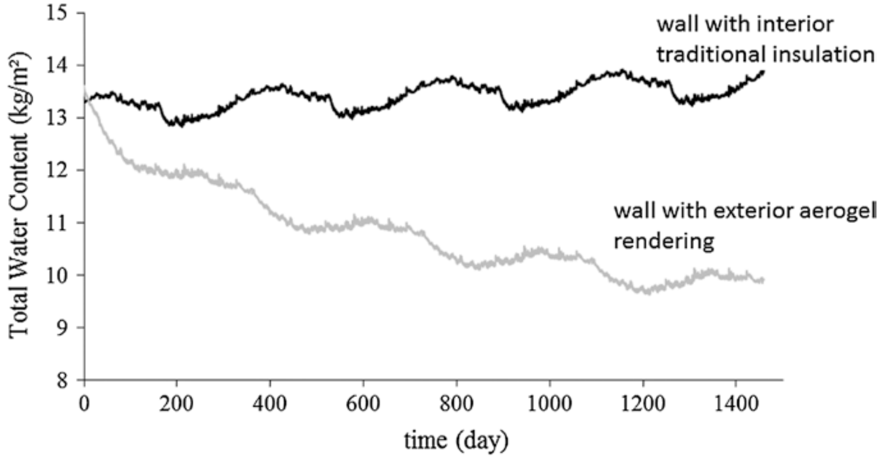


**Fig. 14** Total water content for internal and external insulation configuration

Mold growth due to moisture formation is eliminated when the rendering is added. Also, heat losses reductions up to 70 % could be achieved.

## 3.2 Energy Performance

Figure 15 shows the house's energy load without the ABC and with 5-cm ABC on the exterior facades for the different construction periods and for the different climates. The construction materials for the different periods are shown in Table 3. For the period 1968–1974, we modeled two different houses: the first one "1968–1974(1)" has simple glazed windows with no insulation in the roof; the second one "1968–1974(2)" has double-glazed windows with 6-cm thermal insulation in the roof. Also, for the period after 1990, we distinguish two cases: the first one, >1990(1), has the exterior walls composed of concrete structure with 10-cm internal thermal insulation and the second one, >1990(2), has the exterior walls composed of 42 cm of brick monomur with no internal insulation.

From this figure, it is shown that for the old houses built before 1974, the percentages of energy reductions are between 40 and 53 % for the Mediterranean climate, 37–48 % for the oceanic climate, and 33–40 % for the semi-continental climate. For the houses built in the period 1975–1989, the reductions are about 32, 23, and 17 % for the Mediterranean, oceanic, and semi-continental climates. Lower reductions are achieved in the new houses, 23, 14, and 10 % for the three climates, respectively. Since the new houses have already thermal insulation in the exterior envelope, adding the ABC will not decrease a lot the annual load

The percentage of occupied time where heating is not needed for different coating (rendering) thicknesses for the old house is shown in Fig. 16. As the

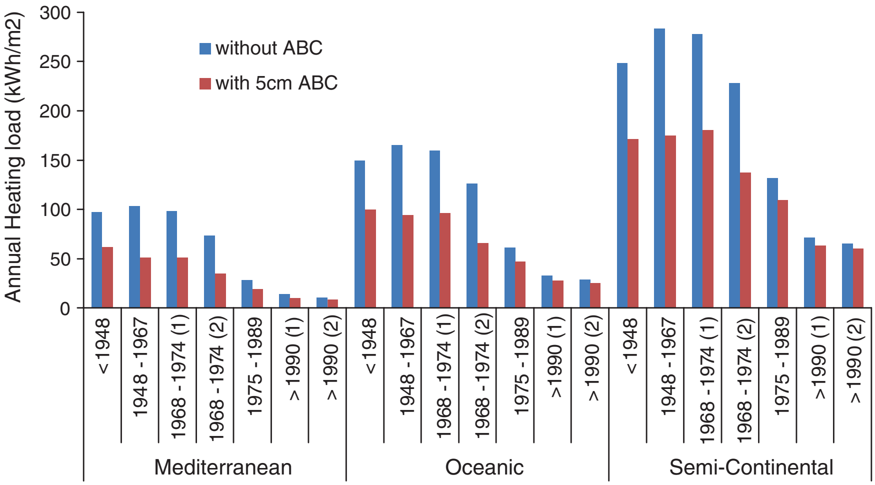


**Fig. 15** Annual heating load for the different climates and the different construction periods with and without the coating [(1) and (2) represent different construction techniques within the same period]

coating thickness increases, the number of hours where heating is not needed increases. Taking the 5 cm as an illustration, the percentage increases by 10, 6, and 3 % for the Mediterranean, oceanic, and semi-continental climates, respectively, compared to the house with no coating.

Figure 17 shows the percentage of occupied time where heating is not needed for the new house for 0-, 5-, and 10-cm interior insulation. The black curves are for the Mediterranean climate, the blue ones are for the oceanic climate, and the red ones are for the semi-continental climate. For the cases with no interior insulation, applying 5 cm of the coating increases the percentage by 28, 17, and 10 % for the Mediterranean, oceanic, and semi-continental climates. For the houses with 5-cm interior insulation, adding 5 cm coating on the exterior facades increases the percentage by 12, 6, and 4 % for the three climates, respectively. For the houses with 10-cm interior insulation, the increase is about 6, 3.5, and 2.5 %, respectively.

### *3.3 Cost Analysis and Thickness Optimization*

Selection and determination of the optimum thickness of insulation has been of prime interest for many researchers in recent years. The concept of optimum thermal insulation thickness considers both the initial cost of the insulation and the energy savings over the life cycle of the insulation material. The optimum insulation thickness corresponds to the value that provides minimum total life cycle cost. The optimum insulation thickness based on heating requirement depends mainly on the yearly heating load, the costs of electricity and insulation material, the building lifetime, and the interest and inflation rates.

**Table 3** Houses' construction in France during the different periods

| | | Period | | | | | |
|---|---|---|---|---|---|---|---|
| | | <1948 | 1948–1967 | 1968–1974 | 1975–1981 | 1982–1989 | 1990–2000 |
| Space heating | Final energy use for space heating | 214 (kWh/m$^2$/year) | 226 (kWh/m$^2$/year) | 177 (kWh/m$^2$/year) | 142 (kWh/m$^2$/year) | 106 (kWh/m$^2$/year) | 95 (kWh/m$^2$/year) |
| Opaque wall | Construction | – Stone rubble: (such as sandstone, limestone, granite…) | – Hollow concrete blocks | – Hollow concrete blocks | – Masonry blocks | – Concrete hollow blocks (67 % of houses) | – Concrete blocks |
| | | – Mud-brick | – Hollow bricks | – Hollow bricks | – Cellular concrete | – Hollow bricks (15 %) | – More energy-efficient hollow bricks (such as brick monomur) |
| | | – Solid bricks | – Reinforced concrete | – Reinforced concrete | – Hollow brick | | |
| | | – Timbered structure with soil, brick, or mixed filling | | | – Stone | | |
| | Thermal insulation | No | No | No | R = 2.3 (m$^2$ K)/W | R = 2.4 (m$^2$ K)/W | R = 3 (m$^2$ K)/W |
| Roof/ceiling | Construction | Wood with a final finishing based on local materials | Wood with interlocked tiles or asphalt shingles | Wood with interlocked tiles or concrete shingles | Wood with cement finishing | Wood with cement finishing | Concrete insulated beam |
| | Thermal insulation | No | No | Some houses start to have insulation (4–10 cm glass wool) | R = 4.8 (m$^2$ K)/W | R = 4.8 (m$^2$ K)/W | R = 6 (m$^2$ K)/W |

(continued)

**Table 3** (continued)

| | | Period | | | | | |
|---|---|---|---|---|---|---|---|
| | | <1948 | 1948–1967 | 1968–1974 | 1975–1981 | 1982–1989 | 1990–2000 |
| Space heating | Final energy use for space heating | 214 (kWh/m$^2$/year) | 226 (kWh/m$^2$/year) | 177 (kWh/m$^2$/year) | 142 (kWh/m$^2$/year) | 106 (kWh/m$^2$/year) | 95 (kWh/m$^2$/year) |
| Floor | Construction | Wood (on arcs) or slab on ground | Wood | concrete slab or terracotta | concrete slab or terracotta | concrete slab or terracotta | Concrete slab |
| | Thermal insulation | No | No | No | R = 1 (m$^2$ K)/W | R = 0.8 (m$^2$ K)/W for ground floor or R = 1.9 (m$^2$.K)/W for crawl spaces | R = 3 (m$^2$ K)/W |
| Window | Construction | Simple glazed | Simple glazed | Simple/double | Simple/double | Simple/double | Simple then double |
| | Window to wall ratio | 10 % | 20–27 % | 37 % | 25 % | 25 % | 20 % |

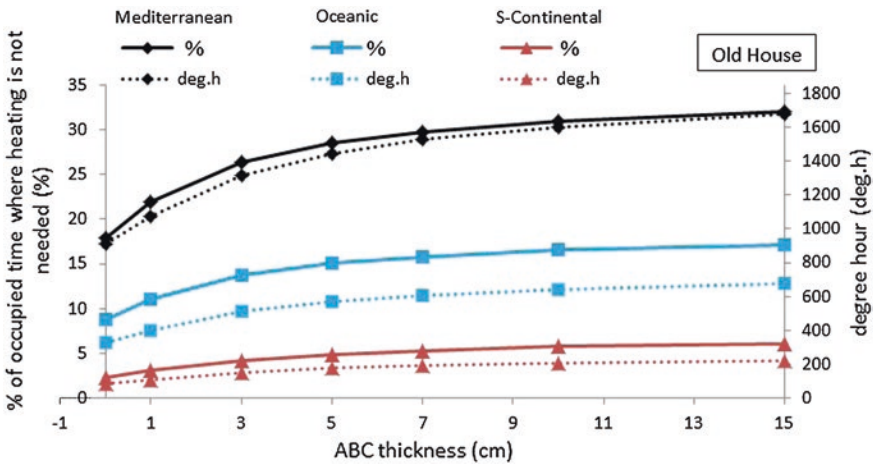


**Fig. 16** Percentage of occupied time where heating is not needed and its degree hour for different coating thickness and different climates (*old house*)

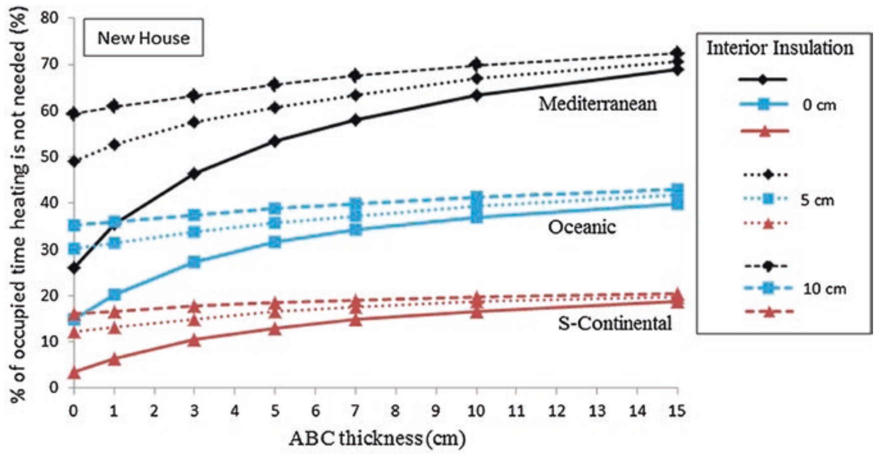


**Fig. 17** Percentage of occupied time where heating is not needed its degree hour for different coating thicknesses and different climates (*new house*)

The coating's thickness optimization is carried out for different climates. Three cities of France are chosen representing different climates: Nice (Mediterranean climate; latitude 43.7°N, longitude 7.266°E), Bordeaux (oceanic climate; 44.84°N, 0.58°W), and Strasbourg (semi-continental; 48.58°N, 7.748°E). Other than France, we have also chosen three cold Nordic cities: Moscow (Russia; 55.75°N, 37.616°E), Stockholm (Sweden; 59.329°N, 18.068°E), and Montreal (Canada; 45.50°N, 73.566°W). The analyses are carried out for a typical house built before 1974. The majority of these houses have no thermal insulation in their envelope. The heating system is electric with an efficiency of 0.9. The heating set point is taken as 19 °C. The cost of electricity is 0.13 €/kWh. The cost of aerogels is very erratic in the current market. However, it has a decreasing trend with time. According to Koebel et al. (2012), this cost could drop below 1500 US\$/m$^3$ (≅1100 €/m$^3$) by the year 2020. Cuce et al. (2014b) in their study assumed a value of 600 €/m$^3$ for the cost of aerogel insulation based on future predictions. In our study here, 800 €/m$^3$ (including labor cost) is considered as a base case; then, this value as well as the values of the other parameters are changed to examine the sensitivity of the optimum thickness to these inputs. Note that for the cities out of France, the simulations are carried out with the same electricity tariff just for comparison purposes.

Excessive insulation as well as low insulation is not desired from an economic perspective. Excessive insulation means high initial investments, while low insulation means high energy consumption costs. Here comes the necessity to find the optimum insulation levels that represents a compromise between the two. Figure 18 shows the coating's cost, the heating consumption cost, and the total cost for the different climates. From these figures, we can deduce that the heating cost decreases exponentially as the coating's thickness increases. The cost of

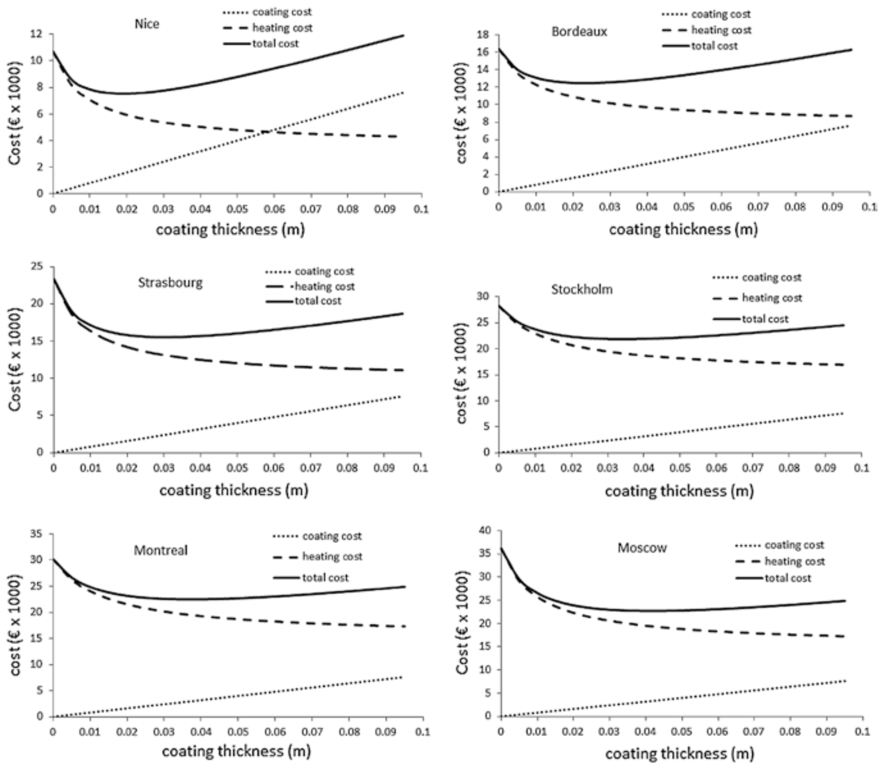


**Fig. 18** Aerogel-based coating, heating, and total costs for the different climates

**Table 4** optimum coating thickness for the different climates

| City | Optimum thickness (cm) |
|---|---|
| Nice | 1.71 |
| Bordeaux | 2.10 |
| Strasbourg | 2.93 |
| Stockholm | 3.26 |
| Montreal | 3.61 |
| Moscow | 4.37 |

**Table 5** Payback period

| City | Payback period (year) |
|---|---|
| Nice | 2.7 |
| Bordeaux | 2.21 |
| Strasbourg | 1.64 |
| Stockholm | 2.1 |
| Montreal | 1.96 |
| Moscow | 1.47 |

insulation always varies linearly with the thickness. The total cost decreases to a certain minimum then starts to increase. The optimum coating's thickness is the one that ensures this minimum of the total cost. For each climate, the optimum thickness is presented in Table 4. We can conclude that as the climate gets colder, the optimum thickness increases. This is due to the increasing heating loads and, as a result, the increasing electricity costs. So, in the cold climates, there is larger potential to reduce energy consumption through applying the insulating rendering. As illustration, applying 2-cm layer of the coating saves around 4000 € for Nice while 9000 € for Strasbourg; however, the initial investment cost remains the same.

After determining the optimum coating thickness, the PP is calculated. It is defined as the time required to recover the initial investment cost. Long PPs are not desired especially in the building sector. Table 5 presents the PP for the different cities when the optimum coating thickness is applied.

From this table, it is understood that the PP ranges between 1.4 and 2.7 years. Due to the relatively low PPs, it is concluded that applying the coating could be seen as a good investment from economical point of view. Several parameters affect the optimum thickness. Among these are the cost of aerogels and the heating set point. Starting with coating cost, Fig. 19 shows the optimum coating thickness for different aerogel's costs: 600, 800, 1000, 1500, and 2000 €/m$^3$. It is expected that as the cost increases, the optimum value decreases. This is due to the higher initial cost associated with the application of the coating making it difficult to recover this cost from the energy savings.

Concerning the heating set point, the variation of the optimum thickness as a function of the heating set point is shown in Fig. 20. It is illustrated that the optimum thickness varies linearly with the heating set point. As the heating set point increases, meaning that the annual heating consumption increases, the optimum thickness increases.

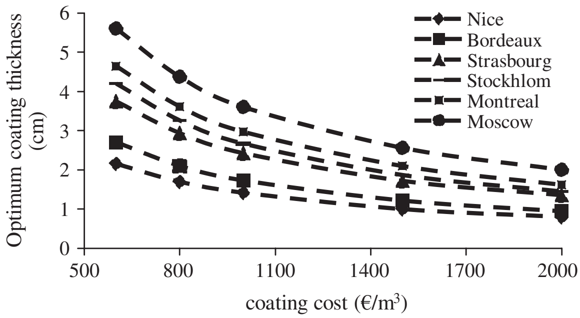


**Fig. 19** Effect of the coating cost on the optimum thickness

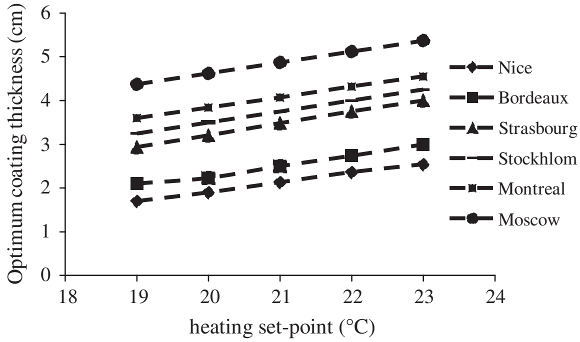


**Fig. 20** Effect of the heating set point on the optimum coating thickness

## 4 Conclusion

In this study, a brief review on aerogels applications in buildings has been presented. They have shown a high potential for energy savings and improving the envelope's thermal performance. Aerogels can reduce significantly the building's energy consumption and enhance the indoor thermal comfort. In addition, aerogels are also very promising in terms of embodied energy data and provide slimmer construction when compared to other conventional insulation materials. The extraordinary low thermal insulation and optical transparency of aerogels allow its applications in window panes and solar collector covers.

Concerning the aerogel-based rendering, it is concluded that it has a maximum impact on the old houses which are poorly insulated. The heating load can be reduced up to 50 %. Also, it increases the thermal comfort during the winter season by decreasing the cold wall effects. For moderately insulated buildings, such as those built in the 80s and 90s with their exterior walls made of brick monomur (20 cm) or made of concrete with a 5–7 cm layer of interior thermal insulation, the reductions in the heating load can reach up to 25 % when adding the aerogel-based rendering. This is important for these houses to pass the newly imposed strict thermal regulations for buildings and be classified as energy efficient. For new buildings, lower reductions are achieved (7–12 %) when adding the rendering. This is due to the fact that the exterior envelope is already highly insulated. Thus, we can conclude that the rendering has a significant effect when considering existing building rehabilitation. For new buildings, the rendering has a lower effect on the energy consumption; however, these buildings will be considered as highly energy-efficient ones.

A potential limitation on the use of aerogels as thermal insulation materials in the building sector is the risk of overheating, and thus thermal discomfort, in the warm climates and/or in summers with high heat waves. Moreover, higher thermal inertia at the building envelope might cause an increment in the cooling demand in summer.

Finally, aerogels are upcoming materials in the near future. As energy demand and cost increase, aerogel products are expected to increase in the future, especially in the building sector due to possessing high thermal insulation characteristics. Although the cost of aerogels materials remain high for cost-sensitive industries such as buildings and are much higher than conventional insulation, this cost is expected to decrease in the following years as a result of the advancement in the aerogel production technologies as well as the large-scale material production leading to lower unit costs. This will increase the competitiveness of aerogel insulating products compared to conventional materials.

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# An Overview of Phase Change Materials for Building Applications

**Helia Taheri and Atul Sharma**

**Abstract** The increasing level of greenhouse gas emissions and the rise in fuel prices are the main reasons for efforts to effectively use various sources of renewable energy. One of the effective ways to reduce the consumption of fuel is by using thermal energy storages. The use of a latent heat storage (LHS) system using phase change materials (PCMs) is an effective way of storing thermal energy and has the advantages of high-energy storage density and isothermal nature of the storage process. Nowadays, for using lightweight materials in buildings, architects need lightweight thermal storages, hence the use of PCMs started. In this chapter, the authors discuss the benefits of using PCMs as thermal mass instead of the common thermal mass. Next, the characteristics of PCMs, their categories, and building applications that can use PCMs as thermal mass are discussed. Finally PCMs can provide benefits for lightweight buildings as thermal mass for reducing building loads and fuel consumption.

**Keywords** Lightweight buildings · Phase change materials · Building loads · Fuel consumption

## 1 Introduction

The increasing level of greenhouse gas emissions and the rise in fuel prices are the main reasons for efforts to effectively utilize various sources of renewable energy. In many parts of the world, direct solar radiation is considered to be one

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of the most prospective sources of energy. One of the options is to develop energy storage devices, which are as important as developing new sources of energy. The storage of energy in suitable forms, which can be converted into the required form, is a present-day challenge to technologists. The high demand for energy in a single day is a continued and unsolved problem to maintain a consistent desired temperature in a sustainable way.

Energy storage not only reduces the mismatch between supply and demand, but also improves the performance of energy systems and plays an important role in conserving the energy (Garg et al. 1985). Better power generation management and significant economic benefits can be achieved if some of the peak load could be shifted to the off-peak load period. It leads to saving of premium fuels and makes the system cost-effective by reducing the wastage of energy and capital cost. This can be achieved by thermal storage for space heating and cooling purposes.

In past architecture, architects were interested in using thermal energy storage systems due to some benefits and reasons. Some of these reasons are as follows:

- During certain hours of the day solar energy is greater than the usage required for applications; in such case thermal energy storage can store this energy and supply it for the hours when we need the energy and access to solar energy is not available.
- In thermal energy storages the coldness of the night could be saved and later used for cooling during hot summer days and heat in the winter day can be saved and use for heating during cold winter nights. Therefore, natural sources of heating and cooling during the winter and summer could be matched with thermal energy storage systems and technologies.
- Thermal energy storage systems lead to efficient use of heating and cooling units. Research has indicated that a chiller without thermal energy storage systems has seasonal coefficience of 25–50 % lower than the design value (Hauer et al. 2001).

The increased electrical energy consumption for cooling and heating loads in peak hours causes a large difference between electrical usage during peak hours and off-peak hours. With use of thermal energy storage systems in HVACs the electrical energy consumption decreases and leads to substantial peak saving and thus increased power capacity for electricity production. There are various other reasons for using thermal energy storage, which are discussed below.

Thermal energy can be stored as heat, as a change in internal energy of a material is sensible heat, latent heat, and thermochemical or a combination of these.

## 2 Sensible Heat Storage

The usual way for storing heat is when there is increase and decrease in the temperature of materials; this is called sensible heat storage (SHS). In SHS, thermal energy is stored by raising the temperature of a solid or liquid, without change in the phase of the material. Sensible heat energy can be measured by a thermometer. The amount of heat stored depends on (i) the specific heat of the medium, (ii) the temperature change, and (iii) the amount of storage material. These systems use specific heat and temperature change during charge and de-charge processes (Lane 1983).

High specific heat of materials causes a time lag in using heat energy and use in the needed time of the day. For instance, if we have a 4 inch concrete wall, its time lag is 4 h. If we increase the thickness of the concrete wall to 24 inch the power of storage of the wall becomes is 18 h. For passive systems we specify 4–12 h as the storage and time lag. We should select among the vast number of materials that can adapt to our building characteristics.

## 3 Latent Heat Storage

Latent heat storage (LHS) is based on the heat absorption or release when a storage material has a phase change from solid to liquid, or liquid to gas, or vice versa. LHS is only used for change in phases of the materials and does not affect their temperature. This energy does not sense directly and cannot be measured by a thermometer. For example, changing from vapor to water causes release in energy, while changing of water to vapor requires energy.

Phase change materials (PCMs) operate by storing energy at a constant temperature, while phase change occurs, for example, from a solid to a liquid. As heat is added to the material, the temperature does not rise; instead heat drives the change to a higher energy phase. The liquid, for example, has kinetic energy of the motion of atoms that is not present in the solid, so its energy is higher.

Some aspects of LHS are solid–liquid, liquid–gas, solid–gas, and solid–solid, and vice versa. But the solid–liquid and solid–solid is more practical. The solid–solid transitions generally have small latent heat and smaller volume changes than solid–liquid transitions. The solid–liquid phase change is more practical and usable in applications, and more research has been done on it. Liquid–gas and solid–gas phase change are not used widely in applications because of the large volume of the systems.

LHS provides greater thermal storage capacity in the unit volume and certain temperature (phase change temperature) is more considerable than other ways, although practically this method causes problems such as decrease in thermal conductivity, changes in density during the phase change process, phase segregation, etc.

## 4 Thermochemical Energy Storage

This method relies on the energy absorbed and released in breaking and reforming molecular bonds in a completely reversible chemical reaction. In this case, the heat stored depends on the amount of storage material, the endothermic heat of reaction, and the extent of conversion. All of the chemical reactions are along with a change in energy. There are two kinds of reactions due to energy, endothermic and exothermic. Endothermic reaction gains energy that is ambient during the reaction and cause decrease in ambient energy. Exothermic reaction releases energy during the process and causes increase in ambient energy.

## 5 What Are the Benefits of PCMs?

Of the above thermal heat storage techniques, latent heat thermal energy storage is particularly attractive due to its ability to provide high-energy storage density and its characteristics to store heat at constant temperature corresponding to the phase transition temperature of the PCM, which stores and releases latent heat energy; this has been studied for more than 30 years.

As mentioned above, the solid–liquid transition because of small change (10 % or less) in volume is one of the practical and economical transitions for using the latent heat thermal storage material (Sharma et al. 2009).

Unlike sensible storage materials, PCM absorbs and releases heat at a nearly constant temperature. PCM stores heat in the form of latent heat fusion which is about 100 times more than sensible heat; they (PCMs) store 5–14 times more heat per unit volume than sensible storage materials such as water, masonry, or rock. This aspect (Low volume and high thermal storage) is significant in lightweight buildings that are being constructed nowadays (Sharma et al. 2009).

PCMs cannot be used as a heat transfer medium. A separate heat transfer medium must be employed with a heat exchanger in between to transfer energy from the source to the PCM and from PCM to the load. The heat exchanger to be used has to be designed specially, in view of the low thermal diffusivity of PCMs in general.

The volume changes in the PCMs on melting would also necessitate special volume design of the containers to the whole PCM. It should be able to absorb these volume changes and should also be compatible with the PCM used.

Any latent heat energy storage system, therefore, possesses at least the following three components:

(i) A suitable PCM with its melting point in the desired temperature range;
(ii) A suitable heat exchange surface; and
(iii) A suitable container compatible with the PCM (Abhat 1981).

The latent heat capacity of the PCM is used to capture solar energy or man-made heat or cold directly and decrease the temperature swings in the building.

A large number of PCMs are known to melt with heat fusion in any required range. However, for their use as LHS materials, they must exhibit certain desirable thermodynamic, kinetic, and chemical properties. Moreover, economic considerations and easy availability of these materials has to be kept in mind, shown in Table 1.

**Table 1** Thermo-physical properties of PCMs (Abhat 1981, Buddhi 1994)

| | |
|---|---|
| Thermal | • Proper melting point for each application |
| | • High latent heat of transition for reducing the volume of storage systems |
| | • High specific heat capacity |
| | • Good heat conductivity, which prevents super cooling during phase transition |
| Physical | • High density for decrease in storage system volume |
| | • Low volume change and low vapor pressure during phase transition, for reducing the problem of system controlling |
| Kinetic | • No super cooling |
| | • Sufficient crystallization rate |
| Chemical | • Long-term chemical stability |
| | • Compatibility with materials of construction |
| | • Nontoxic |
| | • No fire hazard |
| Economic | • Available |
| | • Cost-effective |

## 6 How Do PCMs Help in Energy Sustainability?

LHS can be more efficient than SHS because it requires a smaller temperature difference between the storage and release functions. The use of PCM in developing and constructing sustainable energy systems is crucial to the efficiency of these systems because of PCMs ability to harness heat and cooling energies in an effective and sustainable way.

Currently, it is possible to improve thermal comfort and reduce the energy consumption of buildings without substantial increase in the weight of the construction materials by application of micro and macro encapsulated PCM. The maximum and minimum peak temperatures can be reduced by the use of small quantities of PCM, either mixed with the construction material or attached as a thin layer to the walls and roofs of a building. In addition, the energy consumption can also be reduced by absorbing part of the incident solar energy and delaying/reducing the external heat load.

## 7 Characteristics of PCMs

There are a large number of organic and inorganic chemical materials, which can be identified as PCMs from the point of view of melting temperature and latent heat fusion. However, except for the melting point in the operating range, the majority of PCMs do not satisfy the criteria required for an adequate storage media. As no single material can have all the required properties for ideal thermal-storage, one has to use the available materials and try to make up for the poor physical property by an adequate system design. For example, metallic fins can be used to increase the thermal conductivity of PCMs (Sharma et al. 2009).

## 8 Organic Phase Change Materials

Organic materials are further described as paraffin and non-paraffin. Organic materials include congruent melting and melt and freeze repeatedly without phase segregation and consequent degradation of their latent heat fusion, while self nucleation means they crystallize with little or no supercooling and are usually non-corrosive (Sharma et al. 2009).

### *8.1 Paraffin*

Paraffin wax consists of a mixture of mostly straight chain n-alkanes $CH_3$–($CH_2$)–$CH_3$. The crystallization of the ($CH_3$)-chain releases a large amount of latent heat. Both the melting point and latent heat fusion increase with chain length (Sharma et al. 2009).

### *8.2 Non-paraffin*

Non-paraffin is the most numerous of PCMs with highly varied properties. Each of these materials has their own properties. Abaht et al. (1981) and Buddhi and Sawhney (1994) conducted extensive survey of organic materials and identified a number of esters, fatty acids, alcohols, and glycols suitable for energy storage.

## 9 Inorganic PCMs

Inorganic materials are further classified as salt hydrate and metallics.

### *9.1 Salt Hydrates*

The most important categories of inorganic PCMs are salt hydrates. Salt hydrates may be regarded as alloys of inorganic salts and water forming a typical crystalline solid of general formula AB_n$H_2O$. The solid–liquid transformation of salt hydrates is actually a dehydration of hydration of the salt, although this process resembles melting or freezing thermodynamically. At the melting point the hydrate crystals break up into anhydrous salt and water, or into a lower hydrate and water. One problem with most salt hydrates is that of incongruent melting caused by the fact that the released water of crystallization is not sufficient to dissolve all the solid phase present (Sharma et al. 2009).

**Table 2** Advantages and disadvantages of PCMs

| | |
|---|---|
| Advantages | • High latent heat |
| | • Low volume change during phase transition |
| | • Frequent phase change |
| | • Thermal stability in solid–liquid phase transition and vice versa |
| | • High density |
| | • Chemical stability |
| | • Noncorrosive, nontoxic, and not flammable |
| | • Low cost |
| | • Accessible |
| Disadvantages | • Low thermal conductivity |
| | • Super cooling during crystallization |
| | • Need for container to prevent PCM leakage |

### *9.2 Metallics*

This category includes low melting metals and metal eutectics. These metallics have not yet been seriously considered for PCM technology because of weight penalties. However, when volume is a consideration, they are likely candidates because of the high heat fusion per unit volume.

Some of the features of these materials are as follows: (i) low heat fusion per unit weight (ii) high heat fusion per unit volume, (iii) high thermal conductivity, (iv) low specific heat, and (v) relatively low vapor pressure (Sharma et al. 2009).

## 10 Eutectics

A eutectic is a minimum-melting composition of two or more components, each of which melts and freeze congruently forming a mixture of the component crystals during crystallization (George 1989). Eutectic nearly always melts and freezes without segregation since they freeze to an intimate mixture of crystals, leaving little opportunity for the components to separate (Sharma et al. 2009). A comparison of the advantages and disadvantages of PCMs is given in Table 2.

## 11 PCM Applications in Buildings

PCMs have been developed for various applications due to their different phase change intervals. Materials that melt below 15 °C are used to maintain a cool temperature in air conditioning applications, while materials that melt above 90 °C are used to reduce the temperature if there is a sudden increase in heat to avoid ignition. Materials with intermediate melting points can be applied in solar heating applications.

The applications of PCM in a building can have different aspects. First, using natural heat, i.e., is solar energy for heating or night cold for cooling; and second, through using man-made heat or cold sources. In both cases, the storage should be adapted according to these sources and PCMs selected wisely to have good efficiency. Besides, we can have a combination of passive and active applications for storage. PCMs can be used in many aspects of the buildings such as in the walls, floors, and ceilings, in the louvers, etc. PCM applications in buildings can be categorized into three parts.

1. PCM applications on building surfaces (walls, floors, ceilings, windows, etc.);
2. PCM applications in heat and cold storage units (HVACs);
3. PCM application in other aspects of buildings (such as solar water heating systems and solar cookers).

All the above categories can help in reducing energy consumption for heating and cooling of buildings. There are many ideas for using these categories that are explained below. Most aspects of the first category are passive systems and the second category is an active system. Some of the applications are in the first category and they are active systems.

## *11.1 PCM Applications on Building Surfaces*

This part explains the applications that assign PCMs to building surfaces. The applications can be active or passive applications that are mentioned later. We categorize this part with two types of surfaces.

1. Opaque surfaces (Walls, floors, ceiling, and PCM integrated with other materials such as concrete);
2. Glazed surfaces (Windows).

## *11.2 Opaque Surfaces*

PCMs can be used on opaque surfaces with a wide range of products. The opaque surfaces of buildings are walls, floors, and ceiling.

## *11.3 PCMs in the Walls of Buildings*

### 11.3.1 PCM Wallboards

PCM wallboards are one of the simplest ways of using PCMs in buildings. This usage of PCM is passive and uses the natural heat and cold. The wall boards are cheap and are used in various applications and in the simplest way make it suitable for PCM encapsulation.

Feldman carried out extensive research on the use and sustainability of organic compound for LHS (Feldman et al. 1989a, b 1991). In addition to studies of their properties, research was also carried out on materials that act as PCM absorbers. Various materials were considered, such as different types of concrete and gypsum. The PCM gypsum board contained about 25 % by weight proportion of PCM. The PCM used in this study was butyl stearate. The result of this study was an increase in the thermal storage capacity in the range of 10–130 %.

Neeper summarized that gypsum wallboards impregnated with PCM could be installed in place of ordinary wallboards during new constructions of buildings. This will help in increasing the thermal storage of the buildings and caused the time-shifting of mechanical cooling and heating load (Neeper 1986).

For wallboards heated by absorption of direct solar radiation, Drake (1987) found the optimal melt temperature to be proportional to the absorbed solar energy. Peippo et al. (1991) also considered heating only by direct solar radiation, and concluded that optimal diurnal storage occurs with a melt temperature of 1–3 °C above the average room temperature.

Follmann (Hauer et al. 2001) conducted a study on using PCMs in the internal plaster of lightweight buildings (Figs. 1 and 2). Simulations show that peak temperatures in summer can be reduced by about 2–3 K. Importantly, suitable micro-encapsulated PCM for product development is not available. Follmann studied PCM usage in external plaster of well-insulated walls and compared it with normal plaster. His main focus was the duration of condensation on the wall and the biological growth on composites. Simulations exist in the case of retrofit of an existing wall with the following layer structure: Wall + composite insulation + old plaster + new plaster with PCM. The results show a significant increase in heat capacity by adding the plaster with PCM and the duration and amount

**Fig. 1** Detail of the plaster

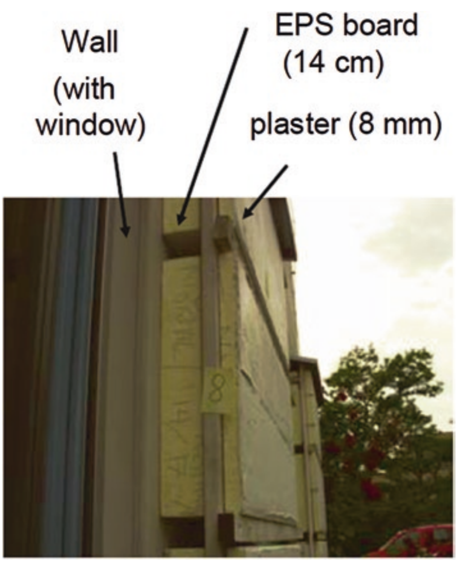


**Fig. 2** Comparison of plaster with and without PCM

**Fig. 3** The PCM panel

of condensation on the wall are reduced by 20 %. Using the results of this study Follmann and Remmers plan to develop PCM plaster commercial for combating biological growth on composite insulation facades.

Kissock et al. (1998) presented the results of a study on the thermal performance of wallboards with 30 % weight with commercial paraffin PCM in the simple structure. The results indicated that peak temperature in the phase change test cell was up to 10 °C less than in the control test cell during sunny days.

Muruganantham and Phelan (2010) conducted a study on using PCM panels (Fig. 3) in walls and compared it with walls without PCMs. His simulation results show that the maximum decrease in consumption for heating and cooling demand was during September (26 %) and November (30 %). This method can shift the peak load by about 60 min in the month of June.

Shilei et al. (2006) describe the formation of compound phase change wallboards by combining gypsum boards with PCM. By contrasting the impact on the indoor thermal environment between the phase change wall room and ordinary wall room in a winter season experiment, it can be proved that phase change wallboards can *weaken* indoor air fluctuation, reduce heat transfer to outdoor air, and improve indoor thermal comfort by maintaining the warmth. Furthermore, the phase change wall room can reduce the scales of heating equipment and related investment cost, and hence play a role in "removing the peaks and filling out the valleys" in the electricity demand. Therefore, the application of phase change wall room will surely bring more benefits to the building energy conservation field.

Ahmad et al. (2006) presented the performance of a test-cell with a new structure of light wallboards containing PCMs subjected to climatic variation and a comparison made with a test-cell without PCMs. To improve the wallboard efficiency, a vacuum insulation panel was associated with the PCM panel. The results show that such a system can be constructed with commonly available materials and equipment, the optimal use of solar energy remains an essential element of the problems in the current context.

Shapiro et al. (1987) investigated methods for impregnating gypsum wallboard and other architectural materials with PCM. The manufacturing techniques, thermal performance, and applications of gypsum wallboard and concrete block were impregnated with PCMs.

### 11.3.2 PCMs in Trombe Wall

Trombe wall is a primary example of an indirect gain approach and a passive application. It works with thermal mass and saves thermal energy in the mass which is a thermal mass and releases heat at the required time. For greater heat storage per unit mass, the PCM trombe wall is an attractive concept to be studied. A wall filled with PCM is constructed on the south side window of a house. This wall will be heated and stored energy during the day and at nighttime it releases heat and makes the living space of the house to be warmer. For a given amount of heat storage the PCM units require less space than water or mass. Many experimental and theoretical researches have been conducted on this concept in different ways (Tyagi and Buddhi 2007). Ghoneim et al. (1991) and Chandra et al. (1985) used sodium sulfate decahydrate (melting point 32 °C) as a PCM in a south facing trombe wall. They report that trombe wall with PCM is smaller in thickness and more desirable in comparison to a masonry trombe wall to provide efficient energy storage. Castellon et al. studied a trombe wall that was added to the south façade and studied it in the Mediterranean weathers to reduce both cooling and heating demands (Fig. 4).

Farouk and Guceri (1979) studied the usefulness of the PCM wall installed in a building for nighttime home heating using glauber salt mixture and SUNOCO P-116 wax. It was observed that if the PCM wall is designed properly, it eliminates some of the undesirable features of the masonry walls with comparable results. Schematic diagram of PCM trombe wall is given in Fig. 5.

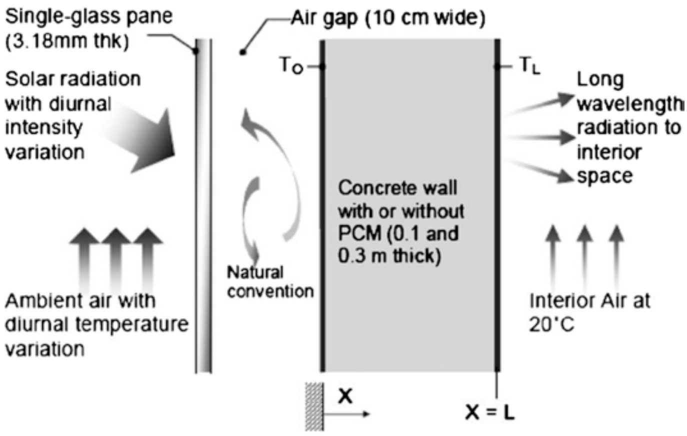


**Fig. 4** Castellon Trombe wall shematic diagram

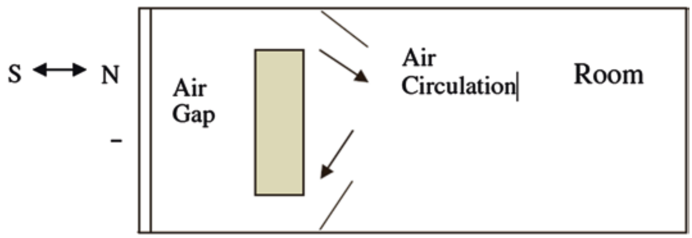


**Fig. 5** Farouk and Guceri Trombe wall shematic diagram

### 11.3.3 Floor Heating

Floor is also an important part of a building and we can use it for heating and cooling the space. This type of PCM usage can be used in two ways: passive and active way.

In the passive concept of floor heating with usage of PCM, using HVACs or man-made energies is omitted and PCMs store heat with natural sources. Athienties and Chen (2000) investigated the transient heat transfer in floor heating systems. Their study focused on the influence of the cover layer and incident solar radiation on the floor temperature distribution and energy consumption. Experimental and simulation results in an outdoor test room reveal that solar beam radiation can cause a local floor surface temperature in the illuminated area of 8 °C higher than that in the shaded area. Partial carpet cover further increases the floor surface temperature difference up to 15 °C when solar radiation was absorbed. Solar radiation stored in the floor thermal mass was found to reduce heating energy consumption significantly (30 % or more).

Active concept of floor heating with use of PCM can be used for off-peak storage of thermal energy in buildings. Therefore, peak loads may be reduced and

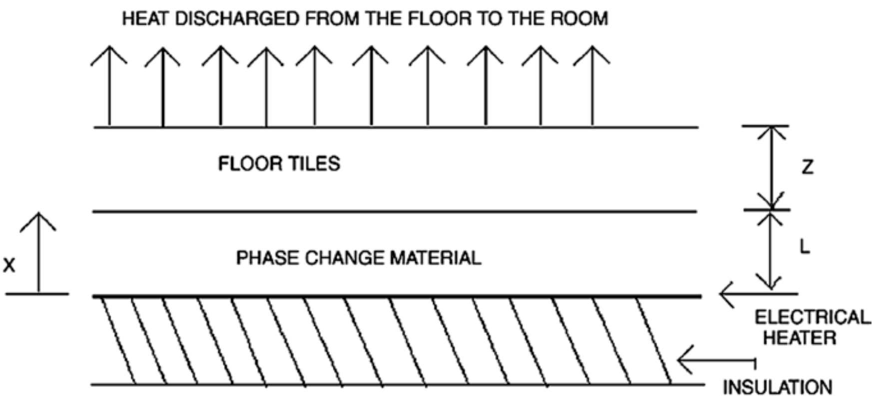


**Fig. 6** Sketch of underfloor heating system incorporating heat storage system

shifted to nighttime when electricity costs are lower. Farid and Chen (1999) studied the active floor heating concept (Fig. 6). In this study was used an electrical under floor heating system with paraffin wax (melting point 40 °C) as PCM. A 30 mm layer of PCM was placed between the heating surface and the floor tiles. The results of the simulation show that when PCM storage is used, the heat output of the floor can be raised significantly from 30 to 75 W/m$^2$.

Lin et al. (2005) studied electric radiant floor heating systems in buildings using SSPCM plate. Their study shows that 75 wt% paraffin is used as PCM with 25 wt% polyethylene as assistance material. The temperature of phase change and melting point of paraffin are 52 °C. This indicates that PCM having sufficiently high melting point is applied as an example, unlike PCM having a melting point between 20 and 30 °C in typical buildings. The following conclusions can be made based on the study results. (a) The room temperature of the system increased without increasing the thermal difference. (b) The temperature of the PCM plate is preserved for a long time after the heating is stopped. This offers effective economic profit based on the difference in electricity charges because more than half of the entire electric thermal energy is moved from the peak load to the non-peak load. (c) The difference in the indoor temperature according to the vertical direction is small because the radiant floor heating system heats the indoor air comfortably and efficiently.

### 11.3.4 Ceiling PCMs

This type of PCM usage is mostly used in the active way and in suspended ceilings with the purpose of using for shifting the peak load and increasing the HVAC efficiency. Kondo and Ibamoto (2002) conducted a study on using thermal storage (PCM) in the ceiling. In this study, the author used PCM with melting point 25 °C (the temperature near room temperature). During overnight thermal storage was

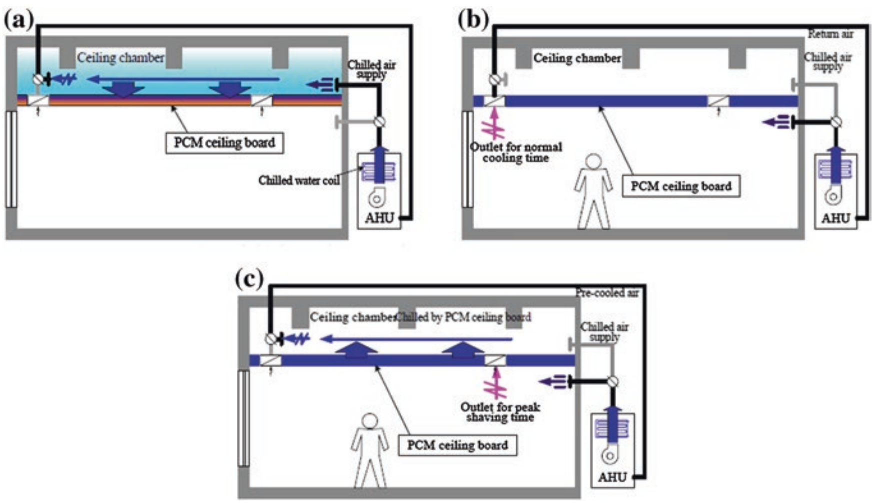


**Fig. 7** Schematic diagram showing an outline of the ceiling board system having PCM. **a** Overnight thermal storage time, **b** normal cooling time and **c** peak shaving control time

cooled by cool air from the HVAC that flows into the ceiling chamber space and stores cooling thermal energy. During peak load, the air from the room returns to the HVAC via the ceiling chamber space. As a result of passing through the cooled-down PCM ceiling board, the warm air returning from the room cools down before returning to the HVAC. The maximum thermal load and the capacity of heat source can thus be reduced. In this study, the thermal capacity of the PCM ceiling board was measured by using a small experimental chamber. The thermal capacity of the PCM ceiling board is approximately 663 kJ/m$^2$, which is 4.9 times that of an ordinary rock wool ceiling board. The maximum thermal load using the PCM ceiling board was 85.2 % of that using the rock wool ceiling board. As the maximum thermal load was reduced by 14.8 % by the rock wool ceiling board, it can reduce the load on the HVAC. However, the integrated thermal load was 5.3 % greater than that using the rock wool ceiling board. The transition rate of the thermal load to the night was 25.1 %. Discounted nighttime electricity, which is 75 % cheaper than daytime electricity, is used in Japan. The running cost is 91.6 % lower than that by using the rock wool ceiling board. The schematic sketch is shown in Fig. 7.

## 12 PCM Integrated with Concrete

PCM can be integrated with some building materials such as concrete in order to increase thermal capacity of materials. There are some studies on this issue. Castellon et al. (2007) studied an experimental model to show the effects of using PCM in concrete in Lleida (Spain). An innovative concrete with PCM was developed using a commercial micro-encapsulated PCM, with melting point of 26 °C and phase change enthalpy of 110 kJ/kg.

This novel concrete was used in the construction of a test cubic room. The south and west walls and the roof were constructed with the new concrete. The test room was instrumented to monitor and evaluate the thermal characteristics: temperature sensors in every wall, temperature sensors in the middle of the room at heights of 1.2 and 2.0 m, and one heat flux sensor in the inside wall of the south panel.

A second test room with the exact characteristics and orientation, but built with standard concrete, was located next to the first one as reference case. In this way conventional elements and new developments are being tested simultaneously (Fig. 8).

A meteorological station was installed nearby and one irradiation sensor on top of each test room gives the irradiation measures, and also the possibility of shadows in each one (Fig. 9). All the instrumentation is connected to a data logger connected to a computer to work with the obtained data.

**Fig. 8** Veiw of the test rooms

**Fig. 9** Meteorological station

During summer and autumn 2005, the behavior of such test rooms was tested. Results were in good agreement with the expected enhanced performance of the PCM cubicle. While the maximum outdoors temperature was 32 °C, the west wall of the cubicle without PCM reached 39 °C, and the west wall of the cubicle with PCM reached only 36 °C, showing a temperature difference of 3 °C. This difference could also be seen in the minimum temperatures.

Other different situations were tested, namely the effect of opening windows all day, and the effect of opening windows only at night, as a free cooling system.

When comparing the temperatures in the experiments, it can be seen that in all cases the effect of the PCM is present in the walls that contain PCM, with wall temperature differences of 2–3 °C. The maximum temperature in the wall with PCM appears about 2 h later than in the one without PCM. This thermal inertia appears in the afternoon due to freezing of the PCM, but also early in the morning due to melting of PCM. The morning temperatures are approximately the same in both test rooms, but the temperatures show differences in cooling down in the afternoon.

The heat flux in the south wall in the experiments follows the same patterns, the heat flux has the same tendency in both cubicles when the PCM is out of its melting/freezing zones, but changes totally its behavior when there is a phase change.

The thermal inertia in all the experiments shows that the PCM included in the cubicle walls freezes and melts in every cycle. Their results also show that night cooling is important to achieve this full cycle everyday (Castellon et al. 2007)

## *12.1 Glazing Surfaces*

There is a problem with using traditional thermal storages on the surfaces of buildings. The problem is, using thermal energy storages prevents the effect of direct and indirect gain in the living spaces and reduces the area of windows in the walls. One of the ideas for using PCMs in buildings is using them on glazed surfaces. Some PCMs are semitransparent and can increase the daylighting and the natural light of the buildings.

### 12.1.1 PCM in Glasses

Weinlader et al. (2005) describe that double glazing combined with PCMs result in daylighting elements with promising properties. Light transmittances in the range of 0.4 can be achieved with such façade panels. Compared to double glazing without PCM, a façade panel with PCM shows about 30 % less heat loss in the south facades. In addition, solar heat gains are reduced by about 50 %. GlassX Company produced a panel that was used in the façade and let the natural light come in (Fig. 10). They studied the effects of using these panels and the results are very significant. In the solid phase, these panels are semitransparent and in the

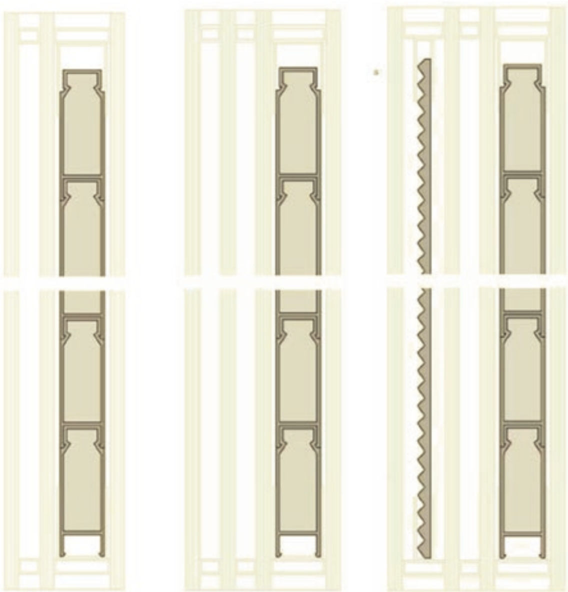

**Fig. 10** Glass X product section

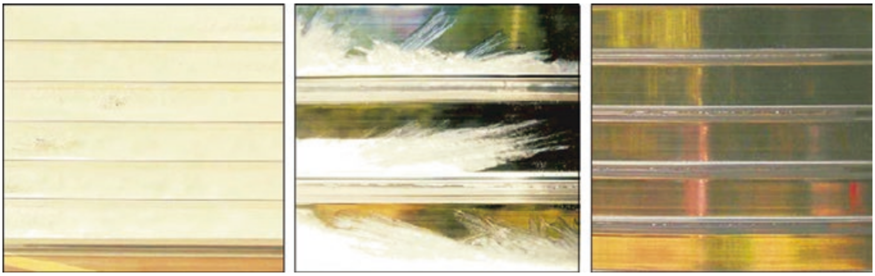

**Fig. 11** Transition phase of the PCM in GlassX product

liquid phase, they are transparent, which helps buildings to improve the quality of the spaces, in addition to reducing the heating and cooling load of the buildings. The phase transition is shown in Fig. 11.

### 12.1.2 PCM Blinds

This application is defined as a passive application. Solar blinds are preferably installed on the inner side of windows because, if installed on the outside, strong winds require high mechanical stability. A drawback of the installation on the inner side however is that the solar radiation absorbed on the surface of the blind heats up the blind very fast. The blind then acts as a solar heater and is known to

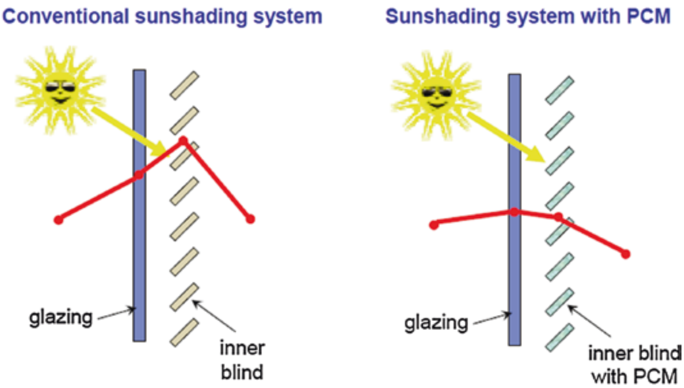


**Fig. 12** Solar blind with PCM


**Fig. 13** Experimental solar blinds

cause significant problems in contributing to overheating of the rooms. Therefore, PCM was put into the blinds to increase their heat storage capacity. This can delay the temperature rise to the late afternoon hours and then the stored heat can be ventilated to the outside easily. Warema (Hauer et al. 2001) used these blinds with PCM with temperature close to room temperature; this prevented the blind from acting as a heat source. The results were (i) significant decrease in maximum blind temperature (10–15 K), (ii) significant decrease in operative temperature (≈3 K), (iii) time shift of heat gains from noon to evening, and (iv) improved thermal comfort during working hours. The schematic diagram and experimental solar blinds are shown in Figs. 12 and 13.

Buddhi et al. (2003) studied the thermal performance of a test cell (1 m_1 m_1m) with and without PCM. CG lauric acid (melting point, 49.1 °C) was used as LHS material. He found that the heat storing capacity of the cell due to the presence of PCM increases up to 4.1 °C for 4–5 h, which was used during nighttime.

### 12.2 PCM Applications in HVAC Systems

PCM applications in HVACs are used for peak shifting and increase the HVAC systems' efficiency. This application is defined as the active application. Yamaha and Nakahara (2011) used PCMs in HVAC systems. The schematic diagram of the system is shown in Fig. 14. An air conditioning system for an office was assumed. The calculated area was part of one floor of an office building with a floor area 73.8 $m^2$ located in Nagoya city, Japan. The storage tank was filled by paraffin waxes and fatty acids. For charging operation, the air runs through the closet circuit of the PCM storage tank and the air conditioner. After the end of the charging cycle, the ordinary air conditioning operation was started. The conditioned air is projected into the room and returned to the air conditioner after mixing with a volume of outdoor air. In this operation, the air is assumed to bypass the PCM storage tank. For the discharging operation, the air passes into the room through the PCM storage tank. In the charging and discharging operations, the air flow rate is reduced to half the ordinary air conditioning in order to store and recover heat effectively. The heat transfer between a container of PCM and the air in the duct was enhanced by fins extended toward the air. The fins increased the surface 18.2 times compared to the flat surface. The charging hours were set to be equal to the discharging hours. The system used for cooling and could take advantage of discounted electricity rated at night. The PCM was cooled from 5:00 to 8:00 am using discounted electricity. The stored heat was discharged from 13:00 to 16:00, when the peak load of cooling occurred. The inlet temperature to the PCM storage tank for charging operation was 12 °C, and the inlet temperature to the room during ordinary air conditioning was 16 °C. During ordinary air conditioning the air flow rate to the room was controlled in order to maintain the temperature of the room at 26 °C.

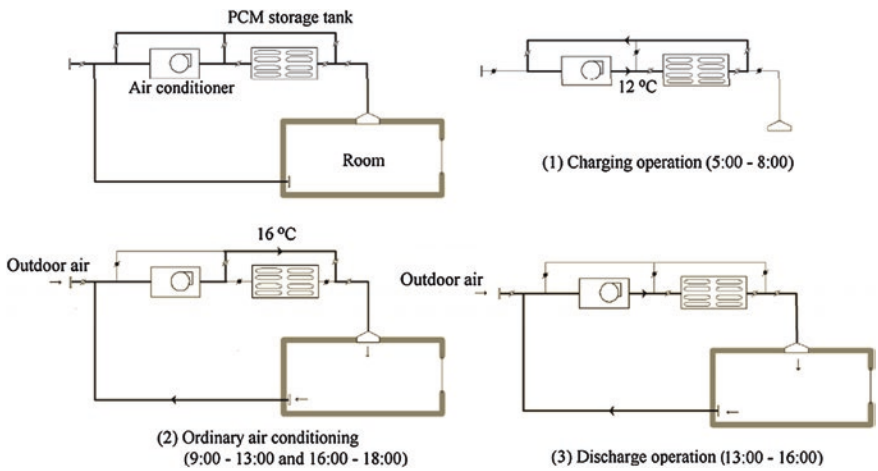


**Fig. 14** Schematic diagrams of HVAC systems used in the simulations

Telkes (1974), Herrick (1978) and Gawarn and Scroder (1977) studied LHS system for air conditioning. Inorganic hydrous salts were used as storage material. However, these studies focused more on the development of new heat storage materials. Lane et al. (1975) suggested some PCMs for cooling and dehumidification. The PCM is frozen during off-peak hours and coolness is withdrawn as needed during the day. Recently the Department of Atomic Energy, Govt. of India sanctioned an R&D project to develop LHS materials for the temperature range 5–158 for storage of coolness using off-peak power and to develop the pilot plant for the same (Buddhu et al. 2001).

## *12.3 PCMs in Other Aspects of Buildings*

There are numerous applications in other aspects of buildings such as solar water-heating system, solar cookers, etc. that can use PCM for increasing the thermal capacity and efficiency of the device.

### 12.3.1 Solar Water Heating System

Solar water heaters are gaining in popularity (Tanishita 1970; Richards 1967) since they are relatively inexpensive and simple to fabricate and maintain. Prakash et al. (1985) analyzed a built-in storage type water heater containing a layer of PCM filled at the bottom. During sunshine hours, the water gets heated up which in turn transfers heat to the PCM below it. The PCM collects energy in the form of latent heat and melts. During off-sunshine hours, the hot water is withdrawn and is substituted by cold water, which gains energy from the PCM. The energy is released by the PCM on changing its phases from liquid to solid. This type of system may not be effective due to poor heat transfer between PCM and water.

A comparative study of solar energy storage systems based on the latent heat and sensible heat technique was carried out to preserve the solar heated hot water for night duration by Chaurasia (2000). For this purpose, two identical storage units were used. One storage unit contained 17.5 kg paraffin wax (m.p. about 54 °C) with storage material packed in a heat exchanger made of aluminum tubes and another unit simply contained water as a storage material in a GI tank. Both units were separately charged during the day with the help of flat plate solar collectors having the same absorbing area. This study reveals that the LHS system comparatively yields more hot water the next morning compared to sensible storage system.

Kayguz et al. (1995) conducted a study to determine the performance of phase change energy storage materials for solar water-heating systems. $CaCl_2\_6H_2O$ was used as PCM. The author also compared the performance of PCM, water, and rock-based storage system (Fig. 15). Whenever solar energy is available, it is collected and transferred to the energy storage tank that is filled with 1500 kg

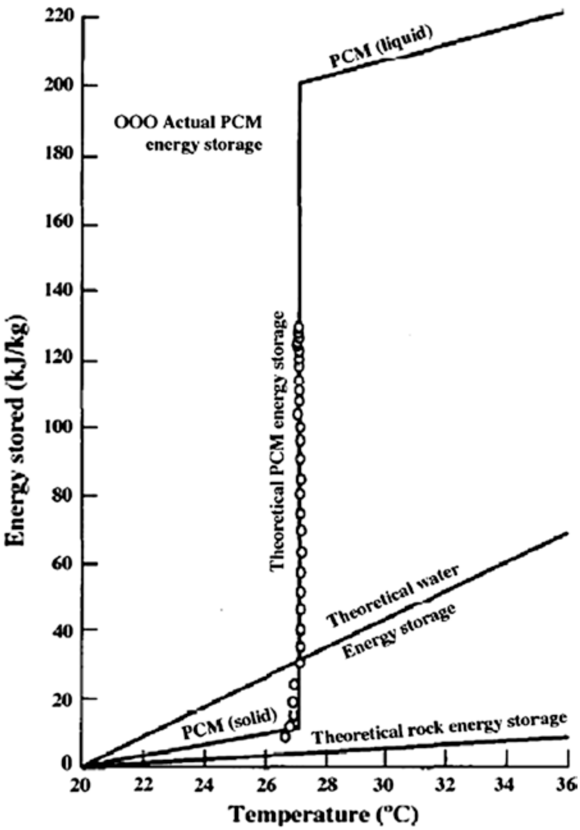


**Fig. 15** Performance comparison of PCM, water, and rock storage system

encapsulated PCM. It consisted of a vessel packed in the horizontal direction with cylindrical tubes. The energy storage material ($CaCl_2\_6H_2O$) is inside the tubes (the tube container made of PVC plastic) and heats transfer fluid (water) flow parallel to them.

Sharma et al. (2003) designed, developed, and evaluated an LHS unit for evening and morning hot water requirements, using a box type solar collector. Paraffin wax (m.p. 54 °C) was used as LHS material and it was found that the performance of the LHS unit in the system was good to obtain the hot water in the desirable temperature range.

### 12.3.2 Solar Cookers

One of the major uses of solar energy is in cooking, using different types of solar cookers. Use of these solar cookers is limited, as cooking of food is not possible in the evening. If storage of solar energy is provided in a solar cooker, then the utility and reliability of these solar cookers would increase. Domanski et al. (1995) studied the use of PCM as a storage medium for a box-type solar cooker designed to

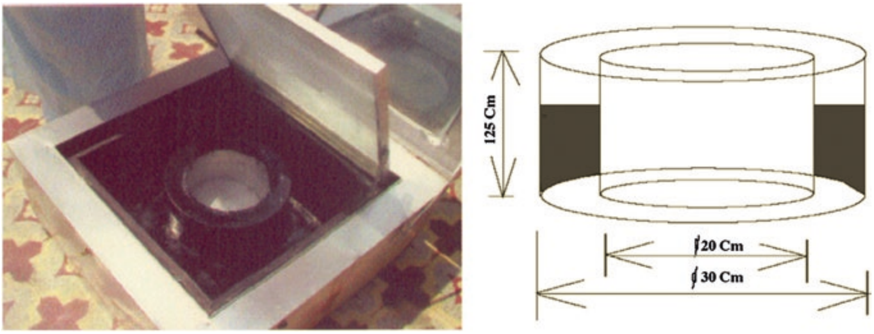


**Fig. 16** Schematic diagram of the box of a solar cooker with storage

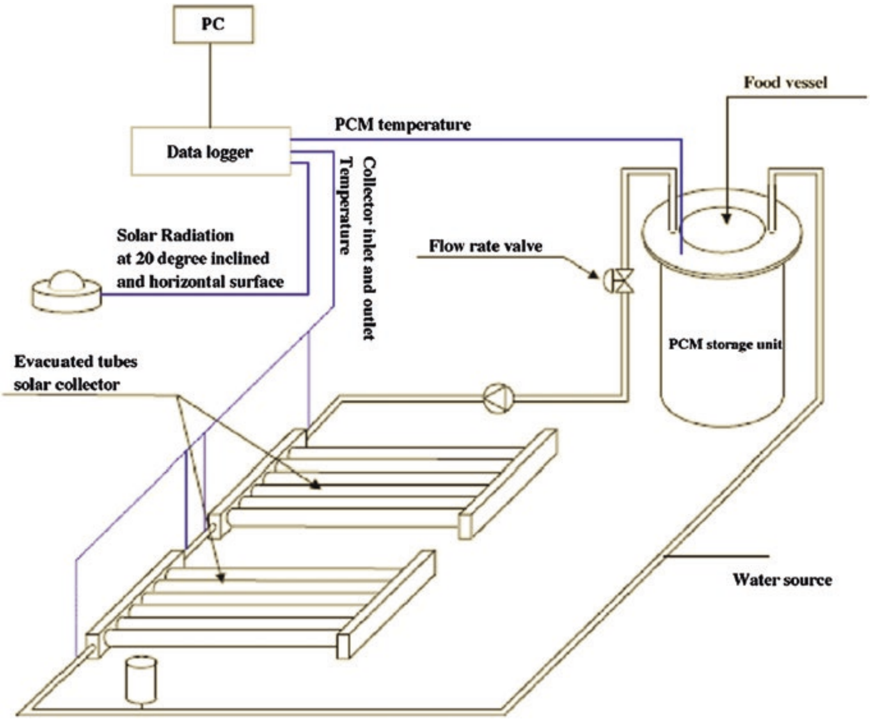


**Fig. 17** Outline of the prototype solar cooker based on evacuated tube solar collector with PCM storage unit

cook food in the late evening hours and/or during the non-sunshine hours. They used magnesium nitrate hexahydrate ($Mg(NO_3)_2\_6H_2O$) as PCM for heat storage. Buddhi and Sahoo (1997) filled commercial grade stearic acid below the absorbing plate of the box type solar cooker. Sharma et al. (1997) developed a PCM storage unit with acetamide for a box type solar cooker to cook food in the late evening (Fig. 16).

They recommended that the melting temperature of PCM should be between 105 and 110.8 °C for evening cooking. Sharma et al. (2005) also used erythritol as LHS material for a solar cooker based on an evacuated tube solar collector (Fig. 17).

## 13 Conclusion

Thermal energy storage through PCMs provides a flexible heating and cooling technique by both conserving energy and increasing energy while utilizing natural renewable energy resources. In this chapter, applications of PCM in buildings were reviewed. PCM can be used for temperature regulation in order to minimize the heat loss or gain through building walls. PCMs can also be used to capture solar heat and decrease the temperature fluctuations in buildings. Moreover, since a small amount of PCM is sufficient to store solar energy, thermal comfort is achieved without substantial increase in the weight of the construction materials. PCM applications have proved to be efficient and financially viable, yet they have not been exploited sufficiently in the commercial market. The advantages of PCMs are not known by many people and, therefore, their applications and benefits should be offered to consumers. Even though there is a lot of ongoing research on PCMs and its applications in all possible research areas, they are yet to become a widely used technology for sustainable energy.

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# Part IV
# Thermal Energy Storage

# Phase Change Materials—A Sustainable Way of Solar Thermal Energy Storage

**G. Raam Dheep and A. Sreekumar**

**Abstract** Renewable energy sources are time-dependent in nature and the effective utilization of devices based on renewable energy requires appropriate energy storage medium to commensurate the mismatch between energy supply and demand. Solar energy is the primary source of energy among renewable energy sources which can be used for a wide variety of electrical and thermal applications. Intermittent and unpredictable nature of solar energy generally necessitates a storage medium in between that stores energy whenever is available in excess and discharges energy whenever it is inadequate. Therefore, the storage of thermal energy becomes necessary in order to meet the larger energy demand and to achieve high efficiency. Thermal energy storage using latent heat-based phase change materials (PCM) tends to be the most effective form of thermal energy storage that can be operated for wide range of low-, medium-, and high-temperature applications. This chapter explains the need, desired characteristics, principle, and classification of thermal energy storage. It also summarizes the selection criteria, potential research areas, testing procedures, possible application, and case studies of PCM-based thermal energy storage system.

**Keywords** Solar energy · Thermal energy storage · Latent heat · Phase change materials · Thermo-physical properties

## 1 Introduction

The increase in price, global warming, and decrease in availability of conventional fossil fuels have led to an imperative action to find alternative sources of energy. Renewable energy is found to be a viable alternative and clean source of

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energy, which has lower or no adverse impact on environment than the conventional energy sources. Most of the renewable energies such as solar and wind can be used for commercial and industrial applications such as heating, cooling, and electricity generation. Energy from renewable sources is harnessed excessively by utilizing advanced equipments, but most of the quantities remain unutilized due to lack of effective energy storage system.

Energy storage plays an important role next to generation which acts as a bridge and enables the intermittent solar energy to be feasible and reliable by balancing the peaks and troughs of generated output and demand. Therefore, energy storage improves flexibility and efficiency of the system, retains quality, meets fluctuations, and gives security with high economic value to the energy generated. Recent technological advancements and increased energy requirement necessitate the identification and development of robust, cost-effective, and low-loss energy storage system which tends to be foremost challenges for future renewable and sustainable energy utilization.

## 2 Necessity of Thermal Energy Storage for Solar Thermal Applications

Solar thermal energy storage system tends to be a buffer zone for many thermal applications such as space heating and cooling, food crops drying, hot water production, and electricity generation. The following illustrations and Fig. 1 explain the need for thermal energy storage system, in particular to solar thermal energy applications (Dincer and Rosen 2011)

(i) The energy supplied from the source to the load will be constant, but sometimes, there will be unforeseen increase in the demand, which cannot be

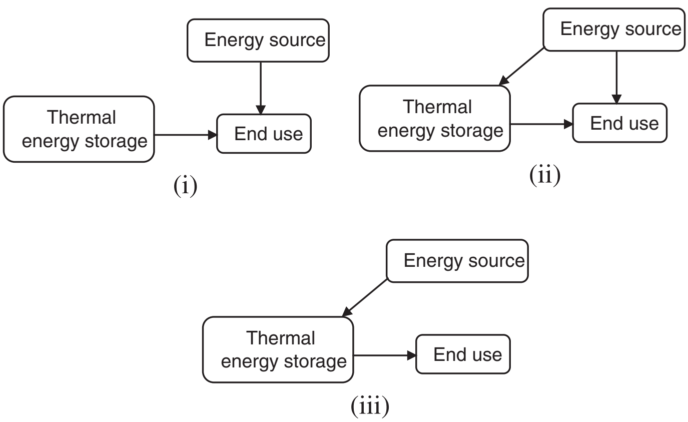



**Fig. 1** Illustrations on need for thermal energy storage

supplied by the source due to its rating capacities. But this small excess demand for load can be met from thermal energy storage reserve without affecting the efficiency of the system. Fig. 1 (i).

(ii) Consider a solar drying system, which requires a constant energy demand, but there will be variable energy supply during solar hours. Therefore, it becomes necessary to store the excess energy supplied, which can be used during non-solar hours. Fig. 1 (ii).

(iii) In solar space heating application, thermal energy is required only during night times. Hence, the total energy received during solar hours is stored, which can be used for space heating during night hours. Fig. 1 (iii).

(iv) Apart from these examples, it is also possible to store thermal energy for longer duration. The thermal energy collected during the entire summer season is stored, which can be discharged in winter season for various thermal applications. This type of storage is known as long-term storage.

Thus, the solar thermal energy storage system eliminates the incongruity between energy generation and demand thereby increasing the efficient utilization of solar energy devices for thermal applications.

## 3 Principle of Operation

Thermal energy is stored either by heating or melting or vaporizing a material or through thermochemical reactions. The stored energy is recovered by either heating or cooling when the process is reversed. The principle used in storing and retrieving thermal energy is same for all thermal applications (Dincer and Rosen 2011; Garg and Prakash 2000).

Solar thermal energy storage involves three basic steps:

(i) Charging: collection of thermal energy from solar heat source.
(ii) Storage: to store the collected thermal energy.
(iii) Discharging: to utilize the stored thermal energy for applications.

Solar concentrators are used to focus the solar radiation on to a small area known as receiver. This receiver acts as a heat source, through which thermal energy is collected by circulating the heat transfer fluid and transferring it to the thermal energy storage system. Thermal energy is stored in the reserve depending upon its operating temperature, size, duration of storage, and application. The stored thermal energy is discharged whenever it is required through heat exchanger mechanism using water, oil, or air as heat transfer medium depends on the application. In solar flat-plate collectors, thermal energy storage medium is either integrated with the absorber plate of the collector or arranged as a standalone unit in between collector and load. Therefore, one complete cycle involves all three steps which occur concurrently or consecutively as shown in Fig. 2.

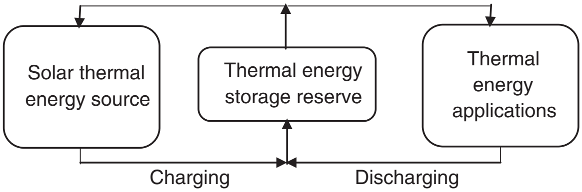



**Fig. 2** Operating principle of thermal energy storage system

# 4 Characteristics of Thermal Energy Storage

Some of the desired characteristics of thermal energy storage (Dincer and Rosen 2011; Sharma 2009; Garg and Prakash 2000) are as follows:

(i) High storage efficiency
(ii) High heat storage capacity per unit mass and volume
(iii) Capable of charging and discharging without degradation in mass, temperature gradient, and efficiency
(iv) Should be compact and low cost
(v) Long life and should not be corrosive to container materials
(vi) Losses should be very less with high speed of charging and discharging rates
(vii) Should not be toxic and fire hazard

# 5 Classification of Thermal Energy Storage

Thermal energy storage is classified based on various parameters such as material properties like specific heat capacity, latent heat capacity, or based on chemical properties. It is also classified with respect to storage size and duration such as seasonal storage and diurnal storage or to its operating temperature such as low-temperature, medium-temperature, and high-temperature thermal energy storage (Garg and Prakash 2000; Dincer and Rosen 2011; Raam Dheep and Sreekumar 2014).

In diurnal storage, thermal energy is stored for a period one or two days, whereas in seasonal storage, the energy collected for few months (summer season) is stored which is capable of delivering for prolonged period (winter season). Some of the advantages of diurnal storage are low energy loss, compact size, small capital investment, and designing and installation is not a complex process. Seasonal thermal storages have large surface to volume ratio, lower heat loss, no need of backup system, and also capable of absorbing heat from environment which makes the system more efficient and advantageous for thermal applications. Thermal energy storage can also be classified based on properties of the materials as shown in Fig. 3.

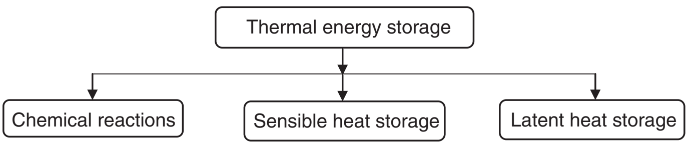



**Fig. 3** Classification of thermal energy storage

### 5.1 Thermochemical Storage

Thermal energy is stored and retrieved by breaking and reforming of molecular bonds through reversible chemical reactions. Heat is stored during endothermic reaction and released through exothermic reaction. Thermochemical energy storage is more advantageous compared to sensible and latent heat storage techniques, such as high energy density, ambient temperature storage, low cost, compactness, high efficiency, long-term storage, and possibility of heat pumping and long distance transport (Garg et al. 1985). But some disadvantages such as understanding thermodynamics and kinetics of various reactions, technical compatibility, and efficiency of this method are yet to be proven, which makes this type of storage system unnoteworthy.

Thermal energy stored using thermochemical reactions is proportional to the amount of storage material ($m$), endothermic heat of reaction ($\Delta h_r$), and fraction reacted ($a_r$) and is given by Eq. 1.

$$Q = a_r m \Delta h_r \tag{1}$$

Three types of thermal energy storage are possible through chemical heat storage technique as shown in Fig. 4. It can be either reversible reaction (exothermic and endothermic reactions) or through thermochemical pipeline energy transport where reversible reactions occur over a long distance capable of transporting thermal energy or finally through chemical heat pump storage where a carrier gas is used to carry the heat evolved from the chemical reactions. A few examples of thermochemical thermal energy storage are given in Table 1.

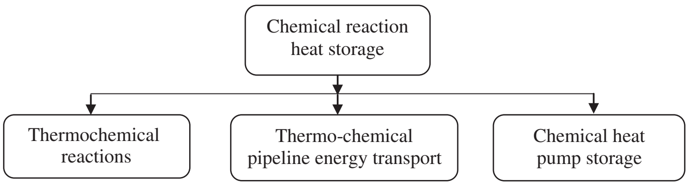



**Fig. 4** Classification of thermochemical thermal energy storage

**Table 1** Examples for thermochemical heat storage

| Chemical reaction | Heat of reaction [$\Delta H^o$(kJ)] |
|---|---|
| $Mg(OH)_{2(S)} \leftrightarrows MgO_{(S)} + H_2O_{(g)}$ | 81.6 |
| $SO_{3(g)} \leftrightarrows SO_{2(g)} + ½O_{2(g)}$ | 98.94 |
| $NH_4F_{(S)} \leftrightarrows NH_{3(g)} + HF_{(g)}$ | 149.3 |
| $C_6H_{12(g)} \leftrightarrows C_6H_{6(g)} + 3H_{2(g)}$ | 206.2 |
| $CH_{4(g)} + CO_{2(g)} \leftrightarrows 2CO_{(g)} + 2H_{2(g)}$ | 247.4 |

### 5.2 Sensible Heat Storage

In sensible heat storage, thermal energy is stored based on the specific heat capacity of the material. Here, the temperature of the storage varies without any alteration in phase of the material. During charging and discharging, energy is absorbed or released with the increase or decrease in temperature of the storage medium as shown in Fig. 5. The ratio of stored heat to the temperature raise gives the heat capacity of the storage system. Large quantities of thermal energy are stored in a given volume if the material possesses high specific heat capacity and density.

The amount of thermal energy stored in sensible heat storage system depends upon the amount of storage material ($m$), specific heat of the medium ($C_p$), and difference between the change in temperature at initial ($T_i$) and final ($T_f$) stage and is given by Eq. 2.

$$\begin{aligned} Q &= \int_{T_i}^{T_f} mC_p \mathrm{d}t \\ &= mC_p(T_f - T_i) \end{aligned} \tag{2}$$

Sensible heat storage has got the advantages such as inexpensive, good thermal capacity, charging and discharging of energy is completely reversible, stable for large number of cycles, and has got longer life without any degradation in the storage medium. The performance of the system depends on operating temperature, thermal conductivity and thermal diffusivity of storage medium, vapor pressure, compatibility between the storage material and the container, stability of the material at high temperature, and cost of the system.

The efficiency of sensible heat storage can be defined as the ratio of heat output to heat input, which is based on the energy balance by first law of thermodynamics. It is necessary to consider the amount of losses incurred, quantity and quality of energy delivered; therefore, the efficiency is defined as the ratio of availability of the energy discharged to the availability of the energy charged, which is according to the second law of thermodynamics (Dincer and Rosen 2011).

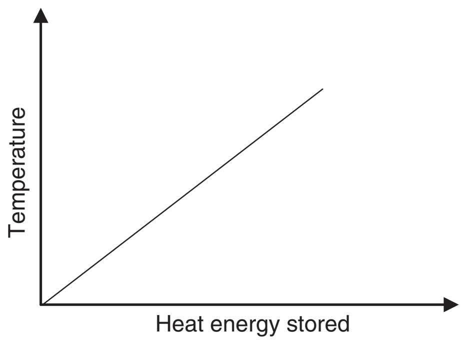



**Fig. 5** Sensible heat stored as function of temperature

**Table 2** Examples for sensible heat storage

| Materials | Operating temperature (°C) | Heat capacity (J/kg K) | Density ($kg/m^3$) |
|---|---|---|---|
| Water | 0–100 | 4.190 | 1000 |
| Therminol | −9 to 343 | 2.100 | 750 |
| Engine oil | Up to 160 | 1.880 | 888 |
| Lithium | 180–1300 | 4.190 | 510 |
| Sodium | 100–760 | 1.300 | 960 |
| Ethanol | Up to 78 | 2.400 | 790 |
| Butanol | Up to 118 | 2.400 | 809 |
| Octane | Up to 126 | 2.400 | 704 |
| Aluminum | Up to 660 | 0.896 | 2707 |
| Brick | 1000 | 0.840 | 1698 |
| Concrete | 1000 | 1.130 | 2240 |
| Cast iron | Up to 1100 | 0.837 | 7900 |
| Copper | Up to 1000 | 0.383 | 8954 |
| Sodium | Up to 850 | 1.090 | 2510 |
| carbonate | Up to 825 | 0.900 | 2500 |
| Limestone | Up to 2800 | 0.960 | 3570 |

Thermal energy is stored based on sensible heat either in solid or liquid phase. For example, water serves as the best liquid sensible heat storage medium up to 100 °C, and rock with heat capacity of 800–900 (J/kg K), as a solid sensible heat storage. Some more examples of the solid and liquid sensible heat storage medium are given in Table 2.

### *5.3 Latent Heat Storage*

Materials undergo phase change at a particular temperature is called PCM. In PCM, thermal energy is stored based on the latent heat capacity of the material. PCM are capable of absorbing or releasing large quantities of energy at constant temperature. Usually, melting or vaporization of the material takes place during heat absorption, and solidification or condensation occurs when heat extracted (Garg and Prakash 2000; Sharma and Sagara 2005).

Heat is stored and absorbed in phase change materials based on the sensible and latent heat properties of the material. Thermal energy is stored as sensible heat until reaching the phase transition temperature (Sharma 2009). Temperature becomes constant during phase transition, thereby storing thermal energy based on latent heat of fusion. Sensible and latent heat stored in PCM is extracted while retrieving thermal energy. Figure 6 and Eq. 3 explain the process of charging and discharging of thermal energy using phase change materials.

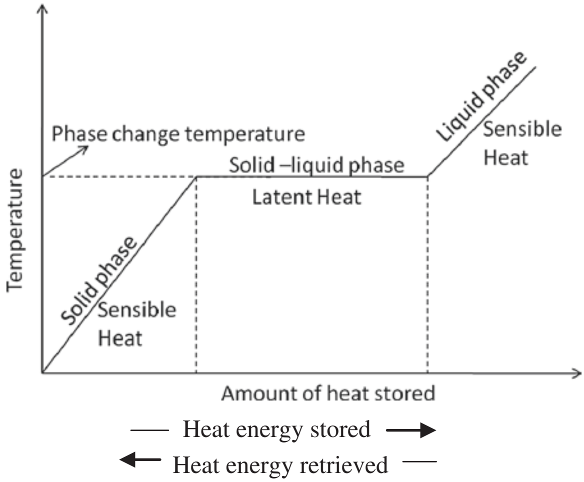



**Fig. 6** Principle of latent heat storage

The amount of thermal energy stored in phase change material is given by the formula:

$$Q = \int_{T_i}^{T_m} m\mathrm{C}_{\mathrm{sp}}\mathrm{d}t + ma_m\Delta h_m + \int_{T_m}^{T_f} mC_{\mathrm{lp}}\mathrm{d}t \tag{3}$$

where ($m$) mass of heat storage medium, ($C_{\mathrm{sp}}$) specific heat at solid state, ($C_{\mathrm{lp}}$) specific heat at liquid state, ($\Delta h_m$) heat of fusion per unit mass, ($a_m$) fraction melted, ($T_f$) final temperature, ($T_i$) initial temperature, and ($T_m$) melting temperature.

### 5.3.1 Various Forms of Phase Change Materials

In latent heat storage system, thermal energy is stored and extracted using the phase change characteristics of the material. Phase change materials are capable to undergo three different types of phase modifications, such as solid to gas, solid to liquid, and solid to solid. Each phase transition not only involves in phase modifications but also experiences certain changes in physical properties (Paksoy 2007).

(a) ***Solid to gas***: The material is changed to gas phase from solid through evaporation, with large phase change enthalpy. But this process leads to large change in pressure and volume which makes the storage system complex and impractical.

(b) ***Solid to liquid***: In this process, the material is changed to liquid from solid phase through melting. Usually solid-to-liquid phase transition has large phase change enthalpy with small volume change. Both melting and solidification progresses at constant temperature, and pressure is not changed significantly. Many organic and inorganic materials are available at various ranges of transition temperature and heat of fusion. Therefore, solid-to-liquid phase change storage system is found to be most suitable for many solar thermal applications.

(c) ***Solid to solid***: In solid-to-solid phase transition, the crystal structure is transformed from one phase to other. For example, lithium sulfate at 573 °C changes its crystalline nature from monoclinic to face-centered cubic with latent heat of fusion 214 kJ/kg. This solid-to-solid phase change storage system has low phase change enthalpy which makes it less suitable for many thermal applications.

### 5.3.2 Classification of Phase Change Materials

Latent heat storage materials can be classified into three types based on materials used (Sharma 2009; Zalba 2003) as shown in Fig. 7.

***Organic PCM***: A phase change material which contains carbon compound is known as organic PCM. It is broadly classified into two types: paraffin and non-paraffin. PCM materials with molecular formula of $C_nH_{2n+2}$ are called alkanes or paraffin, where the heat of fusion and melting point depend upon the increasing value of molecular weight. For example, $CH_4$ to $C_5H_{12}$ are gases, $C_6H_{14}$ to $C_{15}H_{32}$ are liquids, and from $C_{16}H_{34}$ onward are solids at room temperature. Organic PCM with functional groups of esters, fatty acid, and alcohols are categorized under non-paraffin organic PCM. Few examples of organic phase change materials are shown in Table 3.

***Inorganic PCM***: Inorganic PCM are the materials which consist of salt hydrates. Inorganic salts are soluble in water and also form crystalline salt hydrates. Crystals release water on heating during charging, and salts dissolve in water forming a liquid phase. This process is reversed during discharge process, where the dissolved salts change to crystals. Salt hydrates are given by the formula $XY{\cdot}nH_2O$. Few examples of inorganic phase change materials are shown in Table 4.

$$XY \cdot nH_2O \rightarrow XY \cdot mH_2O + (n-m)H_2O \quad \text{or} \quad XY \cdot nH_2O \rightarrow XY + nH_2O$$

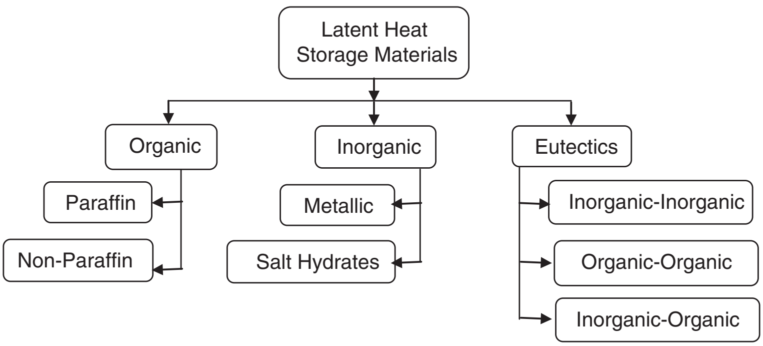



**Fig. 7** Classification of latent heat storage

**Table 3** Examples for organic phase change materials

| Name | Melting point (°C) | Latent heat of fusion (KJ/Kg) |
|---|---|---|
| Lithium chloride ethanolate | 21 | 188 |
| Dimethyl sabacate | 21 | 120–135 |
| Capric acid–lauric acid (45–55 %) | 21 | 143 |
| D-Lactic acid | 26 | 184 |
| Vinyl stearate | 27 | 122 |
| 1-3 Methyl pentacosane | 29 | 197 |
| Capric acid | 32 | – |
| Erucic acid | 33 | 152.7 |
| Camphenilone | 39 | 205 |
| Caprylone | 40 | 259 |
| 1-Cyclohexyl octadecane | 41 | 218 |
| Methyl-12 hydroxy stearate | 42–43 | 120–126 |
| Cyanamide | 44 | 209 |
| Methyl eicosanate | 45 | 230 |
| Elaidic acid | 47 | 218 |
| 3-heptadecanone | 48 | 218 |
| Cetyl alcohol | 49.3 | 141 |
| Camphene | 50 | 239 |
| 9-heptadecanone | 51 | 213 |
| Methyl behenate | 52 | 234 |
| Pentadecanoic acid | 52.5 | 178 |
| Diphenylene amine | 52.9 | 107 |
| P-Dichloro benzene | 53.1 | 121 |
| Myristic acid | 54 | 199 |
| O-xylene dichloride | 55 | 121 |
| β-chloroacetic acid | 56 | 147 |
| Nitro naphthalene | 56.7 | 103 |
| Heptadecanoic acid | 60.6 | 189 |
| Glyolic acid | 63 | 109 |
| Palmitic acid | 64 | 185.4 |
| Stearic acid | 69 | 202.5 |
| Di-nitro toluene(2, 4) | 70 | 111 |
| Oxazoline wax | 74 | – |
| Arachic acid | 76.5 | 227 |
| Bromocampher | 77 | – |
| Benzylamine | 78 | 174 |
| Durene | 79.3 | 156 |
| Acetamide | 81 | 241 |
| Alpha naphthol | 96 | 163 |
| Glutaric acid | 97.5 | – |

(continued)

**Table 3** (continued)

| Name | Melting point (°C) | Latent heat of fusion (KJ/Kg) |
|---|---|---|
| P-Xylene dichloride | 100 | 138.7 |
| Methyl fumarate | 102 | 242 |
| Catechol | 104.3 | 207 |
| Quinone | 115 | 171 |
| Succinic anhydride | 119 | 204 |
| Benzoic acid | 121.7 | 142.8 |

**Table 4** Examples for inorganic phase change materials

| Name | Melting point (°C) | Latent heat of fusion (KJ/Kg) |
|---|---|---|
| $P_4O_6$ | 23.7 | 64 |
| $Mn(NO_3){\cdot}6H_2O$ | 25 | 148 |
| $FeBr_3{\cdot}6H_2O$ | 27 | 105 |
| Cs | 28.3 | 15 |
| $CaCl_2{\cdot}12H_2O$ | 29.8 | 174 |
| $LiNO_3{\cdot}2H_2O$ | 30 | 296 |
| $Na_2SO_4{\cdot}10H_2O$ | 32 | 251–254 |
| $KFe(SO_4)_2{\cdot}12H_2O$ | 33 | 173 |
| $LiBr.2H_2O$ | 34 | 124 |
| $Na_2HPO_4{\cdot}12H_2O$ | 35–40 | 256–281 |
| $Zn(NO_3)_2{\cdot}6H_2O$ | 36 | 134–147 |
| $FeCl_3{\cdot}6H_2O$ | 37 | 223 |
| $CaCl_2{\cdot}4H_2O$ | 39 | 158 |
| $CuSO_4{\cdot}7H_2O$ | 40.7 | 171 |
| $KF{\cdot}2H_2O$ | 42 | 162 |
| $Ca(NO_3)_2{\cdot}4H_2O$ | 43–47 | 106–140 |
| $K_3PO_4{\cdot}7H_2O$ | 45 | 145 |
| $Fe(NO_3)_3{\cdot}9H_2O$ | 47 | 155-190 |
| $Na_2S_2O_3{\cdot}5H_2O$ | 48 | 209 |
| $Ca(NO_3)_2{\cdot}3H_2O$ | 51 | 104 |
| $Na(NO_3)_2{\cdot}6H_2O$ | 53 | 158 |
| $Zn(NO_3)_2{\cdot}2H_2O$ | 55 | 68 |
| $FeCl_3{\cdot}2H_2O$ | 56 | 90 |
| $Ni(NO_3)_2{\cdot}6H_2O$ | 57 | 168 |
| $LiC_2H_3O_2{\cdot}H_2O$ | 58 | 251–377 |
| $NaOH{\cdot}H_2O$ | 58 | 272 |
| $Cd(NO_3)2{\cdot}4H_2O$ | 59 | 98 |
| $Fe(NO_3){\cdot}6H_2O$ | 60 | 125 |
| $NaAl(SO_4)_2{\cdot}12H_2O$ | 61 | 181 |

(continued)

**Table 4** (continued)

| Name | Melting point (°C) | Latent heat of fusion (KJ/Kg) |
|---|---|---|
| $FeSO_4 \cdot 7H_2O$ | 64 | 200 |
| $Na_3PO_4 \cdot 12H_2O$ | 65–69 | 168 |
| $Na_2B4O_7 \cdot 10H_2O$ | 68 | – |
| $Na_2P_2O_7 \cdot 10H_2O$ | 70 | 186–230 |
| $Al(NO_3)_2 \cdot 9H_2O$ | 72 | 155–176 |
| $Ba(OH)_2 \cdot 8H_2O$ | 78 | 265–280 |
| $AlK(SO_4)_2 \cdot 12H_2O$ | 80 | – |
| $KAl(SO_4)_2 \cdot 12H_2O$ | 85.8/91 | – |
| $Al_2(SO_4)_3 \cdot 18H_20$ | 88 | 218 |
| $Sr(OH)_2 \cdot 8H_20$ | 89 | 370 |
| $Mg(NO_3)_2 \cdot 6H_2O$ | 90 | 162–167 |
| $(NH_4).Al(SO_4) \cdot 6H_20$ | 95 | 269 |
| $Na_2S \cdot 5\ ½\ H_2O$ | 97.5 | – |
| $LiCl \cdot H_2O$ | 99 | 212 |
| $CaBr_2 \cdot 4H_2O$ | 110 | – |
| $Al_2(SO_4)_2 \cdot 16H_2O$ | 112 | – |
| $MgCl_2 \cdot 6H_2O$ | 115–117 | 165–169 |

***Eutectics***: Eutectic PCM are the mixture of two or more compounds which can be organic–organic, inorganic–inorganic, and organic–inorganic. These types of PCM melts and freezes congruently without any segregation. They freeze to an intimate mixture of crystals, leaving less opportunity for the compounds to separate. Few examples of eutectic phase change materials are shown in Table 5.

Comparison between organic and inorganic PCM based on thermal, physical, chemical, and economic properties are given in Table 6.

### 5.3.3 Criteria for Selection of Phase Change Materials

Phase change materials melt with high heat of fusion in the temperature range of 0–1500 °C, but it is necessary to have a suitable PCM to achieve high efficiency and viable for solar thermal applications (Sharma 2009). Here are few selection criteria that must be possessed by the PCM before it is subjected for enactment (Dincer and Rosen 2011; Garg and Prakash 2000; Raam Dheep and Sreekumar 2014).

1. Phase change temperature must be suitable for required thermal application.
2. High heat of fusion per unit weight and volume, so that small amount of material can hold large magnitudes of thermal energy.
3. High specific heat enables the PCM to store more sensible heat.
4. Thermal conductivity in both the phases should be high; this enables less temperature gradient required for storing and extraction of thermal energy from the storage.

**Table 5** Examples for eutectic phase change materials

| Compound | Composition (wt%) | Melting point (°C) | Latent heat of fusion (KJ/Kg) |
|---|---|---|---|
| $C_{14}H_{28}O_2 + C_{10}H_{20}O_2$ | 34 + 66 | 24 | 147.7 |
| $Na_2S_4 + MgSO_4 + H_2O$ | 25 + 21 + 54 | 24 | – |
| $CaCl_2 + MgCl_2{\cdot}6H_2O$ | 50 + 50 | 25 | 95 |
| $CH_3CONH_2 + NH_2CONH_2$ | 50 + 50 | 27 | 163 |
| $Ca(NO_3).4H_2O + Mg(NO_3)_3{\cdot}6H_2O$ | 47 + 53 | 30 | 136 |
| $CH_3COONa{\cdot}3H_2O + NH_2CONH_2$ | 40 + 60 | 30 | 200.5 |
| $NH_2CONH_2 + NH_4NO_3$ | 53 + 47 | 46 | 95 |
| $Mg(NO_3)_2{\cdot}6H_2O + NH_4NO_3$ | 61.5 + 38.5 | 52 | 125.5 |
| $Mg(NO_3)_2{\cdot}6H_2O + MgCl_2{\cdot}6H_2O$ | 58.7 + 41.3 | 59 | 132.2 |
| $Mg(NO_3)_2{\cdot}6H_2O + Al(NO_3)_2{\cdot}9H_2O$ | 53 + 47 | 61 | 148 |
| $CH_3CONH_2 + C_{17}H_{35}COOH$ | 50 + 50 | 65 | 218 |
| $Mg(NO_3)_2{\cdot}6H_2O + MgBr_2{\cdot}6H_2O$ | 59 + 41 | 66 | 168 |
| Napthalene + Benzoic Acid | 67.1 + 32.9 | 67 | 123.4 |
| $AlCl_3 + NaCl + ZrCl_2$ | 79 + 17 + 4 | 68 | 234 |
| $AlCl_3 + NaCl + KCl$ | 66 + 20 + 14 | 70 | 209 |
| $LiNO_3 + Mg(NO_3)_2{\cdot}6H_20$ | 14 + 86 | 72 | >180 |
| $NH_2CONH_2 + NH_4Br$ | 66.6 + 33.4 | 76 | 151/161 |
| $LiNO_3 + NH_4NO_3 + NaNO_3$ | 25 + 65 + 10 | 80.5 | 113 |
| $LiNO_3 + NH_4NO_3 + KNO_3$ | 26.4 + 58.7 + 14.9 | 81.3 | 116 |
| $AlCl_3 + NaCl + KCl$ | 60 + 26 + 14 | 93 | 213 |
| $KCl + ZnCl_2$ | 68.1 + 31.9 | 235 | 198 |
| $MgCl + NaCl$ | 38.5 + 61.5 | 435 | 328 |

5. High density, so that the container required for storage would be small and low cost.
6. Should possess low vapor pressure; this gives mechanical stability to PCM containers.
7. Volume change during phase transition should be low, so that simple container and heat exchanger can be used.
8. Material should completely melt, i.e., congruent melting, so that segregation can be avoided and homogeneous solid and liquid phases can be obtained.
9. Little or no supercooling with high rate of crystal growth; this enables melting and solidification to occur at same temperature.
10. Completely reversible and temperature-dependent.
11. Reliable without any degradation for long time.
12. Chemically stable and non-poisonous.
13. Should not corrode the container and heat exchanger materials.
14. Should be non-hazardous and inflammable.
15. Inexpensive and easily available.
16. Long life.

**Table 6** Comparison between organic and inorganic PCM

| Properties | Organic PCM | Inorganic PCM |
|---|---|---|
| Heat of fusion | Increases with chain length and higher than salt hydrates | Increases with degree of hydrates, but higher hydrates have incongruent and semi-congruent melting |
| Specific heat | Higher specific heat capable of storing more sensible heat | Lower specific heat than organic PCM |
| Thermal conductivity | Low thermal conductivity | Inorganic PCM has higher thermal conductivity |
| Density | Less dense than inorganic PCM results in low storage effectiveness per unit volume | More dense with large efficiency per unit volume, but lower heat of fusion |
| Reversibility | Completely reversible | Rate of crystal growth is low; therefore, incongruent and semicongruent melting occurs |
| Supercooling | No or little supercooling occurs | Degree of supercooling is greater |
| Vapor pressure | Low vapor pressure attributes long-term loss of material | High vapor pressure and induce water loss |
| Stability | Chemically stable and unreactive | Less chemical stability, degrades by oxidation, hydration, thermal decomposition, etc. |
| Toxicity | Innocuous neither toxic nor irritants | Less toxic. Irritation occurs, and contact with skin should be avoided |
| Flammability | Flammable in presence of $O_2$ at elevated temperature due to low vapor pressure. Low fire hazard | Low flammability based on material |
| Corrosion | Not corrosive | Corrosive in presence of $H_2O$ |
| Cost and availability | High cost and less availability | Low cost and easily available |

### 5.3.4 Research and Development in Latent Heat Thermal Energy Storage

Numerous research activities are being carried out in designing and developing latent heat-based thermal energy storage system for solar thermal applications. Field performance characteristics and evaluation, design fundamentals, thermal analysis, process optimization, experimental and numerical analysis on thermo-physical properties of new thermal energy storage materials and its integration, and studies on economic and environmental effects are a few of the major research areas in the field of thermal energy storage (Duffie and Beckman 2013; Raam Dheep and Sreekumar 2014).

Latent heat-based thermal energy storage system must possess three different components which are as follows,

(i) Suitable phase change material that undergoes phase transition at desired operating temperature based on application.
(ii) A containment system for PCM.
(iii) A heat exchanger system capable of holding the PCM to undergo large number of charging and discharging cycles to store and deliver thermal energy.

The various steps involved in developing latent heat-based thermal energy storage system for solar thermal applications are shown as flowchart in Fig. 8. The research activities involved in thermal energy storage is divided into three categories. First step involves selection and optimization of kinetic and thermo-physical properties of PCM. Designing of suitable heat exchanger followed as the second step. Finally, performance evaluation based on technical and economic aspects must be optimized for the commercialization of the system. Therefore, it is necessary to perform all these analyses through numerical and experimental analysis to develop the solar energy based thermal storage system.

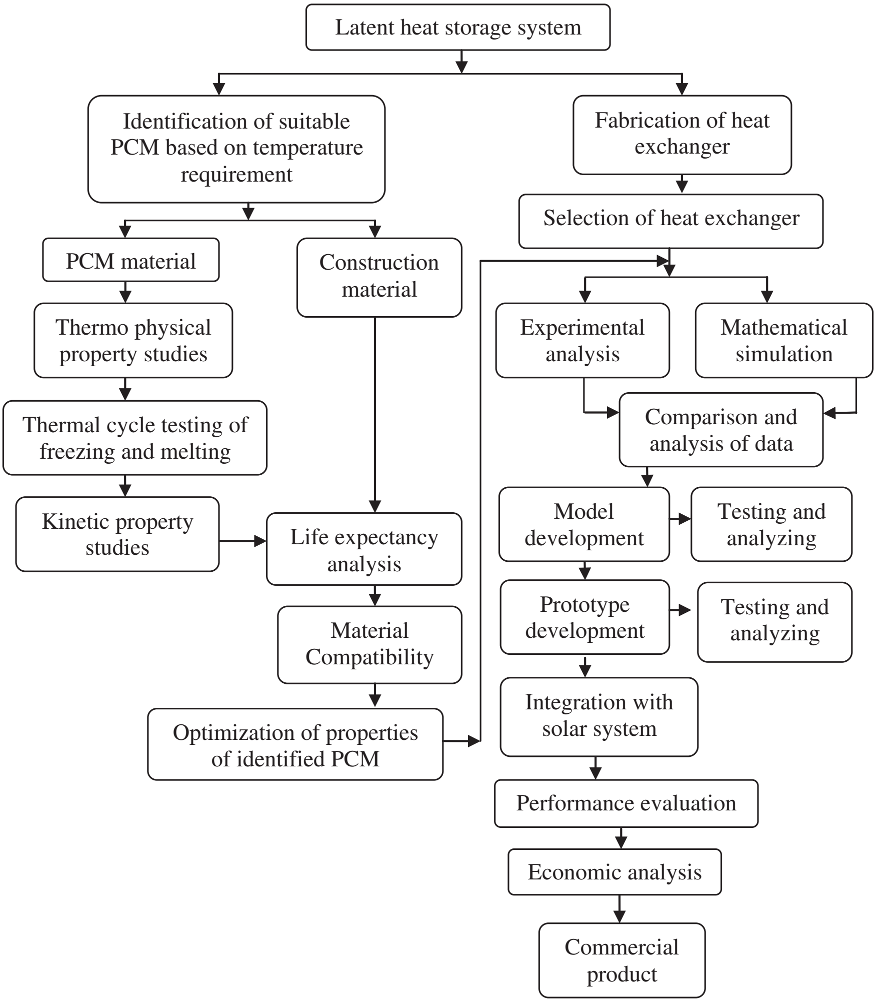



**Fig. 8** Steps involved in development of LHTES

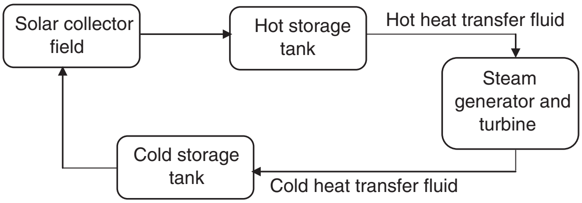
Thermo-physical properties of the PCM are studied using differential scanning calorimetry (DSC), differential thermal analysis (DTA), and T-history method. With the help of these analyses, it is possible to know about the heat of fusion, heat capacity, melting and solidification temperature, stability of PCM, supercooling, and thermal conductivity. Thermal reliability of PCM can be determined by performing large number of charging and discharging cycles and then measuring thermo-physical properties (Dincer and Rosen 2011). Corrosion analysis of PCM is also to be studied to check the suitability of heat exchanger containment materials.

Some of the complications associated with PCM and the possible approaches to resolve it are as follows:

(i) ***Phase separation***: Water present in inorganic salt hydrates is not enough to dissolve the solid present; therefore, it settles down due to difference in density. This issue is solved by incorporating thickening agent or mechanical stirring or use of excess water, so that the salt dissolves completely without any segregation.
(ii) ***Supercooling***: The difference between melting and solidification temperature is called degree of supercooling. Due to slow growth of nuclei, the temperature drops below the melting point during freezing and prevents the withdrawal of thermal energy. Supercooling of PCM can be avoided by adding nucleating agents or parts of PCM to be kept in cold region or by using rough containment walls.
(iii) ***Thermal conductivity***: Usually organic PCM possess low thermal conductivity, which leads to poor heat transfer during charging and discharging. Thermal conductivity can be increased by the addition of high thermally conductive nanoparticles or through the use of extended fins.
(iv) ***Thermal stability***: In order to achieve efficient heat transfer without degradation, PCM is encapsulated using micro- or mesoporous materials. This enables the PCM to improve heat transfer through large surface area to volume ratio. This technique also improves the cycling stability of PCM.
(v) ***Corrosion***: The compatibility of PCM with the heat exchanger container is considered to be the most important issue in developing the latent heat-based thermal energy storage system. Therefore, after selecting the suitable PCM, corrosion analysis of PCM on different containment materials has to be studied to achieve long-lasting and high-efficient thermal energy storage.

Once the thermo-physical properties, thermal reliability, and corrosion analysis of PCM are studied and optimized, it is necessary to design the heat exchanger to hold the PCM and store thermal energy. A suitable heat exchanger is selected and designed based on overall heat transfer coefficient on hot and cold side, log mean temperature difference, and effective NTU methods. The designed parameters are numerically simulated and iterated by changing the parameters to achieve high-efficient heat exchanger geometry. Heat exchanger filled with suitable PCM and integrated with solar collector field at charging side and load on discharging side. Performance of the overall system such as energy, exergy, and economics

**Fig. 9** Thermal energy storage-incorporated solar thermal electricity generation system




are analyzed and evaluated. These are the various steps involved in developing the latent heat-based thermal energy storage system for thermal application utilizing solar energy. Figure 9 represents the solar thermal electricity generation system incorporating thermal energy storage.

Many researchers (Sarier and Onder 2012; Sharma et al. 2004, 2009; Sharma and Abhat 1980; Al-Abidi 2013; Sagara 2005) presented reviews on low- and high-temperature phase change materials based on classification, need, selection criteria, long-term characteristics, compatibility with heat exchanger materials, numerical models, methods of enhancing thermal and physical properties, and thermo-physical properties like melting and cooling temperature, latent heat of melting and crystallization, thermal conductivity, degree of supercooling, viscosity, thermal stability, and thermal reliability.

Kenisarin (2010) has reviewed on the investigations and developments of various high-temperature inorganic PCM of salt hydrates and metal alloys that are capable of storing thermal energy from 120 to 1000 °C along with the thermo-physical properties and corrosion behavior of containers for repeated cycles. Feldman et al. (1986) have reported the measurements of melting point, freezing point, and the latent heat of melting and fusion of 12 organic materials of fatty acid, esters, ethoxylated alcohols, alkyl phenol, and sulfur compounds with melting points in the range 10–43 °C for space heating and cooling applications. Sharma et al. (2013) also reported the capability of PCM for building applications. Thermo-physical properties of different combinations of eutectic-based PCM such as capric acid (CA), lauric acid (LA), myristic acid (MA), palmitic acid (PA), and stearic acid (SA) were analyzed. Arndt et al. (1984) have reported the melting range, enthalpy of fusion, flash point, and thermal stability of few organic PCM for thermal energy storage in the temperature range of 60–90 °C. Aboul-Enein and Olofa (1991) analyzed the thermo-physical properties of hexadecane, decanol and caprilic acid PCM for solar energy application that can be used in the latent cold storage systems (0–20 °C). Arndt et al. (1981) also experimentally studied the thermal cycling of organic PCM naphthalene for 220 cycles. It is found that the melting onset temperature was 81 °C and solidification onset temperature was 67 °C with latent heat of fusion 148 J/g. Thermal cycle testing of calcium chloride hexahydrate as a possible PCM for latent heat storage has been performed by Tyagi and Buddhi (2008) for 1000 cycles. It is reported that calcium chloride hexahydrate as a good inorganic PCM for low-temperature applications which have only small variations in the latent heat of fusion and melting in the stable range of temperature.

## 6 Standards for Testing Thermal Energy Storage

The increase in interest of utilizing solar thermal energy and its storage for various applications has created cognizance to develop standards and testing procedures. This would help in achieving high efficiency for newly designed and developed system, comparison of different storage devices, act as a source of information for designers and fabricators, and to avoid unwarranted claims.

The performance of solar thermal device depends on many parameters such as type of storage device, thermal capacity of storage device, operating temperature range, temperature stratification in the storage tank, heat charging and discharging, thermal losses, and thermo-physical properties of the storage material and container. (Hill et al. 1976).

Hill et al. (1976, 1977) proposed three different methods to test and compare the storage devices which are as follows:

(i) In first method, transient response of the storage system can be determined by measuring the outlet temperature with increase in inlet fluid temperature.
(ii) In second method, the heat flux of the inlet fluid is kept constant thereby measuring the variation in outlet temperature with time.
(iii) In third method, heat flux of the inlet fluid is varied and the outlet temperature is measured as a function of time.

However, the first attempt was made by a group of scientists at the National Bureau of Standards Information Report (NBSIR). They developed a test procedure for thermal storage systems for both sensible and latent heat storage system. Later, the American Society of Heating Refrigeration and Air-conditioning Engineers (ASHRAE) also formulated few standards for thermal energy storage system. Based on the theoretical and experimental work, two standard test procedures, namely ASHRAE 94-77 and NBSIR 74-634, were made and accepted for testing thermal storage devices (Garg 1985).

In both test procedures, the storage system has single inlet and outlet through which the energy charged and discharged is measured. The measurements to be made are the same except in the number of charge and discharge rates. The parameters such as temperature difference between inlet and outlet, fluid flow rate, pressure, pressure drop, and time are measured with accuracy.

**ASHRAE 94-77**

Following are the test procedures prescribed by ASHRAE for testing of storage unit.

1. One test to determine overall thermal loss from the storage unit.
2. Two charge tests to determine charge capacity of the storage unit with increase in inlet fluid temperature.
   (a) When heat transfer fluid is liquid, tests are conducted at fluid rates ($\dot{m}$) such that
      (i) At ($\dot{m}$) for $t_f$ 2 h with $\Delta T$ of 15 °C
      (ii) At ($\dot{m}$) for $t_f$ 4 h with $\Delta T$ of 15 °C

3. Two discharge tests to determine discharge capacity of the storage unit with decrease in inlet fluid temperature.
   (a) When heat transfer fluid is liquid, tests are conducted at fluid rates ($\dot{m}$) such that
      (i) At ($\dot{m}$) for $t_d$ 2 h with $\Delta T$ of 15 °C
      (ii) At ($\dot{m}$) for $t_d$ 4 h with $\Delta T$ of 15 °C

If air is used as heat transfer medium, then the tests are conducted with the change in temperature of 35 °C, where ($t_f$) and ($t_d$) are fill time (charging) and discharge time.

**NBSIR 74-634**

1. One test to determine overall thermal loss from the thermal storage unit.
2. Four charge tests to determine charge capacity of the storage unit with increase in inlet fluid temperature.
   (a) When heat transfer fluid is liquid, tests are conducted at fluid rates such that
      (i) At ($\dot{m}$) for $t_f$ 2 h with $\Delta T$ of 8 °C
      (ii) At ($\dot{m}$) for $t_f$ 2 h with $\Delta T$ of 16 °C
      (iii) At ($\dot{m}$) for $t_f$ 4 h with $\Delta T$ of 8 °C
      (iv) At ($\dot{m}$) for $t_f$ 4 h with $\Delta T$ of 16 °C

   (b) when air is used as heat transfer fluid, then
      (i) At ($\dot{m}$) for $t_f$ 4.5 h with $\Delta T$ of 28 °C
      (ii) At ($\dot{m}$) for $t_f$ 4.5 h with $\Delta T$ of 50 °C
      (iii) At ($\dot{m}$) for $t_f$ 9 h with $\Delta T$ of 28 °C
      (iv) At ($\dot{m}$) for $t_f$ 9 h with $\Delta T$ of 50 °C

3. Similar to (2), four charge tests are conducted to determine discharge capacity of the storage unit with decrease in inlet fluid temperature based on heat transfer fluid.
   Where, $t_f$ is fill time given by

$$t_f = \frac{\mathrm{TSC}}{\dot{m} c_p \Delta T}$$

TSC—Nominal thermal capacity of storage (J)

$\dot{m}$—Mass flow rate of fluid (kg/s)

$C_p$—Specific heat of fluid (J/kg K)

$\Delta T$—Increase or decrease in fluid inlet temperature (°C)

The heat loss ($Q_L$) from the storage system can be determined by passing the fluid at certain mass flow rate at an inlet temperature of 25 °C above the ambient temperature until steady state condition (outlet temperature less than 0.5 °C) is achieved. The temperature difference between the outlet and inlet fluid and the ambient temperature are measured at an interval of 1 h. From the measured values, heat loss rate (J/s °C) is calculated using Eq. 4,

$$Q_L = \frac{mc_p}{3000\,\mathrm{s}\ 25\,^\circ\mathrm{C}} \int_{t=o}^{t=3600} (T_{in} - T_{out})\mathrm{d}t \tag{4}$$

To determine the heat loss rate, mass flow rate can be adjusted and calculated using the fill time equation. The mass flow rates of heat transfer fluid for charging ($\dot{m}_c$) and discharging ($\dot{m}_d$) tests for a specific thermal storage system are calculated using the fill time ($t_f$) and discharge time ($t_d$).

$$m_c = \frac{\mathrm{TSC}}{t_f c_p \Delta T}$$

$$m_d = \frac{\mathrm{TSC}}{t_d c_p \Delta T}$$

The effective charge capacity $C_c$ (J) of the thermal storage device is determined from the following equation (Eq. 5):

$$C_c = m_c c_p \int_{t=0}^{t=t_f} (T_{in} - T_{out})\mathrm{d}t - Q_L\left[(T_i)\frac{T_{in} - T_{out}}{2} - T_a\right] \tag{5}$$

where

$T_i$—initial inlet temperature (°C)
$T_{in}$—constant inlet temperature (°C)
$T_{out}$—outlet temperature (°C)
$T_a$—ambient temperature (°C)

The effective discharge capacity $C_d$ (J) of the thermal storage device is determined from Eq. 6,

$$C_d = m_d c_p \int_{t=0}^{t=t_d} (T_{out} - T_{in})\mathrm{d}t \tag{6}$$

The charging and discharging process is repeated until all the values, specified in the Standard, for $t_f$ and $\Delta T$ are satisfied. In ASHRAE 94-77 Standard, charging and discharging are repeated twice for two different values of fill times, while in NBSIR 74-634 Standard, each set of tests is repeated four times. Figure 10a, b shows the setup for testing thermal energy storage system for both liquid and air flow.

The charge and discharge coefficients $\eta_c$ and $\eta_d$ of the storage system can also be found using the following equations:

$$\eta_c = \frac{C_c}{\mathrm{TSC}}$$
$$\eta_d = \frac{C_d}{\mathrm{TSC}}$$

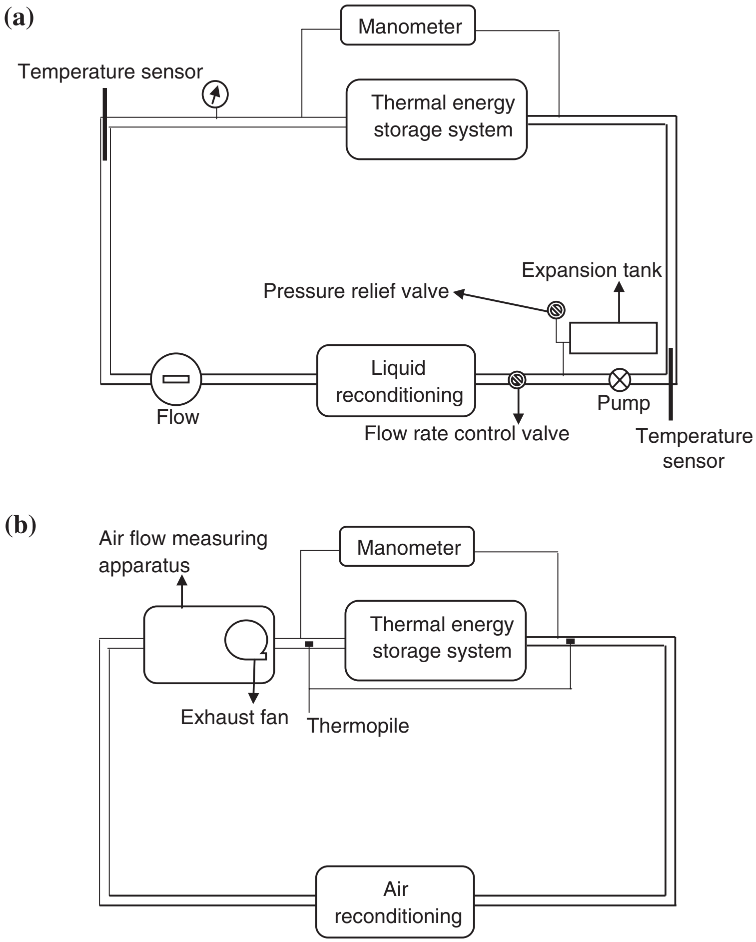



**Fig. 10** Experimental setup for testing thermal energy storage system: **a** liquid flow (Hill 1976), **b** air flow (Hill 1976)

# 7 Applications

Solar energy has enormous potential that can be used for many thermal applications, but it's unpredictable and intermittent nature necessitates the use of a storage medium to meet the energy delivery during non-solar hours. Therefore, it has to be stored during its availability which can be used during non-solar hours. Solar thermal applications are classified based on operating temperature as low-, medium-, and high-temperature applications. Some of the applications reported in the literature that utilizes solar thermal energy integrated with energy storage are given below.

**Solar air heating**

Fath and Hassan (1995) developed a simple solar air heater integrated with thermal energy storage system. Paraffin wax and $Na_2SO_4 \cdot 10H_2O$ were used as PCM. It is reported that the system has achieved daily average efficiency of 63.35 % compared to 59 % with sand as the storage material and 38.7 % for the conventional flat-plate heater system. Strith and Novak (2002) used transparent insulation material and translucent PCM in the walls of house to heat the air. Sixty kilogram of paraffin wax (melting point 25–30 °C, latent heat of fusion 150 kJ/kg) was used as PCM. It is reported that the system has achieved an efficiency of 45 %. Sagara et al. (1994) estimated coefficient of performance of an air-based solar heating system using PCM with respect to capacity of the PCM storage tank, melting temperature, collector area, and air flow rate. A detailed survey on solar dryer for drying agricultural food products integrated with thermal energy storage system was reviewed by Bal et al. (2010).

Sari and Kaygusuz (2002) developed an eutectic PCM (lauric acid 75.5 wt% + stearic acid 24.5 wt%) that melts at 37 °C with latent heat of 183 kJ/kg for space heating. The properties of PCM were found to be most promising for passive solar space heating applications such as building and greenhouse heating. Mehmet (2000) investigated the thermal performance of solar-aided latent heat storage for space heating with heat pump. It is reported that 1090 kg of encapsulated PCM ($CaCl_2 \cdot 6H_2O$) was used. Author concluded that effectiveness of the system depends upon the thickness and length of the pipes used.

**Solar water heating**

Numerous studies are being performed in design and development of PCM-based solar water heating system due to its wide popularity. Many researchers reported the thermal performance based on latent heat, transition temperature, and thermal conductivity of PCM, such as paraffin wax, stearic acid, myristic acid, palmitic acid, and its eutectics, by incorporating into the solar water heating system. Apart from material development, the efficiency of the system for various designs with built-in PCM storage has also been studied. Prakash et al. (1985) reported the storage-type solar water heater filled with PCM at the bottom. During solar hours, water gets heated and transfers the heat to the PCM beneath it. During non-solar hours, the hot water is withdrawn and is substituted by cold water, which gains energy from the PCM. This system achieved low efficiency due to poor heat transfer from PCM to water and vice versa. Numerical and experimental analysis of closed-loop, cylindrical latent heat storage was studied by Bansal and Buddhi (1992). During charging of PCM, cylindrical capsule is in closed loop with a solar water heater and while discharging, water flows through storage unit extracts energy. Tiwari et al. (1988) studied the PCM storage for water heater in which water is allowed to flow at the solid–liquid interface and reported a rise in water temperature of 10–20 °C than ambient. Tayed (1993) made simulations on inorganic PCM-based domestic hot water generation to achieve constant temperature at the outlet by controlling the flow rate of the water. Kurklu et al. (2002)

developed and studied the thermal performance of a new PCM-based solar water heater for domestic applications. It was designed in such a way that PCM store was above the water store and it was found that the temperature of water was 30 °C during the whole night.

**Greenhouse heating**

Solar green houses are used to increase the quality and productivity of plant by controlling the temperature, humidity, solar irradiance, and internal gas composition. Development of solar greenhouse involves studies on new materials, heat storage analysis, and designing heat exchange devices. Nishina and Takakura (1984) used $Na_2SO_4 \cdot 10H_20$ with some additives to prevent phase separation and degradation for heating a greenhouse in Japan. It is reported that temperature difference of 8 °C was achieved with only 40–60 % of PCM. Takakura and Nishina (1981) also used polyethylene glycol and $CaCl_2 \cdot 6H_2O$ as PCM in greenhouse heating for 7.2 $m^2$ ground area. Efficiency of the greenhouse integrated with PCM-based solar collector was 59 % and provides 8 °C inside the greenhouse, whereas the outside temperature was −0.6 °C during night. Similar studies were also carried out by Jaffrin and Cadier (1982, 1987) using 13.5 tons of $CaCl_2 \cdot 6H_2O$ and compared with conventional and double-covered greenhouses. It is found that solar greenhouse with thermal energy storage saves 60 % when compared other two systems. Levav and Zamir (1987) also analyzed the performance of the solar greenhouse using $CaCl_2 \cdot 6H_2O$.

Paraffin (48–60 °C, Latent Heat of Fusion 190 kJ/kg) was first used by Bagetinelik et al. (1994) for greenhouse heating. The author reported that paraffin-based PCM is more efficient than other organic PCM. Ktirklti et al. (1996, 1997) used two different PCM, one that melts in the range of 22–25 °C to reduce peak temperature during summer, and other at 8 °C for frost prevention. It was reported that the efficiency was 29 % for PCM with higher melting temperature and 30 % during the frost prevention. Therefore from all these studies, it is concluded that phase change materials are the effective thermal energy storage medium for solar greenhouse applications.

**Solar cooking**

Solar cookers are mostly used nowadays for domestic and community cooking. But, these cookers are of limited use, as they cannot be utilized during cloudy days or night times. Many researchers came forward in developing new designs for solar cooker integrated with thermal energy storage.

A detailed review on solar cooker incorporated with latent heat storage system was presented by Sharma et al. (2009). Ramadan et al. (1987) analyzed the performance of the solar cooker filled with barium hydroxide octahydrate as PCM and found that additional 6 h of cooking after sunshine hours and achieved 28.4 % of conversion efficiency.

Similar studies were also carried out by Bushnell (1988) on solar ovens with pentacrythritol, a solid–solid PCM, and studied the performance from efficiency and figure of merit. Table 7 gives the details of the PCM used by scientists to

**Table 7** List of some PCM used for solar cooking applications

| S. no | Author (Ref) | PCM | Mass of PCM (kg) | Melting temperature and latent heat of fusion | Description |
|---|---|---|---|---|---|
| 1 | Domanski (1995) | Stearic acid | 1.1 | 55 °C and 161 kJ/kg | Two concentric cylindrical vessels |
| 2 | Sharma et al. (2000) | Acetamide | 2 | 82 °C and 263 kJ/kg | Cylindrical PCM storage unit for a box-type solar cooker |
| 3 | Sharma et al. (2003) | Acetamide | 4 | 82 °C and 263 kJ/kg | Hollow concentric aluminum cylinders |
| 4 | Sharma et al. (2004) | Erythritol | 45 | 118 °C and 339.8 kJ/kg | Evacuated tube solar collector (ETSC) with PCM storage |

develop the thermal energy storage-incorporated solar cooker. They concluded that the efficiency of the solar cooker depends upon charging and discharging capacity of PCM, solar irradiance, mass of cooking medium, and thermo-physical properties of PCM. Various study concluded that identification of a storage material with suitable transition temperature and quantity required to cook the food in the late evening are necessary for the design of a solar cooker with thermal energy storage. Larger quantity of heat energy has to be stored to achieve high efficiency, which can be met through the use of reflectors to focus the solar radiation. Acetanilide (melting point 118 °C, latent heat of fusion 222 kJ/kg) was used as PCM for night cooking.

### Solar thermal electricity generation

Phase change materials are extensively used as storage material in solar thermal power generation systems. Thermal energy is harvested from the collectors and receivers of the solar field, which is transformed to the thermal energy storage reserve through heat transfer fluid. Steam is generated with the help of heat exchangers that runs the turbine for electricity generation. Table 8 gives the list of solar thermal plants with installed capacities of thermal energy storage along with operating duration and location. (www.energystorageexchange.org, Department of Energy Global Energy Storage Database, Sandia National Laboratories.)

**Table 8** List of solar thermal electricity generation plants with thermal energy storage

| S.No | Name | Rated power (MW) | Duration (HH:MM) | Location |
|---|---|---|---|---|
| 1 | Planta Solar 20 (PS 20) | 20 | 01:00 | Spain |
| 2 | Planta Solar 10 (PS 10) | 11 | 00:30 | Spain |
| 3 | Arcosol 50 | 50 | 07:30 | Spain |
| 4 | Lio Solar Thermal Project | 9 | 01:00 | France |
| 5 | Archimede Solar Power Plant | 4.72 | 08:00 | Italy |
| 6 | Thermesol 50 CSP | 50 | 07:30 | Spain |
| 7 | Julich Solar Tower | 1.5 | 01:30 | Germany |
| 8 | Pennsylvania ATLAS | 2.01 | 05:00 | United States |
| 9 | Vcharge Maine ATLAS | 0.3 | 05:00 | United States |
| 10 | Andasol 3 CSP | 49.9 | 07:30 | Spain |
| 11 | Lake Cagelligo | 3 | 24:00 | Australia |
| 12 | Isentropic Demonstration Project | 1.4 | 04:00 | United Kingdom |
| 13 | Halotechnics Advanced Molten Glass Of Heat Transfer | 0.005 | 06:00 | United States |
| 14 | Airlight Energy | 0.65 | 09:00 | Morocco |
| 15 | Kaxu Solar One | 10 | 03:00 | South Africa |
| 16 | Khi Solar One Power Plant | 50 | 02:00 | South Africa |
| 17 | Minera El Tesoro CSP | 10.5 | 06:30 | Chile |
| 18 | Crescent Dues | 110 | 10:00 | United States |
| 19 | Rice Solar Energy Project | 150 | 08:00 | United States |
| 20 | Solano Solar Generating Plant | 280 | 06:00 | United States |
| 21 | Ashalim 2 Solar Power Plant | 110 | 04:30 | Israel |
| 22 | Casablanca Solar | 50 | 07:30 | Spain |
| 23 | Caceres Solar | 50 | 07:30 | Spain |
| 24 | Andasol 1 | 49.9 | 07:30 | Spain |
| 25 | Andasol 2 | 49.9 | 07:30 | Spain |
| 26 | Vcharge Concord | 0.175 | 05:00 | United States |
| 27 | India One Solar Thermal Plant | 1 | 16:00 | India |
| 28 | Puerto Errado | 1.4 | 00:30 | Spain |
| 29 | Manchasol 2 | 50 | 07:30 | Spain |
| 30 | Manchasol 1 | 49.9 | 07:30 | Spain |
| 31 | La Florida | 49.9 | 07:30 | Spain |
| 32 | La Dehesa | 50 | 07:30 | Spain |
| 33 | La Africana | 50 | 07:30 | Spain |
| 34 | Extresol 2 | 50 | 07:30 | Spain |
| 35 | Extresol 3 | 50 | 07:30 | Spain |
| 36 | Extresol 1 | 50 | 07:30 | Spain |
| 37 | Astexol 2 | 50 | 08:00 | Spain |
| 38 | Aste 1b | 50 | 08:00 | Spain |

(continued)

**Table 8** (continued)

| S.No | Name | Rated power (MW) | Duration (HH:MM) | Location |
|---|---|---|---|---|
| 39 | Aste 1a | 50 | 08:00 | Spain |
| 40 | Augustin Fresnel 1 | 2.5 | 00:15 | France |
| 41 | Alba Nova 1 | 12 | 01:00 | France |
| 42 | Thermosol 1 | 50 | 09:00 | Spain |
| 43 | Thermosol 2 | 50 | 09:00 | Spain |
| 44 | Kvk Energy Solar | 100 | 04:00 | India |
| 45 | Gujarat Solar One | 25 | 09:00 | India |
| 46 | Diwikar CSP | 100 | 04:00 | India |
| 47 | Beijing Badaling | 1.5 | 01:00 | China |
| 48 | Supcon Power Tower | 50 | 02:30 | China |
| 49 | Maria Elena CSP | 50 | 07:00 | Chile |
| 50 | Noori Csp | 16 | 03:00 | Morocco |
| 51 | Holaniku | 2 | 02:00 | United States |
| 52 | Jemalong Solar | 1.1 | Na | Australia |
| 53 | Arenales CSP | 50 | 07:00 | Spain |
| 54 | Bokpoort CSP | 50 | 09:00 | South Africa |
| 55 | Pedro De Valdivia | 360 | 10:30 | Chile |

## 8 Conclusion

The need, characteristics, and different methods of thermal energy storage for solar application are elaborated here. Phase change material-based latent heat storage system is found to be most suitable for various solar thermal applications. Therefore, the review presented for PCM is based on different nature of phase change, classification, selection criteria, possible research areas, standard testing procedures, applications, and case studies. The content of this chapter will facilitate researchers to undertake studies in identification and characterization of PCM materials and also develop new phase change material-based storage system. The possible integration of thermal energy storage system with solar thermal devices will cause a leap in the acceptance level of solar thermal technologies and hence sustainable development.

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# Latent Heat Thermal Storage (LHTS) for Energy Sustainability

**M.R. Anisur, M.A. Kibria, M.H. Mahfuz, R. Saidur and I.H.S.C. Metselaar**

**Abstract** In order to restrain the trend of present fossil fuel consumption, latent heat thermal storage (LHTS) using phase change material (PCM) has been received a common interest among scientists as it has high energy storage capacity. In this chapter, LHTS system and their applications for solar thermal power generation and building application have been discussed. The prospect of LHTS in reducing present fossil fuel consumption also has been demonstrated. Moreover, the recent development of PCM has been reported for practical LHTS application.

**Keywords** Latent heat thermal storage · Phase-change material · Energy sustainability · Solar thermal power generation · HVAC

## 1 Introduction

Worldwide, there is a growing research interest on renewable energy as sustainable energy. It has been a great concern about two present problems, such as rapid fossil fuels' depletion and its environmental impacts with global warming. Melting of

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icebergs, rising sea level, natural calamities, etc. is being observed with respect to the global warming rate (Nema et al. 2012). On the other hand, the prices of these fossil fuels have been increased in last years and it is expected to continue increasing because energy demand is increasing while fossil fuels in reserves are decreasing. Hence, many scientists are involved to explore sustainable green technologies to reduce fossil fuel consumption. Renewable energies are sustainable and do not cause any pollution for the environment while fossil fuels are not sustainable and cause an extensive pollution that damages the environment. Renewable energies are solar energy, wind energy, bio energy, geothermal energy, tidal energy, and hydropower. However, these forms of energy are quite challenging because of their high harvesting costs. Moreover, solar energy, wind energy, and tidal energy are characterized by their intermittent nature, as they are not available all the time. This intermittent problem can be solved by energy storage. In this context, energy storage can have a significant impact on modern technology. In particular, energy storage is very important to the success of any intermittent energy source in meeting demand. A large variety of energy storage techniques are under development. The storage of energy can be mechanical, thermal, chemical, biological, or magnetic. Thermal energy may be stored by elevating or lowering the temperature of a substance (sensible heat), by changing the phase of a substance (latent heat) or through a combination of the two. Latent heat thermal storage (LHTS) system with phase change material (PCM) can be more potential as they have large heat storage capacity as compared with other materials which are used to store only sensible heat (Jeon et al. 2013).

In spite of this great advantage, most of the PCM has a limitation of its own, that is, very low thermal conductivity (Cabeza et al. 2011). To reduce the thermal energy charging/discharging time of LHTS system, enhancing the thermal conductivity of PCM is one of the ways to improve the effectiveness of the PCM-based LHTS systems. As a result, from the previous findings, to increase the performance of LHTS, PCM has been the main research priority topic at present (Fernandes et al. 2012).

## 2 Fundamentals of LHTS System

Materials with latent heat are named as latent heat storage material or simply PCM (Mehling and Cabeza 2007). These materials can be used for heat or cold storage. In order to use these materials to store thermal energy, the latent heat property of PCM is an important factor for suitable applications. As shown in Fig. 1, at the very beginning, the material receives sensible heat. As soon as it reaches the melting point, the material absorbs heat without changing temperature until it is melted fully. Subsequently, it takes sensible heat. Similarly, during solidification, the storage material follows the reverse path.

Hence, the amount of latent heat storage by a material depends on the mass of material and its latent heat of storage which can be found from Eq. (1) (Scalat 1996).

$$E = ML \tag{1}$$

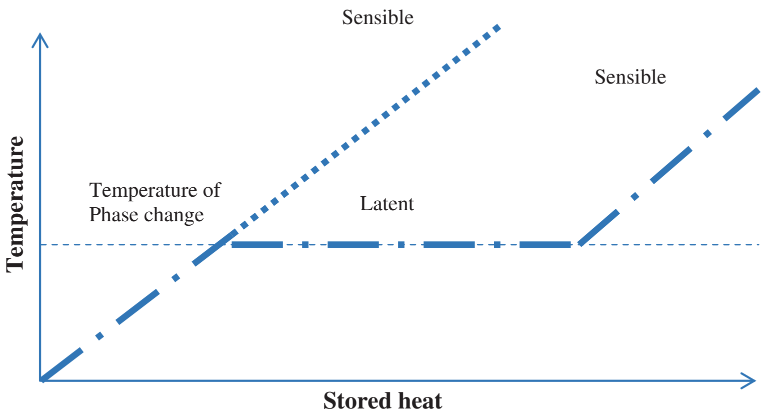


**Fig. 1** Latent heat storage with PCM

Here,

$E$ The quantity of latent heat storage, kJ
$M$ The mass of material, kg
$L$ Latent heat of phase change, kJ/kg

This phase-change behavior is useful for charging or discharging these materials with heat without increasing or decreasing the temperature of the system. Using this isothermal behavior during solidification or melting, PCM can easily be applied to store thermal energy (Ewing 2011). In this context, PCM with suitable thermophysical properties should be selected for different applications such as space heating, space cooling, power generation, green house heating, solar cooking, waste heat recovery system, and latent heat storage exchanger (Sharma and Sagara 2005).

## 3 Potential Applications of PCM in LHTS System

Among many potential PCMs, the phase-change temperature or melting point is the main important difference between them. Moreover, each material has different latent heat and thermal conductivity. Hence, the selection of PCM for a suitable application depends on its thermophysical properties. In general, there is no specific material as an ideal material to be used as PCM in LHTS system. Every type of PCM has some advantages and disadvantages.

### *3.1 Types of PCM*

In general, three kinds of PCMs such as organic, inorganic and eutectic mixture of PCMs have been used for different thermal applications (Sharma et al. 2009). Figure 2 shows the types of PCMs.

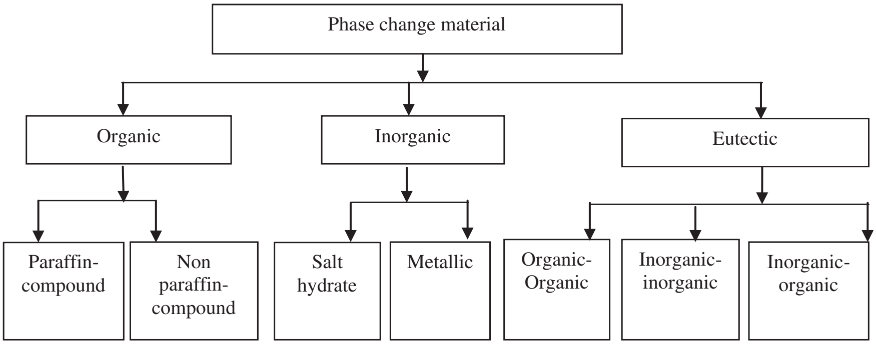


**Fig. 2** Types of phase-change materials (Sharma et al. 2009)

Paraffin and non-paraffin are two types of organic PCMs. Non-paraffin organics are fatty acids, esters, alcohols, and glycols (Baetens et al. 2010). Generally, organic PCMs are used for heating and cooling applications in building containing melting point range 20–32 °C (Tyagi and Buddhi 2007). Baetens et al. (2010) reported the advantages and disadvantages of organic PCMs.

- Advantages
  - Chemically stable
  - Supercooling free
  - No phase segregation
  - Non-corrosive
  - Non-toxic
  - High heat capacity
- Disadvantages
  - Low thermal conductivity
  - Flammable

On the other hand, in general, the inorganic PCMs as salt hydrates are used in solar thermal application (Zalba et al. 2003). The advantages and disadvantages of inorganic PCMs are also given below (Baetens et al. 2010).

- Advantages
  - High heat capacity
  - Better thermal conductivity
  - Fire resistance
  - Inexpensive
- Disadvantages
  - Corrosive
  - Supercooling
  - Phase segregation

There are three kinds of eutectic mixtures or eutectics as organic–organic, inorganic–inorganic, and inorganic–organic mixtures. These mixtures have advantages of congruent melting and freezing. Generally, eutectics are used in building applications (Tyagi and Buddhi 2007).

In literature, there are number of researches to improve the performance of different PCMs in different applications. Mehling and Cabeza (2007) reported the techniques to reduce the problems associated with phase segregation, subcooling, low thermal conductivity, stability through gelling additive, adding nucleator, dispersing high thermal conductive material, and microencapsulation of PCMs, respectively.

## *3.2 PCM Selection Criteria for Application*

Based on the temperature range of application, PCM with suitable melting temperature should be selected. Furthermore, material should also possess necessary thermophysical, chemical, kinetic, and physical properties. Hence, it is recommended to do pre-characterization of PCM with differential scanning calorimeter (DSC) to get correct thermophysical properties of PCMs as the values supplied by the manufacturer might be varied (Zalba et al. 2003). The pre-characterization also can be done by differential thermal analysis (DTA) and T-history method (Zhou et al. 2012a). Table 1 demonstrates the desired properties of PCMs (Sharma et al. 2009; Baetens et al. 2010; Cabeza et al. 2011).

## *3.3 Different Thermal Applications of PCMs*

For a particular application, selection of a PCM is an important step. In general, the melting temperature or the phase-change temperature range of the PCM is the main observation for using in an appropriate application. Some other important parameters must also be taken into consideration for a suitable usage of LHTS systems. Table 2 demonstrates different thermal applications of different PCMs.

**Table 1** Desired PCM properties (Sharma et al. 2009; Cabeza et al. 2011; Baetens et al. 2010)

| Thermal properties | Physical properties | Kinetic properties | Chemical properties | Economics |
|---|---|---|---|---|
| (i) Suitable phase-change temperature<br>(ii) High latent heat of fusion<br>(iii) Good heat transfer capacity | (i) Favorable phase equilibrium<br>(ii) Density should be high<br>(iii) Small volume change<br>(iv) Vapor pressure should be low | (i) No supercooling<br>(ii) Sufficient crystallization rate | (i) Long-term chemical stability<br>(ii) Complete reversible freeze/melt cycle<br>(iii) Compatibility with materials of construction<br>(iv) No toxicity<br>(v) No fire hazard | (i) Abundant<br>(ii) Available<br>(iii) Cost-effective |

**Table 2** PCM in different thermal applications (Anisur et al. 2013)

| PCM application | Types of PCM | Potential PCMs | Melting point range (°C) |
|---|---|---|---|
| Building application | Organic | Paraffin, non-paraffin compound | 19–32 |
| | | Paraffin(RT 20, RT 26, RT 25, RT 30, RT 27, RT 32) as commercial PCM | 22–31 |
| | | Salt hydrate (Climsel C23, Climsel C24, STL 27, S27, TH 29, Climsel C32) as commercial PCM | 22–31 |
| | Eutectics | Inorganic eutectics, organic eutectics | 25–30 |
| Solar power generation | Organic | Isomalt(($C_{12}H_{24}O_{11}$.$2H_2O$) + ($C_{12}H_{24}O_{11}$)), adipic acid, dimethylol propionic acid, pentaerythritol, AMPL (($NH_2$)($CH_3$)C($CH_2OH$)$_2$), TRIS (($NH_2$)C($CH_2OH$)$_3$), NPG (($CH_3$)$_2$C($CH_2OH$)$_2$), PE (C($CH_2OH$)$_4$) | 147–260 |
| | Inorganic | $MgCl_2$.$6H_2O$, Hitec:$KNO_3$–$NaNO_2$–$NaNO_3$, HitecXL: 48 %Ca($NO_3$)$_2$–45 %$KNO_3$ 7 %$NaNO_3$, Mg($NO_3$).$2H_2O$, $KNO_3$–$NaNO_2$–$NaNO_3$, 68 % $KNO_3$–32 %$LiNO_3$, $KNO_3$–$NaNO_2$–$NaNO_3$, Isomalt, $LiNO_3$–$NaNO_3$, 40 %$KNO_3$–60 %$NaNO_3$, 54 %$KNO_3$–46 %$NaNO_3$, $NaNO_3$, $KNO_3$/KCl, $KNO_3$, KOH, $MgCl_2$/KCl/NaCl, $AlSi_{12}$, $AlSi_{20}$, $MgCl_2$, NaCl, LiF, KF | 115–897 |
| Solar cooking | Organic | Fatty acid (stearic acid), commercial grade of acetamide, and acetanilide | 55.1, 82, 118.9 |
| | | Erythritol | 112 |
| | Inorganic | Magnesium chloride hexahydrate | 116.7 |

(continued)

**Table 2** (continued)

| PCM application | Types of PCM | Potential PCMs | Melting point range (°C) |
|---|---|---|---|
| Engine cold start | Organic | $Na_2CO_3.12H_2O$ | 32–36 |
| | Inorganic | Sodium phosphate dibasic dodecahydrate ($Na_2HPO_4.12H_2O$), sodium sulfate decahydrate ($Na_2SO4.10H_2O$), calcium chloride hexahydride ($CaCl_2.6H_2O$), lithium nitrate trihydrate ($Li\text{-}NO_3.3H_2O$), zinc nitrate hexahydrate ($Zn(NO_3)_2.6H_2O$) | 29–48 |
| | | $Na_2SO4.10H_2O$, $NaOH.H_2O$, NaOH, $Ba(OH)_2.8H_2O$, $CaO.3H_2O$ | 32–64 |
| Waste heat transportation | Organic | Erythritol, NaOH | 118, 320 |
| Lithium-ion battery cooling for electric vehicle | Organic | Graphite composite, paraffin wax | 52–55,40–44 |
| Greenhouse heating | Inorganic | Calcium chloride hexahydrate, glauber's salt (sodium sulfate decahydrate) | 32–35 |

## 4 LHTS and Energy Sustainability

We need the implementation of sustainable development of renewable clean energy with long-term planning and immediate steps to achieve the solution of the present environmental problems. Renewable energy could be the best option to meet the energy demand as the demand is increasing to cope with the civilization and economic growth. It is also attractive because of its environmental friendliness. Global energy demand will increase by 1.5–3 times to cope with the energy services by 2050. Accordingly, realization is likely increased in respect of energy-related environmental impact such as acid precipitation, stratospheric ozone decaying, and global climate change (Dinçer and Rosen 2010). Hence, there is a definite connection in between energy and environment. Figure 3 shows the projection of global energy consumption which would be 769.8 quadrillion Btu in 2035, although the energy consumption growth rate would be decreased from 2015. In this connection, Fig. 4 shows that the world energy-related carbon dioxide emissions will increase from 30.2 billion metric tons in 2008 to 35.2 billion metric tons in 2020 and 43.2 billion metric tons in 2035—an increase of 31 % over the projection period (IEO 2011). Therefore, fuel and energy consumption must be significantly restrained and stabilized for sustainable future by any means.

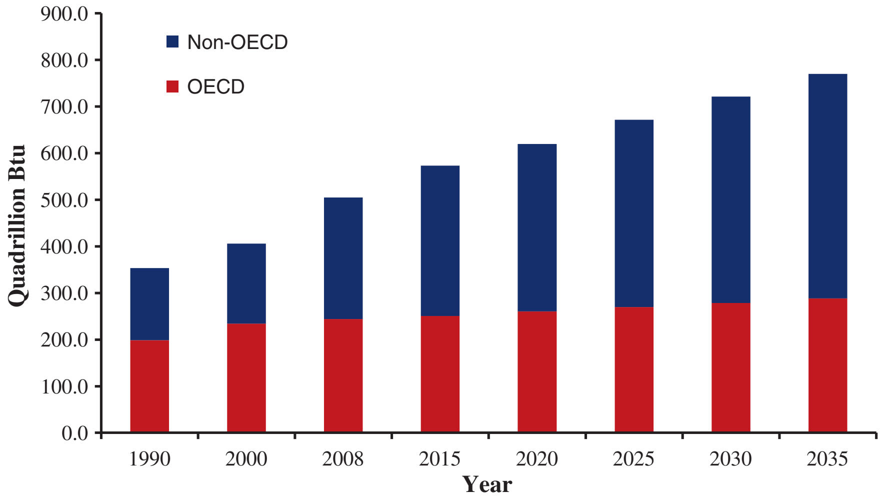


**Fig. 3** World energy consumption, 1990–2035(quadrillion Btu) (IEO 2011)

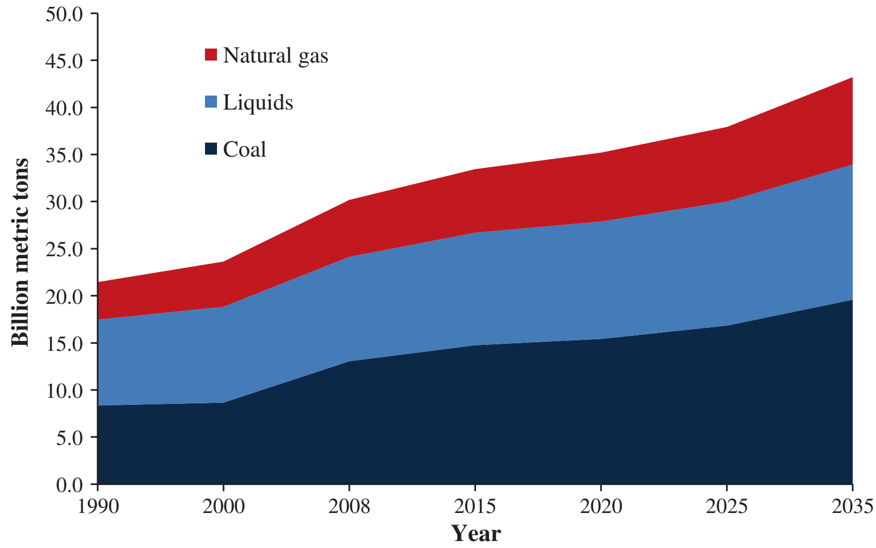


**Fig. 4** World energy-related carbon dioxide emission by fuel, 1990–2035 (IEO 2011)

## *4.1 LHTS System—A Prospect for Future Energy*

Many scientists are involved to explore sustainable green technologies to reduce fossil fuel consumption. Solar energy is one of the green types of energy sources as it is easy to harvest and causes no air pollution. Although this energy source is

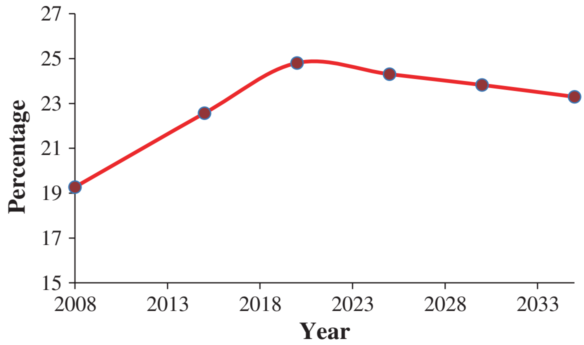


**Fig. 5** Contribution of renewables in percentage for world net electricity generation, 2008–2035 (Anisur et al. 2013)

abundant, it has a limitation due to intermittent energy supply. However, the magnitude and importance of solar energy as a renewable energy source is obvious. The sun radiates energy at a rate of $3.8 \times 10^{23}$ kW. Approximately $1.8 \times 10^{14}$ kW is collected by the earth. Only 60 % of this amount reaches the earth's surface. The other 40 % is returned back and absorbed by the atmosphere. If 0.1 % of this energy can be utilized by solar thermal systems with efficiency of 10 %, then it can generate four times of the world's total generated electricity that is 3000 GW. Furthermore, the total annual solar radiation falling on the earth is more than 7500 times of the world's total annual primary energy consumption that is 450 EJ (Thirugnanasambandam et al. 2010). Cavallaro (2010) studied on the availability of the solar radiation in many parts of the world. He reported that it could be possible to generate about 100–130 GW h of electricity per year from a surface area of 1 $km^2$ by solar thermal technologies. This is the equivalent energy of a traditional 50 MW power station fueled by coal or natural gas in every year. Hence, the applications of solar thermal energy should be increased to maximize the contribution of present renewable energy sources in world energy consumption. Solar thermal energy can be used for maximum proportion of world net energy consumption using the solar thermal energy storage. Figure 5 is showing the contribution of renewable energy resources for world net electricity generation from 2008 and predicting the contribution up to 2035.

The prediction says the contribution of renewable energy will decrease instead of increase by 2020. This can be overcome by immediate utilization of solar energy using energy storage. LHTS is a potential energy storage system to solve the unpredictability of sun radiation. Anisur et al. (2013) reported that LHTS system application in building and solar thermal power system could be able to reduce approximately 3.43 % carbon emission. Their ability to provide or absorb relatively large amount of thermal energy particularly during mismatch in the supply and demand of the energy sources is growing interest among researchers to combat the present alarming trends of fossil fuel consumption. Hence, these storage systems have been growing considerable attention worldwide because of their large potential for fossil fuel savings. Numerous researches have been done to implement this LHTS using solar thermal energy to the primary energy consuming sectors such as electricity generation and residential sector. In order to restrain these huge energy consumption and fossil fuel saving, the LHTS has been explored as a potential candidate utilizing solar thermal energy.

## 4.2 Green Energy Harvesting Using LHTS System

### 4.2.1 LHTS System in Solar Thermal Power Generation

In order to generate solar thermal electricity, concentrating solar collectors are widely used. Although there are different system designs in solar thermal power plant for focusing and accumulating sunlight, the final step of generating electricity is similar to common fossil-fired power plants. Generally, power plant uses a heat engine to generate electric energy from thermal energy. In this process, a working fluid is compressed, heated, and evaporated. Subsequently, the fluid is expanded to drive an electric generator via turbine blades or pistons. After that, the fluid is condensed again and follows the process line. Figure 6 displays this general process. Concentrated solar power (CSP) focuses sunbeams using reflectors to generate heat and then uses the heat to elevate steam to drive turbines and generators.

In absence of solar radiation, the LHTS can be used to produce the required steam to run the turbine. A few researches have been reported in literature about integrating the LHTS with the solar thermal power plant. Bayón et al. (2010) studied on LHTS using 54 % $KNO_3$/46 % $NaNO_3$ PCM for steam production with parabolic trough collector under real working condition. Laing et al. (2011) suggested three-part storage method. One PCM storage was used for two phase evaporation. In addition, sensible heat concrete storage was used for storing heat for

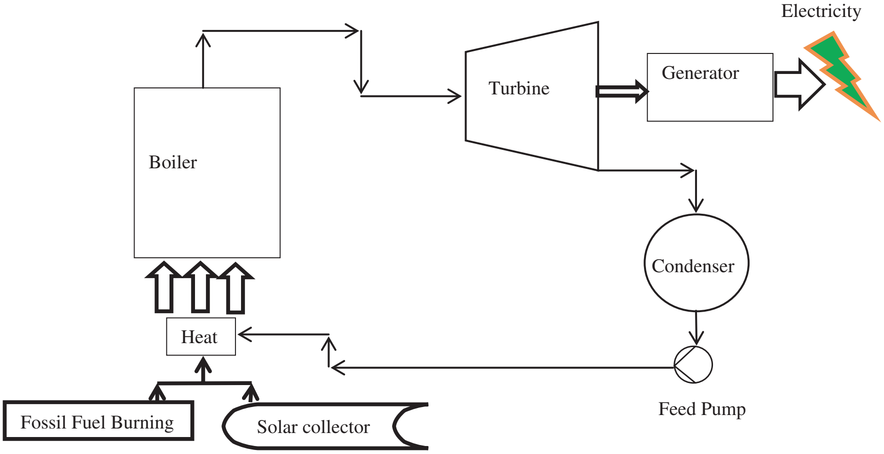


**Fig. 6** Principle of converting solar and fossil heat into electricity (Birnbaum et al. 2010)

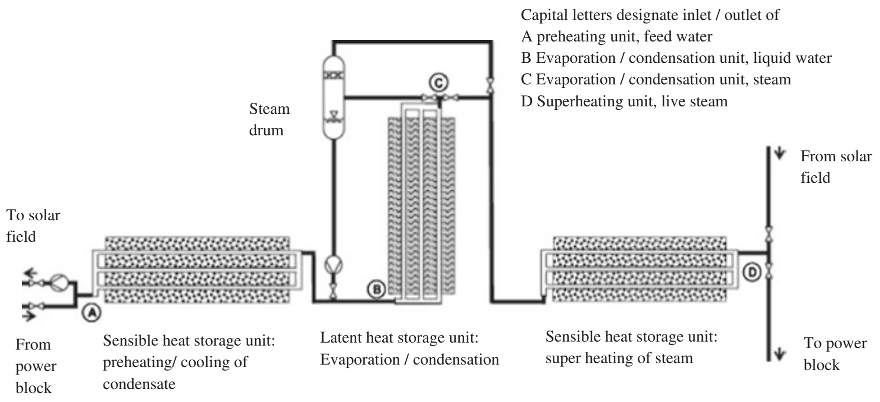


**Fig. 7** Schematic diagram of the three-part thermal energy storage system (Laing et al. 2011)

preheating of water and superheating of steam. The storage capacity of this system was approximately 1 MWh. During discharge, as shown in Fig. 7, water is fed into the preheater A that raises the heat near to the boiling curve at B. Then, the hot water is passed through the LHTS storage, and a portion of the water is evaporated in C. A steam drum is used to separate the steam from the water. The steam passes through the concrete unit D for superheating while the separated water from steam is recirculated on the PCM storage. Specific capacity of 80 kWh/m$^3$ and specific power of 40 kW/m$^3$ could be attained through this system. No degradation was noticed after 172 cycles of melting and solidification. Hence, a three-part combine LHTS are a favorable alternative for application in DSG power plant.

Morisson et al. (2008) used one block of PCM composite. In this composite, water or vapor was used to cross the block through a set of tubes. The PCM composite contains CEG (compressed naturally expanded porous graphite matrix). The CEG holes are then packed with binary eutectic $NO_3K/NO_3Na$. This study designed with 20 kW$_{th}$ storage with charging time of 2 h and average power of 10 kW. Recently, Adinberg et al. (2010) developed and tested new RHTS (reflux heat transfer storage) concept. High temperature (350–400 °C) superheated steam can be produced with this concept. For the target temperature of 400 °C, they selected Zinc–Tin alloy (70 w% Zn) as PCM and eutectic mixture of biphenyl and diphenyl oxide (26.5 and 73.5 %, respectively). They discussed and assessed this RHTS concept by integrating it to a 12 MW solar thermal electric plant.

### 4.2.2 LHTS System Applications in Residential Sector

Air-conditioning is one of the major utility that uses large part of the building energy consumption. Isaac and Vuuren (2009) reported a model to investigate the heating and cooling energy demand in the residential sector. It is increased from about 27 EJ in 2000 to about 35 EJ in 2020 and almost 80 EJ in 2100. Nowadays, rapidly increasing building energy consumption has become a major problem. In developed countries, buildings are responsible for 20–40 % of the total final energy consumption (Pérez-Lombard et al. 2008; Parameshwaran et al. 2012; Tyagi et al. 2011; Nässén et al. 2007; Zhu et al. 2009). In 2006, as demonstrated by the US energy department, the building sector consumed 38.9 % of the total primary energy used in USA, whereas 34.8 % of this energy is used for thermal comfort in buildings (Kwok and Rajkovich 2010). Subsequently, in 2009, about 40 % of the total fossil energy was consumed by the buildings in USA and EU (Zhou et al. 2012b). Al-Abidi et al. (2012) reported that HVAC systems are accountable for around 55 % of the total building energy consumption.

The present building energy consumption with rapidly increasing trend for air-conditioning should get utmost priority to reduce the total energy consumption as well as carbon dioxide emission. The present air-conditioning system can be replaced by LHTS system. The ambient hot air during day time for charging and cold air at night for discharging or vice versa can be used for this purpose. Recent researches have been focused on the energy consumption related to heating and cooling of residential sector. There are mainly two ways to implement the LHTS system for building application such as PCM inclusion in building material and active ventilation using LHTS system.

Many researches have been done by incorporating PCM into building material such as wall, wall board, ceiling board, gypsum board, building blocks, concrete, tile, and cement for thermal comfort in building. Behzadi and Farid (2011) studied experimentally and numerically using SUNREL on PCM-integrated building material performance. They reported that air-conditioning energy could be optimized up to 34.5 % in summer using PCM-integrated building material. Tyagi and Buddhi (2007) reviewed and briefly demonstrated on PCM inclusion in building materials, for example, wall, wall board, PCM shutter, and building blocks. Later, Tyagi et al. (2011) reported PCM encapsulation technique in concrete and wall/wallboard. Su et al. (2012) demonstrated preparation of microencapsulated phase-change materials (microPCMs) for building material application such as gypsum board. Oliver (2012) also examined the performance of gypsum board with different weight percentage of PCM and found remarkable result.

It is quite impossible to impose this passive cooling technology in the present building structure. Rather, there is still an option to replace the present air-conditioning system by active air cooling system. Generally, active cooling with LHTS system consists of a heat exchanger where a passage is kept for air flow and PCM is kept inside a shell or slab. In this active cooling system, the air flow is produced by a fan or pump to be cooled. The study of active air cooling with shell/rectangular type LHTS system is a conjugate phase-change convection problem (Zhang and Faghri 1996b). Here, tube is placed inside a PCM container for HTF flow. In this type of arrangement, forced convective heat transfer is experienced in the thermal and hydrodynamic entry region of the tube. Zhang and Faghri (1996b) reported that a major error is expected, if a steady state fully developed heat transfer correlation is applied to calculate the heat transfer coefficient. Hence, this forced convective heat transfer inside the tube is not occurred due to constant wall temperature and constant heat flux. In order to solve this problem, they demonstrated a simple approach to calculate the local Nusselt number for varying wall temperature using the analytical method given by Kays and Crawford (1980). This simple method can be used to analyze a shell and tube type LHTS system.

Vakilaltojjar and Saman (2001) presented a semi-analytical analysis of LHTS system to predict the performance for air-conditioning application. In their system, the PCMs were embedded inside flat rectangular slabs maintaining a gap between them for laminar air flow. In order to solve this problem, they considered varying wall temperature in the air flow. They received a prospective result with this system for reducing air temperature. They also found the minimal influence of air velocity profile and wall thermal resistance. On the other hand, the air passage between the slabs and slab thickness should be in an optimum range. Afterward, Saman et al. (2005) also carried out a 2-D numerical analyses based on enthalpy formulation to examine thermal performance of a rectangular thermal storage unit. They reported that the heat transfer rate and melting time depended on inlet air temperature and air flow rate. They also compared the predicted outlet air temperatures and heat transfer rates with experimental results and found a good match between them. Halwa et al. (2005) also analyzed the LHTS system with the same rectangular geometry for a roof-integrated solar heating system. They applied finite difference enthalpy method of Voller (1990) considering two dimensional heat transfer mode to analyze the roof-integrated solar heating LHTS system at varying wall temperature. Mainly, they focused on melting and freezing characteristics of PCM slabs in an air flow. Accordingly, they found the greatest heat transfer rate during sensible heat gain and a constant heat transfer rate at the time of latent heat gain. Later, sensible heat was gained with lowest heat transfer rate. They also suggested in their report regarding some important design factors for LHTS system, for example, suitable melting point of PCM, the limit of outlet and inlet air temperature and flow rates. Recently, Mosaffa et al. (2013) again investigated the same storage system using multiple PCM inside flat slab for air cooling. They also performed a 2-D numerical analysis using COMSOL multiphysics and validated with experiment. Certainly, they received a very good agreement between analytical and experimental data. There are very few works on shell and tube type LHTS system for active cooling of air. This shell and tube type of LHTS system for air cooling–heating also should be analyzed to reduce heat loss from the system as there is a scope to reduce heat loss using cylindrical shell geometry (Agyenim et al. 2010). Vyshak and Jilani (2007) investigated numerically on the effect of total melting time of PCM which was embedded inside a rectangular, cylindrical, and cylindrical shell. It was reported that among the three containers, the cylindrical shell takes the least time to store same amount of energy for the identical surface area and PCM mass. In this context, a theoretical model was developed by Esen et al. (1998) to understand the impact of thickness of PCM mass on melting time. This model shows that the cylindrical shell takes the least melting time in comparison with the other two geometries because it contains the least PCM mass thickness maintaining the same surface area and PCM mass. Accordingly, Mosaffa et al. (2012) reported an approximate analytical model for the freezing process using the same geometry with radial fins for air-conditioning applications. Considering identical PCM mass and heat transfer area, they found better performance of shell and tube LHTS system than the rectangular geometry. Therefore, the use of cylindrical shell is well justified to reduce heat loss. Furthermore, Yingqiu et al. (1999) demonstrated a new alternative iteration method with temperature and thermal resistance formulation was demonstrated to solve the error arising from the assumption of constant fluid temperature inside the tube. In this context, they also considered the variation of wall temperature due to different fluid temperature in a turbulent flow of HTF through the tube.

## 4.3 Recent Development of LHTS

Although LHTS system serves as a better thermal energy storage device for their unique properties such as high thermal energy density and isothermal behavior, the limitation with low thermal conductivity of PCMs has been found a major problem in practical applications. The effects of low thermal conductivity in the system are exhibited during energy retrieval or withdrawal process with an appreciable temperature drop during the process. For this reason, the phase-change process has not been shown expected result for extensive use of LHTS system. In order to resolve the drawback mentioned above, it is required to improve the thermal performance of the PCMs. In literature, the present researches related to enhance thermal performance of LHTS system has been reported through fins or extended surfaces and thermal conductivity enhancement in the PCMs.

The main purpose to use fins or extended surfaces is to provide extra heat transfer surface in the storage system. In LHTS units where heat transfer between HTF and PCMs are involved, the location of the fins is generally based on the relative heat transfer coefficient as the efficiency of fins increases with decreases in heat transfer coefficient (Incropera et al. 2011). Most generally, fins are placed in the PCM side as the heat transfer in PCM side is less due to low thermal conductivity. The common geometries consisting of fins in LHTS system have been presented in Fig. 8.

During melting, the main heat transfer mechanism is conduction and later it is dominated by natural convection. The main reason is that the solid region moves away from the heat transfer surface and the thickness of the liquid region increases near the heat transfer surfaces. As the thermal conductivity in liquid PCM is lower than solid PCM, the effects of conduction heat transfer almost become negligible as the melting continues. Again further melting occurs as the temperature gradient exists in the liquid PCM. Integrating fins in PCM could accelerate the melting of PCM by increasing the heat transfer area.

Akhilesh et al. (2005) numerically studied top wall heated rectangular module with PCM. In that case, the natural convection in PCM was ignored. The analysis included the effect of adding more number of fins per unit length on the melting process. More number of fins per unit length led to more heat transfer area and

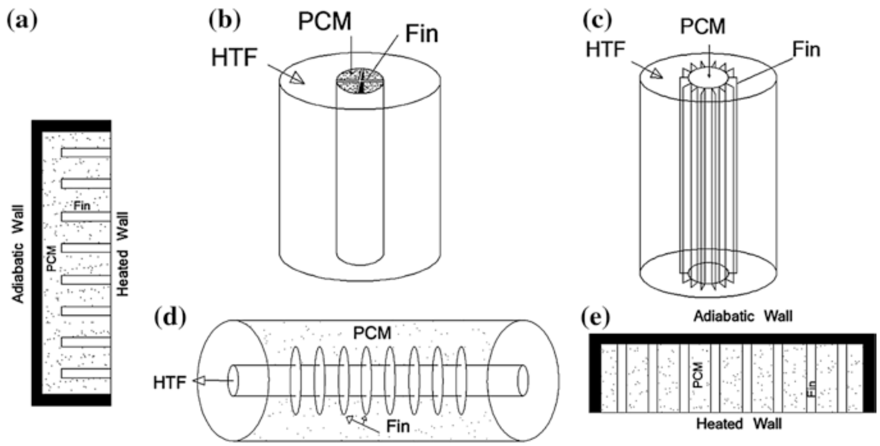


**Fig. 8** **a** Rectangular LHTS unit with horizontal fins emerging from vertical heated wall (Lacroix and Benmadda 1998). **b** LHTS unit with internal longitudinal fins (Velraj et al. 1997). **c** LHTS unit with external longitudinal fins (Castell et al. 2008). **d** Shell and tube LHTS unit with annular fins (Lacroix 1993). **e** Rectangular LHTS unit with vertical fins emerging from top heated wall (Lacroix and Benmadda 1998)

thus energy could be stored. However, reaching a certain value of fins, the heat transfer was not increased.

Performance enhancement of a rectangular geometry including horizontal fins mounted with the vertical heated walls attached to PCM was investigated by Gharebaghi and Sezai (2007). Their results indicated that the heat transfer could be enhanced due to the presence of fins. It was also reported that vertical heated walls with horizontal fins should be preferred to horizontal heated walls with vertical fins. Shatikian et al. (2005) and Shatikian et al. (2008) studied the melting performance of PCM for different thicknesses of PCM and fin thicknesses. From the results, it was revealed that the melting rate in the narrow cases was faster than that of in the wider cases. In wider cases, the fluid motion became stronger as the melting progressed. On the other hand, in narrow cases, the fluid motion was hardly seen even at advanced stages of melting.

For a fixed module size, the number and distance between the fins are important as described by Lacroix and Benmadda (1998). They described that natural convection was prevented when the distance between the fins were decreased. As a result, better natural convection could be experienced if the less number of fins were used. However, too large distance between the fins led to the reduction in total heat transfer surface area. With annular fins, Lacroix (1993) developed a three dimensional numerical model for melting in shell and tube LHTS system where PCM was inside the shell and HTF was flown inside the tube. From the result, it was indicated that large amount of heat was conducted through the fins along the radial direction. Later, similar configuration was studied by Zhang and Faghri (1996a). This numerical study included the effect of fin height. It was shown that the liquid fraction of the PCM at any time during the melting could be increased by increasing the fin height.

During solidification process, the main heat transfer mechanism is conduction. In solidification, the natural convection is present only in the initial stage and it becomes almost zero (Lamberg 2004). In a rectangular storage with and without fins, Stritih (2004) estimated fin effectiveness experimentally. The results showed that the fin effectiveness was significantly high and because of that 40 % reduction in solidification time was observed. Effect of vertical fins attached to horizontal constant temperature wall on solidification of high temperature PCM was simulated by Guo and Zhang (2008). In the simulation, when vertical fins were not attached, the solidification started on the wall and it continuously moved away only in the vertical upward direction. But when vertical fins were attached, the solidification front was observed in vertically as well as in the horizontal direction simultaneously.

In cylindrical storage with radial fins, Choi and Kim (1992) studied the heat transfer characteristics of PCM in solidification. A greater heat transfer was observed in fins arrangement compared to unfinned system. From the above information, it is clear that fins may play an important role both in melting and solidification process. Hence, the optimized fin number for a specific geometry of storage system is needed to be explored.

Apart from this heat transfer area increasing technique, during the last two decades, many researches have been performed with highly conductive nanosized particles for the improvement of PCM thermophysical properties. Nanoparticle dispersed PCM is showing better performance in thermal properties. These PCMs referred to as nanoparticle-enhanced PCM or NEPCM (Fan and Khodadadi 2011).

## 5 Conclusions

In this chapter, LHTS system using PCM has been presented as a potential candidate for energy sustainability. Solar energy can provide an abundant source of energy. However, due to its unsteady nature, the application of solar thermal energy is quite difficult. In this context, the LHTS can be used to store solar thermal energy for future use during the absence of solar radiation. There are different kinds of PCM for different solar thermal application. According to the present statistics, electricity generation and building sector have been considered as the major fossil fuel consuming sector. Both sectors can be optimized with the application of LHTS system. The current researches on LHTS systems for solar thermal electricity and building heating and cooling application have been found quite optimistic. In this chapter, a brief review on present studies of LHTS system application in these sectors has been reported. Moreover, the development studies of PCM also have been highlighted.

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# Part V
# Bio-mass, Bio-fuels, Bio-gas

# Energy Sustainability by Biomass

**Manjari Shukla, Sanjay Singh, Sarfaraj Ahmad Siddiqui and A. Shukla**

**Abstract** With rapidly growing energy demand and concerns over energy security and environment, researchers worldwide are exploring hard to deploy renewable energy sources. Development of economical biofuel at sufficiently large scale may provide major breakthrough in this direction, with strong impact on sustainability. More importantly, environmental benefits may also be achieved by the utilization of renewable biomass resources, which could help the biosphere in longer time. This chapter reviews the availability and bioenergy potentials of the current biomass feedstock. These include the following: (i) food crops such as sugarcane, corn and vegetable oils, classified as the first-generation feedstocks, and environmental and socio-economic barriers limiting its use; (ii) second-generation feedstocks involving lignocellulosic biomass derived from agricultural and forestry residues and municipal waste followed by constraints for their full commercial deployment. Key technical challenges and opportunities of the lignocellulosic biomass-to-bioenergy production are discussed in comparison with the first-generation technologies. (iii) The potential of the emerging third-generation biofuel from algal biomass is also reviewed.

**Keywords** Biomass · Energy security · Environmental benefit · Sustainability

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## 1 Introduction

To meet the expanding demand for fuel and energy, low-carbon biomass can provide a significant fraction of the new renewable energy besides many other traditionally available resources, wind, hydrothermal and solar energy powers. Moreover, we need to reduce our emissions of heat-trapping gases such as carbon dioxide to levels. By reducing the levels of $CO_2$ in the environment will avoid the worst impacts of global warming. Carbon dioxide emissions are expected to reach new record high, increasing from 31 Gt in 2011 to approximately 37 Gt in 2035 (IPCC 2013), which is maximally due to increasing global demand for energy production. Most of the developed countries including USA, UK, European countries, China and Brazil (belonging to the Organisation for Economic Co-operation and Development, shortly known as OECD) have been adopting new policies to avoid serious concerns over many environmental issues and meet increasing energy demand that encourages the growth of renewable energy. The other low-carbon methods for generation of electricity are wind, geothermal, hydroelectric and solar approaches, and these contribute 13 % of the global energy consumption, in which bioenergy accounts for approximately 10 % (summarized in Fig. 1). To define, term 'Bioenergy' refers to the energy content in solid, liquid and gaseous products derived from biological raw materials, that is biomass (IEA 2010). These biofuels

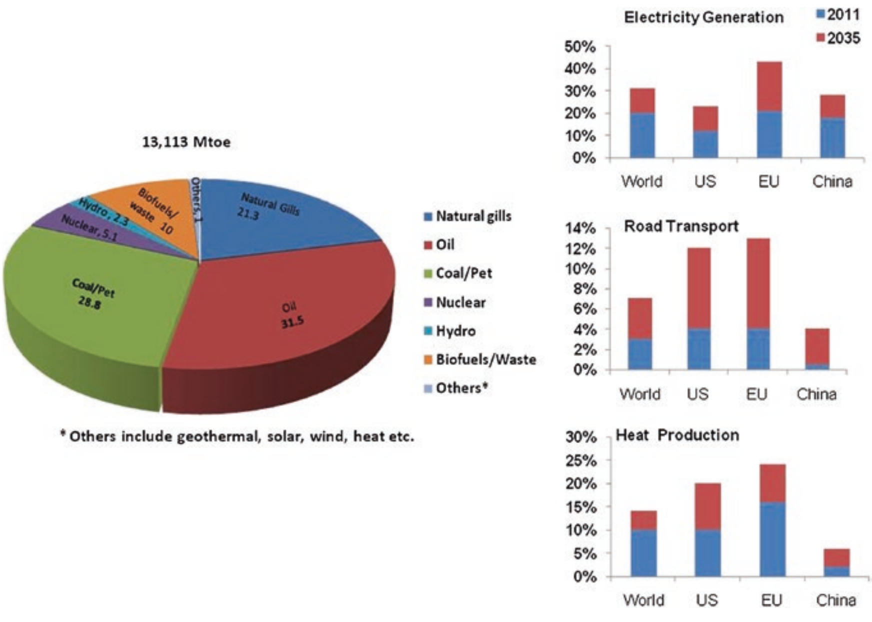


**Fig. 1** World primary energy demand 2011 (*left* modified from IEA 2013a, b) and renewable energy share in total primary energy demand by category and region in the New policies Scenario excluding traditional biomass 2011 and 2035; (modified from WEO 2013) *Note* US – United States, EU – European Union

are used for transport (e.g. bio-ethanol and biodiesel) and products to produce electricity and heat (e.g. wood chips and pellets), as well as biogas (e.g. biomethane and biohydrogen) (IEA 2013a, b), and their production process is still under different steps of technology development for its commercial exploitation, which is discussed in detail in this chapter.

The major fraction of biofuel is used in transport system around the globe. These biofuels are generated in multiple step process from municipal waste and crop waste materials, involving harvesting, extraction, processing, and supply for their utilization. The crops and grains with high sugar and starch content are fermented into bio-ethanol; or seeds producing vegetable oils are used in biodiesel. First-generation biofuels include commonly used vegetable oils, biodiesel, bioalcohols, biogas, solid biofuels, and syngas (IEA 2010). These first-generation technologies are major breakthrough towards using biorenewable resources for producing energy material, but face challenges for land and water competition over food versus fuel generation (Gasparatos et al. 2013; IEA 2010). This led to next step of biofuel generations from non-food biomass, including residues of crops or forestry production (e.g. Miscanthus), lignocellulosic fraction of municipal and industrial solid waste, and algal biomass (Gupta et al. 2014; Sims et al. 2010). Research is still going on for second-generation biofuels including biohydrogen, biomethanol, DMF, Bio-DME, Fischer-Tropsch diesel, biohydrogen diesel, mixed alcohols and wood diesel. However, potential of lignocellulosic biomass varies and depends on the type, abundance and cost of biomass feedstocks, efficiency of the available processing technologies, and the pattern of energy demand. It is apparent now that algae are capable of much higher yield than other feedstock. This emphasized further dedicated research towards biofuel derived from algae and is known as ‘third-generation biofuels’. This chapter is focused on different existing and potential biomass sources with emphasis on algal biofuel resources and identifies the future challenges in the deployment of third-generation resources to meet energy targets.

## 2 Biomass Resources and Their Bioenergy Potential

### *2.1 First-Generation Feedstocks*

First-generation biofuel relates to starch-, lipid- and sugar-derived energy fuel from traditional agricultural crops for food and animal feed purposes. These biofuel products include simply bio-ethanol (from starch and sugar crops) and biodiesel (from oil seeds).

#### 2.1.1 Starch/Sugar Crop Resources for Bio-ethanol

The first-generation bio-ethanol is produced by crops yielding high content of sugar (e.g. sugarcane, sugar beet and sweet sorghum) or starch (e.g. corn, wheat and

**Table 1** First-generation crop, biofuel and co-product yield

| Bio fuel type | Crop | Leading country/region | Crop yield (ton/ha) | Biofuel yield | Co-product yield (ton/ha) |
|---|---|---|---|---|---|
| Bio-ethanol | Corn | USA | 9.9 | 3800 | 4.2 |
| | Sugarcane | Brazil | 79.5 | 7200 | – |
| | Sugarcane | South Africa | 60 | 5000 | – |
| | Sugar beet | EU | 79.1 | 7900 | 4 |
| | Wheat | EU | 5.1 | 1700 | 2.7 |
| | Wheat | China | 4.7 | 1700 | 2.5 |
| | Cassava | Brazil | 13.6 | 137 | – |
| Biodiesel | Rapeseed | EU | 3.1 | 1300 | 1.7 |
| | Soya bean | USA | 2.8 | 600 | 4.2 |
| | Oil palm | South-East Asia | 18.4 | 4200 | 4.2 |

*Source* FAOSTAT (2011), Gupta et al. (2014), Ngo et al. (2014)

cassava) and converted into ethanol by a series of hydrolysis steps followed by fermentation. Ethanol is the most widely used renewable transportation biofuel in the United States, with the production of 13.3 billion gallons in 2012 (John 2013). Corn is also valuable feedstock containing high amount of carbohydrates and is dominating the global market with approximately 60 billion litres produced in 2012. The by-products of ethanol conversion processes, for example dried distillers' grains and solubles (DDGs), are protein-rich sources to feed livestock. USA is the largest supplier of bio-ethanol (corn based), followed by sugarcane-based ethanol at 20 billion litres produced mainly by Brazil (REN21 2013). Other marginal feedstocks that are used to produce bio-ethanol include but are not limited to sugar beet (EU), maize, sweet sorghum (China, USA, Brazil), cereal (Canada, EU), and cassava (Nigeria, Brazil, Thailand, and Indonesia) (Table 1). The process to convert sugar-based biomass to ethanol is rather simple, involving the fermentation of C6 sugars (mostly glucose) using yeast species such as *Saccharomyces cerevisiae* or *Zymomonas mobilis* (Lin and Tanaka 2006). Starch is complex carbohydrate and its fermentation requires it to be hydrolysed to fermentable sugars with aid of enzymes (α-amylase) (Lin and Tanaka 2006). This makes the process and time and energy required to obtain sugar-based ethanol from starch significantly greater than the glucose based. There are about 650 ethanol plants operating globally, together providing a total annual capacity of 100 billion litres (REN21 2013). According to report by Wang et al. (1999), a litre of ethanol contains approximately 66 % of the energy that provided by a litre of petrol.

### 2.1.2 Oil Crops for Biodiesel

Biodiesel is an alternative fuel for diesel engines made from different vegetable oils (e.g. soya bean oil, sunflower oil, rapeseed oil) using alkali catalyst. The majority of biodiesel is produced by alkali-catalysed (like NaOH, KOH) tranesterification with methanol which results in shorter reaction time. Biodiesel operates in compression ignition engines (Van Gerpen 2014). Different resources and utilizing countries are summarized in Table 1. Rapeseed in EU, soya bean in USA and Latin America, and palm and coconut oil in tropical Asian countries (such as Malaysia and Indonesia) are used for biofuel production (Table 1). Resources used by different regions depend upon the availability of the seed and total oil content within. The oil content in rapeseed and soya bean is 35 and 21 %, respectively (Ramos et al. 2009). Palm oil with 40 % of oil content has the highest oil yield per area (5 tons/ha) as compared to other oilseeds (e.g. 1 tons/ha for rapeseed and 0.52 tons/ha for soybean) (Balat and Balat 2010). Global biodiesel production in 2012 was 22.5 billion litres, with the EU (led by Germany) accounted for 41 % of total production, followed by the USA (16 %), Argentina, Brazil and China (>10 % each) (REN21 2013).

The major difference between various oil feedstocks is the types of fatty acids attached in the triacylglycerols (TAG), which determine degree of saturation/unsaturation and molecular structure (Ramos et al. 2009). All these factors, in turn, affect production processes, quality and costs of the biodiesel products (Ramos et al. 2009). The transesterification of oil to biodiesel is a stepwise reaction of TAG with methanol to form esters and glycerol in the presence of catalyst (Balat and Balat 2010). Therefore, the majority of biodiesel can be produced using alkali-catalysed transesterification process as it is the most economical option, requiring low processing temperature and pressure while achieving a 98 % conversion yield (Balat and Balat 2010). On the other hand, enzyme-catalysed processes are gaining interest due to low energy consumption, reduced soap formation and high purity of glycerol (Christopher et al. 2014). However, the process is not cost-effective and is the main obstacle to the commercialization of these processes. The conversion process typically yields valuable by-products such as glycerol for food and pharmaceutical uses and crushed bean 'cake' as a source of animal feed.

### 2.1.3 First-Generation Feedstocks: Disadvantages

The production of biomass feedstocks and its conversion to bioenergy have numerous socio-economic and environmental impacts. Although the first-generation biofuels have been commercialized worldwide with mature technologies and markets, its sustainability has been questioned based on the competition with food crops and the effects on the environment and climate change (Gasparatos et al. 2013). Biofuel use represents an increasingly important share of global cereal, sugar and vegetable oil production.

By 2020, bio-ethanol share will increase to 13 % of annual global corn production compared with 11 % on the average over the 2008–2010 period, and 35 % of global sugarcane production compared with 21 % over the baseline period of 2008–2010 (OECD-FAO 2011). The share of vegetable oil to be used for biodiesel production at the global level is expected to reach 16 % compared with 9 % over the baseline period of 2008–2010 (OECD-FAO 2011). The outlook of OECD-FAO certainly raises concerns about the impact of biofuel on food prices and food supply. An extensive study by Fischer et al. (2009) predicted that biofuel expansion may further increase the price of agricultural commodities by 8–34 % (cereals), 9–27 % (other crops) and 1–6 % (livestock) by 2020.

Furthermore, reduction in water and soil quality due to intensive use of fertilizers and agrochemicals has also been linked to the increased biofuel production, in particular to the expansion of sugarcane ethanol in Brazil and palm oil biodiesel in South-East Asia (Gasparatos et al. 2013). Therefore, increased biofuel production also reduces water availability to food production and adds more pressure on water resources in countries facing increased risk of water scarcity such as India (OECD-FAO 2011). Other impacts of biofuel production and use include greenhouse gases (GHG) emissions, air pollution, biodiversity loss, deforestation and rural development, among several others (Cherubini and Strømman 2011; Gasparatos et al. 2013; Popp et al. 2014). The cumulative environmental and social impacts of biofuel production derived from food crops have stimulated an interest towards less expensive and readily available biomass such as forest, agricultural and municipal wastes.

## *2.2 Second-Generation Biofuel*

Second-generation biofuels are supposed to overcome the problems comparatively to many first-generation bioenergy resources in terms of many issues discussed earlier, namely energy balances, greenhouse gas emission reductions, land-use requirements, and competition for food, fibre and water. However, they do not produce co-products such as animal feeds which should also be considered in a comparison (Renewable Fuels Agency 2007). The second-generation base material is non-food lignocellulosic materials and waste material after food generation, which can be divided into two groups (Sorensen 2010):

1. Biofuels derived from cellulosic and lignocellulosic plant biomass grown on marginal land (i.e. land not used for food crops).
2. Biofuels derived from organic residues or wastes, where the nutrients are taken back to land, implementing nutrient recycling. There is no or little primary energy input into producing these wastes; the energy inputs have already been expended anyway.

In the past few years, there has been extensive research on potential feedstocks and significant progresses for improving the second-generation technologies (Balat and Balat 2010; Christopher et al. 2014; Gupta et al. 2014; Sims et al. 2010). Several demonstration plants have been built in Europe with small capacities in operation.

### 2.2.1 Second-Generation Feedstock

The crops utilized have the potential to grow on wastelands and have short rotation time. These include perennial grasses (such as Miscanthus, switchgrass and reed canary) and short rotation forestry (such as willows and poplar).

(a) **Perennial grasses**. Switchgrass, which originated from North America and Miscanthus from South-East Asia, are among the best choices in terms of low input bioenergy production in the USA and EU because of their tolerance for cool temperature, relatively low water and nutrition requirements, and their ability to grow on a broad range of land types using conventional farming practices (Lewandowski et al. 2013).

**Switchgrass** is a perennial warm season bunchgrass native to North America. It can reach up to the height of 10 ft above the grass with extensive root system and usually requires 3 years to reach productive maturity having a productive life of 10–20 years and produces dry matter yields reportedly between 5 and 19 tons/ha/year, corresponding to 0.8–3.0 ton of oil equivalent (toe) per ton (Heaton et al. 2004).

**Miscanthus** take 2–3 years to obtain full production and require rhizome cuttings, resulting in additional costs associated with propagation. The established stands, however, can maintain productivity for at least 14 years with high biomass yields ranging from 5 to 43 tons/ha/year (Cadoux et al. 2012). Crop yields of perennial grasses strongly depend on local conditions, for example climate and land quality, and management system, for example irrigation and fertilization.

Other potential herbaceous crops include reed canary grass, giant reed and alfalfa adapted to temperate regions, banagrass, napier grass and johnsongrass in tropical and subtropical regions (Prochnow et al. 2009; Ra et al. 2012). These perennial grasses are also effective for carbon sequestration and soil stabilization, thus helping reduce erosion, and improving water quality and wildlife habitat (Lewandowski et al. 2013). Intercropping of perennial crops and annual food crops such as alfalfa and corn has been demonstrated to increase crop yields and to improve land-use efficiency (Zhang et al. 2011).

(b) **Short rotation wood crops**. Some fast-growing trees have also shown promise for biofuel production because of their high yield, wide geographical distribution, low costs and less labour consuming comparing with annual crops (Hauk et al. 2014). In temperate regions, poplar and willow are frequently mentioned and eucalyptus is commonly used in tropical regions. Willow and poplar are used in short rotation of about 3–4 years and the yield can reach up to 8–10 tons dry matter/ha/year, whereas the rotation cycles for eucalyptus are 4–6 years with an average of 12 tons/ha/year (Hauk et al. 2014). While it is evident that short rotation forestry and perennial grasses over annual agricultural crops are well suited than first-generation crops, yet these still require land for implication and thus not entirely escaping the food versus fuel debate. Only where food and fibre crops are not feasible would potential energy crops be the most beneficial.

(c) **Jatropha**, also known as physic nut (*Jatropha curcas*), produces a suitable oil ideal for biodiesel conversion. Jatropha, native in tropical America, is a multi-purpose drought-resistant tree that grows well on degraded or marginal land, and has seeds with high oil content (~40 %) (Koh and Ghazi 2011). Therefore, it benefits semi-arid and remote areas of developing countries. In the last 5–7 years, approximately 1.5–2 million ha of Jatropha have been planted each year, resulted in a total of approximately 13 million ha by 2015,

**Table 2** Oil content and production of non-edible oil seeds

| Species | Oil fraction (%) | Oil yield (tons/ha/year) |
|---|---|---|
| Jatropha | 40–60 | 2.0–3.0 |
| Mahua | 35–40 | 1.0–4.0 |
| Pongamia (Karanja) | 30–40 | 2.0–4.0 |
| Castor | 45–60 | 0.5–1.0 |
| Linseed | 35–45 | 0.5–1.0 |

*Source* Koh and Ghazi (2011)

distributed across India (73 %), South-East Asia (21 %), and Africa (6 %) (Carriquiry et al. 2010). Jatropha oil can be used locally for fuel vehicles, diesel generators or cooking stoves without a transesterification into biodiesel (Koh and Ghazi 2011). Some other species with biodiesel potential include pongamia, mahua, castor and linseed. Their potential seed and biofuel yields are summarized in Table 2.

### 2.2.2 Agricultural/Forestry Residues

Agricultural and forestry residues do not require additional land for cultivation. These include wheat straw, corn stove (leaves, stalks and cobs) and bagasse (sugarcane waste), while forestry residues are comprised of logging residues, fuel wood extracted from forestlands, and primary and secondary wood-processing mill residues. Bagasse (and wood process residues) is concentrated at processing plants, whereas other sources such as cereal straw need to be collected from the field as a separate and more costly operation. It is estimated that annually around 5.1 billion dry tons of agricultural residues and 501 million of forestry residues are produced globally (IEA 2010). However, only 10–25 % of these could be used for bioenergy production. The technical potential from available annual supplies, therefore, has been estimated in terms of energy at over 100 EJ/year, with costs in the range of USD$2–3/GJ (IEA 2010).

Biomass residues differ significantly in their properties and chemical composition (Table 3), consisting mainly of polysaccharides cellulose (hexose sugars, 35–50 %), hemicellulose (a mix of hexose and pentose sugars, 20–35 %) and lignin (Singh et al. 2010). These components are more resistant to being broken down than starch, sugar and oils in the conventional food crops, making the conversion processes more complicated, and more expensive (Hu et al. 2008).

### 2.2.3 Municipal and Industrial Wastes

The composition of Municipal and industrial waste (MSW) is highly variable; its major fraction is biodegradable with a significant calorific (heat) value and makes it suitable to energy recovery operation. A report from IEA (2013a, b) described

**Table 3** Composition and yield of different feedstocks (based on dry mass)

| Feedstocks | Residue/ crop ratio | Dry matter (%) | Cl (%) | Hc (%) | Lg (%) | Heating value (GJ/ton) | Biofuel yield (L/ton) |
|---|---|---|---|---|---|---|---|
| Black locust | – | – | 42 | 18 | 27 | 19.5 | 390 |
| Hybrid poplar | – | – | 45 | 19 | 26 | 19.6 | 416 |
| Eucalyptus | – | – | 50 | 13 | 28 | 19.5 | 411 |
| Spruce | – | – | 43 | 26 | 29 | 19.5 | 417 |
| Pine | – | – | 45 | 20 | 29 | 19.6 | 436 |
| Barley straw | 1.2 | 88.7 | 43 | 30 | 7 | 18.9 | 367 |
| Corn stover | 1 | 86.2 | 46 | 35 | 19 | 18 | 503 |
| Rice straw | 1.4 | 88.6 | 40 | 18 | 7 | 18.2 | 392 |
| Sorghum straw | 1.3 | 89 | 44 | 35 | 15 | 18.6 | 199 |
| Wheat straw | 1.3 | 89.1 | 40 | 28 | 16 | 19 | 410 |
| Bagasse | 0.6 | 26 | 33 | 30 | 29 | 19.4 | 3133 |
| processed paper | – | – | 47 | 25 | 12 | 16.3 | – |
| plastics | – | – | 65 | 15 | 7.5 | 34 | – |
| Food waste | – | – | 45 | 5.3 | 13 | 18.6 | – |
| Poultry waste | – | – | 11 | 16 | 4 | 17.5 | – |
| Solid cattle | – | – | 27 | 2.3 | 4.5 | 17.1 | – |
| Manure | – | – | | | | | – |

*Source* Chang et al. (1997), Singh et al. (2010), Carriquiry et al. (2010), Choi et al. (2014)

approximately 1.3 billion tons of municipal solid waste (MSW) comprising primarily of putrescibles, papers, cardboards and plastics produced in 2012 (IEA Bioenergy 2013), which indicates it can be a good source for fuel derivation. In addition, the food and paper industries also produce a large number of residues and by-products that can be used as biomass for bioenergy production. Industrial solid wastes include but are not limited to peelings and scraps from fruit and vegetables, meat and poultry waste, pulp and fibre from sugar and starch extraction, coffee grounds, etc., and all can be utilized as an energy source. The waste-to-energy approach is closely linked to the recent waste management practices, which have moved away from disposal towards recovery, reuse, recycling and reduction. It offers numerous bioenergy applications replacing fossil fuels with the potential environmental benefits such as landfill space savings, and reduction in GHG emission (Ngo et al. 2014).

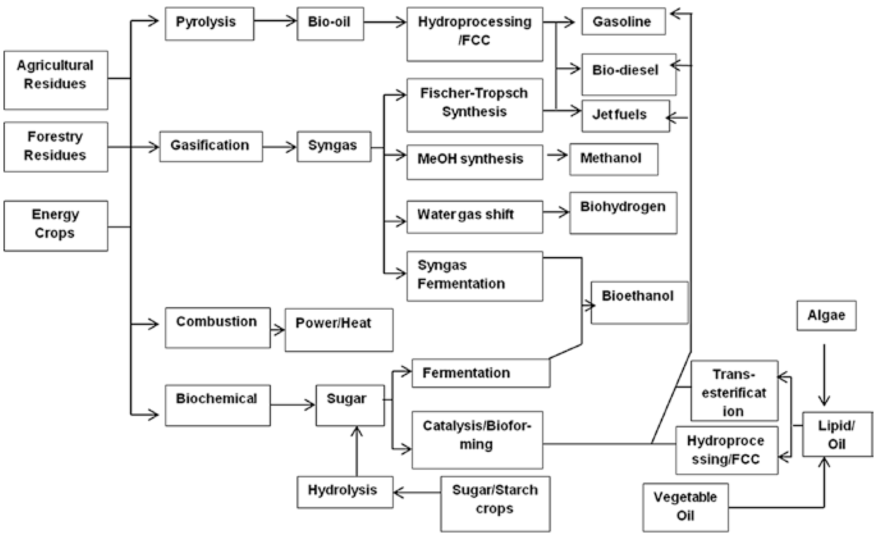


**Fig. 2** Conversion pathways from different biomass feedstocks to intermediates and to final biofuel production (modified from Yue et al. 2014)

### 2.2.4 Conversion Processes Utilized for Bioenergy Production

As lignocellulosic mass have complex chemical structure, it needs to be pretreated to remove the recalcitrance (i.e. lignin) and making the cellulosic material more accessible for hydrolysis. The conversion process of lignocellulosic biomass can be divided into two main routes, namely biochemical and thermochemical routes (Fig. 2). This section onwards, paper mainly focuses on the conversion processes for lignocellulosic biomass and utilization of combination of technologies for production of other value-added chemicals.

Physical Conversion

Crude vegetable oil is prepared by applying mechanical pressure using screw press.

Briquetting of Biomass

Waste materials and forest residues are densified in regular shapes by placing them in compact chambers. It involves two processes, pressing and maceration (chopping, grinding and pulverizing). This would reduce bulky volume and make them dense and compact, therefore processes further are smoothly performed to derive fruitful material (Osamu and Carl 1989; Stevens and Verhe 2004).

Thermochemical Conversion

Biomass can be converted to energy by mainly two processes; thermochemical or biological. The thermochemical conversion process includes direct combustion, gasification, liquefaction and pyrolysis as shown in Fig. 2. Syngas (mainly hydrogen and carbon monoxide) is produced by heating under oxygen-deficient condition. This syngas can be directly burned or further processed for other gaseous or liquid products. In this sense, thermal or chemical conversion of biomass is very similar to that of coal (Lee et al. 2007).

Direct Combustion

Here, the combustion is done in the presence of oxygen of fuel generating material, also commonly called burning. The products are carbon dioxide and water with the release of heat. When the direct combustion of biomass is conducted in a well-vented area, biomass burning used for domestic stoves and boilers can be a sound substitute for combustion of conventional fissile fuel. Sulphur emissions (0.05–0.2 wt%) are much lower, and the formation of particulate can be controlled at the source (Lee et al. 2007).

Gasification

Syngas can be produced from biomass by two routes, namely catalytic and non-catalytic. Non-catalytic process requires a very high temperature of operation, as high as 1300 °C, whereas catalytic process can be operated at substantially lower temperature. With more advances in the catalysis, the temperature requirement is expected to go downward further from the current value of about 900 °C (Lee et al. 2007).

The gasification step involves reacting biomass with air, oxygen or steam to produce a gaseous mixture of CO, $CO_2$, $H_2$, $CH_4$ and $N_2$ either known as producer gas or synthesis or syngas, depending on the relative proportions of the component gases (Rowlands et al. 2008). Producer gas is primarily useful as a fuel for stationary power generation, whereas syngas may be, and is presently, used to make a range of fuels and chemical intermediates. For transportation fuels, the main syngas-derived routes to fuels are hydrogen by water-gas-shift reaction (WGS) (Steen and Claeys 2008), hydrocarbons by Fischer–Tropsch (F-T) synthesis or methanol synthesis followed by further reaction to produce hydrocarbon or oxygenated liquid fuels (Balat 2006). The WGS reaction uses CO and $H_2O$ to give $H_2$ and $CO_2$. It can be used to upgrade producer gas to syngas by enriching the $H_2$ content or to produce $H_2$ as an end product in its own right. F-T synthesis has been used since 1930s to produce hydrocarbon fuels from syngas. The production of methanol from syngas has been practiced since the 1920s (Rowlands et al. 2008).

Liquefaction

The liquefaction of biomass has been investigated in the presence of solution of alkalis, glycerine, propanol, butanol or direct liquefaction (Demirbas 2004). Liquefaction usually produces water-insoluble oils of high viscosity and usually requires solvents, reducing gases such as CO or $H_2$ and/or catalysts to be present in addition to biomass (Rowlands et al. 2008).

In the field of thermochemical conversion of biomass, lignocellulosic materials can be converted directly to a liquid similar to heavy fuel oils by reacting them with synthesis gas in the presence of suitable catalyst (Appell et al. 1971). Aqueous liquefaction of lignocellulosics involves desegregation of the wood ultrastructure, followed by partial depolymerization of the constitutive compounds. In the alkali liquefaction, deoxygenating occurs through decarboxylation from ester formed by hydroxyl group and formate ion derived from carbonate. Alkali salts, such as sodium carbonate and potassium carbonate, can act as catalyst for hydrolysis of macromolecules such as cellulose and hemicellulose into smaller fragments. The heavy oil obtained from the liquefaction process is a viscous tarry lump, which sometimes caused troubles in handling. For this reason, some organic solvents (e.g. propanol, butanol, acetone, methyl ethyl ketone, ethyl acetate) need to be added to the reaction system and are reusable. (Naik et al. 2010). The average oil yield is around 31 % in the non-catalytic process and 63 % in the catalytic process (Demirbas 2004).

Pyrolysis

Charcoal (solid), bio-oil (liquid) and fuel gaseous products are produced by the process of 'pyrolysis', which involves heating in the absence of oxygen. The pyrolysis of biomass has been studied with the final objectives of recovering a biofuel with medium–low calorific power (Demirbas 2004). Conventional pyrolysis occurs under a slow heating rate (0.1–1 K/s), and residence time is 45–550 s and massive pieces of wood. The first stage of biomass decomposition which occurs in between 550 and 950 K is called pre-pyrolysis. During this stage, some internal rearrangements such as water elimination, bond breakage, appearance of free radicals, formation of carbonyl, carboxyl and hydroperoxide group take place (Shafizadeh 1982). The second stage of solid decomposition corresponds to the main pyrolysis process. It proceeds with a high rate and leads to the formation of pyrolysis products. During the third stage, the char decomposes at a very slow rate and it forms carbon-rich solid residues. In fast pyrolysis, the high temperature range of 850–1250 K with fast heating rate (10–200 K/s), short solid residence time (0.5–10 s) and fine particle (<1 mm). The fast pyrolysis is recommended for production of liquid and/or gaseous products. Fast pyrolysis produces 60–75 % of bio-oil, 15–25 % solid char and 10–20 % non-condensed gases depending upon feedstocks (Shafizadeh 1982).

Flash pyrolysis strongly differs from conventional pyrolysis, which is performed slowly with massive pieces of wood. It occurs in the temperature range of 1050–1300 K, fast heating rate (>1000 K/s), short residence time (<0.5 s) and very fine particle (<0.2 mm). Bio-oil production from biomass pyrolysis is typically carried out via flash pyrolysis (Demirbas 2004). The conversion of biomass to crude oil can have an efficiency of up to 70 % for flash pyrolysis process. The so-called biocrude can be used in engines and turbines. Its use as feedstocks for refineries is also being considered (Demirbas 2004; Mohan et al. 2006).

Hydrotreating of Vegetable Oils/Green Diesel

Researchers around the world are in pursuit of different processing routes to convert vegetable oils into a high-quality diesel fuel or diesel blend stock that would fully compatible with petroleum-derived diesel fuel. The isoparaffin-rich diesel known as 'green diesel' is produced from renewable feedstock containing triglycerides and fatty acids by process of catalytic saturation, hydrodeoxygenation, decarboxylation and hydroisomerization.

This technology can be widely used for any type of oil feedstock to produce an isoparaffin-rich diesel substitute. This product, referred to as green diesel, is an aromatic and sulphur-free diesel fuel having a very high cetane blending value. The cold flow properties of the fuel can be adjusted in the process to meet climate-specific cloud point specifications in either the neat or blended fuel (Kalnes et al. 2007). Green diesel has a higher cetane value and good cold flow properties. It is also has excellent storage stability and is completely compatible for blending with the standard mix of petroleum-derived diesel fuels.

Bio-Oil

Bio-oil/pyrolysis oil is produced by fast pyrolysis process. In this process, organic class of compounds, such as cellulose, hemicellulose, and lignin, etc., are thermally decomposed at moderate temperature (400–600 °C) in the absence of oxygen to produce liquid product, viz. bio-oil (60–70 %), char (13–25 %), and gas such as CO, $H_2$ and light hydrocarbons (13–25 %). The yield and chemical composition of bio-oil depends upon feedstocks and process condition: particle size of biomass (2–5 mm), residence time (0.1–2 s) and reactor type. In general, reactor types that are presently used are fluidized bed reactor, circulating fluid bed, fast fluidized bed, etc. (Fig. 2).

Bio-oil has a complex chemical composition contained chemical products of lignocelluloses biomass such as aliphatic alcohols/aldehydes, furanoids, pyranoids, benzenoids, fatty acids and high molecular mass hydrocarbons, etc. These constituents are mixed with water (25–45 %), which is formed in pyrolysis process to form an emulsion with organic constituents.

### 2.2.5 Biorefinery

The economics of the existing processes could be enhanced when surplus heat-power (syngas) and co-product generation (bio-oil and long-chain hydrocarbons) are included in an integrated biorefinery system. Biorefinery is the sustainable processing of biomass into a spectrum of marketable products (e.g. food, feed, materials and chemicals) and bioenergy (e.g. fuels, power and heat) (IEA Bioenergy 2013). As a result, the biorefinery approach can maximize biomass conversion efficiency, minimize raw material requirements, while at the same time enhance the economic values of various market sectors (e.g. agriculture, forestry chemical and energy) (IEA Bioenergy 2013). The new concepts of biorefineries such as Whole Crop, Lignocellulosic Feedstock and Thermochemical Biorefineries, which are still in R&D stage, involve producing a broader range of materials and chemicals by employing several conversion technologies and types of feedstocks. As a result, these facilities offer high processing flexibility and reduce the risk of investment (Gnansounou and Dauriat 2010).

In this context, biomethane also called biogas is another important coproduct during the conversion of lignocellulosic biomass to bioenergy. It is a versatile energy source which can be utilized for residential and industrial heating purposes, for production of electricity with efficiency up to 42 % and productive heat with a thermal efficiency of up to 50 %. Biomethane can also be applied as vehicle fuel if it is compressed (compressed natural gas, CNG) or liquefied (liquefied natural gas, LNG) with energy content of approximately 10 kWh, corresponding to 1 L of petrol. The market for natural gas vehicles (NGVs) has been increasing in many countries due to a combination of low-cost natural gas and higher prices for gasoline and diesel. At the end of 2012, there were about 16.7 million NGVs operating globally in all classes of vehicles including motorcycles, cars, buses and trucks (NGV Global 2014).

### 2.2.6 Technical and Economic Constraints for Commercialization

Substantial progress has been made over recent years for the core technologies (e.g. enhanced hydrolytic enzymes, fermentation strains and process integration). Some larger scale advanced biofuels plants are in operation, and the first commercial scale plants in the USA and EU were recently commissioned (REN21 2013). However, the progress of commercializing advanced biofuels is slower because of high investment requirements (35–50 % of the total cost) combined with several operational and political/policy uncertainties (Yue et al. 2014).

The capital cost for a commercial scale plant is estimated to be in the order of $300–600 million, which is 2–3 times higher than the investment cost for a corn-ethanol plant (Popp et al. 2014). In addition, despite substantial progress and development, many challenges remain to be overcome, such as (Clark 2007; Deswarte et al. 2008; Klein et al. 2012):

- Development of a suitable and economically viable hydrolysis process step
- Feedstock production and transportation
- Several logistics including seasonal nature and annual variability of biomass, their spatial distribution
- Process scale-up; cot associated with preprocessing, storage and supply
- Capital equipment required for commercial demonstrations of some technologies, such as steam explosion, does not exist
- Reusable pretreatment chemicals and wastewater
- Process integration to minimize energy demands

A combination of high production cost [estimated above US$0.8/L of gasoline equivalent (IEA 2010)] and the lack of supporting policies and mandates has limited market acceptance and competition for the second-generation biofuels at the current stage.

### 2.2.7 Third-Generation Feedstocks

Microalgae have been proposed as a third-generation biofuel. They are microscopic photosynthetic entity can be grown on non-arable land under harsh conditions and in different environments, using wastewater as a source of water and nutrient (Amaro et al. 2011; Chen et al. 2011; Pittman et al. 2011). Several studies have shown that producing biodiesel using algae is advantageous (Ginzburg 1993; Dote et al. 1994; Hu et al. 2008; Wang et al. 2013). Algae exhibit faster growth rates than seed plants with a generation time of 2–5 days (Costa and de Morais 2011), with high lipid content (50 % lipid per dry weight in some species), which can be converted to biodiesel and a wide variety of other biofuels, including jet fuel, biogas, ethanol, etc. with the potential to produce useful by-products; nutraceuticals, animal feed, a variety of chemicals including carbohydrates, proteins, lipids, vitamins and pigments making them numerous applications in chemical and pharmaceutical industries, cosmetics, health food and feed supplements (Costa and de Morais 2011; Ugwu et al. 2008). Microalgal species such as *C. vulgaris*, *Chlorella protothecoides*, *Nannochloropsis* sp., *Nitzchia* sp., *Chlamydomonas reinhardtii*, *Schizochytrium* sp., *Scenedesmus obliques* and *Neochloris oleabundans* accumulate mostly lipids at high concentration of 80 % (e.g. TAG), which make adequate for biodiesel production (Costa and de Morais 2011). Other species of cyanobacteria such as *Chlamydomonas* sp., *Cyanothece* sp. *and Spirulina platensis* accumulate mostly carbohydrates, thereby producing bio-ethanol when fermented (Costa and de Morais 2011). Algal colonies produce a high dry weight biomass yield up to 60 tons/ha/year (*Pleurochrysis carterae*), from which approximately 20 tons of oil could be extracted (Moheimani and Borowitzka 2006). This productivity from algae is five times higher than that achieved from oil palm, the highest yielding oil crop plant (Day et al. 2012). In addition, algae have no lignin and low hemicellulose levels, resulting in an increased hydrolysis efficiency, higher fermentation yields and thus reduced cost (Li et al. 2014). Moreover, algal biomass can be harvested and processed by multiple ways to obtain biofuel (Abdelaziz et al. 2013).

There are still many challenges associated with algal biofuel production, which involves the following key processes (Chen et al. 2011).

- **Algal cultivation**: Cultivation of microalgae is considered as one of the major constraints to commercial development. Generally, cultivation can be done either on open bonds requiring low capital costs but having low biomass yield, or in closed bioreactors or hybrid systems with high capital costs and high yield (Chen et al. 2011; Costa and de Morais 2011). Therefore, there is a trade-off between investment cost and algal biomass productivity.
- **Isolation of desirable strain versus production rate**: Algal species and strains vary greatly in terms of growth rate, productivity, photosynthetic efficiency, nutrient requirements and ability to adapt to adverse conditions (John et al. 2011). When screening algal strains for commercial biofuel production, high biomass yield with high carbohydrate and lipid contents is the desirable criterion. However, in order to maximize the production of lipids, cell growth and photosynthesis are often compromised, resulted in a decrease in overall productivity (Day et al. 2012; John et al. 2011).
- **photobioreactor design**
- **and downstream treatment processes**

Addressing this problem might require intensive fundamental research on genetic modification and manipulation of lipids and cellulose synthesis pathways to enhance productivity. Furthermore, improving the efficiency of downstream processing, conversion and extraction techniques would enhance the commercial viability of algal biofuels.

## 3 Future Perspectives

It is an accepted fact that utilizing food crops for biofuel production is not a complete solution due to souring food prices especially in lower income developing countries such as China and India. Besides using food crops for biofuel production, there is increasing interest towards plant that can be grown on wastelands or generation of genetically modified crops and engineered microalgae producing high quantity of oil, lipid and carbohydrates. In the New Policies Scenario, the share of traditional biomass (sugar/starch crops and oil seeds) in total primary energy demand is expected to drop from 5.7 to 3.9 % between 2011 and 2035 (IEA 2013a, b). Bioenergy is certainly becoming a greater part of the global energy mix and is projected to contribute up to 20–30 % of the overall primary energy worldwide by 2035 (IEA 2013a, b). Government policies in different countries have been supporting growth of biofuel production for its commercialization making it feasible source for transport and industrial uses. The first-generation biofuel are relatively in its advanced stage with mature technologies, infrastructure and markets, and it is still very dependent on the supply of raw material and selling price of ethanol and DDGs. Even though the market values of both the raw material and the ethanol have a strong correlation with the price of fossil fuel, individual fluctuations still occur [cf. The World Bank (2013) and Alternative fuels data center (2013)]. Since the profit margins are relatively small, these fluctuations represent a considerable risk to the process economy (Lennartsson et al. 2014).

The advanced biofuels derived from lignocellulosic and algal biomass offers the prospect of increasing biofuels supply with less land requirement while enhancing greenhouse gas mitigation. At the current stage, the second-generation technologies are relatively mature, with a few commercial scale units and around 100 plants at pilot and demonstration scale worldwide, whereas the third-generation technologies are still under research and development. There are still some technical and policy barriers to overcome before the technologies can be commercialized worldwide. High investment expenditure and high unit production cost make lignocellulosic biofuels less competitive to fossil fuel or many first-generation products (Ngo et al. 2014). Integrating second-generation processes to already existing first-generation infrastructures could be a practical option to reduce the investment costs and technological risks. To achieve lower production costs, a consistent and sustainable supply of cheap raw materials is essential. Furthermore, all components of the biomass including intermediates and by-products should also be considered and utilized in a biorefinery system to enhance the economic viability of the process (Lennartsson et al. 2014; Ngo et al. 2014).

## 4 Conclusion

This is evident that biofuels have the potential to satisfy a portion of our needs on road fuel, assist in addressing serious concerns over climate changes, and augment and diversify rural income and security for energy in coming decades. At present, it is necessary to associate first-generation to second-generation biofuels with comparatively advance technologies and commercialized, which is sufficient to provide a relaxation for present day need for extra energy. First- and second-generation biofuels are an attractive alternative to current petroleum-based fuels. Third-generation biofuel based on algal culture is recent introduction, and there are few challenges in obtaining efficient, low-cost conversion processes that require minimal energy inputs. However, extensive research and progress for third-generation technology and development and continual policy support will make it cost-effective and might come as long-term solutions to the fossil fuels and global climate changes.

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# Biofuels as Alternate Fuel from Biomass—The Indian Scenario

**Renu Singh, Arti Bhatia and Monika Srivastava**

**Abstract** Biofuels are produced from living organisms or from metabolic by-products (organic or food waste products). Fuel must contain over 80 % of renewable materials in order to be considered as biofuels. Biomass is carbon dioxide neutral, and its sustainable use minimizes the seasonal variation and pollutants emission into the air, rivers, and oceans. This energy plays an important role in the replacement of renewable energy resources for fossil fuels over next several decades. Enormous range of biomass is processed to produce bioenergy biologically, thermochemically, and biochemically. In developing countries such as India, biomass is the primary source of bioenergy. Global climate change policies would overcome many barriers to secure the future of biomass and indirectly biofuels. Due to social and economic benefits, biomass is considered as a deserving alternative for sustainable development.

**Keywords** Biomass · Biofuels · Fossil fuels · Energy · Sustainable

## 1 Introduction

Biomass comes from a variety of sources which include wood from natural forests and woodlands, forestry plantations, forestry residues, agricultural residues, agro-industrial wastes such as sugarcane bagasse and rice husk, animal wastes, industrial wastes such as black liquor from paper manufacturing, sewage, municipal solid wastes (MSW), and food processing wastes (Fig. 1). The total world biomass content has been estimated at about 1880 billion tones (DIERET 2014). In nature, if biomass is left laying around on the ground, it will break down very slowly, releases carbon dioxide ($CO_2$) and energy stored in it over a long period

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**Fig. 1** Various sources of biomass (www.energyprosandcons.org)

of time. However, burning of biomass releases its stored energy very quickly and mostly in a constructive way. Therefore, it can be concluded that conversion of biomass into a valuable energy emulates the natural processes, but at a faster rate. Biomass energy or "bioenergy" is energy produced from recently living organisms. There are three forms of bioenergy accessible with today's technology: heat, fuels, and electrical power. According to "Biomass regulation 2001/77/EG," biomass is defined as the biodegradable component of products, industrial and household wastes, and agricultural and forests residues. For thousands of years, in the form of heat, bioenergy primarily has been produced, providing a good precedent to build upon in planning for its use in agriculture. This burning of the biomass or products is known as direct combustion. Direct combustion is a relatively proficient means of using bioenergy, due to its minimal processing needs, the diversity of feedstock that can be used, comparatively simple equipment needs, and a relatively high rate of energy recovery. Direct combustion is the only realistic means of harnessing bioenergy for most operations. Anaerobic digestion and gasification of biomass are practical bioenergy technologies for some selected types of farming operations. On-farm production of biodiesel from oil crops is also possible.

Biomass exemplifies all the organic matter that exists on the earth's surface and obtained through the process of photosynthesis. In biomass, all the energy comes from the sun and it acts as a chemical energy store. Under a complex series of physical and chemical transformations, biomass releases energy in the form of heat that can be employed for cooking and warming water or air in our houses. The exploitation of energy from biomass has played a key role in the evolution of mankind. Farmers are potentially in a good position to utilize bioenergy because they are already knowledgeable and well equipped for the production of biomass, including that which can produce energy. Recently, it was the only form of energy which was usefully exploited by humans and is still the main source of energy for more than half the world's population for domestic energy needs. Farmers can produce and utilize bioenergy at the same location.

Biomass is $CO_2$ neutral and considered as renewable source of energy in its entire life cycle (Fig. 2). Sustainable use of natural energy mimics the earth's seasonal variations and minimizes the emission of pollutants into the air, rivers, and oceans. Most of the carbon is captured from the atmosphere and later on returned to it. Similarly, the nutrients are taken from the soil and later returned to it. The residues obtained from one part of the cycle constitute the inputs of the next stage of the cycle. During plant growth, $CO_2$ is withdrawn from the atmosphere and converted into complex biochemical compounds, such as cellulose and lignin through photosynthesis. Sunlight provides the energy for this process, and in fact, solar energy is stored by

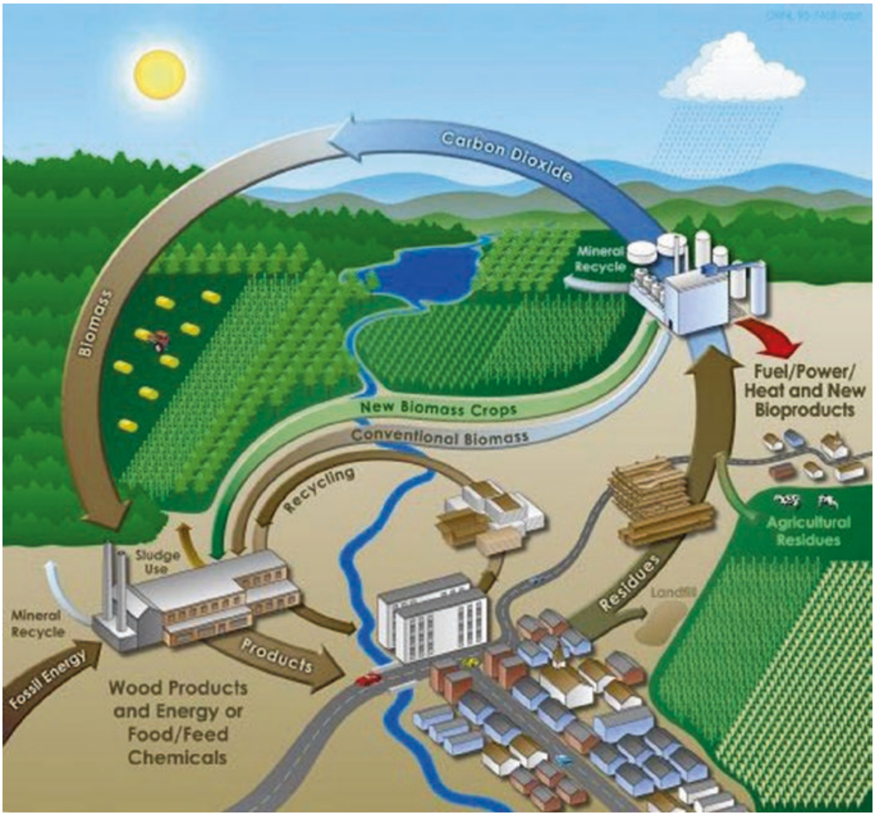


**Fig. 2** Life cycle of biomass energy (McCarter 2013)

means of biomass which can be released or used in later stage. The biomass is produced together with forestry and crop residues and can be converted into fuels, animal feed, and other products such as plant-derived chemicals (waxes, cleaners, etc.) and ecological purposes. Heat and electric power may also be generated by solid biomass. Through the processing facility, organic by-products and minerals may be returned to the land, thereby recycling some of the nutrients such as potassium and phosphorus that were used for plant growth. Throughout the cycle, carbon dioxide from biomass is released back into the atmosphere from the processing plants and from the urban and rural communities with little or no net addition of carbon to the atmosphere. There may even be some net sequestration or long-term fixation of carbon dioxide into soil organic matter, and the growing of bioenergy crops is optimized to add humus to the soil. Sun is the main source of energy; it provides energy to drive the cycle without depletion of resources. With the development of efficient bioenergy technologies, fossil fuel inputs will be reduced. During this conversion process, the same amount of $CO_2$ is released and there is no net increase of $CO_2$, and hence, a closed cycle of $CO_2$ is conserved. Biomass energy is expected to play a major role in the substitution of renewable energy sources for fossil fuels over the next several decades. A life cycle assessment (LCA) on the production of electricity from biomass in a combined cycle system has been performed. LCA is a methodology for assessment of the environmental impact of a product throughout its lifetime from raw material extraction, use and its disposal or recycling, and this is a fundamental approach for analysis of environmental impacts (Rebitzer et al. 2004; Finnveden et al. 2009). The production of electric power from biomass is very much beneficial as it significantly close the carbon cycle, minimize feedstock costs, enhance the feasible size of biomass power plants, and grant economic benefits to agricultural communities. Biomass power systems must be competitive on cost and efficiency in order to realize these potential contributions.

## 2 Features of Biomass Resources

Biomass resources comprises of primary, secondary, and tertiary sources of biomass. Primary biomass resources are obtained through the process of photosynthesis such as perennial short-rotation woody crops, herbaceous crops, seeds of oil crops, and residues resulting from the harvesting of agricultural crops and forest trees (e.g., wheat straw, corn stover, the tops, limbs, and bark from trees). By the processing of primary biomass resources either physically (e.g., the production of sawdust in mills), chemically (e.g., black liquor from pulping processes), or biologically (e.g., manure production by animals), secondary biomass resources are produced. Tertiary biomass resources encompasses postconsumer residue such as animal fats, greases, vegetable oils, food packaging wastes, and construction and demolition debris. A huge range of biomass are processed biologically, thermochemically, and biochemically to produce bioenergy (Fig. 3).

In order to produce energy from biomass fuel, different standardizations are used. Various types of biomass fuels are classified in Table 1. Energy production

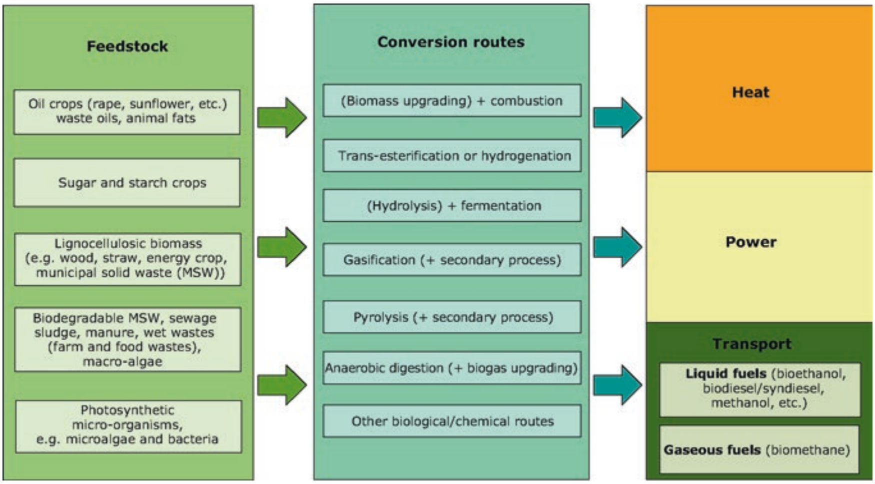


**Fig. 3** Biomass conversion to bioenergy (EU bioenergy potential.eps)

varies depending on type of biomass fuel used. There are several factors upon which production of energy from energy crops depends:

- Availability and fertility of the land
- Regional distribution
- Environmental implications
- Conversion technologies

**Table 1** Types of biomass fuels (w3.tue.nl/fileadmin/tm/TDO/Indonesie/Biomass_Power.pdf)

| Woody biomass | Non-woody biomass | Processed waste | Processed fuels |
|---|---|---|---|
| Trees | Energy crops such as sugarcane | Cereal husk and cobs | Charcoal (wood and residues) |
| Shrubs and scrub | Cereal straw | Bagasse | Briquette/densified biomass |
| Bushes such as coffee and tea | Cotton, cassava, tobacco stems, and roots (partly wood) | Waste from pineapple and other fruits | Methanol/ethanol (wood alcohol) |
| Sweeping from the forest floor | Grass | Nut shells, flesh, and the like | Plant oils from palm, rape, sunflower, and the like |
| Bamboo | Bananas, plantains, and the like | Plant oil cake | Producer gas |
| Palms | Soft stems such as pulses and potatoes | Sawmill wastes | Biogas |
| | Swamp and water plants | Industrial wood bark and logging wastes | |
| | | Black liquor from pulp mills | |
| | | Municipal waste | |

**Table 2** Properties of biomass fuel (w3.tue.nl/fileadmin/tm/TDO/Indonesie/Biomass_Power.pdf)

| Moisture content | Storage, dry matter losses |
|---|---|
| Volatiles | Thermal decomposition, combustion technology |
| Ash content | Dust emission, ash manipulation |
| Fixed carbon | Combustion technology |
| Calorific/Heating Value | Fuel utilization, plant design |
| Ash melting | Safety, process control |
| Fungi | Health risks |
| Bulk density | Logistics |
| Particle density, heat capacity, and conductivity | Thermal decomposition |
| Dimension and shape | Conveying, drying, bridging, and combustion technology |

When waste and residues are employed, energy production from them depends mainly on:

- Agro-industrial by-products and forestry residues
- 30 % recoverable
- Production is inadequate by the impracticality of recovering

Physical properties of biomass fuels are characterized in Table 2. As mentioned earlier, depending on the geographical locations, natural biomass resources vary in type and content. The world's biomass producing areas can split into three distinct geographical regions for convenience sake.

## 2.1 Temperate Regions

Temperate regions produce wood, crop residues, such as straw and vegetable leaves, human, and animal wastes. Short rotation coppicing (SRC) has become popular as a means for supplying wood fuel for energy production on a sustainable basis. To provide fuel for the boiler, fast-growing wood species, such as willow and the wood chipped, are used. For the production of biofuels and biogas, there are many non-woody crops which can be grown and investigation of energy crops for direct combustion is underway. Either from incineration or through recovery of methane gas from landfill sites, large quantities of municipal wastes are processed to provide useful energy.

## 2.2 Arid and Semiarid Regions

Arid and semiarid lands occupy one-third of the earth's surface. Arid and semiarid regions produce very little excess vegetation for fuel. A large number of hydrocarbon yielding plants are able to grow under semiarid and arid conditions, and they also produce valuable hydrocarbons which could be converted into petroleum-like substances and are used as fossil fuel substitute. People living in these areas often have difficulty in finding sufficient wood fuel as they are mostly affected by desertification. These areas are not suitable for cultivation because of the short growing periods (1–74 and 75–119 growing days, respectively). Rainfall patterns are random and are subjected to immense variations. One-year droughts are more recurrent than multiyear droughts. Drought occurrence is more frequent in the arid (lower rainfall) areas than that in the semiarid zones. Clipped herbaceous biomass, cover density of the perennial and annual grass as well as the woody component were available to some extent in these regions. Severe multiyear droughts devastated half the livestock and also cause the temporary migration of 20 % of the human population. In contrast, single-year drought does not cause livestock mortality. The rangeland dominating arid and semiarid areas provides primary products (grasses, legumes, and shrubs), which were converted into animal protein. With the increase in human population, use of bio-resources for other purposes such as fuel and building material has intensified.

### *2.3 Humid Tropical Regions*

In humid tropical regions, agricultural wastes, animal and human garbage, and commercial and industrial residues are produced profusely. To provide process heat for power generation, rice husks, cotton husks, and groundnut shells are widely used. Sugarcane bagasse is processed to provide ethanol as well as being burned directly and to provide oil for combustion many plants such as sunflower and oil palm are processed. Many of the world's poorer countries are found in these regions, and hence, there is a high incidence of domestic biomass use. Currently, tropical areas are most critically affected by large cutting of trees and preparing the timber.

## 3 Conversion Technologies

Generally, biomass-to-energy conversion technologies have to deal with a feedstock having different mass and energy density, size, moisture content, and irregular supply. Thus, modern industrial technologies are generally constitute of hybrid fossil fuel/biomass technologies in which fossil fuel are utilized for drying, preheating, and maintaining fuel supply when the biomass supply is intermittent. Different types of conversion technologies such as thermochemical and biochemical are available, each appropriate for specific biomass types and resulting in specific energy products. Production of molecules for the chemical industry and transportation fuels from plants is made possible through thermochemical conversion. In thermochemical processing of biomass, there are large number of possible

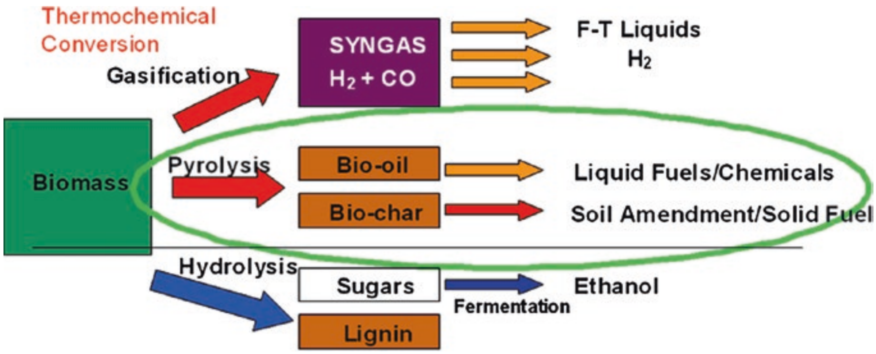


**Fig. 4** Outline view on thermochemical conversion (www.ars.usda.gov)

pathways for converting biomass through the use of heat and catalysts into fuels, chemicals, and power (Brown 2011). In thermal conversion-type technology, heat is used in the presence or absence of oxygen in order to convert biomass materials or feedstock into other forms of energy.

## *3.1 Thermochemical Conversion Processes*

Thermochemical conversion technologies are used for the conversion of biomass into fuel gases and chemicals. An outline view of thermochemical conversion is represented in Fig. 4.

In this technology, the first stage involves converting solid biomass into gases and second stage gases are condensed into oils. In the final stage, oils are conditioned and synthesized to produce syngas. This produced syngas is used to produce ammonia, lubricants, and through some process into biodiesel too. Different thermochemical conversion technologies are used to generate electricity. Many efforts on research and development and proven expertise were taken in order to develop this biomass conversion pathway. Before any process, the biomass should be dried properly either by radiation from flames or from the stored heat in the body of the stove or furnace, as all biomass contains moisture which has to be driven off. Various thermochemical processes are described below.

### 3.1.1 Torrefaction

It is the conversion of biomass with the application of heat in the absence of oxygen, but the temperature range is 200–320 °C, which is less than pyrolysis. In this process, cellulose, hemicellulose, and lignin are partially decomposed and water is removed giving off various types of volatiles (Bates 2012). The final product is referred as bio-coal which is an energy dense solid, dry, and blackened material which is referred as torrefied biomass or bio-coal (DTA 2012). An overview of an integrated torrefaction plant is shown in Fig. 5. In order to allow efficient drying, the biomass is chipped and before sizing, the biomass is usually screened for impurities (Schorr et al. 2012). For drying and torrefaction process, little fraction of feedstock biomass is used. Direct or indirect heating is also possible for biomass with hot air, flue gas, or steam (Melin 2011). During this process, the gases which are leaving are divided into flue gases and combustible gases merged under the name torgas. The ratio of both the gases strongly depends on the type of biomass feedstock and the processing parameters (Bergman 2005). It is difficult to handle torgas, if it contains water, tar, and dust (Englisch 2010).

The torrefaction process is said to be running at the point of autothermal operation when the energy content of the torrefaction gases matches exactly the overall heat input requirements and processing above this point reduces overall thermal efficiency (Bergman 2011). A simpler rotor mill can be used for grinding instead of a hammer mill (Knoope et al. 2013). Cold feeding is essential with current technology to ensure self-ignition temperatures below 130 °C (Hakansson 2012). Lignin undergoes lower degradation at mild torrefaction temperatures (Chen 2011)

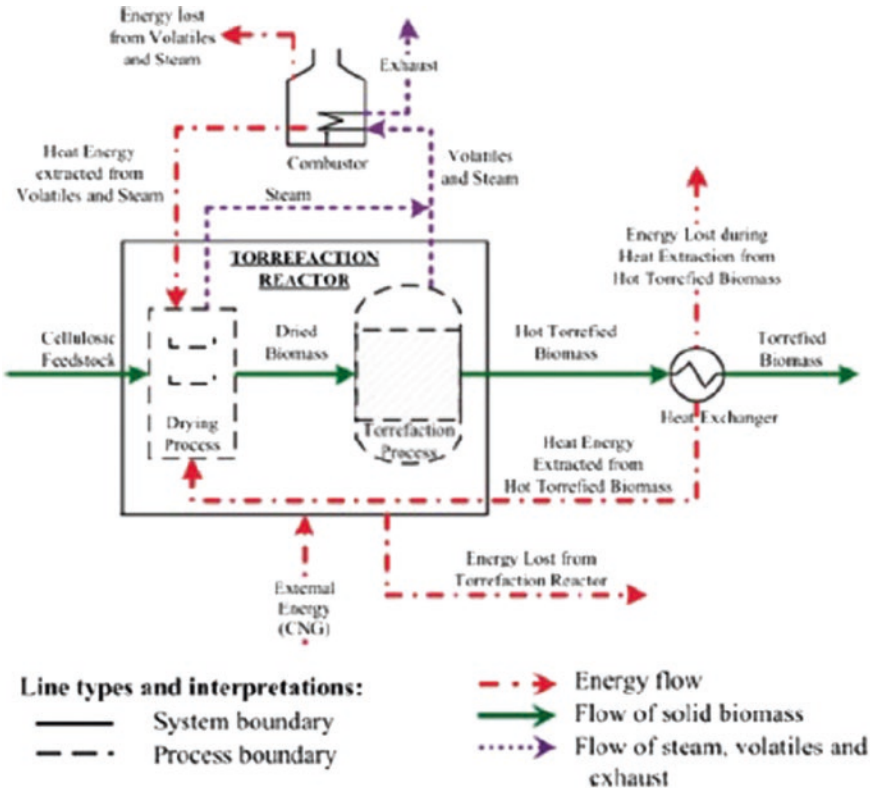


**Fig. 5** Basic principle of torrefaction process (Shah et al. 2012)

as hot feeding is more efficient because it softens the lignin, as it acts as natural binder (Wang 2013). Low moisture content of torrefied biomass can increase the glass transition temperature of lignin which affects the bonding properties.

### 3.1.2 Pyrolysis

Biomass is mainly consisted of carbon, hydrogen, and oxygen whose main chemical compositions are cellulose, hemicellulose, and lignin. Cellulose, hemicellulose, and lignin are decomposed with increase in temperature. When temperature reaches 200–350 °C, the dry biomass is heated and volatile gases are released which are mixed with oxygen and burn with yellow flame. Various types of materials which undergo pyrolysis include plant biomass, human and animal wastes, food scraps, crop residues, pruning, paper, cardboard, plastics, and rubber (Serio et al. 1995). During pyrolysis (Fig. 6), the moisture evaporates first (−110 °C), then the hemicellulose is decomposed (200–260 °C) which is followed by cellulose (240-340 °C), and finally, lignin is decomposed at last (280–500 °C) and pyrolysis is almost finished when temperature is almost reached at 500 °C. This process is self-sustaining as the heat from the burning gases is used to dry the biomass and releases further volatile gases. Biomass undergoes partial combustion and results in liquid fuels and a solid residue called char or bio-char (it is like charcoal and rich in carbon). At very low temperature, all the carbon molecules of

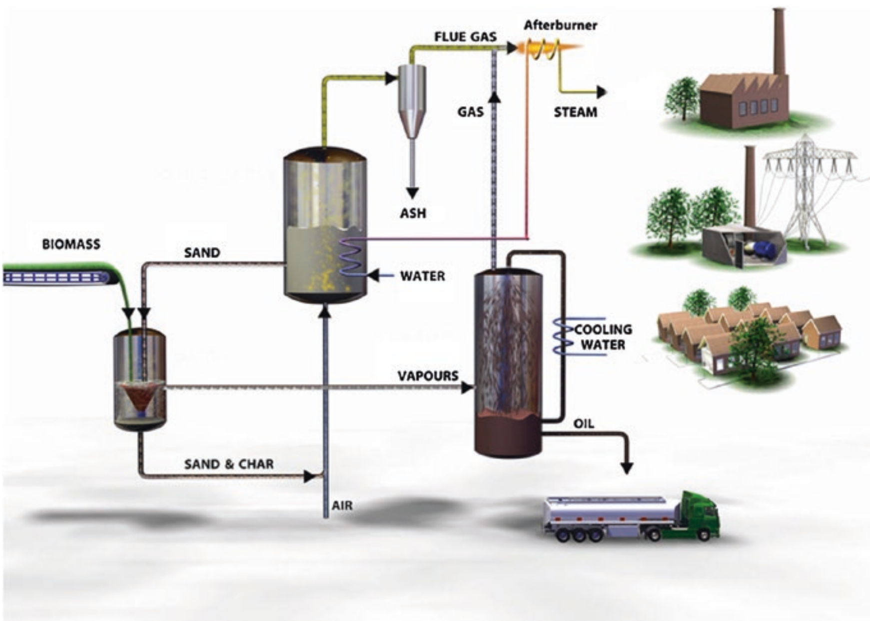


**Fig. 6** Pyrolysis process flow diagram (www.btgworld.com/en/rtd/technologies/fast-pyrolysis)

biomass are not destroyed and this results in the production of tars, oils, methanol, acetone, etc., and in order to sustain this part of the combustion process, oxygen is necessary. For any type of biomass fuel conversion technology, main pre-treatment that is used is pyrolysis. Liquid, gas, and char are obtained by pyrolysis. Main features of pyrolysis are described below:

- Breaking down of a material by heat
- Combustion process
- De-volatilization in the absence of oxidizer
- Temperature range 250–500 °C
- Biomass is heated, and charcoal, gases, and bio-oil are generated
- Char or liquid yield is optimized

Many commercial processes have been developed for plastics and biomass (Klass 1998; Rowell et al. 1992; Dayton 1996; Wang 1997). Several excellent reviews on biomass pyrolysis literature have been cited (Klass 1998; Antal et al. 1984, 1985; Soltes 1986, 1988; Shafizadeh 1984; Bridgwater 1992; Elliott et al. 1991).

### 3.1.3 Gasification

The process in which biomass solid raw material is converted into fuel gas or chemical feedstock gas or syngas is known as gasification or thermochemical gasification. All raw materials are converted into gas at high temperatures and in a controlled environment. This process takes place in two stages: partial combustion of biomass into producer gas and charcoal is the first stage and in the second stage, carbon dioxide and water which is produced in the first stage is chemically reduced by the charcoal, forming carbon monoxide and hydrogen. Main process layout for gasification technology is shown in the Fig. 7. The composition of the gas is 18–20 % $H_2$, an equal portion of CO, 2–3 % $CH_4$, 8–10 % $CO_2$, and the left is nitrogen. The two stages are separated in the gasifier, and gasifier design is very much reliant on the feedstock characteristics. Since the turn of the century gasification technology has existed for the use in power generation, gasifiers were used extensively for transport.

A major future role is envisaged for electricity production from biomass plantations and agricultural residues using large-scale gasifiers with direct coupling to gas turbines. Such systems take advantage of low-grade and cheap feedstock (residues and wood produced using short rotation techniques) and the high efficiencies of modern gas turbines to produce electricity at comparable or less cost than fossil fuel-derived electricity. The use of low-grade feedstocks combined with high conversion efficiencies makes these systems economically competitive with cheap coal-based plants and energetically competitive with natural gas-based plants. For biomass waste treatment, gasification can become a strong challenger to anaerobic digestion, composting, and incineration. Gasification is one of the most important energy conversion processes for biomass fuel, and gasification methods are also classified according to the combination of conditional factors. Gasifier choice

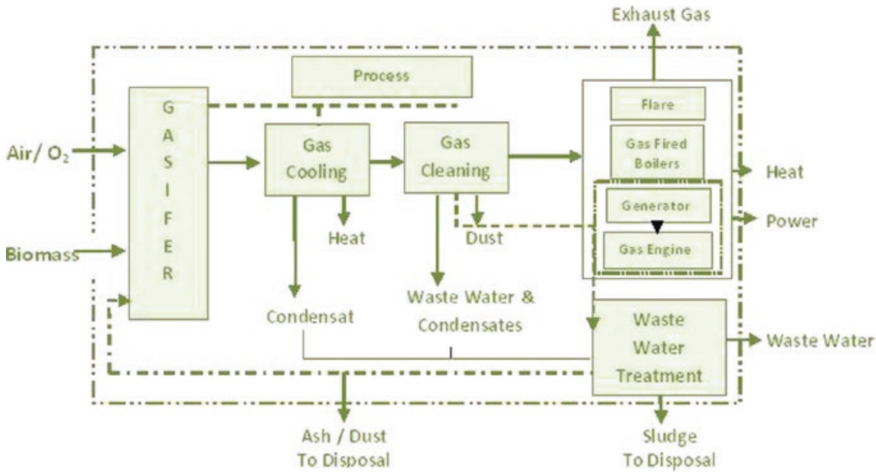


**Fig. 7** Layout for gasification technology (http://www.gasificationguide.eu/gsg_uploads/documenten/Gasification_Guide_D08_State_of_the_Art_Description_V09e)

depends upon fuel, its final available form, its size, moisture content, and ash content. There are several advantages and disadvantages found for different types of gasifiers (Table 3). Main features of gasification are as follows:

- Degradation of biomass thermally in the presence of oxidizer
- Char oxidation with $CO_2$ or $H_2O$
- Temperature 800–1100 °C
- Biomass + limited oxygen → fuel gas

$$CH_{1.4}O_{0.6} + 0.4O_2 \rightarrow 0.7CO + 0.6H_2 + 0.3CO_2 + 0.1H_2O$$

- Ratio $CO/CO_2$ is measure for quality

Biomass gasification processes have some fundamental phenomenon

**Table 3** Advantages and disadvantages of various gasifiers (Rajvanshi 1986)

| Gasifier type | Advantages | Disadvantages |
|---|---|---|
| Updraft | Small pressure drop, good thermal efficiency, little tendency toward slag formation | Great sensitivity to tar and moisture and moisture content of fuel relatively long time required for start up of IC engine poor reaction capability with heavy gas load |
| Downdraft | Flexible adaptation of gas production to load low sensitivity to charcoal dust and tar content of fuel | Design tends to be tall not feasible for very small particle size of fuel |
| Crossdraft | Short design height, very fast response time to load flexible gas production | Very high sensitivity to slag formation high pressure drop |

Evaporation of Surface Moisture

At boiling point of water, surface moisture evaporates from raw material.

Evaporation of Inherent Moisture

At 110–120 °C, inherent moisture evaporates from the raw material.

Volatilization

Thermal decomposition is a heat-generating reaction which is a characteristics phenomenon of biomass. At 200–300 °C, the thermal degradation of biomass commences and carbon dioxide, carbon monoxide, hydrogen, and water are vaporized as gas.

Volatilization and Gasification Reaction

During volatilization, the temperature is raised further and the volatile matter of the lightweight hydrocarbon is transformed into heavy hydrocarbon with a high boiling points. Subsequently, hydrocarbon reacts with the gasifying agent for conversion to lightweight molecule clean gas. Although when diffusion of the gasifying agent is slow, tar and soot are formed and hydrocarbon condenses.

Char Gasification

In the raw material biomass, following volatilization of the volatile content, the fixed carbon and ash become char which is heated to the surrounding temperature. On reaction with gasifying agent, carbon transforms into carbon monoxide and carbon dioxide. Gasifying agent contains excess steam, the surrounding temperature is over 750 °C, and a wet gas reaction occurs producing gas composed mainly of carbon monoxide, carbon dioxide, and hydrogen.

Char Residue

As the reaction rate of the wet gas reaction is slow, char residue can easily be formed but its efficiency reduces due to the formation of tar, soot, and char.

### 3.1.4 Combustion

Combustion is an exothermic chemical reaction accompanied by large heat generation. While using biomass as a fuel, heat is generating oxidation reaction, where carbon, hydrogen, oxygen, combustible sulfur, and nitrogen react with air or oxygen and this process is known as combustion. Combustion process includes gas-phase reaction, surface reaction, evaporation, and fusion. A gas fuels burn directly in gas phase, whereas liquid fuel burns as inflammable gas in gas phase after surface evaporation which is also known as evaporation combustion.

There are different forms of combustion. Direct combustion of biomass incorporates evaporation, decomposition, surface, and smoldering combustion and it occurs in solid form. In evaporation combustion, the fuel with comparatively low fusing point fuses and evaporates by heating and reacts with oxygen in gas phase and burns, whereas in decomposition and combustion, gas produced from thermal decomposition by heating reacts with oxygen in gas phase. Char remains after this form of burns by surface combustion. In case of the component composed of only carbon which contains little volatile portion, surface combustion takes place. Smoldering combustion is the thermal decomposition reaction at temperature lower than the ignition temperature of volatile component.

Combustion temperature and thermal efficiency decrease if the surplus air rate is too high. According to the combustion method of biomass, grate combustion, fluidized bed combustion, rotary hearth furnace combustion, and burner combustion are used. Features of each method are shown in Table 4. Combustion efficiency varies with fuel, moisture content, and calorific value of fuel, etc. Combustion of biomass is used mainly for energy production and the most matured technology. Main characteristics of combustion process are listed below:

- Complete oxidation of fuel
- Pyrolysis and gasification proceed
- Global reaction rate

$$CH_{1.4}O_{0.6} + 1.05O_2 \rightarrow CO_2 + 0.7H_2O$$

- Hot gases used for heating
- Direct
- Water in central heating systems
- Boilers (electricity)
- Process conditions

### 3.1.5 Liquefaction

This technology has the potential to produce higher quality products of greater energy density, and it should also require less processing to produce marketable products. Thermochemical conversion process carried out in the liquid phase at low temperature and high pressure is termed as catalytic liquefaction. Liquefaction requires either a catalyst or a high hydrogen partial pressure. This technology is limited due to some technical problems.

**Table 4** Combustion types and feature of biomass (www.jie.or.jp/biomass/AsiaBiomassHandbook/English/Part-4_E.pdf)

| Combustion method | Combustion type | Feature |
|---|---|---|
| Fixed bed combustion | Horizontal/inclined grate, water cooling grate, Dumbing grate | Grate is level or sloping. Ignite and burns as surface combustion. Used in small-scale batch furnace for biomass |
| Moving bed combustion | Forward moving grate, reverse moving grate, step grate, lower grate | Grate moves gradually and is divided into combustion zone. Due to continuous ash discharge, grate load is large and can be applied to wide range of fuels from chip type to block type |
| Fluidized bed combustion | Bubbing fluidized bed combustion, circulation fluidized bed combustion | Uses sand for bed material, keeps fuel and sand in furnace in boiling state with high-pressure combination air and burns through thermal storage and heat transmission effect of sand. Suitable for high moisture fuel or low-grade fuel |
| Rotary hearth furnace combustion | Kiln furnace | Used for combustion of high moisture fuel such as liquid organic sludge and food residue or large waste. Restricted to fuel size on its fluidity |
| Burner combustion | Burner | Burns wood powder and fine powder such as bagasse pith by burners same as that for liquid fuel |

## *3.2 Biochemical Conversion Processes*

Biochemical conversion entails breaking down of biomass to make the carbohydrates available for processing into sugars, which can then be converted into biofuels and by-products through the use of microorganisms and catalysts. Anaerobic digestion (or biomethanation) and fermentation are the most popular biochemical technologies. It is a series of chemical reactions in which organic material is decomposed through the metabolic pathways of naturally occurring microorganisms in an oxygen-depleted environment. Liquid fuels such as cellulosic ethanol are obtained from biomass which can be used to replace petroleum-based fuels. For the treatment of wet organic wastes, anaerobic digestion is a reliable technology in highly controlled, oxygen-free conditions. Organic waste from various sources is biochemically degraded which results in the production of biogas which can be used to produce both electricity and heat. Fermentation is another biochemical process which is a series of chemical reaction (occurs in the absence of oxygen) that breaks down the glucose within organic materials and finally converts sugars to ethanol.

### 3.2.1 Anaerobic Digestion

The treatment of biomass with naturally occurring microorganisms in the absence of air (oxygen) in order to produce a combustible gaseous fuel comprising primarily of methane ($CH_4$) and carbon dioxide ($CO_2$) and traces of other gases such as nitrogen ($N_2$) and hydrogen sulfide ($H_2S$) is known as anaerobic digestion. The gaseous mixtures are commonly termed "biogas," and all nitrogen (N), phosphorus (P), and potassium (K) remain in the digested biomass. Conversion of complex organic solids into soluble compounds by enzymatic hydrolysis is the first step of this process. During the acidogenesis step, the soluble organic material formed is then converted into mainly short-chain acids and alcohols. The products of the second step are converted into gases by different species of strictly anaerobic bacteria in the methanogenesis step. The percentage of methane has been reported to vary between 50 and 80 % in the final mixture. A typical mixture consists of 65 % methane and 35 % $CO_2$ with traces of other gases. The methane producing bacteria (called methanogenic bacteria) generally require a pH range for growth of 6.4–7.2. The acid-producing bacteria can withstand low pH. The general process flow diagram of anaerobic digestion is shown in Fig. 8.

The conditions become adverse to methane formers if the methane-forming organisms do not rapidly convert these products. This is why the first type of reactors developed for the conversion of biomass wastes into methane has long retention times seeking equilibrium between acid and methane formers. In the future, aquatic biomass such as water hyacinth or micro-algae can be digested and may become valuable sources of energy. Anaerobic digestion of organic wastes may constitute an effective device for pollution control with simultaneous energy generation and nutrient conservation. The main advantage of anaerobic digestion is that it exploits biomass having high water contents approximately 99 %. The availability of conversion systems in smaller units is its another advantage.

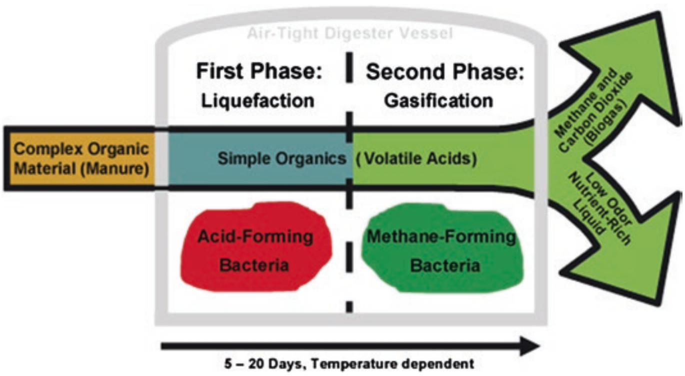


**Fig. 8** Anaerobic digestion process flow diagram (Zafar 2014)

### 3.2.2 Fermentation

The conversion of a plant's glucose (or carbohydrate) into an alcohol or acid is the basic fermentation process. During this process, yeast or bacteria added to the biomass material converts sugars into ethanol (an alcohol) and carbon dioxide. For the required purity to use as an automobile fuel, ethanol is distilled and dehydrated to obtain a higher concentration of alcohol and the solid residue from the fermentation process can be used as cattle feed. Fermentation method generally takes place in three steps: (1) the formation of fermentable sugars solution, (2) the fermentation of these sugars to ethanol, and (3) the separation and purification of the ethanol, usually by distillation. Cellulosic resources are very widespread, abundant, and inexpensive feedstock for ethanol production. Fermentable sugars are converted into ethanol and other by-products in the presence of microorganisms, and these microorganisms typically use the 6 carbon sugars, i.e., glucose. Therefore, biomass materials containing high levels of glucose or precursors to glucose are the easiest to convert to ethanol.

Along with consisting of cellulose and hemicellulose that can be converted into sugars, lignocellulosic biomass also contains a non-fermentable fraction known as lignin. Lignin has very high energy content, and it can be used for the production of electricity and/or heat; however, its presence in the lignocellulosic biomass hinders the decomposition of the biomass into fermentable sugars. Dilute acid and concentrated acid, each with variations, are two basic pretreatment types of acid processes. Fast rate of reaction is the biggest advantage of dilute acid process which facilitates continuous processing. High sugar recovery efficiency, which can be on the order of over 90 % of both hemicellulose and cellulose sugars, is the primary advantage of the concentrated process. Ethanologenic bacteria have higher growth rate than fungi due to which they produce more fermentative enzyme and utilizes both pentose and hexose sugars (Fig. 9). The ability to ferment cellulose directly to ethanol is an important advantage of some bacterial strain. There are different types of pre-treatment methods that degraded lignocellulosic biomass into its constituent sugars and then into ethanol using ethanologenic bacteria cells, after that distillation of ethanol is done and it is ready for the market.

## 4 Characteristics of Ideal Energy Crops

The time lag between the instantaneous release of $CO_2$ from burning fossil fuels and its eventual uptake as biomass is one of the important factors which is often overlooked while considering the use of biomass to assist alleviate global warming. Developed world is facing the dilemmas of this time delay and an appropriate action to alleviate against the lag period. The developing world is also facing an equal dilemma, as it consumes its biomass resources for fuel but does not implement a programme of replacement planting. For commercial energy farming, numerous crops have been proposed or are being tested. Potential energy crops

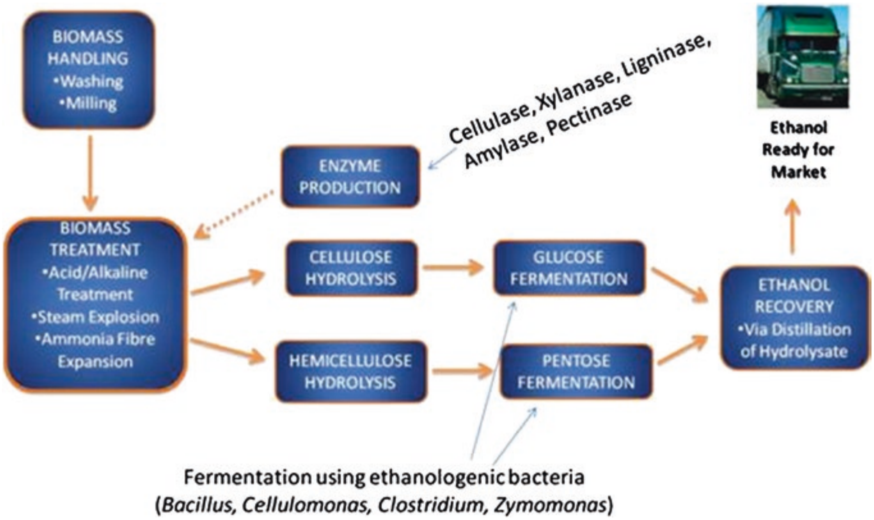


**Fig. 9** Flowchart of lignocellulosic biomass conversion to bio-ethanol (Ibraheem and Ndimba 2013)

include woody crops and grasses/herbaceous plants (all perennial crops), starch and sugar crops, and oilseeds. In general, the characteristics of the ideal energy crop are as follows:

- High yield (maximum production of dry matter per hectare)
- Low energy input to produce
- Low cost
- Composition having less contaminant
- Low nutrient requirements

Desired characteristics will also depend on local climate and soil conditions. Water consumption can be a major constraint in many areas of the world and makes the drought resistance of the crop an important factor. Pest resistance and fertilizer requirements are some of the other important characteristics.

## 5 Biomass Properties

It is the inherent properties of the biomass source that determines both the choice of conversion process and any subsequent processing difficulties that may arise. The choice of biomass source is influenced by the form in which the energy is required and it is the interplay between these two aspects that enables flexibility to be introduced into the use of biomass as an energy source. The categories of biomass are examined by most biomass researchers and technology providers. During subsequent processing, depending on the energy conversion process selected, particular material properties become important. The main material properties during subsequent processing as an energy source are as follows:

- Moisture content (intrinsic and extrinsic)
- Calorific value
- Percentages of fixed carbon and volatiles
- Ash/residue contents
- Alkali metal content
- Cellulose /lignin ratio

The first five properties are of interest for dry biomass conversion processes, while for wet biomass conversion processes, the first and last properties are of prime concern.

## 6 Biomass Use in Developing World

More than two million people in the developing world use biomass for the majority of their household energy needs such as cooking, heating water, and domestic space heating. Biomass is also used widely for non-domestic applications. Throughout the developing world, biomass is available in varying quantities from densely forested areas in the temperate and tropical regions of the world, to sparsely vegetated arid regions. Collection of wood fuel for household needs is a time-consuming and arduous task, and it also leads to the large cutting of trees; therefore, it is crucial to give much focus on efficient use of biomass in areas where wood fuel is in particular shortage. From the effects of deforestation, although domestic fuel wood users suffer greatly, the main cause of deforestation is clearing of land for agricultural use and for commercial timber or fuel–wood use. In many countries, crop and industrial biomass residues are now widely used for electricity production. Also, technologies related to the biomass processing have been improved in order to enhance efficiency of the whole process. In Indonesia, timber-processing plants are using wood waste-fired boilers to provide heat and electricity for their own needs. Biomass remains the primary energy source in the developing countries.

The allocation of biomass in energy varies: high over three quarters in percent in Nepal Laos, Bhutan, Cambodia, Sri Lanka, and Myanmar; nearly half in Vietnam, Pakistan, and Philippines; nearly a third in India and Indonesia, to a low 10 % in China and 7 % in Malaysia (FAO 1997). Biomass is expected to be the source of about 16 % of the energy generated in the USA in 2030 approximately a fourfold increase over modeled use in the current period. During past two decades, due to rapid industrialization and marketization, the higher penetration of commercial fossil fuels in most Asian developing nations has caused decline in the share of biomass energy. The use of growing biomass has sustained due to various factors such as rising population and shortages or unaffordability of commercial fuels in rural and traditional sectors. During the 1980s, regardless of policy interventions by many Asian governments, in tropical areas, the deforestation is more as compare to afforestation. The sustainable growth of biomass energy in Asia would require augmenting existing biomass resources with modern plantations and energy crops and by introducing efficient biomass energy conversion technologies.

## 7 Research and Development for Rural Areas

MNES has maintained 4 gasifier Action Research Centers (ARCs), and they developed 12 gasifier models in different national institutions. Two sugar mills-based co-generation projects (3 MW surplus power capacities) and one rice paddy straw-based power project (10 MW) were developed. In 1992, the 10 MW rice straw-based power projects which were completed ran into technological problems and closed since last two years due to want of suitable raw material. By private rice-processing firm in Punjab, a rice husk-based co-generation plant of 10.5 MW capacities was installed and commissioned in 1991. There are several factors that cause hindrance in the working of this project such as unavailability of critical spares of an imported turbine and highly expensive tariffs from the state utility despite power shortage in the state. The speedy rise in the cost of rice husk and low capacity utilization lead to the cost making of the operation uneconomical. In order to make biomass energy competitive, the experiences with R&D and pilot project suggests the need for considerable technological and institutional improvements.

## 8 Utilization of Biomass at Commercial Level

Biomass can be used for a variety of commercial activities. Several technologies are there for direct combustion of unprocessed or semi-processed biomass in order to produce heat for a variety of end-users. The boiler system is the simplest one which raises steam for such applications such as tobacco curing, electricity generation, and beer brewing. Biomass can also be used for providing direct heat for brick burning, lime burning, and cement kilns. The most important advantage of biomass is that it can be locally sourced, by avoiding shortages associated with poor fuel supply networks and fluctuating costs.

## 9 Issues of Biomass Energy in India

Although biomass energy is beneficial, even then there are some other issues which are necessary to be solved for the betterment of surroundings as well as mankind.

### 9.1 Environment

One of the major inspirations for early research and development work on improved stove was the concern for the environment. Today, this issue has brought a clearer understanding of the true causes of deforestation. Other environmental issues such as the household environment with its smoke, heat, lighting requirements, etc., have also been given greater consideration. On sustainable basis, large-scale combustion of biomass is only environmentally feasible. Without care for biomass replacement and regeneration, continual large-scale exploitation of its resources will cause environmental damage and also jeopardize the fuel source itself.

### 9.2 Women Welfare

The working day of poor women stretched from dawn to long after dark for resources. The most arduous tasks of women are cooking and fuel collection. Inhaling of biomass smoking during cooking causes severe respiratory diseases and eye infections. Women are driven to various coping strategies as fuel shortages make extra demands on time and energy. The quality and quantity of food diminish as less time are being utilized for growing or preparing food due to excess time spent on fuel collection. Malnourished women become more vulnerable to smoke pollution which damage their lungs, eyes, children, and unborn babies. Exposure to biomass smoke level lowers due to improved stoves as it cook fast, burn fuel more efficiently, and release time for other activities, as well as it helps to remove smoke from the cooking area. Greater technology choice can help to emancipate women from drudgery. An improved stove which cooks faster may be a source of delight for the places where cooking is particularly time-consuming task. Fuel management strategies by women save more fuel as compared to planned stove programmes.

## 10 Biomass Energy Status

Biomass delivers most energy for the domestic use (rural 90 % and urban 40 %) in India (NCAER 1992). Trees, crops, and animal waste are the main sources of biomass energy. Biomass has dominated the global energy supply with a 70 % share until the middle of nineteenth century (Grubler and Nakicenovic 1988). Wood fuels are the most prominent biomass energy sources. Wood fuels contribute 56 % of total biomass energy (Sinha et al. 1994). The share of biomass in total energy declined steadily with rapid increase in use of fossil fuel through substitution by coal in the nineteenth century and later by refined oil and gas during the twentieth century. As most of the biomass is not transacted on the market, the estimation of biomass consumption remains highly variable (Ravindranath and Hall 1995; Joshi et al. 1992). Global consumption of wood energy has continued to grow despite of its declining share in energy and it grew annually by over 2 % rate during 1974–94 (FAO 1981, 1986, 1996). About 14 % biomass sources contribute global energy and 38 % of energy in developing countries (Woods and Hall 1994). Globally in agriculture-based industries, the energy content of biomass residue is estimated at 56 exajoules (WEC 1994).

## 11 Biomass Energy Policies and Programmes

India has a huge record on energy planning and programme interventions. As early as in 1940s, the programmes for promoting biogas and improved cookstoves began. Since 1950s, rural electrification programmes and afforestation are pursued. India appointed the Energy Survey Committee, a decade before the oil crisis of 1973. As a component of rural and renewable energy policies as a response to rural energy crisis and oil imports, national biomass policy was originated in the decade of 1970s. In the mid-1970s, the rural energy crisis arose from four factors (i) rise in oil price, (ii) increase in rural household energy demand, (iii) trading of wood in rural and urban areas to meet demand of growing industries, and (iv) over exploitation of common property biomass resources. In order to find economically viable and sustainable energy resources to meet growing rural energy needs, the crisis was called for a national policy resource. Short-time response of importing kerosene and LPG to meet cooking needs and diesel for irrigation pumping was done.

India's oil imports rose rapidly with kerosene and diesel. Share of oil in imports was 8 % in 1970 and 24 % in 1975 which was further increased to 46 % in 1980 (Shukla 1997). The major cause of growing trade deficit and balance of payment crisis was oil imports and it is neither a viable solution at microeconomy level. In late 1970s, programmes for promoting renewable energy technologies (RETs) were initiated, to ameliorate increasing oil import burden and to diffuse the deepening rural energy crisis. Biomass was potentially the most suitable to alleviate macro- and micro-concerns raised by the rural energy crisis, being a local, widely accessible and renewable resource. The institutional response resulted in establishment of DNES (Department of Non-Conventional Energy Sources) in 1982 and state-level nodal energy agencies during the early 1980s decade. A multipronged strategy was followed by biomass policies:

- Improving efficiency of the traditional biomass use (e.g., improved cookstove programme)
- Improving the supply of biomass (e.g., social forestry, wasteland development)
- Technologies for improving the quality of biomass use (e.g., biogas, improved cookstoves)
- More stress on the utilization of biomass-based technologies for several purposes such as irrigation, and electricity generation.

## 12 Future of Biomass Energy in India

Globally, the use of biomass is growing day by day. A best way to reclaim degraded lands and to generate sizable employment is biomass plantation (Miller et al. 1986). Biomass combustion also emits pollutants, much less compared to fossil or nuclear fuel cycle (Sorensen 1997). In India, despite of advancements in biomass energy technologies, most of the bioenergy consumption remains confined to traditional uses. In the past, government have promoted new energy technologies such as nuclear power in France (Johansson et al. 1996), wind power in Denmark (Johansson et al. 1996) and India (Naidu 1997), and ethanol from sugarcane in Brazil (Goldemberg et al. 1993). The modern technologies recommend conversion biomass into synthetic gaseous or liquid fuels (such as ethanol and methanol) and electricity (Johansson et al. 1993). Lack of biomass energy market is the primary barrier to the penetration of modern biomass technologies. In India, the growing experiences with modern biomass technologies suggests that through market pull policies, these technology push policies need to be substituted or augmented. The primary policy lacuna hampering the growth of modern biomass energy is the implicit environmental subsidy which is allowed to the fossil fuels. Among policy makers, the increasing realization about positive externalities of biomass has now created conditions for biomass to make inroads into the energy market.

Modern biomass technology has potential to penetrate in four segments (i) process heat applications in industries generating biomass waste, (ii) in domestic and commercial sectors cooking energy (through charcoal and briquettes), (iii) electricity generation, and (iv) transportation sector with liquid fuels. In India, in energy and electricity sectors, doors have opened for competition through economic reforms. Future of biomass energy lies in its use with modern technologies. In future, under strong global greenhouse gas mitigation scenarios, biomass energy has significant potential to penetrate the Indian energy market. The future of biomass energy depends at competitive cost of providing reliable energy services. To orient biomass energy services toward market and reforming the market toward fair competition through internalizing the externalities of competing energy resources should be the policy priorities. Through potential availability of agro-residues and wood-processing waste, India can sustain 10,000 MW power. So, in order to meet growing non-energy needs, sustained supply of biomass shall require production of energy crops (e.g., wood fuel plantations, sugar cane as feedstock for ethanol) and wood plantations. In India, future of biomass shall determined by critical areas such as land supply, enhanced biomass productivity, economic operations of plantations, and logistics infrastructure. In India, policy support for a transition toward a biomass-based civilization should consider the following:

### *12.1 Short-Term Policies (1–5 Years)*

- Improved utilization of crop residues and wood waste
- Information dissemination
- Niche applications (e.g., remote and biomass-rich locations)
- Transfer of technology (e.g., high-pressure boiler)
- Coordination among institutions
- Demonstration projects
- More involvement of private sector, society, and NGOs
- Wasteland development
- Financial assistance to biomass technologies to balance the implicit subsidies to fossil fuels

### *12.2 Medium-Term Policies (5–20 Years)*

- R&D of conversion technologies
- Species research to match agro-climatic conditions
- Biomass plantation
- Scale economy-based technologies
- Local institutional developments
- Exclusion of distortions in fossil energy tariffs

### *12.3 Long-Term Policies (Over 20 Years)*

- Infrastructure (logistics, T&D)
- Multiple biomass energy products (e.g., gas, liquid, electricity)
- More focus on enhancement of institutions and policies for competitive biomass energy service market
- Land supply for biomass generation

## 13 Conclusions

Biomass is a renewable energy resource which is derived from the carbonaceous waste of various human and natural activities. Bioenergy is the conversion of biomass resources into useful energy carriers including heat, electricity, and transport fuels. Biomass is an energy source which can either be used directly or indirectly to produce energy in various forms. Various technologies exist to convert biomass resources to power. Several technologies for converting bioenergy are commercial today, while others are being piloted or in research and development. The efficiency and reliability of biomass production systems and conversion technologies are enhanced rapidly through the learning effects and the shared knowledge from innovations in conventional technologies. Even though current penetrations of modern biomass energy services is minute, the technological developments and policy reforms which recommend to abolish energy subsidies and internalize externalities from fuel cycle are set to be beneficial to biomass technologies. Awareness of biomass potential shall facilitate many developing countries to make a smooth transition from the present inept biomass energy use in traditional sectors to a competitive, commercial, and competent biomass energy use in the future.

As a result, this will reduce their energy import and conserve sparse finances for national development. In India, during the next decade, the government policies shall play decisive role in penetration of biomass energy. Policies play a major role on the future of biomass; it may overcome many barriers such as myriad economic, social, technological, and institutional. Future of biomass technologies depends on will and ability to overcome these barriers. A key issue before Indian policy makers is to develop a fair market for biomass energy services. A significant social and environmental benefit of biomass make it a deserving alternative for support from governments which have committed to sustainable development.

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# Technology Development and Innovation for Production of Next-Generation Biofuel from Lignocellulosic Wastes

**Vinod Kumar Sharma**

**Abstract** The present communication highlights the evolution of biofuels while giving prior attention to next-generation biofuels from lignocellulosic wastes. Both biochemical (chemicals, enzymes, and fermentative microorganisms) and thermochemical (heat and chemical) processes are addressed. For biochemical processes, topics related to the pretreatment, hydrolysis, and fermentation steps as well as process integration are also discussed. For the thermochemical processes, research topic such as process development and process analysis will be dealt with. Important R&D technical aspects, economic assessment of available technologies, limitations of certain technological approaches, etc., will also be discussed in the present communication.

**Keywords** Carbon emission · Biofuel · Lignocellulosic waste · Fischer–Tropsch liquids

## Abbreviation and Acronym

| | |
|---|---|
| ACOS | Acid catalyzed organosolv saccharification |
| AMOPS | Aquatic microbial oxygenic photoautotroph |
| CBH I enzymes | CelloBioHydrolase I enzymes family |
| DME | Dimethyl ether |
| ENEA | Italian National Agency for New Technologies, Energy and Sustainable Economic Development |
| EU | European Union |
| FICFB | Fast Internally Circulating Fluidized Bed |

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| | |
|---|---|
| FTL | Fischer–Tropsch liquids |
| GHGs | Green house gases |
| IEA | International Energy Agency |
| NREL | National Renewable Energy Laboratory |
| PEG | Polyethylene glycol |
| REN | Renewable energy |
| RPR | Residue to product ratio |
| SPORL | Sulfite pretreatment to overcome recalcitrance of lignocellulose |
| STELE | Steam explosion experimental plant |
| UNIDO | United Nations Industrial Development Organisation |

## 1 Introduction

With current global oil production approaching its peak, billions of tonnes of carbon emissions released into the atmosphere and threats of climatic change, it is obvious that clean energy is certainly an important scientific topic that needs special attention by the scientific community worldwide and, more so, in the context of the developing countries.

It is in the above context that bioenergy has been recognized as a significant component in many future energy scenarios. Many developing countries rely primarily on biomass to satisfy their energy needs. Substitution of fossil fuels by biofuels appears to be an effective strategy not only to avert an impending future energy crisis but also to reduce carbon emissions from fossil fuels.

First-generation biofuel is now exploited for nearly three decades. It is true that the technology applied for the production of bioethanol from sugar and starch crops (sugarcane, sugar beet, maize, etc.) is mature enough to permit to achieve liquid fuel competitive, both for price and performances, to gasoline and diesel but the fact remains that the technologies applied so far are still not adequate to meet the ever increasing global demand. Also, their continued use has contributed toward global food for fuel crisis.

So, production of biofuels which do not compete with food and valorization of agro-waste from bio-based industry is believed to be the main challenge for countries building a sustainable bio-based industry of tomorrow. Hence, the priority is to make use of lignocellulosic biomass from both forest (woody) and agricultural.

Woodchips from slashes and treetops, sawdust from saw mills, and waste paper pulp are common forest biomass feedstocks, whereas switchgrass and miscanthus, etc., are agricultural feedstocks for cellulosic ethanol production.

Lignocellulosic raw materials need to be broken down (hydrolyzed) into simple sugars prior to distillation. This may be achieved using either acid or enzyme hydrolysis. Both approaches have been the subject of continuing research interest since the 1970s, and large investments are being made worldwide to speed up the development of this route to bioethanol. Increasing awareness about power generation and bioethanol production from lignocellulosic materials is certainly creating a lot of interest worldwide. However, once again, the main argument against the second-generation fuels is based on land availability and protection of global ecosystems.

Also, there are indications that third-generation biofuel using algal biomass could well be the panacea to rising global demands for fuels. Various assessments advanced by different scholars indicate that algae offer great potentials as a biomass resource not only for the provision of future green transport fuels but also for direct use in carbon sequestration in many parts of the world.

It is true that a lot of research work and technological advancement have been made available (Evans 2007; Senthilguru et al. 2011; Scott et al. 2010; Joshi et al. 2011; Weber et al. 2010; Gupta et al. 2009; Decker 2009; http://www.rsc.org/delivery/_ArticleLinking/DisplayHTMLArticleforfree.cfm?JournalCode=EE&Year=2009&ManuscriptID=b822951c&Iss=Advance_Article), and demonstration plants for commercial-scale production of cellulosic ethanol are also under development in Europe, but the fact remains that even as on today, it is a must that each step of the processes producing cellulosic ethanol and valuable coproducts together with continuous improvement of the technology used to produce cellulosic ethanol must be addressed properly.

The present communication highlights the evolution of biofuels while giving prior attention to next-generation biofuel from lignocellulosic waste. Both biochemical (chemicals, enzymes, and fermentative microorganisms) and thermochemical (heat and chemical) processes are addressed. For biochemical processes, topics related to the pretreatment, hydrolysis, and fermentation steps as well as process integration are also discussed. For the thermochemical processes, research topic such as process development and process analysis will be dealt with.

Important R&D technical aspects, economic assessment of available technologies, limitations of certain technological approaches, etc., will also be discussed in the present communication.

## 2 Land-Based Biofuel Sources

The oil crisis of the early 1970s triggered interest in the adoption of land-based agriculture-derived fuels known as biofuels (bio-organic fuels) in a bid to augment the supply of fossils. Although it was thought that mass cultivation of these first-generation biofuel resources such as sugarcane, corn, soybean, rapeseed (canola), palm trees, etc., could resolve both problems of edible oil and fuel at the same time, it became obvious with time that the increasing global demand for fuel could not be met in a sustainable way by these fuel sources.

Thus, emerged the adoption of non-edible (second-generation) biofuel sources as supplementary and alternative to fossil-derived fuels, which are finite in nature and portend a great source of greenhouse gas pollutants to the environment. Although established technological approaches for transport biofuel production, such as corn to ethanol and soybean to biodiesel programmes; the EU rapeseed to biodiesel and sweet sorghum to ethanol programmes; the Brazilian sugarcane to ethanol process; the Malaysian palm oil to biodiesel experience, etc., are still heavily dependent on first-generation sources, they only generate about 0.3 % of all global transport fuels presently.

No doubt, bio-energy, with the potential to meet 50 % of world energy demands while reducing carbon emissions (>80–90 %) compared to fossil fuels, appears to be a potential energy resource but increased biofuel production on arable land could have long-term severe consequences for global food supply.

## *2.1 Classification for Liquid Biofuels*

Biofuels can include relatively familiar ones, such as ethanol made from sugarcane or diesel-like fuel made from soybean oil, to less familiar fuels such as dimethyl ether (DME) or Fischer–Tropsch liquids (FTL) made from lignocellulosic biomass. A relatively recently popularized classification for liquid biofuels includes first-generation, second-generation, and third-generation biofuels. The main distinction between them is the feedstock used.

### 2.1.1 First-Generation Biofuels

First-generation biofuels produced primarily from food crops. The most well-known first-generation biofuel is ethanol made by fermenting sugar extracted from sugarcane or sugar beets, or sugar extracted from starch contained in maize kernels or other starch-laden crops. Similar processing, but with different fermentation organisms, can yield another alcohol, butanol. Ethanol is already a well-established industry.

First-generation fuels are already being produced in significant commercial quantities in a number of countries. Brazil (from sugarcane) and the USA (from maize) are the main ethanol-producing countries. China and India are also contributing to global ethanol production, whereas production levels are still lower in other countries using feedstocks such as cane, corn, and several other sugar or starch crops (sugar beets, wheat, potatoes). Many countries are expanding or contemplating expanding their first-generation ethanol production.

First-generation biofuels produced primarily from food crops are limited in their ability to achieve targets for oil-product substitution, climate change mitigation, and economic growth. First-generation energy crops require high agricultural inputs in the form of fertilizers, which limit the greenhouse gas reductions that can be achieved. They are not cost competitive with existing fossil fuels. A possible exception that appears to meet many of the acceptable criteria is ethanol produced from sugarcane.

### 2.1.2 Second-Generation Biofuels

Second-generation biofuels are generally those made from non-edible lignocellulosic biomass, either non-edible residues of food crop production (e.g., corn stalks or rice husks) or non-edible whole plant biomass (e.g., grasses or trees grown specifically for energy). Second-generation fuel technologies have been developed to overcome some important limitations of first-generation biofuels, notably their use as food. The general aim is to reduce the cost of ethanol production and increase the volume so that it can compete with fossil fuels on price without needing subsidy.

This type of fuel is derived from non-food crops or inedible waste products, which have less impact on food, such as switchgrass, sawdust, rice hulls, paper pulp, and woodchips. Lignocellulose is the "woody" structural material of plants.

Cellulose and lignin are complex carbohydrate molecules based on sugar, which are found in all plants. These sugars can be fermented to produce ethanol in a similar way to first-generation bioethanol production. The by-product of this process is lignin, which can be burned as a carbon neutral fuel to produce heat and power for processing plants and possibly for surrounding homes and businesses.

The greenhouse gas emission savings for lignocellulosic ethanol are greater than those obtained by first-generation biofuels. Lignocellulosic ethanol can reduce greenhouse gas emissions by around 90 % when compared with fossil petroleum.

It is, again, to be noted that large-scale use of biomass for second-generation biofuels means constant supply of large amounts of wood, grasses, and "plant waste." The removal of organic residues from fields will require greater use of nitrate fertilizers, thus increasing nitrous oxide emissions, nitrate overloading, and its devastating impacts on biodiversity, land, freshwater and the oceans. It is also likely to accelerate topsoil losses.

### 2.1.3 Third-Generation Biofuels

In order to ameliorate the problems often associated with land-based biofuel feedstock, there have been calls for the adoption of *third-generation biofuel* sources, which require much less land and can be applied for reducing $CO_2$ emissions into the atmosphere. Particularly, biofuels derived from aquatic microbial oxygenic photoautotroph (AMOPS) more commonly referred to as cyanobacteria, algae, and diatoms have been advanced as a more sustainable resource that could address the global fuel demands without affecting food supply in the developing countries.

Of these, biofuels from algae appear to have greater prospects being the only renewable energy source that could meet global demand for transport fuels while addressing the carbon buildup and global warming issues at the same time. This has created unprecedented interest in algaculture (farming algae) for the production of transport biofuels.

## 3 Production of Biofuels from Lignocellulosic Wastes

Production of biofuels which do not compete with food and valorization of agro-waste from bio-based industry is believed to be the main challenge for countries building a sustainable bio-based industry of tomorrow. Second-generation biofuels share the feature of being produced from lignocellulosic biomass (lower cost, non-edible feedstocks such as wheat straw, woodchips, and a wide variety of different types of biomass) thereby limiting direct food versus fuel competition. As shown in the figure given below, second-generation biofuels can be classified in terms of the process used to convert the biomass to fuel: biochemical or thermochemical.

Second-generation ethanol or butanol would be made via biochemical processing. On the other hand, second-generation thermochemical fuels include methanol, refined FTL, and DME, being made from fossil fuels using processing steps that in some cases are identical to those that would be used for biofuel production (Fig. 1). The other thermochemical biofuel as shown in Fig. 1 is green diesel, for which there is no obvious fossil fuel analog. Unrefined fuels, such as pyrolysis oils, are also produced thermochemically, but these require considerable refining before they can be used in engines.

A variety of different process designs have been proposed for production of second-generation ethanol. One relatively well-defined approach for ethanol production is the use of separate hydrolysis (or saccharification) and fermentation steps. Other concepts include one that combines the hydrolysis and fermentation steps in a single reactor (Aden et al. 2002) (simultaneous saccharification and fermentation) and one that additionally integrates the enzyme production (from biomass) with the saccharification and fermentation steps (Zhang and Lynd 2005).

It is in the above context that the scientific community over the last couple of years has concentrated their research activities on the use of lignocellulosic

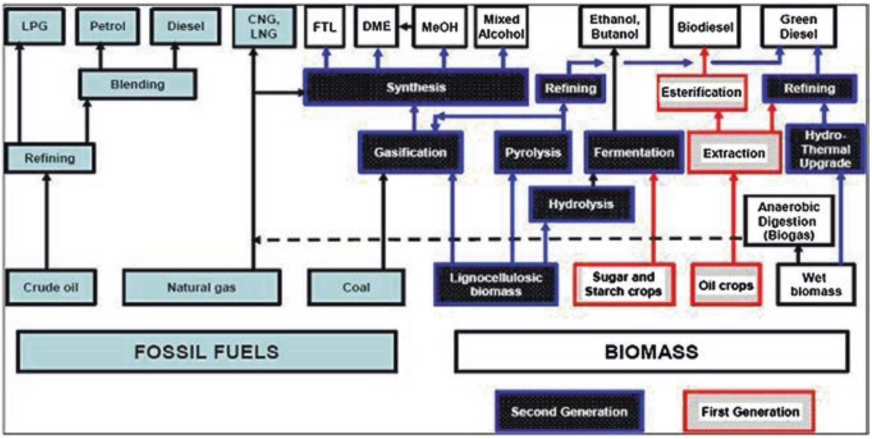



**Fig. 1** Production pathways to liquid fuels from biomass and, for comparison, from fossil fuels (Larson 2008)

biomass that could be specifically cultivated or easily recovered from agricultural, forests, or agro-industrial wastes. Needless to say that increasing awareness about power generation and bioethanol production from lignocellulosic materials is certainly creating a lot of interest worldwide.

Lignocellulosic materials such as agricultural, hardwood, and softwood residues are potential sources of sugars for ethanol production. The cellulose and hemicellulose components of these materials are essentially long, molecular chains of sugars. They are protected by lignin, which is the glue that holds all of this material together.

The technological hurdles that are presented by the materials are as follows:

- The separation of lignin from the cellulose and hemicellulose to make the material susceptible to hydrolysis.
- The hydrolysis of cellulose and hemicellulose takes place at different rates, and over-reaction can degrade the sugars into materials that are not suitable for ethanol production.
- The hydrolysis of these materials produces a variety of sugars. Not all of these sugars are fermentable with the standard yeast that is used in the grain ethanol industry. The pentose sugars are particularly difficult to ferment.

Agricultural residues and hardwoods are similar in that they have a lower lignin content, and the hemicellulose produces significant amounts of pentose sugars. Softwoods have a higher lignin content, which makes the hydrolysis step more difficult, but they generally produce less pentose sugars.

Pretreatment, hydrolysis, fermentation, and product recovery are important processes involved for the bioconversion of cellulose to ethanol, reviewed in the present paper, which take a different approach to the problems that lignocellulosic material presents.

It is, however, to be noted that in spite of good quality and availability of the raw material, it is necessary to improve the technologies for pretreatment, enzymatic hydrolysis, and separation of alcohol from the broth, apart from the valorisation of the current processes that of lignin and hemicellulose.

Breakthrough technologies to realize the potential of cellulosic biofuels can be expedited through below-listed main research and development goals (Houghton et al. 2006).

- Developing biomass feedstocks with physical and chemical structures that facilitate processing to ethanol, e.g., lower lignin content and higher cellulose content;
- Improving enzymes (also called cellulase) to achieve higher activities, higher substrate specificities, reduced inhibitor production, and other features to facilitate hydrolysis;
- Developing new microorganisms that are high-temperature tolerant and ethanol-tolerant and able to ferment multiple types of sugars (6-carbon and 5-carbon).

Achieving these goals may be facilitated significantly by the application of genetic engineering (Jeffries 2006; Stricklen 2006). Genetic modification of organisms appears to be generally accepted for applications involving microorganisms contained in industrial processes, e.g., for cellulose hydrolysis or 5-carbon sugar fermentation.

A focused set of investments linking revolutionary biofuel technologies with advances from the biological, physical, computational, and engineering sciences will quickly remove barriers to an efficient, economic, and sustainable biofuel industry.

## 4 Key Pretreatment Technologies

Cellulose and hemicellulose are densely packed by layers of lignin that offer protection against enzymatic hydrolysis. For production of ethanol using forest waste biomass, woody biomass, and herbaceous biomass crops, it is very important to separate its main components (cellulose, hemicellulose, lignin). So it is a must to break lignin seal and expose cellulose and hemicellulose to enzymatic action. To break down cellulose, the primary source of sugar in fibrous biomass, it is necessary to first get past hemicellulose and lignin, which surround the cellulose in a protective sheath. This is the job of pretreatment.

An effective pretreatment is needed to liberate the cellulose from the lignin seal and its crystalline structure so as to render it accessible for a subsequent hydrolysis step. By far, most pretreatments are done through physical or chemical means. Physical treatment is often called size reduction to reduce biomass physical size. Chemical pretreatment is to remove chemical barriers so that the enzymes can access to cellulose for microbial destruction.

To date, as shown in Fig. 2, the available pretreatment techniques include acid hydrolysis, steam explosion (SE), ammonia fiber expansion, organosolv, sulfite pretreatment to overcome recalcitrance of lignocellulose (SPORL), alkaline wet oxidation, and ozone pretreatment. Besides effective cellulose liberation, an ideal pretreatment has to minimize the formation of degradation products because of their inhibitory effects on subsequent hydrolysis and fermentation processes. In wet oxidation pretreatments, the material is treated with water and air at around 1200 °C. Although acidic wet oxidation (195 °C, 15 min) offered good fractionation of bagasse, a significant part of polysaccharides was lost due to degradation and formation of by-products, mainly carboxylic acids, but the enzymatic convertibility of the pretreated feedstock was poor. Studies have shown that wet oxidation catalyzed transformation of hemicellulose from solid phase to liquid without major hydrolysis of the solubilized hemicellulose molecules accompanied by high production of xylose SE produced more glucose.

Most pretreatment processes are not effective when applied to feedstocks with high lignin content, such as forest biomass. Organosolv and SPORL are the only two processes that can achieve over 90 % cellulose conversion for forest biomass, especially those of softwood species. SPORL is the most energy-efficient (sugar

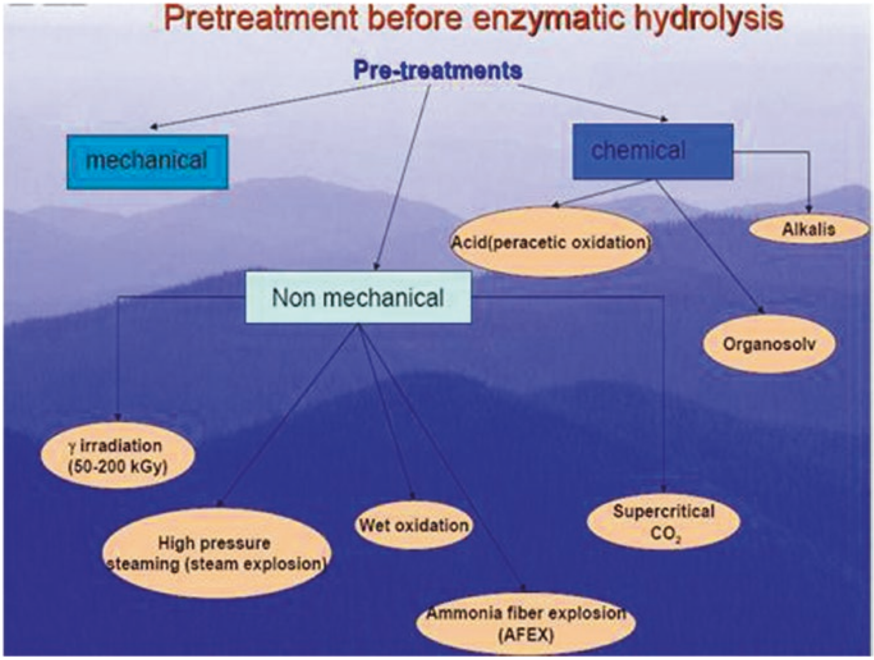



**Fig. 2** Available pretreatment techniques (de Bari 2005)

production per unit energy consumption in pretreatment) and robust process for pretreatment of forest biomass with very low production of fermentation inhibitors. Organosolv pulping is particularly effective for hardwoods and offers easy recovery of a hydrophobic lignin product by dilution and precipitation.

## *4.1 Suitable Pretreatment Based on the Properties of Lignocellulosic Wastes*

Since many lignocelluloses have different physicochemical characteristics, it is necessary to deploy suitable pretreatment technology based on their properties. Agricultural residues and hardwoods have low lignin and high pentose content compared to softwoods, and thus, high-temperature treatments are not effective for such biomass-type thing to high thermal degradation quality of pentoses.

### 4.1.1 Agricultural Residues

Agricultural residues (straws, hulls, seeds, linter and other similar by-products) have high pentose and low lignin content. Dilute acid treatment, low temperature steam treatment with acids, soaking in aqueous ammonia, and microwave-assisted treatment and wet oxidation are used successfully.

### 4.1.2 Straws

Strong crystalline structure of cellulose in rice straw and the complex structure of lignin, hemicellulose, and cellulose limit accessibility of straw to hydrolytic enzymes.

Therefore, various pretreatment methods have been developed to open the crystalline complex of cellulose and so also to increase its exposure to hydrolytic enzymes.

Hydrothermal pretreatments have proven to be effective in increasing enzymatic digestibility of wheat straw for and conversion into fermentable sugars for bioethanol production. It is reported that hydrothermal pretreatments caused profound lignin relocalization and major wax and removal of a small fraction of hemicellulose.

It is possible to pretreat wheat straw sufficiently without disrupting cell wall. It implies that only a modest pretreatment is necessary for carbohydrates to be digested enzymatically.

### 4.1.3 Bagasse

Pretreatment methods for bagasse include SE, hot water per acetic acid, and ammonia water. SE (220 °C) for shorter reaction times, followed by acid hydrolysis, proved very effective for recovery of fermentable sugars from pine hemicelluloses. SE, with $SO_2$ as acid catalyst, effectively fractionates softwood carbohydrates, releasing soluble hemicellulose (80–90 %) and thus enhancing enzymatic hydrolysis of the water-insoluble cellulose fraction.

## *4.2 Steam Explosion*

SE with low environmental impact and producing highly biodegradable substrate seems the best suitable physical pretreatment of straw as it partially hydrolyzes hemicellulose and increases its enzymatic digestibility in the biomass residue.

As shown in Fig. 3, the SE is a hydrothermal treatment for making easier and less impactive the separation between the different fractions of the common vegetal substrates (hemicelluloses, cellulose, and lignin).

The process is based on the natural ability of the water vapor at high temperature and pressure to penetrate and breaking of chemical bonding of the polymeric, cellulose, hemicellulose, and lignin in the vegetal materials. Here, the material is kept at a certain temperature (180–230 °C) for a short period (1–10 min) during

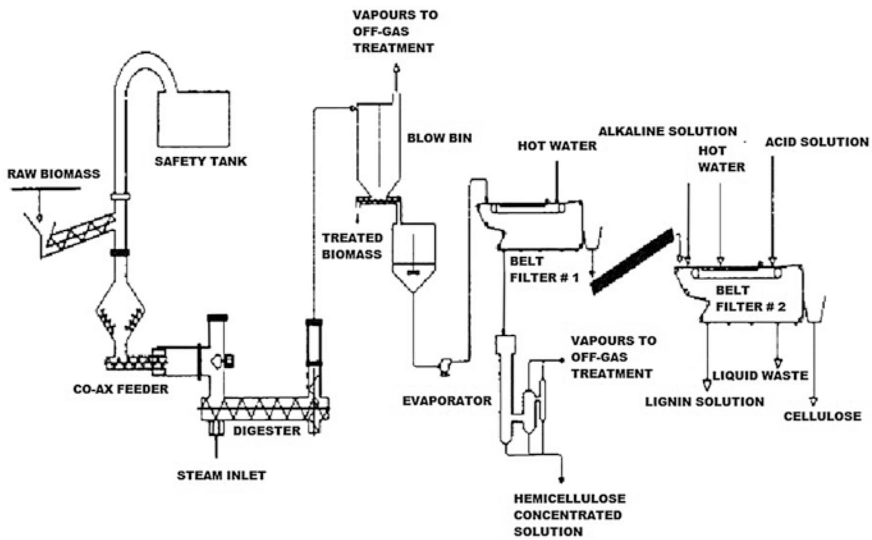



**Fig. 3** Flow diagram of steam explosion plant

which hemicelluloses are hydrolyzed and become soluble. Soon after the pressure is rapidly re-conducted to the atmospheric value to obtain a decompress explosion that further scrapers the biomass.

Steam pretreatment is affected by steam temperature, residence time in the reactor, particle size, moisture content, and the catalyst concentration. The final result is to make available the sugars contained in the feed material that otherwise could not be metabolized easily by the microorganisms used in the successive stages of bioconversion.

Two experimental pilot plants both in batch and continuous version have been realized at Trisaia to study SE. The plant operating in continuous mode, called STELE, is capable of progressing nearly 300 kg/h of wheat straw, woodchips, and a wide variety of different types of biomass (Sharma 2011).

It is equipped with a system for the treatment of the stream of product exposed. Extraction with water, caustic solutions, and filters are made on semi-industrial scale to separate cellulose, hemicellulose, and lignin.

## 5 Enzymatic Hydrolysis

For cellulosic ethanol production, the primary challenge is to break down (hydrolyzing) cellulose into its component sugars. In order that cellulose hydrolysis becomes economically feasible, it is important to identify methods that increase enzyme effectiveness and overcome barriers of enzymatic hydrolysis. Major factors that influence enzymatic conversion of lignocelluloses, the fermentable sugars, include accessible surface area of lignocelluloses, enzyme loading, and presence of inhibitors.

Attempts have been made to explore the causes of biomass recalcitrance and ways to overcome it using cellulases (enzymes that break down cellulose). The hydrolysis of the lignocellulose biomass to release the C6 fermentable sugars will be carried out via enzymatic hydrolysis.

External surface area of lignocelluloses can be increased by mechanical milling and grinding. More recently, addition of xylanase serves the same purpose, and with cellulase, it proved to be the effective method for enzymatic hydrolysis of lignocelluloses. Ohgren et al. obtained a near theoretical glucose yield (96–104 %) from acid-catalyzed steam-pretreated corn stover, using xylanases as supplement to cellulases during hydrolysis. Since high cost of enzyme limits large-scale lignocellulosic bioethanol production, it is desirable to use low enzyme loading to produce fermentable sugars with high yield.

Additives could be promising to improve enzymatic hydrolysis by restricting enzyme activity loss due to nonproductive adsorption. Use of surface-active additives (surfactants, proteins, and polymers) has been reported to enhance enzymatic hydrolysis of lignocelluloses by preventing unproductive binding of cellulase to lignin. Addition of Tween or polyethylene glycol (PEG) increased efficiency of enzymatic hydrolysis by getting adsorbed on the lignin surface. Ethylene oxide containing surfactants also has the same effect.

Addition of PEG to enzymatic hydrolysis medium at 50 °C hindered deactivation of enzymes by their exclusion from lignin surfaces and to increased cellulose conversion up to 70 %. Surfactants have a more pronounced effect on acid- and steam-pretreated straw than that of ammonia- and hydrogen peroxide-treated straws.

In another recent advance, enzymes are employed to enable milder pretreatment. Although dilute acid pretreatment can break down hemicellulose very effectively, the severe conditions require expensive processing equipment and tend to degrade the sugars. A milder pretreatment process could cut process costs dramatically and eliminate sugar degradation losses. The challenge is to maintain a high level of effectiveness with the milder process, which is accomplished by using enzymes to further break down the hemicellulose after pretreatment.

It has been reported that proper mixtures of enzymes can enhance hemicellulose hydrolysis. In an experiment on pretreated corn stover, adding a hemicellulase enzyme to break down the hemicellulose increased the yield of xylose (a sugar resulting from hemicellulose hydrolysis) by 12 % across a range of pretreatment conditions. Breaking down the hemicellulose also enhanced cellulose hydrolysis, resulting in a 6 % higher glucose yield.

To make contact with cellulose, the enzymes must get past complex structures of maize plant. A unique array of microscopy tools and techniques available at NREL's Biomass Surface Characterization Laboratory enables researchers to image plant structures down to the molecular level. To probe even further—visualizing structures and processes at scales that cannot (yet) be observed—NREL and its partners are building a sophisticated molecular dynamics model of the cellulose–cellulase system.

To accelerate cellulose conversion, it is critical to start with the best enzymes. The most active known cellulases are in the cellobiohydrolase I (CBH I) family, derived from fungi. But not all CBH I enzymes are equal.

NREL recently confirmed the existence of CBH I enzymes that are twice as active as those from industrial sources.

These ultra-sharp laser microscope images were created with the Biomass Surface Characterization Laboratory's scanning con focal microscope, which can be used to build 3-D representations of plant structures.

## 5.1 *Iogen Enzymatic Hydrolysis Process*

The block diagram for the Iogen enzymatic hydrolysis process for converting lignocellulosic materials to ethanol is shown in Fig. 4.

The pretreatment step involves SE with dilute acid conducted at elevated temperatures and pressures. The hydrolysis and fermentation steps are undertaken at ambient temperatures and pressures. Distillation is the normal ethanol industry process. The Iogen process is currently suitable for agricultural residues such as wheat straw and corn stover. Hardwood residues are also a suitable feedstock. A single-step pretreatment process for agricultural and hardwood residues is able to produce a material that can be efficiently hydrolyzed by the enzymes.

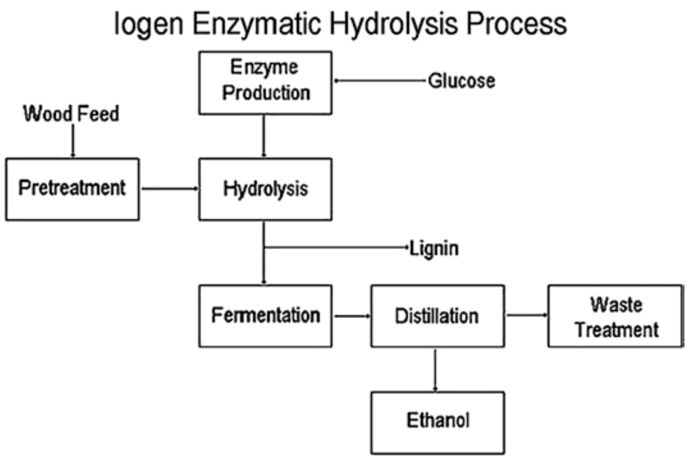



**Fig. 4** Block diagram for the Iogen enzymatic hydrolysis process

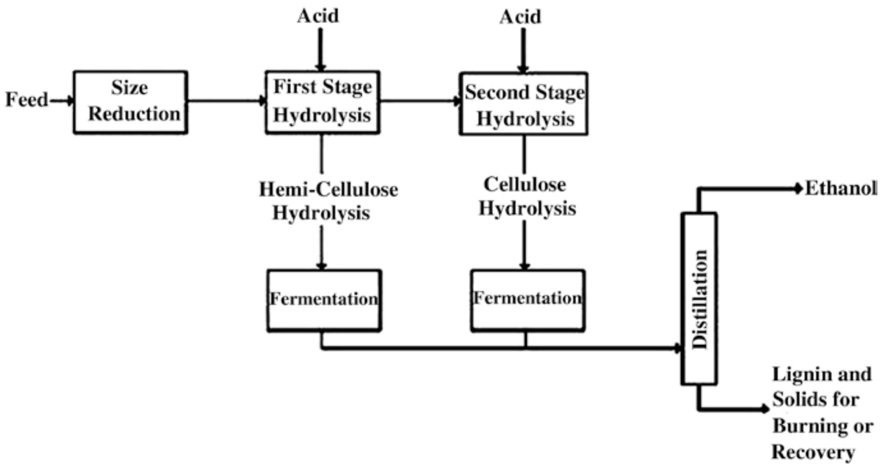



**Fig. 5** A two-stage dilute acid hydrolysis process for the preparation of the sugar streams

## *5.2 A Two-Stage Dilute Acid Hydrolysis Process*

The process is ideally suited to handle agricultural feedstocks and hardwoods. A two-stage dilute acid hydrolysis process for the preparation of the sugar streams from its preferred feedstocks is used. The hydrolysis is done in two stages: the first releasing the hemicellulose and the second the cellulose. Both of these stages involve elevated temperatures and pressures and dilute sulfuric acid to keep the reaction times short.

As shown below (Fig. 5), there are two separate fermentations although both use the same organism.

Advantage of the process is clearly its ability to ferment pentose and hexose sugars. It is true that two-stage dilute acid hydrolysis process is specifically important for agricultural and hardwood residues but it is worth to note that it has some impact on the softwood, as well. *The two-stage hydrolysis is a complicated process with higher capital costs and higher operating costs.*

## *5.3 Concentrated Acid Hydrolysis Technology*

The advantages of the concentrated acid process, as shown below, in Fig. 6, are that the reaction is fast and is carried out at lower temperatures and pressures than those using dilute acid. These advantages result in less unwanted degradation products. The traditional disadvantages have been high costs of construction due to the concentrated acid and multiple process steps, and higher operating costs due to acid losses and high waste levels. *The concentrated acid technology is suited to softwoods.*

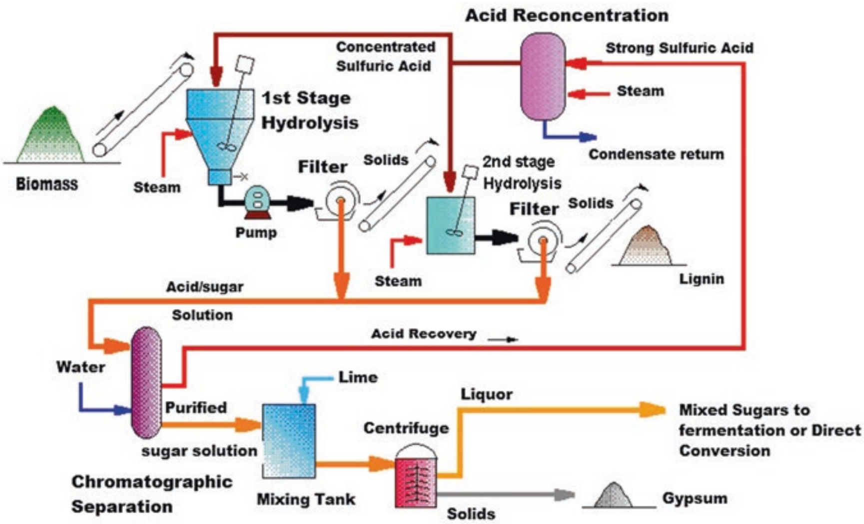



**Fig. 6** Concentrated acid hydrolysis process

The process will produce lignin and gypsum as coproducts of the process. The concentrated acid processes usually produce a lignin that has less potential for upgrading due to the amount of degradation that occurs in the processing.

Depending on the feedstock, other products can also be produced such as silica when rice straw is used.

## *5.4 Acid Catalyzed Organosolv Saccharification Process*

The process involves the solubilization of all components of lignocellulose with a concentrated solution of acetone with a small amount of acid. The reaction is carried out at temperatures around 200 °C and relatively high pressure of 40 bar. Residence times in the reactor are in the order of 0.5 h. The feedstock needs to contain moisture and be hammer-milled. The solvent to substrate ratio is closely monitored and maintained. A secondary hydrolysis is performed at about 100 °C for 20 min that drives off and recovers the remainder of the acetone. The lignin precipitates and is cooled, filtered, and recovered.

The ACOS process, as shown in Fig. 7, has a number of unique aspects. *It is claimed that a wide variety of feedstocks including hardwoods, softwoods, agricultural residues, and grain can be processed with the same conditions. The hydrolysis can process the hemicellulose and the cellulose at the same time without any significant degradation of the pentose sugars resulting in high yields.* This single-stage hydrolysis has the potential to lower capital and operating costs

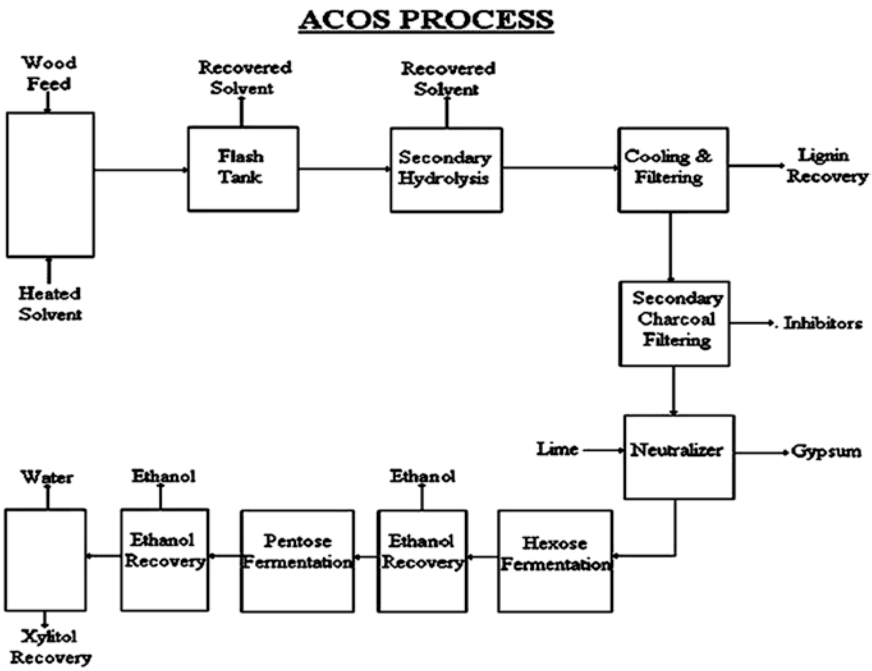



**Fig. 7** Acid catalyzed organosolv saccharification (ACOS) process

of the plant compared to the two stages. There is only one solid filtering step unlike the acid processes. The reaction times are short unlike the enzymatic process; again, this helps to lower capital costs.

## 6 Fermentation

During fermentation, microorganisms (primarily fungi and bacteria) convert the sugars in biomass to ethanol. Under ideal conditions, these "bugs" will work contentedly, consuming sugars and producing ethanol and other products. But conditions in a cellulosic ethanol biorefinery are anything but ideal.

The hot soup, called a hydrolyzate, generated after pretreatment and hydrolysis contains not only fermentable sugars, but also compounds (such as acetic acid) that are toxic to the bugs. Other things that are toxic in the fermentation process and the hydrolyzate are a high-solid concentration and a rising ethanol concentration. Because microorganisms found in nature do not function well in this hostile environment, there is a need to create "super-bugs" that thrive in it.

Yeasts are currently the fermentation organisms of choice for the corn-ethanol industry. They are reasonably tolerant of ethanol, acid, and moderately high temperatures. However, existing yeast strains cannot withstand highly

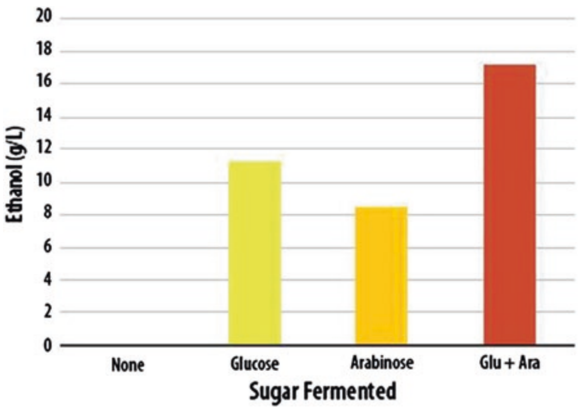



**Fig. 8** Ethanol yield versus arabinose in a defined medium

toxic hydrolyzates or ferment 5-carbon sugars and minor 6-carbon sugars efficiently. Also, development of yeast capable of fermenting a particular 5-carbon sugar, arabinose, which constitutes up to 20 % of the fermentable sugars in corn fiber, was reported. Three genes from a bacterium were inserted into the yeast Saccharomyces cerevisiae. As shown in Fig. 8, this work resulted in the first ever demonstration, in 2000, of arabinose fermentation by yeast.

Use of a yeast alternative, the bacterium Zymomonas mobilis (Zymo) giving a high ethanol yield and tolerating high ethanol concentrations, is another option. Using genetic and metabolic engineering, acetic acid-tolerant Zymo strains that can ferment arabinose and the most important 5-carbon sugar, xylose, was developed by NREL. NREL also pioneered a technique to make the Zymo strain stable (the bacteria's offspring have the same genes as the parents) by inserting key genes into the genome.

These results show an ethanol yield of 83 % from arabinose in a defined medium (not a hydrolyzate). From left to right, initial sugar concentrations were 0 g/L, 20 g/L glucose, 20 g/L arabinose, and 20 g/L glucose +20 g/L arabinose. Expected ethanol from 20 g/L of sugar is 10.2 g/L at 100 % yield.

## 7 Thermochemical Conversion

Thermochemical biomass conversion involves processes at much higher temperatures and generally higher pressures than those found in biochemical conversion systems. Key intrinsic characteristics distinguishing thermochemical from biochemical biofuels are the flexibility in feedstocks that can be accommodated with thermochemical processing and the diversity of finished fuels that can be produced. Thermochemical production of biofuels begins with gasification or pyrolysis. The former is generally more capital-intensive and requires larger scale for best economics, but the final product is a clean finished fuel that can be used directly in engines.

The discussion here focuses on gasification-based processing, by which a variety of different biofuels can be produced, including FTL, DME, and various alcohols.

FTL is a mixture of primarily straight-chain hydrocarbon compounds (olefins and paraffins) that resemble a semi-refined crude oil. Converting biomass into FT liquids involves similar processing as for coal conversion (Larson et al. 2006; Bechtel 1998; Tijmensen 2000; Tijmensen et al. 2002; Hamelinck et al. 2003, 2004; Boerrigter and van der Drift 2004). FTL is synthesized by catalytically reacting CO and $H_2$.

Thus, any feedstock that can be converted into CO and $H_2$ can be used to produce FTL. In particular, coal, natural gas, or biomass can be used as a feedstock for FTL production.

More recent activities are aimed at the development of gasifier dedicated to the production of syngas (to be used in an internal combustion engine), synthetic biofuels as well as hydrogen.

In this approach, heat and chemicals are used to break biomass into syngas (CO and $H_2$) and reassemble it into products such as ethanol. This method is particularly important because up to one-third of cellulosic biomass, the lignin-rich parts cannot be easily converted biochemically. Forest products and mill residues typically have high lignin contents, making them unattractive feedstocks for biochemical conversion yet suitable for thermochemical conversion. In an integrated biorefinery, lignin-rich residues from the biochemical process could also be converted thermochemically.

However, syngas created from biomass is not "clean"—it contains contaminants such as tar and sulfur that interfere with the conversion of the syngas into products. These contaminants must be removed through tar-reforming catalysts and catalytic reforming processes that have demonstrated high levels of tar conversion—converting up to 97 % of the tar into more syngas. This not only cleans the syngas, but it also creates more of it, improving process economics and ultimately cutting the cost of the resulting ethanol.

The major components of the now-clean and concentrated syngas are carbon monoxide (CO) and hydrogen ($H_2$), usually with a small amount of methane ($CH_4$). The CO and $H_2$ react when passed over a catalyst (the $CH_4$ is inert) to produce liquid fuel. The design of the catalyst determines what biofuel is produced. Further research work for regenerating the tar-reforming catalyst after it has been partially deactivated by sulfur poisoning has also been reported recently.

Pure ethanol (or pure butanol) can also be made from syngas by microorganisms that ferment the gas (Spath and Dayton 2003).

A second option for converting syngas to liquid fuel, one that is less well developed commercially than the catalytic process just described, is represented by the dashed lines (Fig. 9). This combined thermo/biochemical route to a pure alcohol, if it can be made commercially viable, would enable the lignin in the biomass feedstock, as well as the hemicellulose and cellulose, to be converted to fuel, unlike the case for purely biochemical "cellulosic ethanol" discussed earlier. With this option, specially designed microorganisms ferment the syngas to ethanol or butanol.

Most of the equipment components needed in a system for producing a thermochemical biofuel by the catalytic synthesis route are commercially available today.

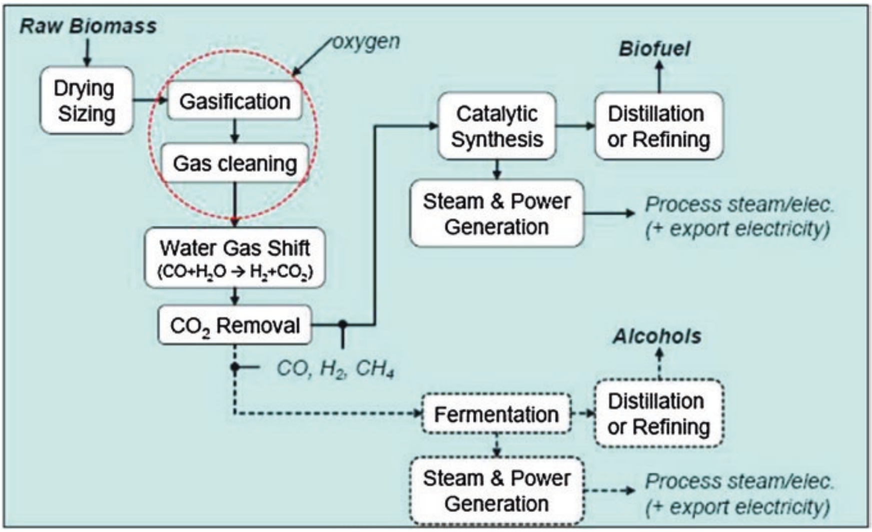



**Fig. 9** Simplified depiction of process steps for thermochemical biofuel production

However, two areas needing further engineering development and demonstration are the feeding of biomass into large-scale pressurized gasifiers and the cleanup of the raw gas produced by the gasifier. The relatively low bulk density of biomass makes it challenging to feed into a pressurized gasifier efficiently and cost effectively.

Development is needed in the area of syngas cleanup (especially tar removal or destruction) because tolerance to contaminants of downstream fuels synthesis processes is low. Tars have been the most problematic of syngas contaminants and have been the focus of much attention since the 1970s. Methods for removal (or conversion to light permanent gases) are known, but still inefficient and/or costly.

Research, development, and demonstration efforts are being pursued for syngas fermentation. The basic process flow for a novel fermentation process can convert carbon monoxide and hydrogen to ethanol as shown in Fig. 10.

The fermentation vessel operates at slightly above ambient temperatures (37 °C) but at moderate pressure (40 psi) so that reaction rates are increased. Ethanol being toxic to the culture its concentrations are kept below 3 % v/v in the reactor. The organism consumes carbon monoxide, carbon dioxide, and hydrogen to produce ethanol and acetic acid. The acetic acid production is minimized by the recycle of distillation bottoms containing some acid back to the fermenter. One of the distinct advantages of this route would be that bark could be processed as well as softwood sawdust and shavings. There would be no coproducts involved other than the excess energy generated by the system. This energy would be in the form of methane and could be used in a variety of applications including a gas turbine cogeneration system.

DME, a colorless gas at normal temperatures and pressures, is also an excellent diesel engine fuel due to its high ketene number and absence of soot production during combustion. However, an adequate purification of the product gas is

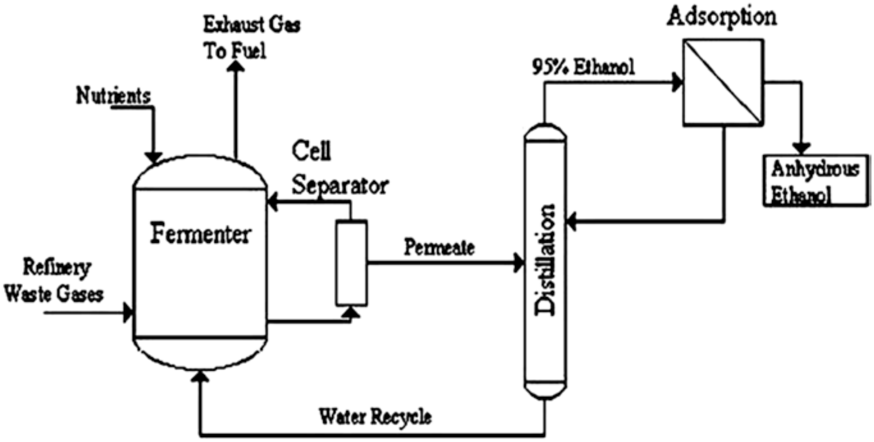
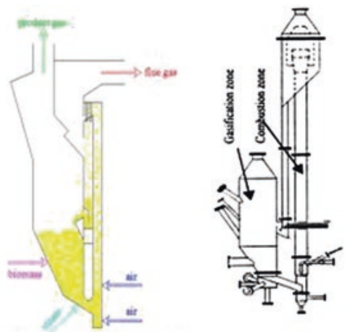



**Fig. 10** Basic process flow for a novel fermentation process

obtained thanks to the inclusion of a high-temperature ceramic filter in the cleaning section. By adding in the reactor a specific catalyst, the hydrogen content in the product gas can go over 50 % and its quality can be further improved.

In the framework of its research activities focused on thermochemical conversion of waste biomass for both thermal and electric power, as shown in Fig. 11,


| CHARACTERISTICS OF THE GAS | | | |
|---|---|---|---|
| | GASEOUS PRODUCTS | | |
| | Without Catalyst | With Catalyst | Exp. data without cat |
| $CO_2$ | 21 % | 11 % | 21 % |
| CO | 25 % | 33 % | 20 % |
| $CH_4$ | 10 % | 0 % | 20 % |
| $H_2$ | 39 % | 53 % | 33 % |
| $N_2$ | 3% | 3% | 14 % |
| $C_2H_n$ | 2 % | 0 % | 0.2 % |
| PCI | | | 11400 KJ/Nmc |

**Fig. 11** Industrial scale FICFB gasifier designed, developed, and experimented by ENEA

ENEA has developed an industrial scale FICFB gasifier at Trisaia (Avella et al. 2003). The design of the reactor and the use of steam as gasification agent give this process a nearly nitrogen-free product gas with a high calorific value of around 12 $MJ/Nm^3$ dry gas. By using a natural catalyst as bed material and gasification temperature above 800 °C, the tar content was reduced below 5 $g/Nm^3$.

## 8 Preferred Technology Route

Presently, there does not seem to be any clear commercial or technical advantage between the two pathways. Both sets of technologies are under continual development and evaluation and have significant technical and environmental barriers yet to be overcome.

For the biochemical route, much remains to be done in terms of improving feedstock characteristics; reducing the costs by perfecting pretreatment; improving the efficacy of enzymes and lowering their production costs; and improving overall process integration. The potential advantage of the biochemical route is that cost reductions have proved reasonably successful to date, so it could possibly provide cheaper biofuels than via the thermochemical route.

Conversely, as a broad generalization, there are less technical hurdles to the thermochemical route since much of the technology is already proven. The main problem appears to be the availability of large enough quantity of feedstock at a reasonable cost. Reliable and economic gasification of biomass still needs to be improved.

One key difference between the biochemical and thermochemical routes is that the lignin component is a residue of the enzymatic hydrolysis process and hence can be used for heat and power generation. In the BTL process, it is converted into synthesis gas along with the cellulose and hemicellulose biomass components.

Both processes can potentially convert biomass to energy carrier in the form of biofuels giving an overall biomass to biofuel conversion efficiency of around 35 %. Overall efficiencies of the process can be improved when surplus heat, power, and coproduct generation are included in the total system.

A second major difference is that biochemical routes produce ethanol, whereas the thermochemical routes can also be used to produce a range of longer chain hydrocarbons from the synthesis gas. These include biofuels better suited for aviation and marine purposes.

As said earlier, currently, there does not seem to be any clear commercial or technical advantage between the two pathways so only time will tell which conversion route will be preferred.

For second-generation biochemical ethanol production, advances in engineering of biological organisms and processes, and in lower cost production of lignocellulosic feedstocks, such as switchgrass, and the commercial ethanol production costs will be competitive with ethanol from corn.

In the longer term, both low feedstock costs and large production scales are projected to be needed to reach costs below corn-ethanol costs. Many developing countries may have a comparative advantage due to natural climatic conditions, and there is a greater probability that sustainable low-cost biomass production can be achieved in such places.

For second-generation thermochemical systems, since many of the equipment components needed for biofuel production are already commercially established from applications in fossil fuel conversion, with relatively modest further development and demonstration efforts, thermochemical biofuels could be in commercial production within a few years. With the present understanding of technology, a large-scale biomass FTL production facility could be realized.

Where thermochemical biofuel production can be integrated with a facility producing biomass by-products usable for energy—e.g., the pulp and paper industry—it could be competitive at much lower oil prices and/or at smaller scale.

Moreover, in countries where biomass production costs are lower and construction and labor costs are also lower, thermochemical biofuels will compete with oil prices.

# 9 Commercial-Scale Cellulosic Ethanol Plants

## *9.1 Biochemical Biomass Conversion Technologies*[1]

***M&G Commercial-Scale Cellulosic Ethanol Plant in Crescentino in Italy***

In April 2011, Mossi and Ghisolfi Group (M&G) (**Chemtex**) commenced construction of a commercial-scale 13 million gallons/year (50 million liters) cellulosic ethanol production facility in Crescentino, Italy. The plant, as shown in Fig. 12, will use Novozymes enzyme technology (Enzyme technology has enabled many industrial processes to operate with lower energy requirements and better sustainability that can be achieved by conventional approach) to convert a range of cellulosic feedstocks to ethanol. The plant started production in 2012.

***Inbicon Biomass Refinery for Production of Cellulosic Ethanol***

In Autumn 2009, **Inbicon** a subsidiary of **DONG Energy** started the construction of a demonstration plant in Kalundborg, Denmark, to showcase the company's second-generation technology for large-scale production of ethanol from straw. The Kalundborg plant (at the Asnæs Power Station) will also demonstrate energy integration with a power station. Steam from the power plant will cook the straw, and residual biofuel from the ethanol plant will be burned by the power plant.

Since the cellulosic ethanol plant produces more energy than it consumes to convert the biomass, the end result is an energy surplus that brings down the cost for both plants and demonstrates the efficiency and financial viability of the Inbicon process.

[1] Website of the European Biodiesel Board (http://www.ebb-eu.org/).


**Fig. 12** M&G commercial-scale 50 million liters/year cellulosic ethanol production plant under construction at Crescentino, in Italy

**Fig. 13** Model of Inbicon demonstration plant (cellulosic ethanol from straw)

The demonstration plant, as shown in Fig. 13, will use 4 t of straw per hour, equivalent to 30,000 t of straw per year. Danisco Genencor and Novozymes have been prequalified as suppliers of enzymes. The output will be 4300 t/5400 $m^3$ of ethanol per year.

The plant will also produce 11,100 t of molasses (65 %DM) per year, which is currently used for feed, but could in future also be used for bioethanol or biogas production

In March 2010, **Great River Energy** announced that it would use Inbicon technology in a $300 m biorefinery to produce cellulosic ethanol primarily from 480,000 t of wheat straw (and other agricultural residues) from a 70 mile radius. The refinery will be operational by 2015. The lignin produced as a by-product will be used to increase the efficiency of a nearby power plant.

***Abengoa 2G Ethanol Demo Plant***

The biomass plant was completed in December 2008 and has been fully operational since September 2009. It is the world's first plant to utilize this technology on such a scale. It is located within the Biocarburantes de Castilla y León plant. This plant, as shown in Fig. 14, is being used to improve the design of the commercial plants to be constructed over the coming years, assess operating costs, identify bottlenecks, and streamline operations. The plant capacity is 70 tpd of lignocellulosic, biomass such as wheat straw, and is able to produce over 5 MMl of fuel grade ethanol per year. The plant is been under operation over 4500 h providing extensive information about the process at demonstration scale.

The production process involves the following:

Preparation of biomass
Thermochemical pretreatment
Enzymatic hydrolysis and fermentation with enzymes and yeast
Distillation to produce ethanol and a solid coproduct

Abengoa Bioenergy is also constructing a commercial plant with output of 34,000 t/annum ethanol from lignocellulosic biomass. Plant developers may have their own enzymes (e.g., Arkenol) or may license these enzymes from their developers (e.g., Novozymes, Genencor, Roal).

**Fig. 14** Abengoa 2G Ethanol Demo Plant in Salamanca

***TMO Process Demonstration Unit (PDU) for Cellulosic Ethanol (Fig. 15)***

In September 2009, **TMO Renewables Ltd** celebrated the first year of operation of its Process Demonstration Unit (PDU), the UK's first Cellulosic Ethanol plant. The PDU has been in operation 24×7 since 2008 processing a wide range of cellulosic feedstocks, which demonstrates the commercial viability of TMO's unique pretreatment and fermentation technology based on a strain of bacteria found in compost heaps.

It is to be noted that TMO Process Demonstration Unit (PDU) has successfully tested feedstock samples from major biofuel companies from US and is now planning to integrate its process at a commercial scale.

***Futurol Pre-industrial Pilot for Cellulosic Ethanol***

In October 2011, the **Futurol project** announced the commissioning of it is the first pre-industrial pilot plant at Pomacle-Bazancourt, France. The plant will validate research into second-generation bioethanol carried out since 2008. The plant will use sustainable, local supply chains of feedstock including agricultural, forestry, and other wastes. The plant on 1:1000 scale will produce 180,000 liters/year.

***Biogasol Demonstration Plant—Bornbiofuel2***

The **BioGasol** process converts straw and other lignocellulosic agricultural residues into ethanol, biogas, hydrogen, and solid fuel with minimum use of water and low production costs. The process features a thermochemical pretreatment and a unique fermentation process based on proprietary microbes, which convert both C6 and C5 sugars to ethanol. A demonstration plant on Bornholm Island will begin operating in 2011, using 27,000 t of dry feedstock to produce 7 Mio liters of ethanol per annum. BioGasol, also in partnership with **Pacific Ethanol Inc**, will build the West Coast Biorefinery, in which BioGasol's technology will be integrated with an existing corn-based bioethanol plant.

The plant capacity will be 5.8 t of dry feedstock per hour (straw, hybrid poplar, and corn stover) and will produce 10 Mio liters of ethanol per year. The project is scheduled to be in 2011.

**Fig. 15** TMO Process Demonstration Unit (PDU) for cellulosic ethanol

***Range Fuels Two-Step Process***
Also in the USA, the **Range Fuels Inc** process uses heat, pressure, and steam to convert cellulosic feedstocks (e.g., wood, grasses, and corn stover) into syngas. In a second step, the gas is passed over a proprietary catalyst to produce **ethanol** or **methanol**.

***Chemopolis Biorefinery for Cellulosic Ethanol*** **Chemopolis**, Finland, has invested €20 m in a biorefinery to produce cellulosic ethanol (as well as biochemicals and fibers) from a wide range of non-food biomass, particularly straw and bagasse. The biorefinery was opened on May 4, 2010. The plant can process 25,000 t/annum of raw material and will also be used for testing raw materials and producing samples of bioethanol. The biorefinery processes are designed to be self-sufficient (with virtually no GHG production) and low in water consumption.
***AE Biofuels, Butte, Montanan, USA,*** has a pilot plant for ethanol synthesis via the biochemical route using multiple lignocellulosic feedstocks such as switchgrass, grass seed, grass straw, and corn stalks. Their 500 t/annum pilot plant has been operational since 2003.

***DDCE DuPont Danisco Cellulosic Ethanol in Vonore***, USA, has demonstrated a 750 t/annum ethanol plant via the biochemical fermentation route using corn stover, cobs, fiber, and switchgrass. The facility has been in operation since 2010.

***KL Energy Corporation, Upton, USA,*** has been using wood waste to produce ethanol via the biochemical pathway. This 4500 t/annum demo plant has been in operation since 2007. KL Energy ***Corporation*** has developed a process using a mild pretreatment. KL Energy ***Corporation*** has 5 commercial projects under development, 2 in the USA, and 3 in Brazil.

***Lignol Energy Corporation, Burnaby, Canada,*** uses hardwood and softwood residues to produce ethanol using the biochemical approach. Their pilot plant of 80 t/annum has been in operation since 2010. Lignol has commissioned a pilot plant using the the Alcell technology, originally developed by General Electric and Repap Enterprises, uses a solvent-based pretreatment, and produces ethanol and high-purity lignin. It is worth to mention that for the realisation of a demonstration plant, Lignol Energy Corporation, is working with Pacufic Ethanol Inc.

The unique technology developed by ***Mascoma Corporation*** called consolidated bioprocessing employs engineered yeast and bacteria which produce large quantities of the enzymes to break down the cellulose and further ferment the resulting sugars into ethanol. Combining these two steps (enzymatic digestion and fermentation) is expected to significantly reduce costs by eliminating the need for enzyme produced in a separate refinery. Its 5 m gallon/yr, biofuels facility is expected to be operational soon.

Mascoma's demonstration plant (0.8–1.9 ML/year) uses multiple feed stocks and works on biochemical technology, and thermophilic bacteria are used. Their 500 t/annum demonstration plant using switchgrass, woodchips, etc., to produce ethanol and lignin is in operation since 2003.

Also, Mascoma is planning a 151 ML/year commercial development in Kinross, Michigan, by 2012 using the CBP biochemical process.

***ZEA chem*** utilizes a hybrid process of biochemical and thermochemical processing in which after fractionating the biomass, the sugar stream (both xylose [C5] and glucose [C6]) is fermented to acetic acid without $CO_2$ as a by-product. The acetic acid is converted to an ester which can then be reacted with hydrogen to make ethanol. Hydrogen necessary for subsequent conversion of ester to ethanol is produced by gasification of lignin to create a hydrogen-rich syngas stream. The hydrogen is separated from the syngas and used for ester hydrogenation, and the remainder of the syngas is burned to create steam and power for the process.

***ICM*** has received DOE funding to construct a 10 ML/year cellulosic ethanol demonstration plant to be colocated at the existing 190 ML/year corn-based ethanol plant in St Joseph Missouri. The process utilizes biochemical conversion technology. Novozymes are a collaborator.

Bluefire Ethanol is utilizing feedstocks such as corn stover, straw, husk, and woody biomass to produce ethanol via the biochemical route. A 50 t/annum pilot plant has been operational since 2009.

***POET, Scotland, UK,*** has been utilizing corn fiber, corn cobs, and corn stalks to produce ethanol. Their 60 t/annum pilot plant have been operational since 2008 in the UK.

***Technical University of Denmark*** (DTU), Denmark, is utilizing wheat straw, corn fiber, etc., as feedstock to produce ethanol, biogas, and lignin via the biochemical approach. The 10 t/annum pilot plant has been operational since 2006.

***Verenium*** have partnered with British Petroleum which is constructing a 136 ML/year in Highland, Florida, and start-up is planned for 2012. Verenium is operating a 5.5 ML/year demonstration facility in Jennings, Louisiana. The Verenium process uses dilute acid hydrolysis followed by SE, liquid/solid separation, followed by separate C5 sugar and C6 sugar fermentation. Proprietary enzymes are used for the saccharification of cellulose.

***Süd-chemie AG Cellulosic Ethanol Plant, Munich***

**Süd-Chemie AG**, Munich/Germany, a member of the Clariant Group, Muttenz/Switzerland, has started construction in Straubing (Lower Bavaria) of what will be the largest German plant for the manufacture of cellulosic ethanol. *The plant will produce up to 1,000 t of cellulosic ethanol per year, primarily from wheat straw.*

***Borregaard Production of Ethanol from Spruce***

Cellulose producer, **Borregaard**, is involved in the development of biorefineries for the production of value-added products from wood, including bioethanol. It currently supplies ethanol derived from spruce for 20 buses in Oslo. Borregaard is a key partner in the FP7 biorefinery projects **Supra-Bio** and **EuroBioRef**

***Fibreetoh Project***

The FibreEtOH project will run from 2010 to 2013. The innovative focus on the FibreEtOH project is to demonstrate for the first time globally in a commercial-scale a cost-efficient paper fiber-based ethanol production with high >70 % overall energy efficiency and with high >50 % greenhouse gas reduction. Second-generation ethanol production technology has been developed using mainly corn stover, straw, or sawdust as raw material. So far, reliable and cost-efficient hydrolysis technology has been the bottleneck for large-scale commercial success. The proposed demonstration plan with 20,000 $m^3$/a ethanol production capacity will be build using 250,000 t/annum waste from Helsinki metropolitan area in Finland. Biogas, district heat, and electricity will be produced from the by-products.

The site and environmental permits have already been granted. The FibreEtOH proposal will demonstrate innovations in a novel 2G EtOH production chain using optimized and cost-effective enzymatic hydrolysis process taking advantage of the adjacent enzyme production and the whole production concept with high overall process integration.

***Petrobras Novozymes Agreement on 2G Ethanol from Sugarcane Bagasse***
In October 2010, Petrobras and Novozymes entered an agreement for the development of enzymes and production processes to produce second-generation lignocellulosic ethanol from bagasse in an enzymatic process. It is estimated that bagasse-to-ethanol technology can increase the country's ethanol production by some 40 % without having to increase the crop area.

## 9.2 Thermochemical Biomass Conversion Technology

*Southern Research Institute* and its team members, Mott Corporation (Mott), and Thermochem Recovery International (TRI) plan to demonstrate an integrated system to convert woody biomass into clean diesel fuel and other high-value liquids using a novel syngas cleaning approach. Syngas cleaning presents a significant challenge and cost for production of liquid fuels from biomass. The Southern Team is conducting a two-phase demonstration to develop and demonstrate the technical and economic viability of a hot syngas cleanup system based on a commercially tested filter technology and proven gas cleanup sorbents and catalysts combined and sequenced.

1 MW thermal biomass gasifier, based on TRI gasification technology, is being operated and optimized by Southern Research's Clean Energy Technology Center in Durham, North Carolina. It will be utilized to generate syngas for operation and testing of the Southern Team's syngas cleaning technology. Cleaned syngas will be routed to a fully integrated FT liquids system, designed by Emerging Fuels Technology (EFT), and the FT products and catalyst performance will be monitored to determine if gas cleaning performance is adequate and robust.

The diesel thus produced will also be tested in a commercial vehicle, on-road, to measure emission performance. The proposed gas cleanup configuration is based on vast working experience relevant to the production of syngas and its cleanup, development of hot gas filter systems for solid removal and fuel conversion technology.

The novel approach to syngas cleanup being used here represents a dramatic improvement over conventional syngas cleaning by integrating hot control of particulates in conjunction with a high level of tar and ammonia cracking, desulfurization, and halide capture.

***Chemrec AB Pitea, Sweden, and SSL*** are constructing a pilot plant in Sweden which will produce DME from lignocellulosic biomass. This 1800 t/annum pilot is under construction since 2010. The plant will produce biofuels such as biomethanol or bio-DME using forest harvest via the gasification followed by catalytic synthesis.

***Choren Fuel Freiberg GMBH*** and Co. KG Freiberg, Germany, are using dry woodchips from recycled wood and residual forestry wood. The company is developing FT liquids via syngas. Their 14,000 t/annum commercial facility is under construction since 2010

***CTU-Conzepte Technik Umwelt AG Güssing, Austria,*** is using the thermochemical route to produce syngas from gasifier which is converted to synthetic natural gas (SNG). The 576 t/annum demonstration plant has been operational since 2008.

***ENERKEM Sherbrooke, Canada,*** has tested 20 types of feedstock to produce methanol, ethanol, and acetates from syngas. A 4000 t/annum demonstration plant is under construction since 2010.

***Gas Technology Institute, Des Plaines, USA,*** is using forest residues, stump material, and bark in both pellet and chip form. They are working on Carbona (Finland and USA) biomass gasification process which is based on cooperation with VTT of Finland and Velocys (USA) Fischer–Tropsch technology. The company FT liquids pilot plant of 26 t/annum using gasification followed by syngas has been under construction since 2010.

***The Iowa State University BioCentury Research Farm*** dedicated to biomass production and processing. The bioprocessing facility is planned to offer three different lines for processing ground and pretreated biomass which include a biochemical train, a thermochemical train, and a bioprocessing train for hybrid technologies. The integrated setup is expected to utilize grains, oilseeds, vegetable oils, and glycerin, and the products generated include ethanol, FT liquids, biodiesel, and pyrolysis oils. The company's 200 t/annum pilot plant has been in operation since 2009.

***Biofuels OY, a Neste Oil and Stora Enso JV Varkaus, Finland,*** is converting forest residues to FT liquids via the conversion of syngas. A 656 t/annum demonstration plant have been operational since 2009.

## 10 Economics

A general characteristic distinguishing second-generation biofuel production from first-generation technologies is the larger capital cost per unit of production. Lower cost feedstocks will offset this greater capital intensity to yield lower total production costs. For second-generation biochemical ethanol production, advances in engineering of biological organisms and processes, and in lower cost production of lignocellulosic feedstocks such as switchgrass are expected to be commercial competitiveness of biological fuel ethanol over the next 10–20 years.

Production of cellulosic ethanol with today's known technologies, especially in many developing countries, may have a comparative advantage due to possible sustainable low-cost biomass production in such places.

For second-generation thermochemical systems, it is expected that with relatively modest further development and demonstration efforts, thermochemical biofuels could be in commercial production within a few years. In case, biofuel production by thermochemical means can be integrated with a facility producing biomass by-products, e.g. the pulp and paper industry,biofuel production by thermochemical route can be competitive at much lower oil prices ($ 40-50/barrel of oil) and/or at much smaller scale (Larson et.al. 2007).

In countries where biomass production costs are lower (due to better growing climates) and where construction and labor costs are also lower, thermochemical biofuels will be more competitive.

Given the still-early point in commercial development of second-generation biofuel technologies, it is difficult to project the role that developing countries will take in a global biofuel economy in the long term.

## *10.1 Cost Prediction*

The chart provided below presents data on what the NREL expects the costs of cellulosic ethanol to be in future.

It can be observed from the above illustration that significant reductions are expected in all the main three cost contributors—feedstock costs, enzyme costs, and conversion costs. In the longer term, both low feedstock costs and large production scales are projected to be needed to reach costs below corn-ethanol costs.

The achievability of supplying large volumes of biomass at an average cost of $30/t or less (as assumed in Fig. 16 by NREL) will be a most challenging task.

In the longer term, both low feedstock costs and large production scales are projected to be needed to reach costs below corn-ethanol costs (Fig. 16)

It is worth to note that as per projection from NREL laboratory, it is expected that by the year 2012, feedstock costs will decrease by over 40 % and conversion costs will decrease by over 40 %, whereas enzyme costs decrease by almost 70 %. Lignocellulosic ethanol is estimated to become cost competitive with fossil fuels currently at a crude price of about $100 per barrel, and by 2030, it is expected to be competitive at a crude price of $75.

Needless to say that processing cost reduction benefits could result from various efficiency efforts. The largest of these reductions are likely to come from concepts

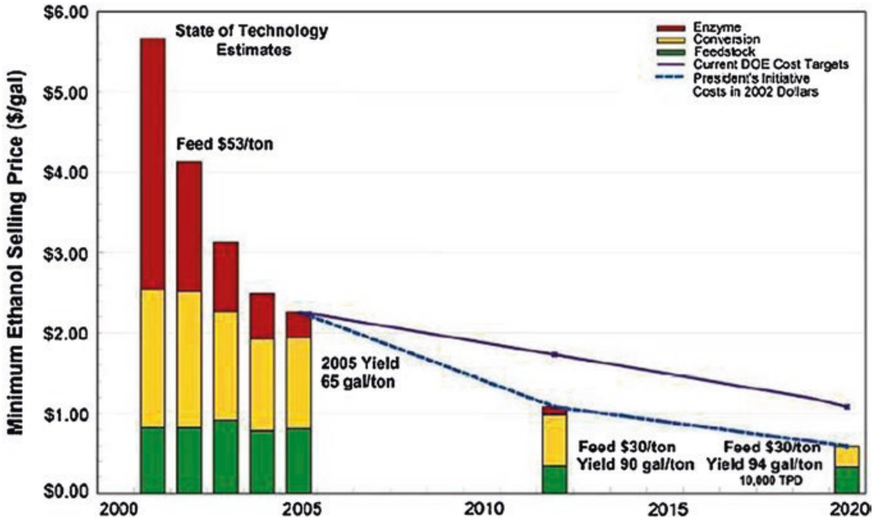



**Fig. 16** Costs and cost targets for cellulosic ethanol production projected by NREL (Larson et al. 2007)

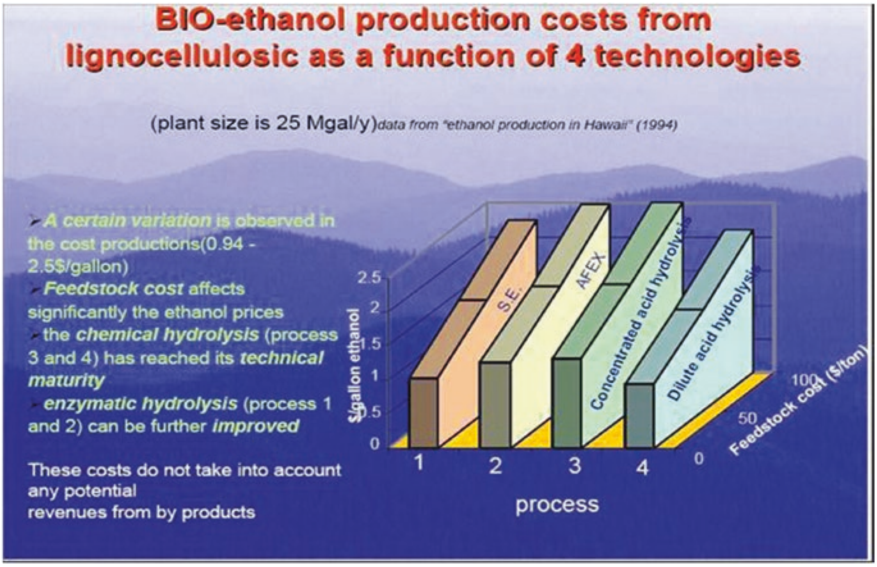



**Fig. 17** Bioethanol production costs from lignocellulosic as a function of technologies

such as consolidated bioprocessing, efficiencies in pretreatment methods, and a more optimal utilization of cellulose enzymes. As shown in Fig. 17, it is expected that through reduced energy usage, reduced enzyme costs, reduced raw material requirements, and capital expenses, it is possible to achieve the target value.

**Table 1** Future projections for cellulosic ethanol costs

| Cost component | 2001 | 2005 | 2012 | 2020 |
|---|---|---|---|---|
| Feedstock | 0.8 | 0.8 | 0.5 | 0.35 |
| Enzyme | 3.2 | 0.4 | 0.3 | 0.1 |
| Conversion | 1.7 | 1.2 | 0.8 | 0.6 |
| Total cost per gallon | 5.7 | 2.4 | 1.6 | 1.05 |
| Total cost per gallon equivalent of gasoline[a] | 9.3 | 3.9 | 2.6 | 1.7 |

All cost data in $/gallon

[a]1.63 gallons of ethanol is the equivalent of 1 gallon of gasoline, in terms of calorific value/energy density

Based on the above information and data and using others reference sources, as shown in Table 1, it is estimated that the following is the likely trend for cellulosic ethanol costs in future.

## 11 Investment Potential

Keeping in view the overall global production and, moreover, to meet its targets for renewable energies, a marketing report produced by the European Renewable Energy Council has predicted an overall investment of €443 billion (by the year 2020) in Europe.

Needless to say that a preset target share of 20 % from renewable in total energy consumption will have economic opportunities for new industries and new industrial and craft jobs through production, installation, and maintenance of such energy systems.

To reach both overall and the sector targets, which is feasible, specific support actions needs to be taken on lignocellulosic wastes technologies. Using biological fuels or other renewable fuels to replace diesel or petrol, in each member state, can guide policy-makers and send important signals to the investors. Moreover, the effective implementation of proposed biofuels directives will certainly need a considerable amount of investments in this sector.

Given the present state of market progress and a strong political support, it is worth mentioning that concrete steps need to be taken to achieve significant contribution from biofuels toward energy consumption in the transport sector.

Ethanol production, as shown in Table 2, is expected to hit 88.7 billion liters in 2012, with net growth of over 3 % compared to the global production during the year 2011 of 85.8 billion liters. The USA continues to be the largest ethanol producer in the world with production levels expected to reach over 51 billion liters, in 2011. Europe is expected to produce 5.4 billion liters of ethanol this year which is a 15 % increase over 2010.

The African continent has tremendous potential for biofuel production. High energy prices and the availability of productive land represent enormous opportunity for African biofuel production.

**Table 2** World ethanol fuel production in million liters

| | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|
| Europe | 1627 | 1882 | 2814 | 3683 | 4615 | 5467 |
| Africa | 0 | 49 | 72 | 108 | 165 | 170 |
| America | 35,625 | 45,467 | 60,393 | 66,368 | 77,800 | 79,005 |
| Asia/Pacific | 1940 | 2142 | 2743 | 2888 | 3183 | 4077 |
| World | 39,192 | 49,540 | 66,022 | 73,047 | *85,763* | *88,719* |

*Source* F.O. Licht

This year will be critical for Europe as member counties ramp up their production and use of ethanol to meet the European Union's Renewable Energy Directive.

There is no doubt that ethanol production today is able to reduce reliance on foreign oil, but still there is lot more to do and we should do.

## 12 International Cooperation

The fact that innovative biofuel technologies are primarily being developed in industrialized countries raises the question of technology relevance for developing countries. Technologies developed for industrialized country applications will typically be capital intensive and labor minimizing and designed for large-scale installations to achieve best economics.

It is also to be noted that the potential raw materials are available worldwide to develop biofuel not only in Europe, but also in North and South America and in Asia to a notable alternative fuel.

Needless to say that developing countries will need to be able to adapt innovative technologies for their own conditions, which raises issues of technology transfer.

Also, in view of the increasing technical requirements of engines, action is particularly required to improve the coordination of the necessary research activities by the biofuel manufacturers as a prerequisite for their further survival in and access to the market. This also means a general improvement in know-how transfer.

It has been found in the course of research conducted for this article that cooperation at the international level must be improved significantly. This includes the production of the corresponding fundamental data on the cultivation and exploitation, marketing strategies, capacity development, and coordination and execution of the necessary (predictive) research.

It is therefore extremely pleasing that the International Energy Agency (IEA) has initiated a study to determine the current state of developments worldwide by direct inquiry from the biofuel manufacturers.

## 13 Conclusions

- It is true that the technology applied for the production of bioethanol from sugar and starch crops (sugarcane, sugar beet, maize, etc.) is mature enough to permit to achieve liquid fuel competitive, both for price and performances, to gasoline and diesel, but the fact remains that have proven grossly inadequate to augment rising global requirements. Also, their continued use has contributed toward global food for fuel crisis.
- Production of biofuels which do not compete with food and valorization of agro-waste from bio-based industry is believed to be the main challenge for countries building a sustainable bio-based industry of tomorrow. Hence, the priority is to make use of lignocellulosic biomass both forest (woody) and agricultural.
- Use of biofuels in transport is important for reducing emission of green house gases (GHG) and the EU duly recognizing the roles biofuels have to play supports the need for increasing the share of biofuels in the transport sector, especially in road transport that generates nearly 85 % of the transport sector's emission. Second-generation biofuel technologies such as cellulosic ethanol or syndiesel, with greater environmental benefits, can save $CO_2$ up to 90 % and higher.
- Innovation in the industrial biotechnology, especially the development of enzymes that can convert (hemi) cellulose with improved efficiency, is a key to the development of second-generation biofuels with focus on using residual non-food parts of current crops as well as other crops that are not used for food purposes, such as switch grass, cereals that bear little grain and more fiber, and woodchips.
- Pretreatment of lignocellulosic biomass for ethanol production, new and advanced technologies for hydrolysis and/or fermentation of lignocellulosic biomass, high-purity syngas cleaning technologies for biofuels, biological conversion of syngas into liquid biofuels, and the development of the Biorefinery concept, as well as alternative routes to renewable fuel production, are important technical aspects that need to be addressed on priority basis.
- For second-generation fuels, many developing countries have the potential to produce biomass at lower cost than in industrialized countries due to better growing climates and lower labor costs and so may be able to gain some comparative advantage.
- In view of significant gains on energy and environmental benefit, it is very important to have a close collaboration with countries having ever-increasing demand for energy for sustainable development, such as India and China, in the near future. For successful technology adoption and adaptation, it will be essential to have in place a technology innovation system in a country. This includes the collective set of people and institutions able to generate fundamental knowledge to assimilate knowledge from the global community to form effective joint ventures with foreign companies, joint collaboration in the field of research and technology development, etc.

- For the purpose of technical know-how transfer, production of the fundamental data on the cultivation and exploitation, marketing strategies, capacity development and coordination and execution of the necessary (predictive) research on various aspects of new-generation biofuels, cooperation at the international level, is a must.
- To build trust, good interface with all stakeholders including the vehicle manufacturers and oil companies is a must.

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# Advancement in Biogas Digester

**Anil Kumar, Biswajit Mandal and Atul Sharma**

**Abstract** Biogas is a renewable energy source with different production pathways and various excellent opportunities to use. Biogas refers to a gas produced by anaerobic digestion (AD) or fermentation of organic matter including manure, sewage sludge, municipal solid waste, biodegradable waste, energy crops, or other biodegradable feedstock. Biogas is comprised primarily of methane and carbon dioxide. In this review, we discussed the worldwide status of biogas production, history of the biogas digester, classification of biogas digester, and their advantages and disadvantages. The government policies on the use of kitchen-waste-based digesters and the social and environmental effects of the digesters are also discussed. More subsidies need to be given and more initiatives need to be taken by the government. The government has many policies for biogas digester plants; however, lack of proper awareness among people inhibits the adaptation of technology.

**Keywords** Biogas digester · Environmental effect · Government policies · Subsidies

## 1 Introduction

Due to increasing prices of fossil fuels and taxes on energy sources, we are compelled to find alternative, clean and economical sources of energy. This has currently become a major apprehension for the economies of nations. In addition, economic prosperity and quality of life are linked in most countries to per capita

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energy consumption, which is a great determinant and indicator of economical development. The demand for energy is a major reason for extensive climate change, resource use, and also restricts the living standards of humans. By the time fuel and fertilizer reach rural areas, the end price is relatively expensive due to high carrying costs, leaving people to find alternative resources other than oil. Wood is used as the conventional source of fuel to produce energy for the household requirements of 4.3 billion people of Asia (Rajendran et al. 2012).

Several traditional methods have been used to utilize energy capacity embedded in carbon neutral biomass sources and anaerobic digestion (AD) is one of them. AD is a natural process whereby bacteria existing in oxygen-free environments decompose organic matter. In AD, organic material is stabilized and gaseous byproducts, primarily methane ($CH_4$) and carbon dioxide ($CO_2$), are released. Anaerobic digesters are designed to run in either mesophilic (20–45 °C) or thermophilic (45–60 °C) temperature. However, methanogenesis is also probable in low temperature (<20 °C) (Balasubramaniyam et al. 2008). Today, farm-based manure facilities are perhaps the most common use of the AD-technology. Six to eight million family-sized low-technology digesters are used in the Far East (People's Republic of China and India) to give biogas for lighting and cooking. There are now over 800 farm-based digesters in service in Europe and North America (Simon 1999).

Biogas typically refers to a gas produced by the breakdown of organic matter in the absence of oxygen. It is a renewable energy source. Furthermore, biogas can be produced from regionally available raw materials such as recycled waste and is environmentally friendly.[1] A biogas digester, also known as a methane digester, is a piece of equipment that can turn organic waste into usable fuel. In addition to providing a source of renewable fuel, biogas digesters also provide low-cost fuel to people in poverty, and help to use waste materials effectively, which would otherwise be discarded. The biogas digester relies on bacterial decomposition of biomass—waste material which is biological in origin, ranging from kitchen scraps to cow dung.[2] The main part of a biogas system is a large tank, or digester. Inside this tank, bacteria convert organic waste into methane gas through the process of AD. Each day, the operator of a biogas system feeds the digester with household by-products such as market waste, kitchen waste, and manure from livestock. The methane gas produced in a biogas system may be used for cooking, lighting, and other energy needs. Waste that has been fully digested exits the biogas system in the form of organic fertilizer.[3] New technologies in the field of biogas digesters include bag-type biogas digester plants, Vacvina biogas digester, and plastic-drum type biogas digesters.

The waste generation rate is increasing in India by 1.33 times per year as shown in recent studies. By 2047, India will produce around 260 million tons of

[1] www.en.wikipedia.org/wiki/Biogas_digester.

[2] www.wisegeek.com/what-is-a-biogas-digester.htm.

[3] www.simgas.com/advantages-of-biogas/how-does-biogas-work/item46.

solid waste and for disposal of this waste, a total land area of around 1400 ha km$^2$ is required. The rate of generation of waste is really impossible to reduce and it is also impossible to supply such a big land area for its disposal. In India, for solid waste management, approx. Rs. 1500 crore is disbursed for its overall management (Bansal 2013).

In this chapter is discussed the efforts made toward the present status of biogas digester, government policy, and market growth in India. The Indian Government started a scheme "Biogas based Distributed/Grid Power Generation Programme" from 2005–2006 (January 4, 2006) with a vision to promote biogas-based power generation, particularly in the small capacity range, based on the accessibility of large amounts of animal wastes and wastes from forestry, rural-based industries (agro/food processing), kitchen wastes, etc.

## 2 Historical Development in Biogas Digesters

Biogas utilization from AD appears to have a long history. Evidence suggests that biogas was used even 3000 years ago for heating bath water in Assyria. As reported by Marco Polo, the ancient Chinese literature mentions covered sewage tanks built for biogas production some 2000–3000 years ago.[4] The technology of biogas production dates back to a long time. In the seventeenth century, Jan Baptita Van Helmont first determined that flammable gases could develop from putrefying organic matter. In 1776, Count Alessandro Volta suggested that there was a direct relation between the quantity of decomposing organic matter and the quantity of flammable gas generated. In 1808, Sir Humphry Davy determined that methane exists in the gases generated during the AD of cattle dung.[5] In 1859, the first sewage plant in modern times was built in Bombay. In 1895 this concept was brought to the UK. The gas produced was used to light street lamps. The arrangement was developed in the UK and Germany in the early 1900s for the management of sewage. The gas produced was sometimes used as a source of energy, especially during the Second World War. Since then, a number of sewage plants drove vehicles on biogas. In the 1930s, the use of farm manure to generate methane was again developed in Bombay. Only in the early 1960s, it was developed for utilization by Indian villagers by the Khadi and Villages Industries Commission (KVIC). The design used a floating gas steel drum and formed the basis of an ongoing Indian Government program to reach out to villagers for providing them with fuel for cooking.[6] In India, a lot of important work on biogas has been done. But only in more recent times did these developments reach the other parts of the world when

[4]http://www.energsustainsoc.com/content/4/1/10.

[5]http://extension.psu.edu/natural-resources/energy/waste-to-energy/resources/biogas/links/history-of-anaerobic-digestion/a-short-history-of-anaerobic-digestion.

[6]http://www.kingdombio.com/history1.html.

almost every nation became attracted to the subject. In India since 1939, research on biogas was undertaken but it was not until 1951 that there was a real start in its use. However, the developments of biogas plants were still slow and unsatisfactory until 1961 when the Indian Khadi and Village Industries Commission took over. About 7000 biogas plants had already been installed by 1973–1974, and the number more than doubled by 1974–1975. The development in the design, construction, and operation of practical digesters was one reason for this increase in the number of biogas plants. Additionally, enough knowledge was obtained for the utilization of the gas not only for cooking but also for lighting and running engines. The involvement of competent scientists can also be attributed for the success. The wide-ranging work on biogas in India may be classified into three stages: experimentation, 1937–1950; pilot studies, 1950–1963; and fully operational stage, from 1964.[7] In 2007, there were 26.5 million biogas plants in China. Meanwhile, in 1999 there were over three million family-sized biogas plants in India. By the end of 2007, the Indian government had given subsidy for construction of nearly four million family-sized biogas plants. Since 1981–1982, the National Project on Biogas Development (NPBD) has run and promotes its own digester designs while providing monetary support and different training and development programs. Subsidies from the State and Central governments to install household bioreactors ranged from 30 to 100 % in the 1980s–1990s (Bond and Templeton 2011).

## 3 Classification of Biogas Digester

Biogas plants are classified in various types. The most important types of biogas plants are described below:

I. Fixed-dome biogas plants
II. Floating-drum biogas plants
III. Balloon biogas plants
IV. Horizontal biogas plants
V. Earth-pit biogas plants
VI. Ferro-cement biogas plants

The two most familiar types in developing countries are the fixed-dome biogas plants and the floating-drum biogas plants. Typical designs in industrialized countries and appropriate design selection criteria have also been considered (Hoerz et al. 2008).

### *3.1 Fixed-Dome Biogas Plant*

The fixed-dome digesters are typically constructed underground. The amount of substrate available per day and the number of heads in the household are the two

[7] http://www.biogastechnologyphils.com/index.php/historical-devt.

main important parameters that determine the size of the digester. The fixed-dome type digesters are also called "Chinese" or "hydraulic" digesters. The digester is filled with inlet pipe until the level reaches the bottom level of the expansion chamber. The produced biogas accumulates in the upper part of the digester, which is called the storage part. The difference between slurry inside the digester and the expansion chamber creates a gas pressure. The collected gas requires space and presses a part of the substrate into an expansion chamber. The slurry flows back into the digester immediately after the gas is released (Rajendran et al. 2012). On-farm biogas plants collect cow dung from adapted cattle sheds, mix it with water, and channel it into fermentation pits. The resulting gas is fed directly to the farmer's household to provide energy for cooking, laundry, and lighting.[8] A gas handling system removes biogas from the digester and transports it to the end-use, such as an engine or flange. Gas handling includes: piping, gas pump or blower, gas meter, pressure regulator, and condensate drain. Biogas produced in the digester is trapped under an airtight cover placed over the digester. The biogas is removed by pulling a slight vacuum on the collection pipe (e.g., by connecting a gas pump/blower to the end of the pipe), which draws the collected gas from under the cover. A gas meter is used to monitor the gas flow rate. Sometimes a gas scrubber is needed to clean or "scrub" the biogas of corrosive compounds contained in the biogas (e.g., hydrogen sulfide). Warm biogas cools as it travels through the piping and water vapor in the gas condenses. A condensate drain removes the condensate produced (Seadi et al. 2013). This biogas produced is further processed so that the carbon dioxide and hydrogen sulfide gases are removed. The result is a gas consisting mostly of methane. This is similar to natural gas obtained from the oil and gas fields. By using compressors in a bottling plant, methane and carbon dioxide gases can be stored under high pressure in cylinders. These gases can be utilized in other industrial applications. Much of the biogas can be used as fuel in vehicles, electrical power generators, and for other heating purposes.

The sketch of the plant with a simple formula for the calculations of its volume is shown in Fig. 1.

The equations used in deriving the volume of the fixed-dome biogas digester are given as (Seadi et al. 2013);

$$v_1 = \frac{\pi}{6} f_1 (3r^2 + f_1^2) \tag{1}$$

$$v_2 = \pi r^2 H_1 \tag{2}$$

$$v_3 = \frac{\pi}{6} f_2 (3r^2 + f_2^2) \tag{3}$$

$$\text{Volume of Digester} = v_1 + v_2 + v_3 \tag{4}$$

[8]http://practicalaction.org/biogas_christmas.

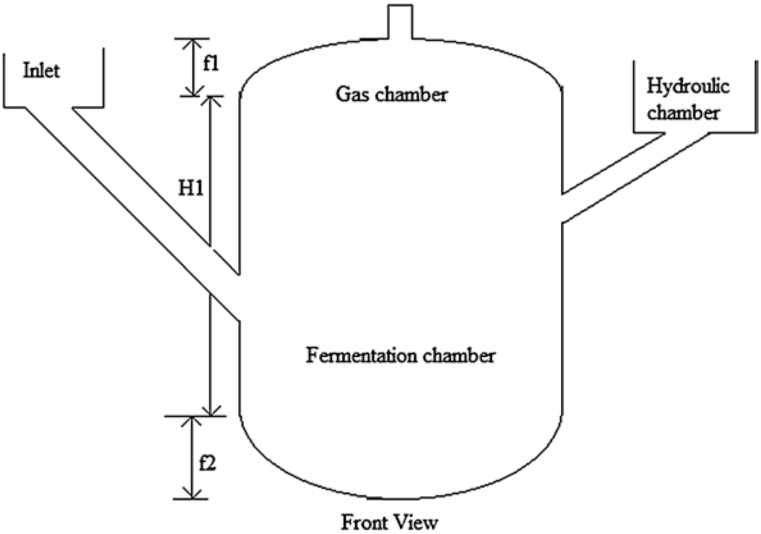



**Fig. 1** Fixed-dome biogas plant (Seadi et al. 2013)

where

| | |
|---|---|
| $v_1$ | volume of upper arc (gas chamber). |
| $v_2$ | volume of fermentation chamber. |
| $v_3$ | volume of lower arc. |
| $r$ | radius of cylinder. |
| $H_1$ | height of fermentation chamber. |
| $f_1$ and $f_2$ | height of upper and lower arcs. |

Figure 2 shows the schematic diagram of a fixed-dome type biogas digester. The various dimensions are marked. Figure 3 is adapted from Fig. 2 for calculation purpose. The link between $h$, $r$, and $R$ is the included angle of the fixed-dome biogas digester. The half-angle φ determines the width of the fixed-dome biogas digester.

$$\tan \varnothing = \frac{r}{R-h} \tag{5}$$

The gas storage volume ($V$) of an underground biogas plant is a segment of a dome, or a cap cut from the top of a dome of radius ($R$). The horizontal radius ($r$) of the base of the cap is related to the height ($h$) of the cap by[9]:

$$R^2 = r^2 + (R-h)^2 \tag{6}$$

[9]http://www.kingdombio.com/equations2.html.

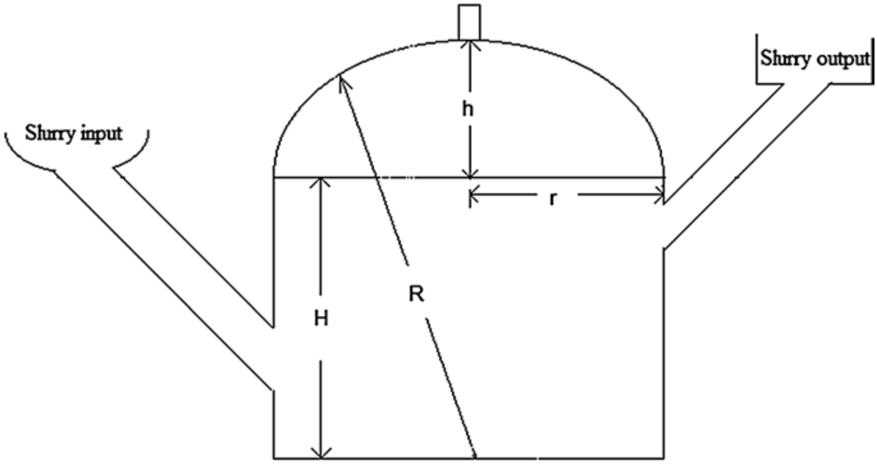
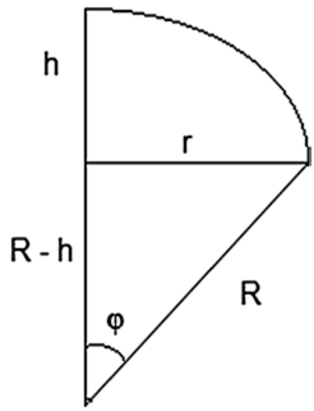



**Fig. 2** Various parameters of fixed dome (http://www.kingdombio.com/ggcdraw.html)

**Fig. 3** Half angle φ determining width of fixed dome (see footnote 10)




This gives:

$$h = R \pm \sqrt{R^2 + r^2} \tag{7}$$

Now:

$$V = 3\pi h^2 (3R - h) \tag{8}$$

Rearranging gives:

$$V = 6\pi h(3r^2 + h^2) \tag{9}$$

**Advantages**:

I. Low initial costs and long useful lifespan.
II. No moving or rusting parts involved.
III. The basic design is compact, saves space and is well insulated.
IV. Construction creates local employment.

**Disadvantages**:

I. Masonry gas-holders require special sealants and high technical skills for gas-tight construction.
II. Gas leaks occur frequently.
III. Fluctuating gas pressure complicates gas utilization.
IV. The amount of gas produced is not immediately visible.
V. Plant operation is not readily understandable.
VI. Fixed-dome plants need exact planning of levels.
VII. Excavation can be difficult and expensive in bedrock (Hoerz et al. 2008).

Fixed-dome biogas plants can be recommended only where construction can be supervised by experienced biogas technicians.

## *3.2 Floating-Drum Biogas Plants*

The basic design consists of a drum that acts as the gas holder, a cylindrical tank that acts as the digestion chamber, a gas meter, a feed pit, and an outlet pit. The gas drum is slightly smaller than the tank opening (Istok 2013). It floats in the cylindrical top of the tank due to the internal gas pressure. This drum is like an upside-down pot and it floats on top of the digesting sludge and captures the gas. It is usually made of mild steel or sometimes fiberglass reinforced plastic (FRP) and High Density Polyethylene (HDPE) mixed material (Mostajir et al. 2013). The gas produced is trapped under this floating cover which rises and falls on a central guide. The pressure of the gas available depends on the weight of the gas holder per unit area and usually ranges from 4 to 8 cm of water pressure. The reactor wall and bottom are usually constructed of brick, although reinforced concrete is sometimes used. The reactor is fed semi-continuously (e.g. once a day) through an inlet pipe, and displaces an equal amount of slurry through an outlet pipe; the underground tank has large inlet and outlet pipe as waste material and fertilizer and the gas pipe comes out of the top of the floating drum (Hagegard 2008). Construction costs vary according to ambient temperature, the size of biogas digester, the manure management system used at the farm, and other factors. The cost of a mild steel gas-holder is approximately 40–50 % of the total cost of the plant. More recently, the steel drum has been replaced by FRP to overcome the problem of corrosion. However, FRP gas-holders are 6–12 % more expensive than the steel drum (Biogas 2007). Gas separation can be achieved by the biogas plant by employing membrane for separation of $CH_4$ and $CO_2$. The membrane gas separation-based process aims at upgrading the biogas to substitute natural gas using low pressure

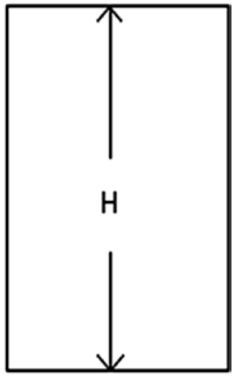



**Fig. 4** Depth of the pit (see footnote 13)

(up to 3 bars) and distributing the substitute natural gas in the natural gas network. The by-product of the membrane gas separation process is a stream rich in $CO_2$ which could be liquefied to produce pure, industrial $CO_2$. After liquefaction, the remaining biogas components, which include $CH_4$, are recycled into the membrane gas separation process, thereby minimizing the loss of biogas. Both gases have high industrial value. Bio-methane also known as SNG has been used as a substitute for vehicle fuel and can also be used to produce electricity (Kalambe et al. 2012). For this method, gas scrubbers or air scrubbers are used, wherein $H_2S$ is absorbed from the biogas. This kind of installation consists of one or more gas scrubbers (scrubbing stages). Inside the air scrubber, the biogas is brought in contact with water out of the aeration tank, which is circulated once over the air scrubbers and re-conducted into the aeration tank. The $H_2S$ absorbed will be oxidated in the aeration tank. For this biological air scrubbing technique, the gas scrubbers are preferably installed in the direct neighborhood of the aeration tanks.[10] 5 $m^3$ biogas plants require 19 kg cow dung (1 or 2 cows) and 47 l of water everyday. One cow gives 10 kg cow dung per day and 1 kg cow dung produces 0.34 $m^3$ gases. So 1 $m^3$ biogas plant requires 3 kg cow dung per day. 1 $m^3$ biogas can be used to cook three meals for a family of 5–6 heads. 1 $m^3$ biogas can be used to light 60–100 W of electric bulbs for 6 h. It is equivalent to fuel replacement of 0.7 kg of petrol.[11]

Figure 4 shows the depth of the pit of a floating-drum type biogas digester. Figure 5 shows the diameter of the base of the pit of the digester. The internal volume ($V$) of a floating-drum biogas plant can be calculated using the volume of a cylinder, where $d$ is the diameter of the pit and $H$ the depth of the pit.[12]

$$V = \left(\frac{\pi d^2}{4}\right) \times H \tag{10}$$

[10] http://task.be/biogasdesulfurization.aspx.

[11] http://www.appropedia.org/Biogas_as_fuel.

[12] http://www.kingdombio.com/equation1.html.

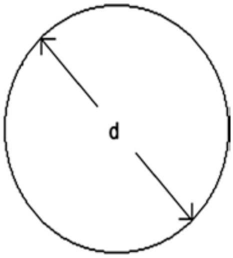



**Fig. 5** Diameter of the base of pit (see footnote 13)

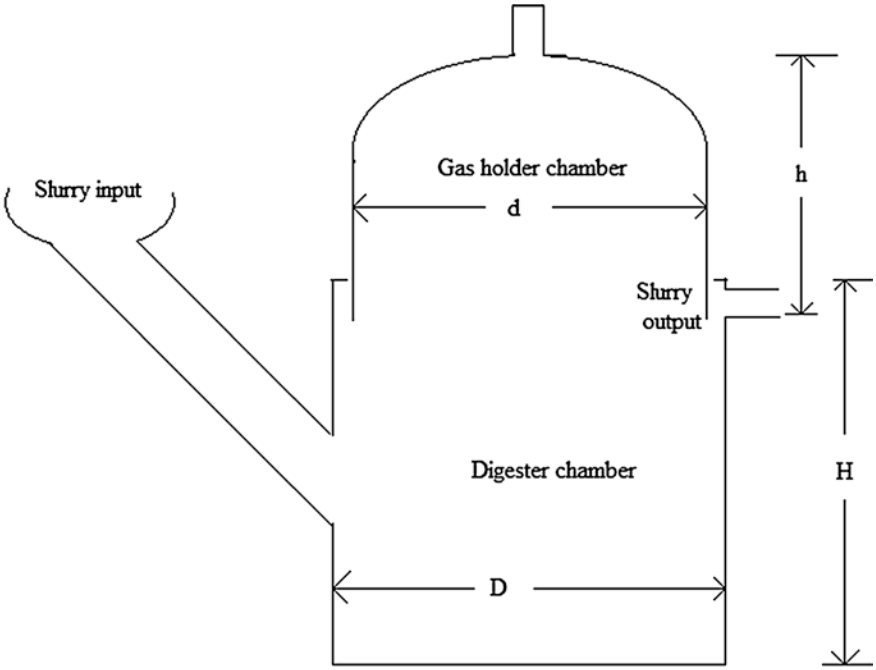



**Fig. 6** Floating-drum type bio gas digester (see footnote 14)

Figure 6 shows that the internal volume of the floating drum can be calculated in the same way, with *d* as the diameter of the drum and *H* the height of the drum.[13]

*D* the diameter of the digester.
*H* the height of the digester/digester pit.
*h* the height of the gas-holder.
*d* the diameter of the gas-holder.

[13]http://www.kingdombio.com/floatdrum.html.

## 3.3 Retention Time

The retention time $R$ is the time that the slurry requires to stay in the digester pit for complete digestion by bacteria. For continuous digester systems, the daily feed rate ($v$) is arrived at by dividing the digester volume ($v_d$) with the slurry retention time ($R$) (Kuria and Maringa 2008).

thus

$$V = \frac{v_d}{R} \tag{11}$$

The retention time is dependent on the prevailing temperature in a digester and on the type of substrate used. Most biogas digesters operate in the mesophilic temperature range (20° < t < 40 °C). For liquid manure undergoing fermentation in this temperature range (Bavutti et al. 2014; SNV Domestic Biogas 2011),

The following approximate retention times apply:

Liquid cow manure 20–30 days
Liquid pig manure 15–25 days
Liquid chicken droppings 20–40 days
Animal manure mixed with plant material: 50–80 days

## 3.4 Dimensioning

In determining the dimensions of digester, the simplifying assumption was made here that the diameter of the digester ($D$) is equal to its height ($H$). A clearance gap of 20 mm between the digester pit and the gas drum was adopted as adequate to allow free rotation of the gas drum, without allowing much leakage of the generated gas. The volume of such a digester pit is given by Kuria and Maringa (2008):

$$V_d = \frac{\pi D^2 H}{4} \tag{12}$$

Since $H$ nearly equals $D$, it becomes:

$$V_d = \frac{\pi D^3}{4} \tag{13}$$

From which the diameter of the digester is obtained as:

$$D = \frac{\sqrt[3]{4} V_d}{\pi} \tag{14}$$

Taking the gas-holder/digester radial clearance to be 20 mm, gives a diameter ($d$) of the gas-holder of:

$$d = (D - 0.04) = \sqrt[3]{(4 V_d / \pi - 0.04)} m \tag{15}$$

Given a gas-holder volume ($V_g$), the height ($h$) of the gas holder is therefore given as

$$h = \frac{4V_g}{\pi d^2} \tag{16}$$

The important parameters for gas to standard temperature and pressure (STP) conversion are the biogas temperature and pressure, temperature of anaerobic environment and ambient temperature and pressure. Most of the research in the field of AD simply quotes gas production volumes without mentioning any correction applied to standard conditions (Parajuli 2011). A "floating drum" storage offers a good, simple way of measuring gas production. Just the change in height of the drum is recorded and volume of gas = area × height. Pressure and volume of any gas are related by $p_1 v_1 = p_2 v_2$, where $p$ is pressure, $v$ is volume, and 1 represents initial conditions and 2, the final conditions. Mass and volume are related by density, where Density = Mass/Volume, and the density of biogas is about 1.18 kg/m$^3$.[14]

**Advantages**:

I. Floating-drum biogas plants are easy to understand and operate.
II. Floating-drum biogas plants provide gas at a constant pressure.
III. The stored gas-volume is immediately recognizable by the position of the drum.
IV. Gas-tightness is no problem.
V. Provided the gas holder is derusted and painted regularly.

**Disadvantages**:

I. The steel drum is relatively expensive and maintenance-intensive.
II. Removing rust and painting has to be carried out regularly.
III. The lifetime of the drum is short (up to 15 years; in tropical coastal regions about five years) (Hoerz et al. 2008).

## *3.5 Balloon Biogas Plants*

A balloon plant consists of a heat-sealed plastic or rubber bag (balloon), combining digester and gas-holder. The gas is stored in the upper part of the balloon. The inlet and outlet are attached directly to the skin of the balloon. The gas pressure can be increased by placing weights on the balloon. If the gas pressure exceeds a limit that the balloon can withstand, it may damage the skin. Therefore, safety valves are required. If higher gas pressures are needed, a gas pump is required. Since the material has to be weather and UV resistant, specially stabilized, reinforced plastic or synthetic caoutchouc is given preference. Other materials that have been used successfully include RMP (red mud plastic), Trevira, and butyl. The useful lifespan

[14]http://biogas.Wikispaces.com/Pressure-Volumecalculations.

**Fig. 7** Balloon digester as seen in Costa Rica (see footnote 16)

usually does not exceed 2–5 years (Hoerz et al. 2008). The bag-type plant is manufactured with high-strength PVC-polyester fabric and other compounds. The bag system can be used with low-pressure stoves and lamps (Fig. 7).[15]

**Advantages**:

I. Low cost.
II. Ease of transportation.
III. Low construction sophistication.
IV. High digester temperature.
V. Shallow installation suitable for use in areas with a high groundwater table.
VI. Uncomplicated cleaning, emptying and maintenance.
VII. Difficult substrates like water hyacinths can be used.

**Disadvantages**:

I. Low gas pressure may require gas pumps.
II. Scum cannot be removed during operation.

[15]http://www.build-a-biogas-plant.com/Types-of-Biogas-Designs.html.

III. The plastic balloon has a relatively short useful lifespan and is susceptible to mechanical damage and usually not available locally.
IV. Local craftsmen are rarely in a position to repair a damaged balloon (Hoerz et al. 2008).

Balloon biogas plants are recommended, if local repair is or can be made possible and the cost advantage is substantial.

## *3.6 Horizontal Biogas Plants*

Horizontal biogas plants consist of a container to hold the slurry, a 'scrubber' to reduce the carbon dioxide ($CO_2$) and sulfur dioxide ($SO_2$) content in the biogas, and a storage container to hold the gas (Figs. 8 and 9) (Forst 2002). Horizontal biogas digester plants are usually chosen when shallow installation is called for (groundwater, rock). They are made of masonry or concrete (Hoerz et al. 2008).

**Advantage**:
I. Shallow construction despite large slurry space.

**Disadvantage**:
I. Problems with gas-space leakage, difficult elimination of scum (Hoerz et al. 2008).

**Fig. 8** Horizontal biogas plants (Forst 2002)

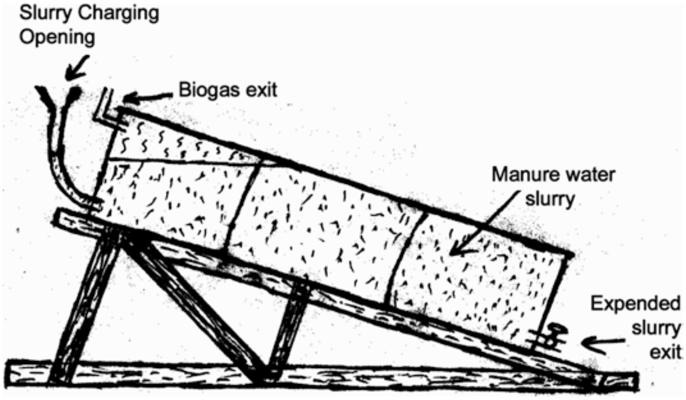



**Fig. 9** Schematic diagram of horizontal biogas plants (Forst 2002)

### *3.7 Earth-Pit Biogas Plants*

Masonry digesters are not necessary in stable soil. It is sufficient to line the pit with a thin layer of cement in order to prevent seepage. The edge of the pit is reinforced with a ring of masonry that also serves as an anchorage for the gas-holder. The gas-holder can be made of metal or plastic sheeting. If plastic sheeting is used, it must be attached to a quadratic wooden frame that extends down into the slurry and is anchored in place to counter its buoyancy. The requisite gas pressure is achieved by placing weights on the gas-holder. An overflow point in the peripheral wall serves as the slurry outlet (Hoerz et al. 2008). This is the new toilet system which works as a biogas plant, which has been designed and based on Earth Bag Shelter. It consists of Digester, Slurry Outlet, and Inlet. Any fermentable organic matter is mixed with water in the inlet tank and introduced from the inlet pipe. It is destroyed by bacteria under anaerobic conditions in the digester. Inflammable methane gas is produced at this stage. The gas pushes the fermented mix out to the slurry outlet and it can be used as good fertilizer. Biogas plants are built all over the world (Fig. 10) (Geiger 2010).

**Advantages**:
I. Low cost of installation (as little as 20 % of a floating-drum plant).
II. The high potential for self-help approaches.

**Disadvantages**:
I. Short useful life; serviceable only in suitable.
II. Impermeable types of soil.

Earth-pit biogas plants can only be recommended for installation in impermeable soil located above the groundwater table. Their construction is particularly inexpensive in connection with plastic sheet gas-holders (Hoerz et al. 2008).

**Fig. 10** Earth bag biogas plant (Geiger 2010)

## *3.8 Ferro-Cement Biogas Plants*

Ferro-cement biogas plants for construction can be applied either as a self-supporting shell or an earth-pit lining. The vessel is usually cylindrical. Very small plants (Volume under 6 $m^3$) can be prefabricated. As in the case of a fixed-dome plant, the ferro-cement gas-holder requires special sealing measures (Hoerz et al. 2008). Appropriate models of family type biogas plants should be selected on the basis of preference of the beneficiaries and considering technical requirements, such as location, distance between the kitchen and cattle shed, availability of water and feedstock like dung, kitchen, loose and leafy biomass, sanitary, and other biomass wastes. Approved models for such plants are available for 1–10 $m^3$ capacities for fixed-dome and floating-dome type plants. The commonly used capacities of these models are 1–4 $m^3$. Pre-fabricated models of biogas plants are also available based on HDPE, FRP, and Reinforced Cement Concrete (RCC) material in addition to ferro-cement and brick-masonry biogas digester plants (Fig. 11). The digesters have a volume of 4–10 $m^3$ and are made of ferro-cement. The gasholder

**Fig. 11** Ferro-cement biogas plants (Construction of a biogas plant in Mirpurkhas Sindh Pakistan 2012)

is made of FRP coated steel for bigger plants or a drum made of FRP for smaller plants (Construction of a biogas plant in Mirpurkhas Sindh Pakistan 2012).

**Advantages**:

I. Low cost of construction.
II. Especially in comparison with potentially high cost of masonry for alternative plants.
III. Mass production possible.
IV. Low material input.

**Disadvantages**:

I. Substantial consumption of essentially good-quality cement.
II. Workmanship must meet high quality standards.
III. Uses substantial amounts of expensive wire mesh.
IV. Construction technique not yet adequately time-tested.
V. Special sealing measures for the gas-holder are necessary.

Ferro-cement biogas plants are only recommended in cases where special ferro-cement is available (Hoerz et al. 2008).

## 4 Some Popular Indian Biogas Designs Approved by MNRES and KVIC the Nodal Agency for Biogas

The most important types of biogas plants used in India are:

I. Janta Fixed-Dome type
II. KVIC Floating-Drum type
III. Deenbandhu fixed-dome type

### *4.1 Janta Fixed-Dome Type Biogas Plant*

This type of biogas plant is economical in design. Janta Fixed-dome type's capacities are 1–6 $m^3$. It works with the constant volume principle. The main structure is made of brick and cement masonry. This type of plant does not have any moving parts so it is safe from wear and tear. The operating pressure varies from 0 to 100 cm of water column. It is also known as Janta model (Fig. 12).[16]

The foundation is a well-compacted base of the digester constructed of brick ballast and cement concrete (CC). The upper portion of the foundation has a smooth plaster surface. The digester is a cylindrical tank resting on the foundation.

[16]http://mechanicalinventions.blogspot.in/2014/06/fixed-dome-type-janata-model-biogas-plant-construction.html.

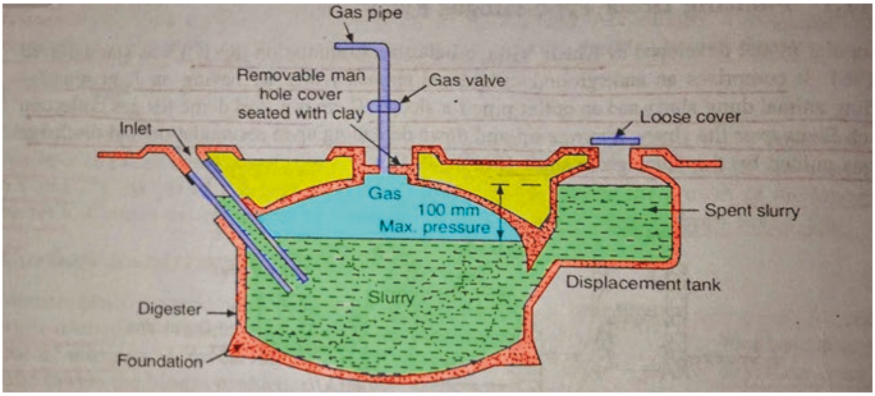



**Fig. 12** Janta fixed-dome type biogas digester

The top surface of the foundation serves as the bottom of the digester. The digester (fermentation chamber) is constructed with bricks and cement mortar. The digester wall has two small rectangular openings in the middle, situated diametrically opposite, known as inlet and outlet gate, one for the inflow of fresh slurry and the other for the outflow of digested slurry. The digester of Janta BGP comprises the fermentation chamber (effective digester volume) and the gas storage chamber (GSC). The GSC is also cylindrical in shape and is the integral part of the digester and located just above the fermentation chamber. The GSC is designed to store 33 % (approx. 8 h) of the daily gas production from the plant. The GSC is constructed with bricks and cement mortar. The gas pressure in Janta model varies from a minimum of 0 cm water column (when the plant is completely empty) to a maximum of up to 90 cm of water column when the plant is completely full of biogas. The hemispherical shaped dome forms the cover (roof) of the digester and is constructed with brick and CC mixture, after which it is plastered with cement mortar. The dome is only an enclosed roof designed in such a way as to avoid steel reinforcement. The upper portion of the inlet chamber is in the shape of a bell mouth and constructed using bricks and cement mortar. Its outer wall is kept inclined to the cylindrical wall of the digester so that the feed material can flow easily into the digester by gravity. The bottom opening of the inlet chamber is connected to the inlet gate and the upper portion is much wider and known as inlet displacement chamber (IDC). The top opening of the inlet chamber is located close to the ground level to enable easy feeding of fresh slurry. The outlet chamber is a rectangular shaped chamber located opposite the inlet chamber. The bottom opening of the outlet chamber is connected to the outlet gate and the upper portion is much wider and known as outlet displacement chamber (ODC). The outlet chamber is constructed using bricks and cement mortar. The top opening of the outlet chamber is located close to the ground level to enable easy removal of the digested slurry through a discharge opening. The level of the discharge opening provided on the outer wall of the outlet chamber is kept at a somewhat lower level than the upper mouth of the inlet opening, as well as lower than the crown of the dome ceiling. This is to facilitate easy flow of the digested slurry out of the plant into the digested slurry pit and also to prevent reverse flow, either in the mixing tank through the inlet chamber or to go inside the gas outlet pipe and choke it. The biogas outlet pipe is fixed on the crown of the dome, which is made of a small length of GI pipe fitted with socket and a gate valve.[17]

**Advantages**:

I. The costs of a fixed-dome biogas plant are relatively low.
II. It is simple as no moving parts exist.
III. There are also no rusting steel parts and hence long life of the plant (20 years or more) can be expected.
IV. Fixed-dome plants are not easy to build.
V. They should only be built where construction can be supervised by experienced biogas technicians.

**Disadvantage**:

I. Due to the porosity and cracks, gas generated may leak.[18]

## *4.2 KVIC Floating-Drum Plant*

The KVIC Model is a floating biogas holder semi-continuous-fed BGP and is of two types, viz. (i) vertical and (ii) horizontal. The vertical type is more commonly used and the horizontal type is only used in the high water table region. Its capacity is 1–10 $m^3$. Though the description of the various components mentioned under this section are common to both the types of KVIC models (vertical and horizontal types), some of the details mentioned pertain to vertical type only. In the KVIC model, the gas is stored in a tank. The tank is floating in slurry. The tank goes up as the gas gets generated and it lowers when the gas is consumed. The size of the tank depends on the size of the feed. Normally it is 50 times the amount of feed available per day. Generally, the tank is made of iron sheets, therefore, the cost of the biogas goes up. Recently, many organizations have started using PVC tanks.

Foundation is a compact base made of a mixture of CC and brick ballast. The foundation is a well-compacted using wooden ram and then the top surface is cemented to prevent any percolation and seepage. Digester (Fermentation Chamber) is a cylindrical shaped well-like structure, constructed using the foundation as its base. The digester is made of bricks and cement mortar and its inside

[17] http://arizonaenergy.org/Analysis/FossilFuels/Biogas.htm.

[18] http://oer.nios.ac.in/wiki/index.php/Biogas_Plant.

walls are plastered with a mixture of cement and sand. The digester walls can also be made of stone blocks in places where they are easily available and cheap instead of bricks. All the vertical types of KVIC Model of 4 $M^3$ capacity and above have a partition wall inside the digester. The biogas holder drum of the KVIC model is normally made of mild steel sheets. The biogas holder rests on a ledge constructed inside the walls of the digester well. If the KVIC model is made with a water jacket on top of the digester wall, no ledge is made and the drum of the biogas holder is placed inside the water jacket. The biogas holder is also fabricated out of FRP, high-density polyethylene (HDP) or ferroconcrete (FRC). The biogas holder floats up and down on a guide pipe situated in the center of the digester. The biogas holder has a rotary movement that helps in breaking the scum-mat formed on the top surface of the slurry. The weight of the biogas holder is 8–10 kg/$m^2$ so that it can store biogas at a constant pressure of 8–10 cm of water column. The inlet pipe is made of CC or Asbestos Cement Concrete (ACC) or Pipe. One end of the inlet pipe is connected to the mixing tank and the other end goes inside the digester on the inlet side of the partition wall and rests on a support made of bricks of about 1 feet height. The outlet pipe is made of CC or ACC or Pipe. One end of the outlet pipe is connected to the outlet tank and the other end goes inside the digester, on the outlet side of the partition wall and rests on a support made of bricks of about 1 feet height. In the case of KVIC model of 3 $M^3$ capacities and below (Fig. 13), there is no partition wall, hence the outlet pipe is made of short and horizontal, which rest fully immersed in slurry at the top surface of the digester. The biogas outlet pipe is fixed on the top middle portion of the biogas holder, which is made of a small GI pipe fitted with a socket and a gate valve. The biogas generated in the plant and stored in the biogas holder is taken through the gas outlet pipe via pipeline to the place of utilization.[19]

**Advantages**:

I. Floating-drum plants are easy to understand and operate.
II. They provide gas at a constant pressure, and the stored gas-volume is immediately recognizable by the position of the drum.
III. Gas-tightness is no problem, provided the gas holder is de-rusted and painted regularly.

**Disadvantages**:

I. The steel drum is relatively expensive and maintenance-intensive.
II. Removing rust and painting has to be carried out regularly.
III. The lifetime of the drum is short (up to 15 years; in tropical coastal regions about 5 years).
IV. If fibrous substrates are used, the gas-holder shows a tendency to get "stuck" in the resultant floating scum.[20]

[19] http://arizonaenergy.org/Analysis/FossilFuels/Biogas.htm.

[20] http://www.appropedia.org/Floating_drum_biogas_digestor.

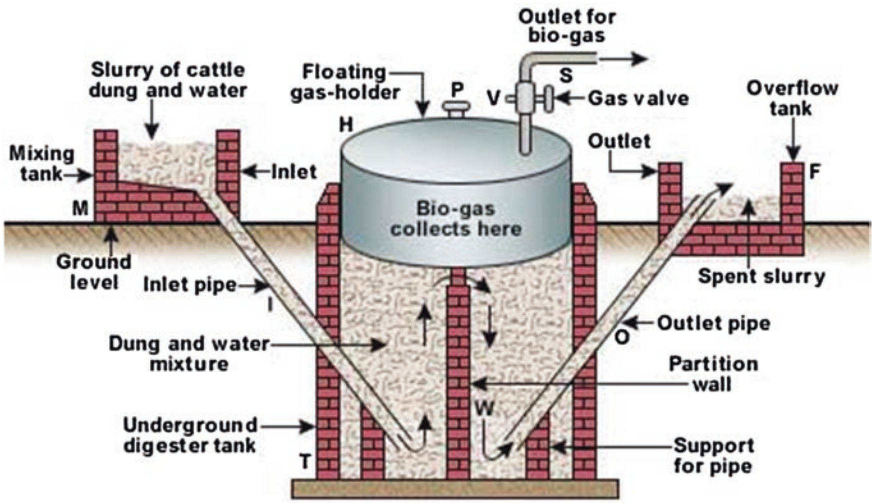



**Fig. 13** KVIC floating-drum plant biogas digester (see footnote 19)

## *4.3 Deenbandhu Fixed-Dome Plant*

The Deenbandhu Model is a semi-continuous-fed fixed-dome biogas plant. While designing the Deenbandhu model, attempt has been made to minimize the surface area of the BGP with a view to reduce the installation cost, without compromising on the efficiency. The design essentially consists of segments of two spheres of different diameters joined at their bases. The structure thus formed comprises of (i) the digester (fermentation chamber), (ii) the GSC, and (iii) the empty space just above the GSC. The higher compressive strength of the brick masonry and concrete makes it preferable to go in for a structure that could be always kept under compression. A spherical structure loaded from the convex side will be under compression and therefore, the internal load will not have any effect on the structure.

The digester of the Deenbandhu BGP (Fig. 14) is connected with the inlet pipe and the outlet tank. The upper part (above the normal slurry level) of the outlet tank is designed to accommodate the slurry to be displaced out of the digester (actually from the GSC) with the generation and accumulation of biogas and known as the ODC. The inlet pipe of the Deenbandhu BGP replaces the inlet chamber of Janta Plant.[21]

[21]http://arizonaenergy.org/Analysis/FossilFuels/Biogas.htm.

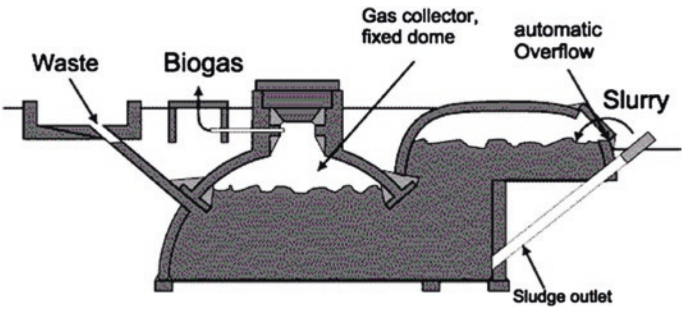



**Fig. 14** Deenbandhu fixed-dome plant biogas digester (https://energypedia.info/images/d/df/Camartecfixdome.gif)

**Advantages**:

I. Capital investment for corresponding size of the plant is less.
II. As there are no moving parts.
III. Steel gas holder is not required.
IV. Life of the plant is expected to be comparatively more.
V. As the unit is underground, the space above the plant can be used for other purposes.
VI. Effect of low temperature is less.

**Disadvantages**:

I. The maintenance cost is high.
II. Construction of a dome portion of the unit is a skilled job and only trained mason can do it.
III. Requires more excavation work.
IV. Location of defects in the dome and their repair is difficult.
V. Release of gas is at variable pressure and it may cause a reduction in efficiency of gas appliances.
VI. It could be easily modified and adopted for use of other types of organic wastes.[22]

## 5 Worldwide Status of Biogas Production

Biogas usage is gaining increasing attention worldwide. It is about to become a popular energy source and is being utilized more in the United States. In 2003, the United States consumed 147 trillion BTU of energy from “landfill gas”; about 0.6 % of the total U.S. natural gas consumption.[23] Methane biogas has

[22] http://arizonaenergy.org/Analysis/FossilFuels/Biogas.htm.

[23] http://en.wikipedia.org/wiki/Biogas.

been tested to show that it can reduce 99 million metric tons of greenhouse gas emissions or about 4 % of the greenhouse gases produced by the United States (Cuellar and Webber 2008). In 2010, the total installed electrical capacity of these power plants was 2291 MW. The electricity supply was approximately 12.8 TWh, which is 12.6 % of the total generated renewable electricity (Bavutti et al. 2014). Nearly 62,000 biogas plants have been established through SNV-supported country programs in 2010, which is an increase of 18 % compared to 2009. The East African nations such as Tanzania, Kenya, Uganda and Ethiopia have also made good progress. Progress in West Africa has been restricted so far. The program has been initiated in Burkina Faso and Senegal as recently as 2011. The target for 1000 biogas plants by 2010 was achieved in Indonesia, Rwanda, and Tanzania. Cambodia surpassed 10,000 units and Vietnam even crossed 100,000. Up till now, 360,000 biogas digester plants have been installed through SNV-supported programs. But these figures are much lower compared to the achievements in the leading biogas nations like China and India. In 2010, China installed another 4.9 million units arriving at a total of 40 million operational plants. India constructed almost 120,000 units within the fiscal year 2009–2010 under the National Biogas and Manure Management Programme (NBMMP), making its total 4.25 million biogas plants in March 2010 (SNV Domestic Biogas 2011).

Upgrading of biogas has gained increased attention due to rising oil and natural gas prices and increasing targets for renewable fuel quotes in many countries. New plants are continually being built. The number of upgrading plants was around 100 in 2009 (Fig. 15).

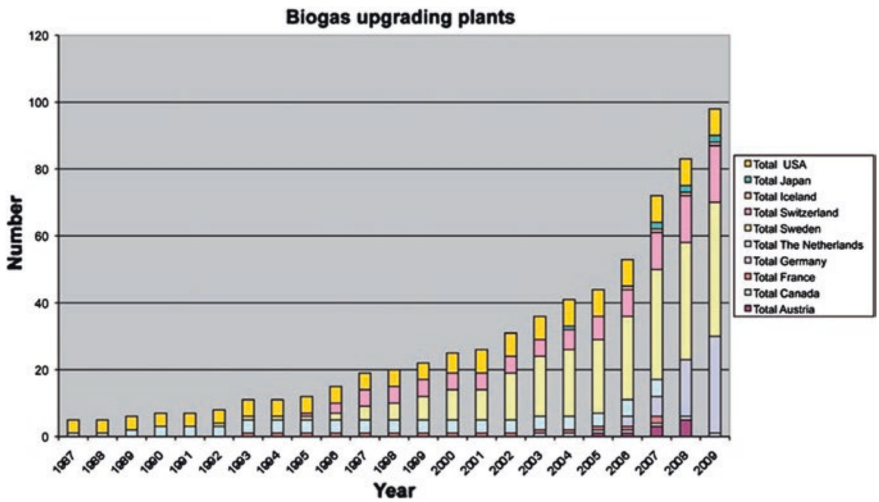



**Fig. 15** Total number of upgrading plants from 1987 to 2009 (Pitersson and Wellinger 2009)

### 5.1 United States (U.S)

The United States has realized the various benefits of biogas. It has become a popular source of energy and is starting to be used more in the United States. In 2003, the United States consumed 147 trillion BTU of energy from "landfill gas", about 0.6 % of the total U.S. natural gas consumption. Methane biogas derived from cow manure is being tested in the U.S. According to a 2008 study, collected by the Science and Children magazine, methane biogas from cow manure would be sufficient to produce 100 billion kilowatt hours—enough to power millions of homes across America. Furthermore, methane biogas has been tested to prove that it can reduce 99 million metric tons of greenhouse gas emissions or about 4 % of the greenhouse gases produced by the United States (See footnote 24).

### 5.2 United Kingdom (U.K)

There are around 60 no sewage biogas plants in the UK. Most are on-farm, and some larger facilities exist off-farm, which take food and consumer wastes. On 5 October 2010, biogas was injected into the UK gas grid for the first time. Sewage from over 30,000 Oxfordshire homes is sent to Didcot sewage treatment works, where it is treated in an anaerobic digester to produce biogas, which is then cleaned to provide gas for approximately 200 homes (See footnote 24).

### 5.3 Germany

Germany is Europe's largest producer of biogas and leads the market in biogas technology. In 2010 there were 5,905 biogas plants operating throughout the country; Lower Saxony, Bavaria, and the eastern federal states are the main regions. Most of these plants are employed as power plants. Usually, biogas plants are directly connected with a CHP which produces electric power by burning the bio-methane. The electrical power is then fed into the public power grid. In 2010, the total installed electrical capacity of these power plants was 2291 MW. The electricity supply was approximately 12.8 TWh, which is 12.6 % of the total generated renewable electricity. Biogas in Germany is primarily extracted by the co-fermentation of energy crops (called 'NawaRo', an abbreviation of 'Nachwachsende Rohstoffe', which is German for renewable resources) mixed with manure. Due to guaranteed feed-in tariffs for "green" electricity under the Renewable Energy Sources Act (EEG) of 2001 and its amended versions of 2004, 2009, and 2012, the number of biogas plants has grown rapidly and reached 5,905 in 2010, with an installed electrical capacity of 2291 MW. According to certain predictions, the number of biogas plants in Germany will increase approximately to 7521, with an installed electrical capacity of 3185 MW by the end of 2012 (Naegele et al. 2012). The share of biogas in electricity supplied from renewable energy sources reached 14.4 % in 2011. The first challenge to be noticed is the high area-consuming of the biogas electric power supply. In 2011, energy crops for biogas production consumed an area of circa 800,000 ha in Germany. This high demand of agricultural areas generates new competitions with the food industries that did not exist yet. Moreover, new industries and markets were created in predominately rural regions entailing different new players with an economic, political and civil background. Their influence and acting has to be governed to gain all advantages this new source of energy is offering. Finally, biogas will furthermore play an important role in the German renewable energy supply if good governance is focused (See footnote 24).

### 5.4 China

In China, after 1975, slogans such as "biogas for every household" led to the construction of 1.6 million digesters per year, mainly being concrete fixed-dome digesters, which were cheap but of low quality. Up to 1982, more than seven million digesters were installed in China. In 1980, more than 50 % of all digesters were not in use. The consequence was that in 1979, construction activity slowed to less than one third of the previous one. This is equivalent to a targeted number of 80 million units by 2020.[24] It was reported there were about five million family sized plants operating in China in 1992, many of them redesigned to avoid leaking. According to some figures, only about three million digesters were in operation in 1991. This was because they were so crudely built and lack of well-trained personnel needed to fix them. These weaknesses have been the consequences of the concrete digester construction. Attention has recently been paid to combine quantity with the quality of plants and to match the technology with local conditions. Climatic as well as social and cultural conditions are being studied first before digesters are introduced. The rapid development of biogas in China received strong government support and sometimes, subsidies from local government and village government were up to 75 %. The biggest constraint in the biogas programs has been the price of the digesters. It was also learned that the popularization of biogas would only be successful when the direct benefits to the farmers were obvious. In 2009 about 34,000 small-scale biogas plants and 22,900 medium and large-scale biogas plants (MLBGPs, Fermenter > 50 $m^3$), with 3717 large-scale installations (Fermenter > 300 $m^3$) were included (See footnote 25). The increase in the number of biogas plants installed in China in the years 2004, 2005, 2006, 2007, 2008 was respectively 15.4, 18, 22, 26.5, 30.5 million. The biogas project of China is projected to increase to 10,000 livestock farms and 6000 industrial plants by 2020.[25]

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[24] http://www.biogaschina.org/index.php?option=com_flexicontent&view=category&cid=18&Itemid=35&lang=en.

[25] http://www.ecotippingpoints.org/our-stories/indepth/china-biogas.html.

## 5.5 India

India had an extended and wide-ranging familiarity in the construction of simple and easy-to-operate biogas technologies to meet diverse climatic conditions and socioeconomic groups of users. Implementation of various management models of the sizeable biogas extension program had been developed and tried successfully. Central Government subsidies and campaigns for publicity have encouraged people to adopt biogas plants and make the biogas program very successful. The most common type used in India is the floating cover design digester which was introduced by the All-Indian Coordinated Biogas Program. This system is more expensive than the fixed-dome (Chinese) digester. India has placed far more emphasis on the survival of small-scale farmers than ensuring their efficiency and growth in a competitive environment through various policy instruments including biogas programs. The subsidies given to biogas programs have frozen the technologies, and created inefficient and fragile industries.[26] India has shown great development in biogas digester installation. The Indian Deenbandhu model of Floating-Drum type biogas digester has been a huge success throughout the world. In 1999, there were over three million family-sized biogas plants in India and by the end of 2007, the Indian Government provided subsidy for the construction of nearly four million family sized biogas plants (Bond and Templeton 2011). The numbers of biogas plants installed in India in the financial years 2007–08, 2008–09, 2009–10 and 2010–11 were 88,840, 107,929, 119,914, and 71,165 respectively.[27]

## 5.6 Mexico

In Mexico, Nestlé collects fresh milk in several dairy production areas where biogas digesters have been built to capture methane from cow manure and use it as energy. Additional biogas plants are under construction as a result of the sustainability analysis at the farm level (RISE assessment). In 2011, we project that around 35 % of the milk supplied for Nestlé in Mexico will come from dairy farms with biogas plants.[28]

## 5.7 Europe

Development of biogas technology shows a marked variation in Europe. Countries such as Germany, Austria, and Sweden are fairly highly developed in their use of

[26] http://www.mekarn.org/procbiod/an.htm.

[27] http://mnre.gov.in/schemes/decentralized-systems/schems-2/.

[28] http://www.dairy-sustainability-initiative.org/Public/CaseStudy.php?ID=472.

biogas. But there is a lot of prospective for biogas energy source in the rest of the continent, mainly in Eastern Europe. The major reasons behind this unexploited potential are due to different legal frameworks, education schemes, and the availability of technology. Also, negative public perception is another reason for slow growth (Energy technology developments 2013). The EU project "Sustainable and Innovative European Biogas Environment" (SEBE) was started after the gas crisis of Europe during December of 2008. It is financed by the CENTRAL program. The main aim is to deal with the energy dependence of Europe by establishing an online platform to combine knowledge and launch pilot projects aimed at raising awareness among the public and developing new biogas technologies. In February 2009, the European Biogas Association (EBA) was founded in Brussels as a non-profit organization to promote the deployment of sustainable biogas production and use in Europe. EBA's strategy defines three priorities: establish biogas as an important part of Europe's energy mix, promote source separation of household waste to increase the gas potential, and support the production of bio-methane gas vehicle fuel. In July 2013, it had 60 members from 24 countries across Europe (See footnote 24).

### *5.8 Australia*

With feedstock from any organic waste, biogas technology can be deployed. But in Australia, the major area of potential utilization is within the agriculture sector. The industry accounts for 16.3 % of national inventory emissions in 2007. Methane recovery from animal waste is presently not largely practiced in Australia, primarily due to the large capital costs involvement. At feedlots, solid cattle manure is normally composted in open air facilities, and sold as fertilizer. Waste from pig and dairy farms is usually kept in the lagoon. Presently, the development of biogas sector in Australia is still in the nascent stage. In spite of the widespread applications of biogas technology worldwide, Australia has a very limited record of biogas projects. Because the agricultural sector accounts for a significant share of national emission, there is significant potential for biogas plants. In Australia, while there is no sign of the potential of biogas to CNG, past examples show that electricity generation from biogas is commercially viable (Doan 2009).

### *5.9 South Africa*

With regard to using biogas for energy, South Africa lags behind the rest of the developed and developing world. In South Africa, there are nearly 200 small-scale biogas digesters, mostly developed by NGOs. Eskom's announced in July 2012 that its rebate program would extend to small-scale renewable projects. It became more feasible for companies than ever before to advance in the renewable energy sector in South Africa. Besides Eskom's rebate program, biogas investors could also approach the DTI (Department of Trade and Industry) for grant funding through their manufacturing incentive scheme (MCEP).[29]

### 5.10 Bangladesh

Grameen Shakti is one of the most prominent NGOs in the field of biogas having constructed 13,500 biogas plants. The Seed Bangla Foundation had proposed a 25 KW biogas-based power plant in Rajshahi. IDCOL, a government owned investment company had set up a target to establish 37,669 biogas plants in Bangladesh by 2012, under its National Domestic Biogas and Manure Programs (NDBMP). Target has also been set of 25 % of the total number of biogas plants in the northern region, which are yet to be brought under the national gas grid. Besides working in partnership with IDCOL, some organizations have established domestic biogas plants with their own money. These are Grameen Shakti (3664 plants), BRAC (3664 plants of their own), and some other private organizations which promote biogas plants independently. Moreover, since May 2011, IDCOL along with its partner organizations has constructed 18,713 biogas plants in different parts of Bangladesh (Rahman et al. 2013).

## 6 Environmental Considerations

### 6.1 Sustainability

Biomass energy production involves annual periodic removals of crops, residues, trees, or other resources from the land. These harvests and removals need to be at levels that are sustainable, i.e., ensure that current use does not deplete the land's ability to meet future needs, and also be done in ways that do not degrade other important indicators of sustainability. Because biomass markets may involve additional removals of residues, crops, trees, we should be careful to minimize impacts from whatever additional demand biomass growth makes on the land. As a result of established science and policy, farmers generally leave a certain percentage of crop residues on fields, depending on soil and slope, to reduce erosion and maintain fertility. Existing best management practices (BMPs) were developed to address forest management issues, especially water quality, related to traditional sawlog and pulpwood markets, with predictable harvest levels. But the development of new biomass markets will entail larger biomass removals from forests, especially forestry residues and small diameter trees. Sustainability standards

[29]http://www.engineeringnews.co.za/article/company-announcement-the-time-is-ripe-for-biogas-investment-says-sabia-ahead-of-launch-at-africa-energy-indaba-2013-01-31.

should ensure nutrients removed in a biomass harvest are replenished and that removals do not damage long-term productivity, especially on sensitive soils. Coarse woody material that could be removed for biomass energy also provides crucial wildlife habitat; depending on a state's wildlife, standards might protect snags, den trees, and large downed woody material. Biodiversity can be fostered through sustainability standards that encourage retention of existing native ecosystems and forest restoration. Lastly, sustainability standards should provide for regrowth of the forest—surely a requirement for woody biomass to be truly renewable.[30]

### *6.2 Air Quality*

Especially with the emissions from combustion systems, biomass can impact air quality. Emissions vary depending on the biomass resource, the conversion technology, and the pollution controls installed at the plant. Because most biomass resources and natural gas contain far less sulfur and mercury than coal, biomass and natural gas power plants typically emit far less of these pollutants than do coal-fired power plants. Sulfur emissions are a key cause of smog and acid rain. Mercury is a known neurotoxin (See footnote 31).

### *6.3 Carbon Emissions and Control*

Some of the environmental considerations and other concerns about the widespread implementation of bio-energy with carbon capture and storage (BECCS) are similar to those of Carbon Capture and Storage (CCS). However, much of the critique toward CCS is that it may strengthen the dependency on depleting fossil fuels and environmentally invasive coal mining. This is not the case with BECCS, as it relies on renewable biomass. There are, however, other considerations which involve BECCS and these concerns are related to the possible increased use of biofuels. Biomass production is subject to a range of sustainability constraints, such as: scarcity of arable land and fresh water, loss of biodiversity, competition with food production, deforestation, and scarcity of phosphorus. It is important to make sure that biomass is used in a way that maximizes both energy and climate benefits. There has been criticism to some suggested BECCS deployment scenarios, where there would be heavy reliance on increased biomass input.[31] Burning or gasifying biomass does emit carbon into the atmosphere. With heightened interest in renewable energy and climate change, scientists have put biomass carbon

[30]http://www.ucsusa.org/clean_energy/our-energy-choices/renewable-energy/how-biomass-energy-works.html.

[31]http://en.wikipedia.org/wiki/Bio-energy_with_carbon_capture_and_storage.

emissions under additional scrutiny, and are making important distinctions between biomass resources that are beneficial in reducing net carbon emissions and biomass resources that would increase net emissions (See footnote 31).

There is however presently no need to expand the use of biofuels in energy or industrial applications to allow for BECCS deployment. Today, there are already considerable emissions from point sources of biomass derived $CO_2$, which could be utilized for BECCS. Though, due to possible future bio-energy system upscaling scenarios, this may be an important consideration. The BECCS process allows $CO_2$ to be collected and stored directly from the atmosphere, rather than from a fossil source. This implies that any eventual emissions from storage may be recollected and restored simply by reiterating the BECCS process. This is not possible with CCS alone, as $CO_2$ emitted to the atmosphere cannot be restored by burning more fossil fuel with CCS (See footnote 32).

## *6.4 Conclusion*

Renewable sources of energy have become indispensable for growth to meet the energy demands of any country and of the world in general. It is the same scenario in India. India is one of the leading countries in the field of renewable energy. It is fifth in the world in terms of installed wind capacity; it has developed a large amount of energy from solar. India had also taken interest in other types of renewable energy sources like biomass energy, wave energy, small hydro, geothermal, etc. As of December 27, 2012 in India 12.45 % of total energy was produced from renewable energy sources. In the electricity sector, India is the fifth largest in the world, having 210.936 GW of installed capacity as of 2012. Yet, per capita energy consumption of India is as low as 778 kWh. To increase energy consumption, India needs to look more into renewable sources.

India has huge potential for generating biomass energy. Biomass energy can be used to a great degree, especially in rural areas. The major need for energy in rural India is for cooking where people mainly use virgin wood. This creates a lot of pollution due to smoke and is a major health issue. Hygiene is also a major issue for rural India.

Biogas digester plants provide a sustainable way to meet concerns related to hygiene and also to meet the energy requirements in rural areas. Raw materials for the operation of biogas digester plant are found aplenty in villages, mainly cattle waste. Many biogas digester plants have already been set up in villages all across India, but the technology has not yet reached most parts because of the lack of initiatives and education. The installation cost of a biogas digester plant is also very high which is another deterrent for larger scale setup of plants. The government has many policies for biogas digester plants, which have been already discussed. But there needs to be proper awareness among people. This presents a challenge for the government.

Another thing that needs to be taken care of is reduction of cost. Typically, a biogas plant of around 1 $m^3$ costs about US$444 or about INR 20,000 to install. This needs to be reduced by better technology. Newer technology like implementation of plastic tanks as digesters can reduce the cost greatly, but this technology is still at the research stage. More subsidies need to be given and more initiatives need to be taken by the government.

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# Part VI
# Other Green Energy

# Natural Gas to Drive Green and Sustainable Developments in India

**Sanjay Kumar Kar**

**Abstract** The per capita primary energy consumption in India has been increasing and there is a great scope for growth to reach somewhere closer to the leading economies such as the United States, Russia, and China. India's primary energy consumption is still dominated by coal with 54.5 % followed by oil (29.5 %), natural gas (7.8 %), hydro (5 %), renewables (2 %), and nuclear (1.2 %). India being one of the leading emerging economies requires plenty of energy to keep the pace of its economic growth. India's economic development should be driven by green energy, with desirable level of environment protection and ecological preservation. Along with the renewable sources of energy, natural gas is considered to be the fuel for green and sustainable developments in India. The outcomes of green economy are green production, green marketing, green transport, green housing, green electricity, and green consumption. Current scenario suggests that natural gas could be one of the most preferred greener fuel by 2030 in India. Some of the enabling factors likely to drive gas based sustainable economy in India are: higher domestic production, import of equity gas, import of relatively cheaper shale gas (in the form of LNG) from the USA, import of dry gas through pipeline from central Asia, development of regasification infrastructure in India, and development of fully functional national gas grid.

**Keywords** Green energy · Green economy · Natural gas

## 1 Primary Energy Demand in India

World Bank indicators suggest that per capita primary energy consumption in India stood at 614 kg of oil equivalent in 2011, a significant improvement from 294 kg in 1980. However, India's per capita energy consumption has been the lowest

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**Table 1** Per capita primary energy consumption in leading economies of the world (kg oil equivalent)

| | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|---|---|---|---|---|---|
| USA | 7794 | 7882 | 7847 | 7697 | 7758 | 7488 | 7056 | 7162 | 7032 | 6793 |
| China | 1108 | 1265 | 1362 | 1479 | 1551 | 1601 | 1717 | 1881 | 2029 | NA |
| Japan | 3964 | 4090 | 4074 | 4069 | 4032 | 3879 | 3702 | 3916 | 3610 | 3539 |
| Germany | 4096 | 4129 | 4064 | 4133 | 4020 | 4075 | 3825 | 4033 | 3811 | 3754 |
| France | 4272 | 4303 | 4284 | 4194 | 4117 | 4114 | 3917 | 4016 | 3868 | 3831 |
| UK | 3728 | 3701 | 3697 | 3613 | 3460 | 3391 | 3179 | 3241 | 2997 | 3043 |
| Brazil | 1095 | 1141 | 1157 | 1184 | 1239 | 1296 | 1243 | 1362 | 1371 | NA |
| Russia Fed. | 4463 | 4500 | 4553 | 4706 | 4733 | 4850 | 4559 | 4932 | 5113 | NA |
| Italy | 3115 | 3128 | 3137 | 3085 | 3025 | 2942 | 2739 | 2815 | 2757 | 2604 |
| India | 448 | 467 | 479 | 496 | 522 | 539 | 587 | 600 | 614 | NA |

*Source* http://data.worldbank.org/indicator/EG.USE.PCAP.KG.OE/countries?page=2

amongst the top ten economies in the world (Table 1). Per capita energy consumption in the USA, Russia, and China is 11, 8, and 5 times higher, respectively, than India. Russia and the USA are energy-rich countries as far as their domestic reserves are compared with India. It is observed that the per capita energy consumption in the USA, Japan, Germany, France, and Italy has been on the decline. However, India's per capita consumption has been increasing, albeit from a lower base. India registered 72 % per capita energy consumption growth since 2003 and will continue to grow for next couple of decades. According to the World Energy Council (2013, p. 7), "highly-industrialized" countries, such as India and Mexico, wrestle with providing accessible and environmentally sensitive energy to achieve double-digit economic growth. It is to be noted that India scores low on energy security (76), energy equity (110), and environmental sustainability (121), awarded an overall rank and score of 115 and "CDD", respectively (WEC 2013).

## *1.1 Coal*

According to BP Statistics (2014) at the end of 2013 total coal reserves in India stood at 60,600 million metric tonne (MMT) with 6.8 % share of global reserves. The USA was the leader in terms of reserves (237,295 MMT, 26.6 %) followed by Russian Federation (15,7010 MMT, 17.6 %), China (114,500 MMT, 12.8 %), and Australia (76,400 MMT, 8.6 %). At the end of 2013, reserve-to-production (R/P) ratio of coal in India stood at 100 years compared to USA (266 years), Russian Federation (442 years), and Australia (177 years). Only China had a lower R/P ratio of 31 years amongst the leading developed and developing countries because China had the largest production share of 46.6 % (3680 MMT). In terms of coal production share, USA was placed in second position with 11.3 % (892.63 MMT) followed by India with 7.7 % (605 MMT), Australia with 6 % (478 MMT), Indonesia with 5.3 % (421 MMT), and Russia with 4.4 % (347.1 MMT). In most parts of the world, coal is used to run coal-fired power plants, especially in the USA, China, and India. For instance, in India 66 % of the installed capacity of power plants are coal-fired. One of the reasons for higher percentage of coal-fired power plant could be lower domestic coal price compared to international standard. According to the Planning Commission (2012, p. 167), the price of domestic coal is about Rs. 342/MkCal compared Rs. 363/MkCal in the USA and Rs. 636/MkCal in China. The price differential between domestic and imported coal creates distortions in the power sector.

### *1.2 Oil*

At the end of 2013, India was placed at 4th position with a consumption figure of 175.2 MMT of oil with a consumption share of 4.2 % just behind Japan with 5 % (208.9 MMT). The USA and China with consumption share of 19.9 % (831 MMT) and 12.1 % (507.4 MMT), respectively, were far ahead of India. However, from consumption point of view India is a larger market compared to developed countries such as Russian Federation, Canada, Germany, and the United Kingdom. Even oil consumption in India was marginally higher than entire Africa (170.9 MMT). Considering the very thin spread of proven oil reserves, high demand, and moderate production at the current production rate of 5.7 thousand million barrels, India's oil resources could be exhausted by 2030–2031. At the end of 2013, reserve-to-production (R/P) ratio (in years) of crude oil for countries such as the United Kingdom, Indonesia, China, and the USA stood at 9.6, 11.6, 11.9, and 12.1 years, respectively. If the R/P ratio to be believed, then at the current rate of production the leading consumer of oil will have to import 100 % oil just after a decade. Therefore, most of the countries are constantly looking for economically viable and environmentally sustainable alternatives to oil. Many believe probably natural gas could be one of the viable alternatives for the future.

### *1.3 Renewables*

At the end of 11th Five Year Plan (FYP), installed capacity of renewable power was around 25 GW and the 12th FYP envisages for capacity addition of about 30-GW grid-connected power. The 12th FYP (2012–2017) is giving a significant thrust on wind energy with an estimated capacity addition of 15GW, followed by solar (10,000 MW) and other renewable sources (5 GW). The costs of power produced from various renewable sources are coming down and getting increasingly affordable. The costs of producing one unit of power (kWh) from various renewable sources are estimated to be small hydro (Rs. 3.54–4.88), wind (Rs. 3.76–5.96), biomass (Rs. 5.12–5.83), bagasse cogeneration (Rs. 4.61–5.73), and solar (Rs. 10.39–12.46).

## 1.4 Coal-bed Methane (CBM)

Coal-bed methane (CBM) is an eco-friendly natural gas, extracted from underground coal reserves. India, having the fourth largest proven coal reserves in the world, holds significant prospects for exploration and exploitation of CBM. According to DGH, the prognosticated CBM resources in the country are about 92 TCF (2608 BCM). Coal-bed methane extraction seems to be another alternative solution to meet the demand supply gap. However, efficient production of CBM is becoming a real challenge for the exploration and production companies due to lack in detailed reservoir characterization (Ojha et al. 2011), low quality of coal, low porosity, and permeability (PNGRB 2013). Also, regulatory challenges related to the delineation of blocks for mining and CBM exploitation need immediate attention. Environmental challenges linked to higher requirement of the land and disposal of water need review and reconsideration. Logistic challenges associated with the requirement to drill a large number of wells at low cost need to be addressed at the earliest. Another area which demands greater attention is linked to safety of workers in the CBM mines. As most of the prospective coal mines lie in areas affected by insurgency, and workers face a serious threat to safe operations.

Efforts have been made to mobilize resources, facilitate processes, and remove existing bottlenecks to make India one of the largest producers of CBM. It is well known that CBM gas is clean and having similar calorific value as compared to natural gas and can be directly fed into the pipeline for end use. Since 1997 total prognosticated CBM resources, contracts awarded, for 33 CBM blocks with a potential of about 63.85 TCF (1808 BCM), of which, so far, 8.92 TCF (252.69 BCM) has been established as gas in place (GIP). According to the DGH estimation, the total CBM production is expected to be around 4 MMSCMD by the end of 12th plan. Experiences of CBM production in some of the states like West Bengal suggest that few critical areas such as easier land acquisition, affordable technology, well-developed pipeline infrastructure, and suitable pricing could prove instrumental for faster progress in the field of CBM gas production and consumption in India. The CBM production can improve the supply of gas in states such as West Bengal, Jharkhand, and Odisha. Currently, these states lack cross-country gas pipeline infrastructure. But the availability of CBM gas locally will encourage investors and companies to build desirable infrastructure for distribution and consumption of CBM.

## 1.5 Natural Gas

Natural gas is considered to be a cleaner fossil fuel, and for several decades, it had been driving economic growth and prosperity in countries such as the USA, Canada, Mexico, Argentina, Belarus, Italy, the UK, Japan, and Malaysia. Natural gas found to have a better geographical spread compared to crude oil.

# 2 Natural Gas in India

## *2.1 Domestic Production*

Compound annual growth rate (CAGR) of net domestic natural gas production (Table 2) for the period 2003–2004 to 2012–2013 had been only 3 %. During the period, Tamil Nadu had shown the highest CAGR of 9 % and Gujarat had shown the lowest with −6 %. Net production from the private/JVs had achieved 12 % CAGR during the stated period. Mumbai High had a marginally negative CAGR (−0.02 %).

## *2.2 Domestic Natural Gas Availability*

Net availability of domestic natural gas increased from 30.91 billion cubic meter (BCM) in 2003–2004 to 39.71 BCM in 2012–2013. Net availability data presented in Table 3 suggest that there was a marginal increase during 2003–2004 and 2007–2008 and a substantial surge for the next two years followed by a visible fall in the years 2011–2012 and 2012–2013. This has been due to fall in production in D-KG blocks.

## *2.3 Demand–Supply Gap Analysis*

Current demand scenario suggests that India's natural gas demand is higher than domestic gas availability. India is a gas deficit country and projections suggest that domestic requirements will be met primarily by importing gas.

According to a recent report by the Petroleum and Natural Gas Regulatory Board (PNGRB), the gas import dependence is projected to reach 70 % by 2030 from the current level of 58 % in 2012–2013. The total realistic demand is projected to reach 746 MMSCMD by 2030 from current 242.7 MMSCMD in 2012–2013. The gas deficit figure is going to exceed 500 MMSCMD by 2030 (Table 4) which is higher than the total expected demand in 2022–2023. The situation looks very scary considering the limited domestic gas availability and increasing dependence on imported gas.

Historical consumption statistics clearly indicate that power sector has been the largest offtaker of natural gas (Table 5) followed by fertilizer and captive use/LPG shrinkage. This has been due to favourable government policy towards these sectors. Urea plants, LPG plants, gas-based power plants, and city gas distribution (CGD) have been given priority for domestic gas supply from the fields under New Exploration Licensing Policy (NELP).

**Table 2** Trend of natural gas production in India (2003–2004 to 2012–2013), (in MMSCM)

| State | 2003–2004 | 2004–2005 | 2005–2006 | 2006–2007 | 2007–2008 | 2008–2009 | 2009–2010 | 2010–2011 | 2011–2012 | 2012–2013[a] |
|---|---|---|---|---|---|---|---|---|---|---|
| A. onshore | | | | | | | | | | |
| Assam and Arunachal Pradesh | | | | | | | | | | |
| Net production | 2213 | 2272 | 2493 | 2570.11 | 2666.00 | 2623.00 | 2529.53 | 2516.73 | 2741.34 | 2721.70 |
| Gujarat | | | | | | | | | | |
| Net production | 3389 | 3662 | 3810 | 3277.39 | 2913.00 | 2574.00 | 2404.23 | 2230.24 | 1999.68 | 1995.45 |
| Tamil Nadu | | | | | | | | | | |
| Net production | 537 | 628 | 867 | 1112.95 | 1152.00 | 1233.00 | 1163.62 | 1105.95 | 1277.13 | 1199.15 |
| Andhra Pradesh | | | | | | | | | | |
| Net production | 1914 | 1697 | 1655 | 1515.78 | 1557.00 | 1517.00 | 1478.13 | 1382.62 | 1360.54 | 1248.11 |
| Tripura | | | | | | | | | | |
| Net production | 508 | 497 | 480 | 519.78 | 534.00 | 553.00 | 562.35 | 609.87 | 643.90 | 646.69 |
| West Bengal (CBM) | | | | | | | | | | |
| Net production | 0.00 | 0 | 0 | 0.00 | 0.57 | 3.02 | 5.22 | 36.38 | 69.26 | 100.07 |
| Rajasthan | 0.00 | 0 | 0 | 0.00 | 0.00 | 0.00 | 238.59 | 430.79 | 223.37 | 685.43 |
| Net production | 0.00 | 0 | 0 | 0.00 | 0.00 | 0.00 | 221.58 | 382.11 | 222.91 | 635.34 |
| A. onshore total | | | | | | | | | | |
| Net production | 8561 | 8756 | 9305 | 8996.01 | 8822.57 | 8503.02 | 8364.66 | 8263.90 | 8314.76 | 8546.51 |
| B. offshore | | | | | | | | | | |
| Mumbai High | | | | | | | | | | |
| Net production | 17,235 | 16,769 | 16,351 | 16,010.6 | 15,879 | 16,027 | 13,452.23 | 17,035.2 | 16,850.4 | 17,521.6 |
| Private/JVCs | | | | | | | | | | |
| Net production | 5110 | 5250 | 5669 | 5784.83 | 6777.00 | 7221.00 | 18,371.89 | 25,930.2 | 20,827.4 | 13,637.6 |
| Total (A&B) | | | | | | | | | | |
| Net production | 30,906 | 30,775 | 31,325 | 30,791.4 | 31,478.6 | 31,751.0 | 46,485.9 | 51,229.3 | 41,025.9 | 39,705.7 |
| Net production (BCM) | 30.9 | 30.8 | 31.3 | 30.8 | 31.5 | 31.8 | 46.5 | 51.2 | 41.0 | 39.7 |

[a]Provisional figure for 2012−13
*Source* Petroleum planning analysis cell, Government of India

**Table 3** Trend of domestic gas availability and sales in India

| | 2003–2004 | 2004–2005 | 2005–2006 | 2006–2007 | 2007–2008 | 2008–2009 | 2009–2010 | 2010–2011 | 2011–2012 | 2012–2013 |
|---|---|---|---|---|---|---|---|---|---|---|
| Net availability (BCM)[a] | 30.91 | 30.78 | 31.33 | 30.79 | 31.48 | 31.75 | 46.49 | 51.23 | 41.03 | 39.71 |
| Sales by producing companies (BCM)[b] | 26.71 | 26.51 | 26.86 | 26.77 | 26.97 | 27.06 | 40.83 | 46.04 | 41.03 | 34.30 |

[a]Denotes natural gas available for consumption, which is derived by deducting gas flared from gross production by producing companies
[b]Denotes gas available for sale, which is derived by deducting internal use of gas by producing companies from net availability
*Source* Petroleum planning and analysis cell

**Table 4** Natural gas demand–supply projections in India unit: MMSCMD

| Year | Power | Fertilizer | City gas | Industrial | Petchem/refineries/internal consumption | Sponge iron/steel | Total realistic demand | Domestic supply | Gas deficit |
|---|---|---|---|---|---|---|---|---|---|
| 2012–2013 | 86.5 | 59.9 | 15.3 | 20.0 | 54.0 | 7.0 | 242.7 | 101.0 | −141.7 |
| 2013–2014 | 104.6 | 60.0 | 16.2 | 20.0 | 56.6 | 8.0 | 265.3 | 102.5 | −162.8 |
| 2014–2015 | 122.7 | 60.4 | 17.2 | 22.0 | 59.3 | 8.0 | 289.5 | 110.9 | −178.6 |
| 2015–2016 | 140.8 | 17.2 | 18.2 | 25.0 | 62.1 | 8.0 | 271.3 | 120.4 | −150.9 |
| 2016–2017 | 158.9 | 18.2 | 22.3 | 27.0 | 65.0 | 8.0 | 299.4 | 156.7 | −142.7 |
| 2017–2018 | 173.9 | 22.3 | 26.6 | 28.0 | 68.1 | 9.0 | 327.9 | 161.0 | −166.9 |
| 2018–2019 | 188.9 | 26.6 | 31.2 | 32.0 | 71.3 | 9.0 | 359.0 | 166.0 | −193.0 |
| 2019–2020 | 203.9 | 31.2 | 35.9 | 35.0 | 74.7 | 10.0 | 390.7 | 171.0 | −219.7 |
| 2020–2021 | 218.9 | 35.9 | 41.0 | 37.0 | 78.3 | 10.0 | 421.1 | 176.0 | −245.1 |
| 2021–2022 | 233.9 | 41.0 | 46.3 | 37.0 | 82.0 | 10.0 | 450.1 | 182.0 | −268.1 |
| 2022–2023 | 248.9 | 46.3 | 50.0 | 39.6 | 85.9 | 10.4 | 481.0 | 187.0 | −294.0 |
| 2023–2024 | 263.9 | 110.1 | 54.0 | 42.4 | 90.0 | 10.8 | 571.1 | 193.0 | −378.1 |
| 2024–2025 | 278.9 | 110.1 | 58.3 | 45.4 | 94.2 | 11.3 | 598.1 | 198.0 | −400.1 |
| 2025–2026 | 293.9 | 110.1 | 62.9 | 48.6 | 98.7 | 11.7 | 625.9 | 204.0 | −421.9 |

(continued)

**Table 4** (continued)

| Year | Power | Fertilizer | City gas | Industrial | Petchem/ refineries/ internal consumption | Sponge iron/ steel | Total realistic demand | Domestic supply | Gas deficit |
|---|---|---|---|---|---|---|---|---|---|
| 2026–2027 | 308.9 | 110.1 | 68.0 | 52.1 | 103.4 | 12.2 | 654.6 | 211.0 | −443.6 |
| 2027–2028 | 323.9 | 110.1 | 73.4 | 55.8 | 108.3 | 12.7 | 684.1 | 217.0 | −467.1 |
| 2028–2029 | 338.9 | 110.1 | 79.3 | 59.7 | 113.5 | 13.2 | 714.5 | 223.0 | −491.5 |
| 2029–2030 | 353.9 | 110.1 | 85.6 | 63.9 | 118.9 | 13.7 | 746.0 | 230.0 | −516.0 |

*Source* Compiled from PNGRB (2013)

**Table 5** Sectorwise natural gas offtakes (MMSCM) in India

| Industry | 2004–2005 | 2005–2006 | 2006–2007 | 2007–2008 | 2008–2009 | 2009–2010 | 2010–2011 | 2011–2012 | 2012–2013[a] | CAGR[c] (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| *Energy purposes* | | | | | | | | | | |
| Power generation | 12,099 | 11,878 | 11,963 | 12,037 | 12,603 | 21,365 | 23,583 | 18,912 | 12,849.0 | 7 |
| Industrial fuel | 3569 | 3780 | 3205 | 3323 | 5912 | 2322 | 999 | 1127 | 1139.0 | −15 |
| Tea plantation | 142 | 151 | 170 | 160 | 154 | 167 | 193 | 175 | 182.0 | 3 |
| Domestic fuel | 343 | 75 | 443 | 38 | 102 | 246 | 1584 | 1913 | 1996.0 | 28 |
| Captive use/ LPG shrinkages | 4944 | 5048 | 5034 | 1804 | 1885 | 5433 | 5770 | 6343 | 5921.0 | 4 |
| Others | 231 | 1120 | 40 | 1324 | 1535 | 1838 | 6551 | 5759 | 3224.0 | 58 |
| Total | 21,328 | 22,052 | 20,855 | 18,686 | 22,191 | 31,371 | 38,680 | 34,229 | 25,311 | 7 |
| *Non-energy purposes* | | | | | | | | | | |
| Fertilizers | 8173 | 7762 | 8497 | 9823 | 9082 | 13,168 | 13,429 | 10,406 | 10,702.0 | 4 |
| Petrochemicals | 1236 | 1175 | 1377 | 1432 | 1105 | 1264 | 1183 | 576 | 437.0 | −10 |
| Others[b] | 38 | 36 | 639 | 638 | 611 | 703 | 1098 | 1508 | 1950.0 | 69 |
| | 9447 | 8973 | 10,513 | 11,893 | 10,798 | 15,135 | 15,710 | 12,490 | 13,089 | 4 |
| Grand total | 30,775 | 31,025 | 31,368 | 30,579 | 32,989 | 46,506 | 54,390 | 46,719 | 38,400 | 6 |
| Grand total (MMSCMD) | 84.3 | 85.0 | 85.9 | 83.8 | 90.4 | 127.4 | 149.0 | 128.0 | 105.2 | 6 |

[a]Provisional, [b]Sponge Iron use, [c]CAGR has been calculated for 7 years only (2004–2005 to 2011–2012)
*Source* Adapted from Petroleum Statistics (2012, 2013)

As India is not self-sufficient in terms of meeting increasing natural gas requirements, importing of gas through various modes is holding paramount importance for the country. Therefore, being one of the crucial gas consumption centres, the country is all set to play critical role in the global gas trade. Considering the significant gas import in future India could influence gas trading in a bigger way. Over the last couple of years, this was visible to a certain extent. The following section on gas trade discusses important developments.

## 2.4 Natural Gas Trade

In recent years, natural gas trade has become very prominent in global energy trade. In 2012, 1033.4 BCM of gas was traded across the globe. About 68 % of total gas trade was contributed by dry gas (pipeline) and 32 % by liquefied natural gas (LNG). Europe imported about 377 BCM of dry natural gas, which is 53 % of global dry gas import. Whereas Asia contributed about 57 % of LNG import. Asia has become a major destination for LNG exporters. It is expected that Asia would continue to remain as a major destination for LNG suppliers. Strong demand from China and India, in addition to traditional importers such as Japan and Korea, will ensure that the Asia Pacific market remains profitable for LNG suppliers (IGU 2013).

In some of the developed and emerging markets, gas is increasingly becoming a fuel of choice for electricity generators, provided heating and cooling, and driving economic growth. Such developments could prove beneficial for natural gas trade in the near future. Natural gas trade statistics suggest that the USA has been historically one of the largest importers of natural gas, especially dry gas from Canada and Mexico. But the recent shale gas revolution in the USA could change the dynamics of future global natural gas trade. Probably, USA would emerge as one of the largest exporter of natural gas, especially LNG in future.

### 2.4.1 Import in the Form of LNG

Gas resources are not uniformly distributed across the globe, the consumption centres are away from production centres. The consuming countries do not have adequate gas reserves and production, creating a need for importing natural gas. Due to geographical positioning and distance from production centres, countries such as Japan and India do not have many options but to rely on importing LNG. India, of course, wishes to get gas from Iran, Turkmenistan, Myanmar, and Burma. However, till date no progress has been made to build pipeline from Iran to India.

Due to fall in domestic production and unavailability of gas import through the pipeline from the neighbouring countries, India's LNG import has been rising constantly and will continue to rise in future also. As per the Petroleum Planning and Analysis Cell, India imported less than 1 BCM in 2003–2004 and the figure reached 16 BCM by 2011–2012 and came down to 15 BCM by 2012–2013 (Table 6). However, the BP statistics (2013) indicate that India imported 20.4 BCM of natural gas in 2012. Qatar was the prime source contributing 79 % of supply (Fig. 1) followed by Nigeria (10 %), Egypt (3.84 %), Algeria (2.75 %), and Yemen (2.70 %).

**Table 6** Import of LNG in India (2003–2004 to 2012–2013)

| Year | Unit | 2003–2004 | 2004–2005 | 2005–2006 | 2006–2007 | 2007–2008 | 2008–2009 | 2009–2010 | 2010–2011 | 2011–2012 | 2012–2013 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Total LNG imports | MMT | 0.25 | 2.50 | 5.06 | 6.81 | 8.25 | 7.96 | 8.922 | 9.73 | 11.632 | 10.901 |
| Total LNG imports | BCM | 0.34 | 3.45 | 6.98 | 9.40 | 11.38 | 10.98 | 12.31 | 13.43 | 16.05 | 15.04 |

*Source* Petroleum planning and analysis cell, Government of India

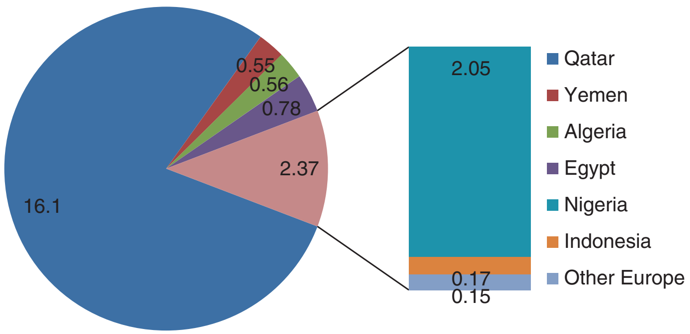


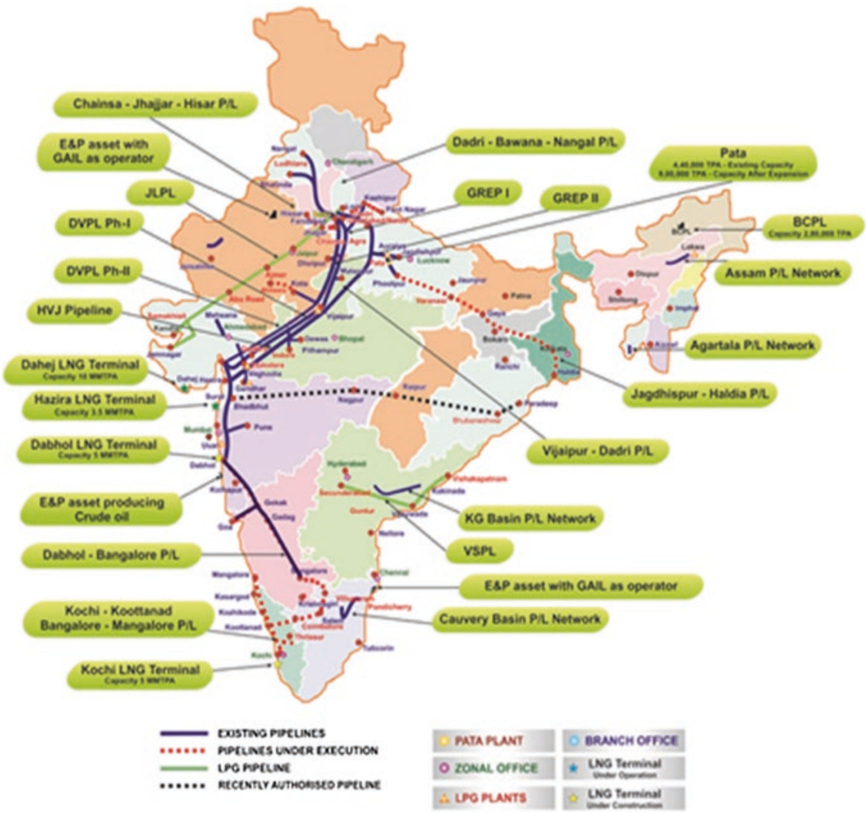

**Fig. 1** LNG import (BCM) in India, 2012

## LNG Infrastructure

As India does not have cross-border pipelines to import dry natural gas, it has no option but to build infrastructure for importing liquid natural gas. LNG has limited direct use so needs regasification for transportation through pipelines and final consumption. This necessitates LNG regasification plants in the country. Such infrastructures are bound to develop near the costal belt as the LNG imported through the ships under cryogenic condition.

Considering rising gas demand, Petronet LNG Ltd. was formed to set up LNG terminal in India. The first LNG terminal came up in Dahej, Gujarat, with a name-plate capacity of 5 MMTPA. This terminal has been operational since January 2004 and since then it received more than 1000 cargoes. Currently, four LNG terminals at Dahej, Hazira, Dhabol, and Kochi (Map 1) are operational with total capacity of 25 MMTPA (Table 7). It is learnt that in the near future, the Dahej terminal to be expanded to 12.5–15 MMTPA and Kakinada (Andhra Pradesh) terminal to be operational by 2014–2015. Additional terminals are planned in Ennore (Tamil Nadu), Mundra (Gujarat), Pipavav (Gujarat), Paradip (Odisha), and Dhamara (Odisha). It is projected that by 2030, India will have regasification capacity of about 105 MMTPA[1] (391 MMSCMD). Due to this, the projected

[1] 1MMTPA of LNG = 3.726 MMSCMD.




**Map 1** Location of LNG regasification facilities in India

deficit would come down 125 MMSCMD. The deficit could be brought down further by setting up additional terminal or expanding the existing terminal. Else, dry natural gas could be imported to bridge the demand–supply gap.

## Current Sources

Current statistics suggest that Middle East and African region have been the preferred destination for LNG import to India. The primary reason for this could be (i) availability of gas at a cheaper price, (ii) availability of long-term contracts, especially in the case of Qatar, and (iii) transportation cost.

Sourcing natural gas from the Middle East is cheaper compared to sourcing from Trinidad. LNG freight cost from Peru to West of India is the costliest option (Table 8). Therefore, while exploring sources of gas, buyers are very careful about freight cost along with the cost of gas.

**Table 7** LNG regasification capacity in India

| | Dahej | Hazira | Dhabol | Kochi | Ennore | Mundra | Pipavav | Kakinada | Gangavaram | Paradip | Dhamra | Total capacity (MMTPA) | Total capacity (MMSCMD) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2012–2013 | 10 | 3.6 | 1.2 | 2.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 17.3 | 64.5 |
| 2013–2014 | 10 | 5 | 5 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 25 | 93.2 |
| 2014–2015 | 12.5 | 5 | 5 | 5 | 0 | 0 | 0 | 2.5 | 0 | 0 | 0 | 30 | 111.8 |
| 2015–2016 | 15 | 5 | 5 | 5 | 5 | 5 | 0 | 5 | 0 | 0 | 0 | 45 | 167.7 |
| 2016–2017 | 15 | 10 | 5 | 5 | 5 | 5 | 0 | 5 | 5 | 0 | 0 | 55 | 204.9 |
| 2017–2018 | 15 | 10 | 5 | 5 | 5 | 10 | 3 | 5 | 5 | 4 | 5 | 72 | 268.3 |
| 2018–2019 | 15 | 10 | 5 | 5 | 5 | 10 | 3 | 5 | 5 | 4 | 5 | 72 | 268.3 |
| 2019–2020 | 15 | 10 | 5 | 5 | 5 | 10 | 3 | 5 | 5 | 4 | 5 | 72 | 268.3 |
| 2020–2021 | 15 | 10 | 5 | 5 | 5 | 10 | 3 | 5 | 5 | 4 | 5 | 72 | 268.3 |
| 2021–2022 | 15 | 10 | 5 | 5 | 5 | 10 | 3 | 5 | 5 | 4 | 5 | 72 | 268.3 |
| 2022–2023 | 15 | 10 | 10 | 10 | 5 | 10 | 5 | 5 | 10 | 10 | 5 | 95 | 354.0 |
| 2023–2024 | 15 | 10 | 10 | 10 | 5 | 10 | 5 | 5 | 10 | 10 | 5 | 95 | 354.0 |
| 2024–2025 | 15 | 10 | 10 | 10 | 5 | 10 | 5 | 5 | 10 | 10 | 10 | 100 | 372.6 |
| 2025–2026 | 15 | 10 | 10 | 10 | 5 | 10 | 10 | 5 | 10 | 10 | 10 | 105 | 391.2 |
| 2026–2027 | 15 | 10 | 10 | 10 | 5 | 10 | 10 | 5 | 10 | 10 | 10 | 105 | 391.2 |
| 2027–2028 | 15 | 10 | 10 | 10 | 5 | 10 | 10 | 5 | 10 | 10 | 10 | 105 | 391.2 |
| 2028–2029 | 15 | 10 | 10 | 10 | 5 | 10 | 10 | 5 | 10 | 10 | 10 | 105 | 391.2 |
| 2029–2030 | 15 | 10 | 10 | 10 | 5 | 10 | 10 | 5 | 10 | 10 | 10 | 105 | 391.2 |

*Source* Compiled from published sources

**Table 8** LNG freight costs ($/MMBTU)

| | Japan/ Korea | South China/ Taiwan | West India | South-west Europe | North-west Europe | North-east USA | Argentina |
|---|---|---|---|---|---|---|---|
| Middle East | 2.05 | 1.81 | 0.66 | 1.93 | 2.33 | 2.42 | 2.55 |
| Australia | 1.32 | 1.19 | 1.37 | 2.94 | 3.26 | 3.06 | 2.7 |
| Trinidad | 4.44 | 4.18 | 3.03 | 1.28 | 1.26 | 0.6 | 1.49 |
| Nigeria | 3.37 | 3 | 2.23 | 1.28 | 1.37 | 1.35 | 1.5 |
| Algeria | 3.37 | 3.13 | 2.02 | 0.42 | 0.73 | 0.97 | 1.83 |
| Belgium | 3.84 | 3.47 | 2.35 | 0.63 | | 0.88 | 2.04 |
| Peru | 2.83 | 3.18 | 3.44 | 2.88 | 2.97 | 2.48 | 1.3 |
| Russia | 0.71 | 0.93 | 1.99 | 3.5 | 3.7 | 3.75 | 3.26 |

*Note* Cost data is for in July 2011
*Source* LNG Daily (2013)

## Future Prospects for LNG Sourcing

LNG sourcing from India's standpoint is going to change dramatically by 2020. Over dependence on Qatar is bound to reduce and the LNG sourcing mix is going to spread across the globe. In particular, Australia and USA are going to play all important roles in the changing dynamics of LNG sourcing. Sourcing gas from Australia found to be costlier compared to sourcing from Middle East and Africa. Angola and Algeria could be important destinations in the future. Many liquefaction projects coming up in the USA could prompt not only India but also many Asian buyers to source LNG linked to Henry Hub pricing. Sourcing gas from USA may be a better option compared to Australia because the gas price found to be cheaper in the USA. According to industry sources, landing cost of US LNG in India could be around $9–10/MMBTU compared Australian LNG costing about $13–14/MMBTU. Even sourcing of LNG from Israel through Egypt could be a possible option.

## LNG Pricing

LNG pricing is very important and critical component of LNG trade. There have been many variations in LNG pricing formula across the globe. Some of the important prevailing prices are based on the following: gas-on-gas competition, oil price escalation, bilateral monopoly, and netback from the final product (IGU 2011). Gas-on-gas competition is the dominant pricing mechanism prevalent in the USA and UK. The price of gas is determined by the demand–supply over a variety of periods ranging from weekly to annually or even longer. Trading takes place at physical hubs, such as Henry Hub (US), and National Balancing Point (NBP) in the UK. Trading has been supported by well-developed future markets such as New York Mercantile Exchange or Inter Continental Exchange and online commodity exchange such as an Online Capital Markets Limited. Long-term contracts rely on gas price indices rather than competing fuel indices.

Oil price escalation is visibly dominant in the continental Europe and Asia. Essentially, the gas price is determined by having a base price and an escalation clause, linked to the price(s) of one or more competing fuels, for example, competing fuel in Europe being gas oil and/or fuel oil, and that is in Asia typically being crude oil. The escalation clause takes care of price adjustment in the upward direction and also inflation.

Bilateral monopoly negotiations are very commonly observed in interstate gas dealings in the former Soviet Union, and Central and Eastern Europe. Gas prices determined through government-level negotiations for a period of one year. Such negotiations often involve elements of barter, with buyers paying for portion of their imported natural gas as the transit services or investing in field developments or pipeline projects.

Net back price from final product-based price is derived from the final price the buyer gets from the consumer by selling the final product. For example, the price received by a gas supplier such as GAIL India from the power sector should be based on the market determined price of electricity. The net back price is commonly seen when gas is used as a feedstock to produce derived products such as ammonia or methanol, and constitutes a major component of variable cost in producing the finished product.

Because of the theoretical link between oil and natural gas, oil is traded frequently and globally and therefore has an established price, a large number of exporters price natural gas based on oil. LNG pricing is certainly derived from the pricing mechanism prevalent in the country/continent of origin or consumption.

In the recent years, pricing of LNG has seen significant interest, but still the diversity of pricing remains as it is. Pricing is expected to continue to be a major issue with buyers demanding that LNG Selling Purchase Agreements (SPAs) be indexed to North American gas prices. For instance, Gas Authority of India Limited (GAIL) signed a 20-year deal with Sabine Pass Liquefaction to import LNG from the USA from 2017 to secure long-term supplies at prices linked to the US benchmark Henry Hub. LNG import from Sabine Pass could be about $5–6/MMBTU cheaper compared to Gorgon gas project in Australia. It can be observed that the oil linked Gorgon LNG deal ($15.8/MMBTU) significantly expensive compared to Henry Hub-linked Sabine Pass deal ($10–11/MMBTU). Gas buyers are looking for an optimal sourcing mix with supply security, so more hybrid deals using both gas hub and oil-indexed pricing are likely to emerge in future.

### 2.4.2 Import Via Pipeline

Current Status

Currently India does not import natural gas through pipelines. Due to unnecessary delay or inaction with respect to proposed pipelines such as Turkmenistan–Afghanistan–Pakistan–India (TAPI), Iran–Pakistan–India, and Myanmar–Bangladesh–India, natural gas import through the pipeline has remained as a dream for India. TAPI pipeline is expected to feed imported natural gas to the national gas grid by 2017–2018. As per the gas sale purchase agreement (GSPA), India is going to receive 38 MMSCMD of gas for 30 years from the year of operations. That means if the TAPI venture materializes, then India's gas deficit could be about 87 MMSCMD by 2029–2030. According to informed sources in the industry, TAPI project is progressing well and the consortium leader to be finalized soon.

### Possible Sources of Dry Gas Import

India has been exploring 2700-km on-land gas pipeline from Iran to India via Pakistan; discussions are also on over the possibility of laying an alternate 1400-km sub-sea deep-water pipeline from Iran to India crosses the sea of Oman (Airy 2014). Turkmenistan and other central Asian countries and the Russian Federation could be possible sources of importing dry gas through pipelines. There has been a proposal to build 15,000 km Asian Gas Grid to enhance gas demand–availability scenario in Asia. The proposed grid could be an extension of the $7.6-billion Turkmenistan–Afghanistan–Pakistan-–India (TAPI) 1735-km pipeline (Jayaswal 2013). Gas availability (38 MMSCMD) through TAPI is certainly going to impact the economic prosperity in India, especially north Indian states where infrastructure has not developed owning to unavailability of gas.

India has been eying sourcing natural gas from gas-rich eastern neighbours such as Bangladesh and Myanmar. In recent times, there has been a renewed interest to revive a 16-year-old proposal for a 900-km pipeline covering Myanmar, Bangladesh, and India. However, progress on this front seems to be insufficient and may not bring any medium term result.

If all ambitious cross-border pipeline projects materialize, then the gas market in India could see a faster transformation than anticipated. But such projects are not free from multifaceted challenges, including geopolitical tensions in the zone. However, from energy security and economic prosperity point of view, all stakeholder countries are likely to rise above differences to make the project happen at the earliest.

### Challenges of Building Transnational Pipelines

Striking transnational pipeline deals are full of challenges from conceptual stage to operational stage and even further. Some of the possible challenges are as follows: aligning with the interest of multiple independent and sovereign countries, understanding the inherent interest of resource-rich countries, understanding the interest of the transit countries, getting investors for diversifying risks, and identifying and understanding geopolitical risks and project risks.

Strategic Steps Needed

It is very important to categorically identify and understand all the possible risks involved with transnational pipelines and working towards avoiding such risks with carefully developed legally binding contracts. Prior to reaching the contract stage, taking path breaking steps needs kind attention at various levels. Some of the steps are as follows: developing trained and dedicated energy diplomats, building continuous and meaningful government to government relationship, developing fruitful Indian industry to foreign government relationship, and choosing companies in the resource-rich countries as strategic partners in Indian projects. The Government of India should identify key energy diplomats, train, and deploy them for dealing with energy diplomacy.

## 3 Gas Pricing in India

The Indian gas market is predominantly monopolistic in its operation due to a huge demand and supply gap (Rangarajan Committee 2012, p. 78). Price is administratively determined for each source of domestic supply, and the imported gas pricing is more or less determined by the market factors. The following section discusses the issues, challenges, and future of gas pricing in India.

### *3.1 Existing Pricing Regimes*

There are broadly two pricing regimes for gas in the country, namely (a) administered pricing mechanism (APM), and (b) non-APM (market-driven). The price of APM gas is set by the Government principally on a cost-plus basis. On the other hand, the market-driven pricing is broadly divided into two categories: (i) imported LNG and (ii) domestically produced gas from NELP and pre-NELP fields.

The pricing mechanism of domestic gas under the NELP is driven by the production sharing contract. Under the last round of NELP, 100 % cost recovery was allowed. Many economists argue that the full cost recovery incentivizes the contractor to artificially build higher cost and recover. Of late, the regulatory body has been very stringent while allowing cost recovery. On the other hand, some do argue in favour of cost recovery as this allows the contractor to de-risk investments to a greater extent. The matter is so complex that multiple committees have been set up to come up with the right kind of solution to address concerns of the industry and the government. The Rangarajan committee[2] recommends for profit sharing model and the Kelkar panel argues in favour of cost sharing. The Kelkar panel[3]

[2]Committee on the PSC Mechanism in Petroleum Industry.

[3]Kelkar panel on ‘Roadmap for Reduction in Import Dependency in Hydrocarbon Sector by 2030’.

argues that gold plating is not possible in oil and gas exploration and production as the contractor needs to invest upfront without any assured return. Technically speaking, the argument sounds very logical as, for any capital structure higher risk-adjusted capex could reduce returns for the contractor so there is no incentive for over investment. An expert in the regulatory body closely involved in NELP opined that both the committees probably address a part of the problem. Arguably India needs a balanced approach to attract foreign investment in this sector, allow the foreign companies to operate, produce more oil and gas domestically, and create win–win–win situation for the contractor, the government, and the consumer.

### *3.2 Challenges of Gas Pricing*

At this point in time, in India, gas prices cannot be completely market-driven because the government being the owner of the natural resources cannot ignore socioeconomic sentiments of the consumer and society at a large. The bottom line of such thinking process is moving away from market determined pricing. The Planning Commission acknowledges that high LNG pricing in Asia can "kill the goose that lays the golden eggs". It is neither in the producer's interest nor in the national interest to take natural gas to unviable levels by linking to crude prices. Reliance Industry, producer of gas from the KG-D basin, has been arguing in favour of aligning domestic gas prices with international prices, essentially implementing import parity price.

Asian LNG price is linked to the Japan Customs-cleared Crude (JCC) and found to be on the higher side compared to Henery hub price. Very often the government is not quite sure of which benchmark to follow for deciding "arm's length" price. In the presence of multiple natural as pricing mechanisms across the globe, any one of them may not fit into India's the requirements.

In a free market the entire stakeholder's interest needs to be protected, the government seems to be at least concerned about some of them. The Government is very careful while increasing gas price, as would have immediate impact on fertilizer, power, and other priority sectors. Every dollar increase in gas price likely to have Rs. 3000–4000 crore/year burden on fertilizer producers and Rs. 10,000 crore/year on gas-based electricity generation units (Chandrasekhar 2013). The pricing formula suggested by Rangarajan Committee would have more than doubled gas price to around \$8.8 per million British thermal unit (Ranjan 2014) and every dollar increase in gas price could have lead to a Rs. 1370 per tonne rise in urea production cost and a 45 paise per unit increase in electricity tariff (for just the 7 % of the nation's power generation capacity based on gas).

The stiff price rise would have impacted the CNG and PNG users. It is estimated that \$1/MMBTU price increase likely to push CNG and PNG (domestic cooking) price by a minimum of Rs. 2.81 per kg increase in CNG price and a Rs. 1.89 per standard cubic metre (TOI 2014). Considering the socio-economic implications, the new (NDA) government decided to review the earlier price hike decision of the earlier (UPA-II) government. In the August-end, the government constituted a four-member panel comprising of secretaries of power, fertilizer, and expenditure with additional secretary in the Oil Ministry as its member secretary to relook at the proposed gas price revision.

On the other hand, the increase in gas price would have brought windfall for the government—about USD 2.08 billion (Rs. 12,900 crore) from additional profit petroleum, royalty, and taxes accruing from doubling of domestic gas price.

The government sounds interested to safeguard the interest of the investors, preserve end user sentiments, address popular constituencies, and sanitize political outburst. For obvious reasons, Government tries to balance between social equity and economic rationality while deciding on critical matters such as gas allocation and pricing.

### *3.3 Role of Government*

The central government plays important role in setting the price of natural gas in India. Often the right pricing, price for producers justifiably is not the right price from a consumer standpoint. Energy economists argue in favour of reducing subsidy and increasing domestic gas price closer to price prevalent in international market. On the other hand, some of the socio-economists clearly favour lower domestic gas price for enhancing affordability and accessibility. Historically, the government prefers the socio-economist's approach of improving energy equity and enhancing desirable infrastructure. However, the government should not treat affordability and accessibility in isolation; rather, it should be linked to the availability of natural gas. Setting an import parity gas price for domestic producers could lead to higher investment in exploration and production (E&P) activities leading to more exploration and commercial production. This could possibly improve domestic gas supply and reduce costly import leading to better balance of payment conditions.

### *3.4 Future of Gas Pricing in India*

On 27 June 2013, the Cabinet Committee of Economic Affairs (CCEA), based on the recommendations made by the Rangarajan Committee, cleared the new gas pricing mechanism, the domestic gas price would be computed based on the trailing 12-month average of the following:

(a) volume-weighted net back pricing of Indian LNG imports and
(b) volume-weighted price of USA's Henry Hub, UK's NBP, and Japan's JCC-linked price

The new pricing mechanism was due on 1 April 2014 for the period of April 2014–2019. However, the new pricing was delayed for more than 6 months and revised price is determined on the basis of Gross Calorific Value (GCV) instead of Net Calorific Value (NCV).

The gas price is proposed to be determined as per the formula given below

$$P = VHH\ PHH + VAC\ PAC + VNBP\ PNBP + VR\ PR\ VHH + VAC + VNBP + VR$$

where

(a) VHH = Total annual volume of natural gas consumed in USA and Mexico.
(b) VAC = Total annual volume of natural gas consumed in Canada.
(c) VNBP = Total annual volume of natural gas consumed in EU and Former Soviet Union (FSU), excluding Russia.
(d) VR = Total annual volume of natural gas consumed in Russia.
(e) PHH and PNBP are the annual average of daily prices at Henry Hub (HH) and National Balancing Point (NBP) less the transportation and treatment charges.
(f) PAC and PR are the annual average of monthly prices at Alberta Hub and Russia, respectively, less the transportation and treatment charges.

The new gas price is effective from 1 November 2014 and needs revision every 6 month. The revised price will be announced 15 days before the date of implementation (CCEA 2014). The pricing is for all natural gas domestically produced—conventional, shale, or coal-bed methane (CBM)—with a few exceptions to be reviewed every quarter. The new pricing guidelines exclude contacts fixed for certain period, till the end of such period and contracts where a specific formula for natural gas price indexation/fixation, e.g., Panna–Mukta–Tapti (PMT), Ravva, PY-1, and RJ-ON/6 has been operations.

## 4 Independent Downstream Regulator

Indian petroleum industry was controlled by the government for a long time. Downstream market, especially marketing of petroleum products, was deregulated in the 2002. Decontrol meaning there is going to be free and fair competition in the market, therefore, need of an independent regulator. So, the government mooted the idea of establishing an independent regulator for the downstream petroleum industry. The Petroleum Regulatory Board Bill was first introduced in the Lok Sabha on 06 May 2002 and was then referred to a Group of Ministers, which, in turn, referred it to the Parliamentary Standing Committee on Petroleum and Chemicals for examination on 17 May 2002. The report of the Committee was presented to the Lok Sabha on 08 May 2003 that suggested nearly 26 amendments. After incorporating those amendments, the Bill was then renamed as the PNGRB Bill, 2003. However, the Bill lapsed on account of the dissolution of the 13th Lok Sabha, in terms of Article 107(5) of the Constitution. The Ministry of Petroleum and Natural Gas (MoPNG), therefore, introduced the Petroleum and

Natural Gas Regulatory Board (PNGRB) Bill, 2005, in the Rajya Sabha, on 21 December 2005. The Bill provided for the setting up of the PNGRB, to regulate the downstream petroleum and natural gas sectors. The PNGRB Act (2006) received assent of the President, Government of India, on 31 March 2006.

### 4.1 Objectives of Petroleum and Natural Gas Regulatory Board (PNGRB)

The primary objective of setting up to "protect the interests of consumers and entities engaged in specified activities relating to petroleum, petroleum products and natural gas and to ensure uninterrupted and adequate supply of petroleum, petroleum products and natural gas in all parts of the country and to promote competitive markets and for matters connected therewith or incidental thereto" (PNGRB Act 2006). The mandate of the board is to regulate the downstream business of petroleum and natural gas is to (i) protect the interest of the consumers and entities, (ii) phase out monopoly and establish competition, and (iii) ensure much needed transparency.

### 4.2 Role of the PNGRB

The PNGRB Act (2006) received assent of the President, Government of India, on 31 March 2006. As per the PNGRB Act (2006), the board is authorized to regulate refining, processing, storage, transportation, distribution, marketing, and sale of petroleum, petroleum products, and natural gas-related activities excluding the production of crude oil and natural gas. The Board has been empowered to authorize entities to (i) market any notified petroleum, petroleum products or natural gas; (ii) establish and operate LNG terminals; (iii) lay, build, operate, or expand a common carrier or contract carrier; and (iv) lay, build, operate, or expand a city or local natural gas distribution network. In addition to the above-mentioned role, PNGRB has been given a mandate to protect consumer interest by fostering fair trade and build competition environment in the downstream oil and gas sector (Table 19).

## 5 Gas Pipeline Infrastructure

### 5.1 Cross-Country Gas Pipeline Network

Cross-country pipeline truly works as the circulatory system of economic activity in India. Most importantly for green manufacturing, growth, development, and economic progress, the cross-country pipeline network having pan-India presence is most desirable. As of 31 December 2013, India had 15,340 km of functional cross-country pipeline with designed capacity of 395 MMSCMD. However, the average capacity utilization rate was just about 48 % in 2013. The pipeline network having highest designed capacity with maximum capacity utilization is Hazira–Vijaipur–Jagdishpur (HVJ) pipeline (Table 9). This pipeline proves to be the most important connecting link between sources of gas and consumption points in central and north India. Because of gas supply through this pipeline, many power plants, fertilizer plants, and industrial consumers are getting green fuel/feedstock. Also, green transport drive through CNG in Delhi and NCR completely relies on the HVJ pipeline. We can infer that the HVJ pipeline is source of green prosperity.

In addition to the already operational pipeline network, an additional pipeline network of 10,470 km is under execution or construction stage (Table 10). Also, pipeline network between Kakinada–Srikakulam (350 km) and Duragpur–Kolkata (160 km) is under proposal stage. The cross-country pipelines under discussion would cover almost entire country with coverage of 26,320 km. But the intention of the government of India is to take the network beyond 30,000 km at the earliest.

### *5.2 Entities*

Natural gas infrastructure is developed by companies authorized to sell natural gas in designated geographical areas or cities (Table 11). Similarly, the cross-country pipeline network is developed by companies authorized by the government or PNGRB.

### *5.3 National Gas Grid*

CGD network development is not uniform across India. States such as Gujarat, Maharashtra, and Delhi have better developed CGD network. States such as Haryana, Rajasthan, Madhya Pradesh, Uttar Pradesh, Tamil Nadu, and Andhra Pradesh have moderately developed CGD network. But most of the other states such as Karnataka, Kerala, Chattishgarh, Punjab, Jammu and Kashmir, Himachal Pradesh, Uttarakhand, Goa, Bihar, West Bengal, Jharkhand, and Odisha lack CGD network. Except Assam and Tripura, other north-eastern states like Manipur, Meghalaya, Mizoram, and Nagaland severely lack the pipeline infrastructure necessary for effective natural gas distribution. For sustainable green economic growth, India needs to have a well-developed national gas grid and CGD network. The government of India has been actively pursuing the objective of building a national gas grid to reach maximum number of cities, villages, households, and industries to provide natural gas-a greener energy option. By 2029–2030, the design capacity of pipeline network in India is expected to reach 815 MMSCMD

**Table 9** Gas pipeline network, capacity, and capacity utilization in India (as on 31 December 2013)

| Network/region | Entity | Length (km) | Design capacity (MMSCMD) | Average flow in 2013–2014 (April–Dec) (MMSCMD) | % capacity utilization as on 31 December 2013 | Pipeline size |
|---|---|---|---|---|---|---|
| HVJ GREP–DVPL & Spur (Hazira–Vijaipur–Jagdishpur) | GAIL | 4435 | 57.3 | 44.0 | 77 | 36″ |
| DVPL-I (42″) (Dahej–Vijaipur)-GREP Upgradation | GAIL | 1112 | 54 | 14.85 | 28 | 42″/48″ |
| VDPL-1(36″), DVPL-2 (48″) (Vijaipur–Dadri) | GAIL | 262 | 5 | 0.68 | 14 | 48″ |
| Chhainsa–Jhajjar–Hissar P/L (Including Spur lines) commissioned up to Sultanpur, Jhajjar–Hissar under hold (111 km). Flow of 5 Million up to 2011–2012 | GAIL | 873 | 20 | 9.51 | 48 | 36″/16″ |
| Dahej–Urann–Panvel (DUPL/DPPL) including spur lines | GAIL | 803 | 11 | 2.60 | 24 | 30″/18″ |
| Dadri Bawana Nangal P/L, Dadri–Bawana: 106 km Bawana–Nangal: 501 km, spur line of BNPL: 213 km. Flow of 11 Million up to 2011–2012 | GAIL | 1004 | 16 | 0.89 | 6 | 36″/30″/24″/18″ |
| Dhabol–Bangalore pipeline (including spur) | GAIL | 41 | 6 | 0.33 | 5 | 36″-4″ |
| Assam (Lakwa) | GAIL | 8 | 2.5 | 0.55 | 22 | 24″ |
| Tripura (Agartala) | GAIL | 61 | 2.3 | 1.46 | 65 | 12″ |
| Ahmedabad | GAIL | 144 | 3.0 | 0.38 | 13 | 12″ |
| Rajastan (Focus Energy) | GAIL | 154 | 2.35 | 1.02 | 43 | 12″ |
| Bharuch, Badodara (Undera) included RLNG + RIL | GAIL | 670 | 15.4 | 2.25 | 15 | 24″,16″ |
| Mumbai | GAIL | 129 | 24.0 | 22.9 | 95 | 26″ |
| KG Basin (included RLNG + RIL) | GAIL | 877 | 16.0 | 6.0 | 37 | 18″ |
| Cauvery Basin | GAIL | 268 | 9.0 | 3.51 | 39 | 18″ |
| East–West Pipe Line (RGTIL) | Reliance | 1469 | 80.0 | 48.0 | 60 | 48″ |
| GSPCL Network including spur lines | GSPCL | 1874 | 50.0 | 22.0 | 44 | Assorted |
| Assam Gas Company (Duliajan to Numaligarh) | AGC | 1000 | 6.0 | 4.50 | 75 | 16″ |
| Dadri–Panipat | IOCL | 132 | 9.5 | 2.97 | 31 | 30″/10″ |
| Uran Trombay | ONGC | 24 | 6.0 | | | |
| Sub total | | 15,340 | 395 | 188 | 48 | |

*Source* Petroleum planning analysis cell

**Table 10** Gas pipeline execution/construction

| Network/region | Entity | Length (km) | Design capacity (MMSCMD) | Pipeline size |
|---|---|---|---|---|
| Kochi–Kottanad–Bangalore–Mangalore | GAIL | 1156 | 16 | 24″/18″/12″ |
| Dhabhol–Banglore (DBPL) | GAIL | 1414 | 16 | 36″/30″/24″/18″ |
| Surat–Paradip | GAIL | 1550 | 75 | 36″/24″/18″ |
| Jagdishpur–Haldia[a] | GAIL | 2050 | 32 | |
| Mallapuram–Bhilwada[a] | GSPL | 1600 | 30 | |
| Mehsana–Bhatinda[a] | GSPL | 1670 | 30 | |
| Bhatinda–Srinagar[a] | GSPL | 740 | 15 | |
| Vijaipur–Kota (Kota) extended up to Chittorgarh | GAIL | 290 | 2 | 18″/16″/12″ |
| Sub total | | 10,470 | 216 | |

[a]Competitive bidding
*Source* Petroleum planning analysis cell, Government of India

**Table 11** City gas distribution network coverage in India

| Name of the CGD network | Area covered | Entity authorized by PNGRB/Govt. |
|---|---|---|
| Sonipat CGD, Meerut CGD, Dewas CGD, Kota CGD | Network Sonipat, Network Meerut, Network Dewas, Network Kota | Gail Gas Limited |
| Kakinada | CGD Network Kakinada | Bhagyanagar Gas |
| Mathura CGD | Network Mathura | JV of M/s DSM Infratech Ltd. and M/s Saumya Mining |
| Agra CGD | Network Agra | Green Gas Limited |
| CGD Network Hyderabad | Hyderabad | Bhagyanagar Gas |
| Indore CGD Network | Indore including Ujjain | Aavantika Gas |
| Ghandhinagar, Mehesana, and Sabarkantha CGD Network | Ghandhinagar, Mehesana, and Sabarkantha | Sabarmati Gas Ltd. |
| Pune City CGD Network | Pune and Pimpri-Chinchwad city including adjoining areas of Hinjewadi, Chakan and Talegaon | Maharashtra Natural Gas Limited (MNGL) |
| Kanpur CGD, Bareilly CGD Area | Network Kanpur GA, Bareilly GA | Central UP Gas Limited |
| Delhi CGD Network | National Capital Territory of Delhi | Indraprastha Gas Limited (IGL) |

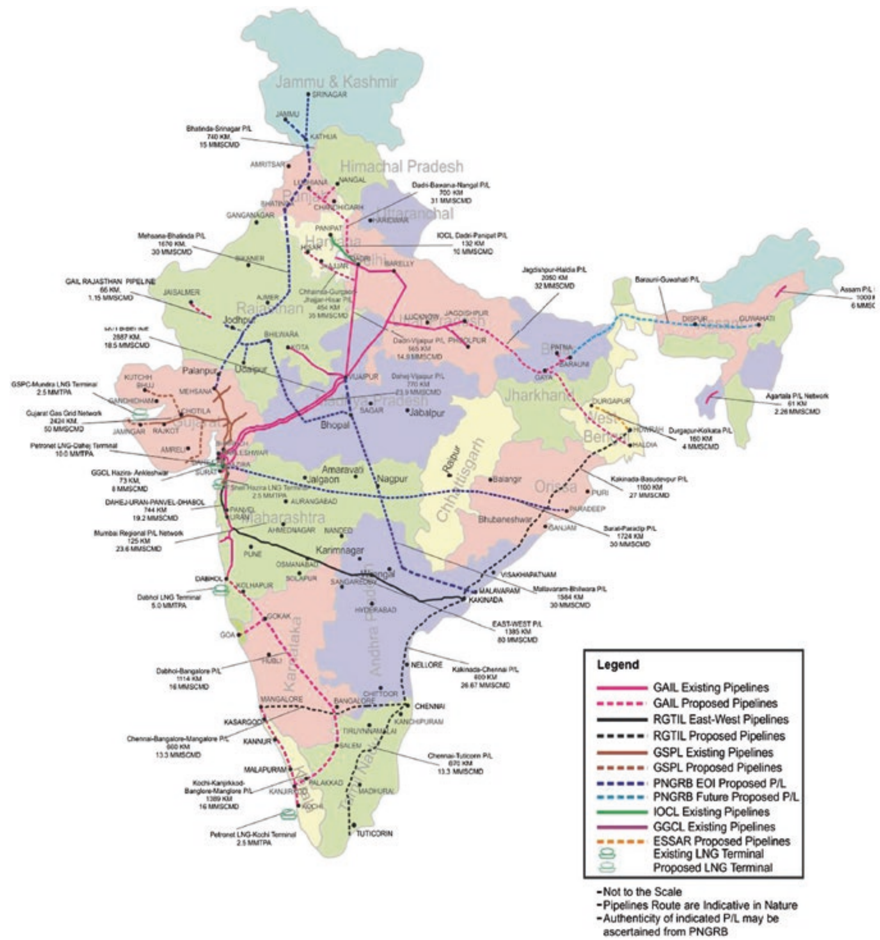
(continued)

**Table 11** (continued)

| Name of the CGD network | Area covered | Entity authorized by PNGRB/Govt. |
|---|---|---|
| Mumbai CGD Network | Mumbai and Greater Mumbai | Mahanagar Gas Limited (MGL) |
| Vijayawada CGD | Vijayawada GA | Bhagyanagar Gas Limited (BGL) |
| Mumbai CGD Network (GA2) | Thane City and adjoining contiguous areas including Mira Bhayender, Navi Mumbai, Thane City, Ambernath, Bhiwandi, Kalyan, Dombivily, Badlapur, Ulhasnagar, Panvel, Kharghar and Taloja. | Mahangar Gas Limited (MGL) |
| Rajkot, Navsari, Nadiad, Surendranagar | Rajkot GA, Surendra Nagar GA, NAVsari GA, Nadiad GA | GSPC Gas Ltd. |
| Ahmedabad, Faridabad, Khurja | Ahmdebad GA, Faridabad, and Khurja Geographical Area | Adani Gas Limited (AGL) |
| Chandigarh, Allahabad | Ahmdebad GA, Allahabad | JV of IOCL and AGL |
| Jalandhar CGD Network | Jalandhar | M/s Jay Madhok Energy Pvt. Ltd. |
| Gwalior CGD Network | Gwalior | Aavantika Gas Limited |
| Surat-Bharuch-Ankleshwar | Surat-Bharuch-Ankleshwar Geographical Area | Gujarat Gas Company Limited |

*Source* Compiled from the Website of PNGRB

and length of the pipeline network is estimated to reach 32,727 km in length from 12,144 km in 2012. The gas grid capacity in India (pipeline emanating from the source) is expected to reach 517 MMSCMD in 2021–2022 from the present 243 MMSCMD (PNGRB 2013). Currently the supply or receiving points of natural are predominantly in the south/west India. Consumption centres are developed in the west and gradually shifting towards north and central India. For a longer period of time, the eastern India remained gas starved due to lack of production and distribution network (Map 2). A fully developed and functional national gas grid will ensure fair and equitable access to natural gas across the country. So, by 2030 the eastern India is likely to play an important role in terms of LNG regasification facilities, gas transmission, and consumption.




**Map 2** Gas pipeline network in India. *Source* GAIL

## 6 Natural Gas Demand and Supply

Currently about 42 % of the natural gas demand comes from the western Indian states such as Gujarat and Maharashtra. The west and north region will remain as major demand drivers of natural gas even in 2029–2030 (Table 12). This is due to better gas infrastructure leading to greater accessibility of natural gas attracting more end users.

In India, natural gas has been a preferred fuel for many end users ranging from power sector to domestic consumers. End users across various segments use natural gas as a fuel or feedstock (Table 13). Domestic, commercial, transport, and

**Table 12** Gas demand and supply (MMSCMD) in India

| Zone | States | 2012–2013 | 2016–2017 | 2021–2022 | 2026–2027 | 2029–2030 |
|---|---|---|---|---|---|---|
| North | Uttar Pradesh, Uttaranchal, J&K, Haryana, Punjab, Delhi, Himachal Pradesh, Rajasthan | 62.98 | 88.4 | 144.66 | 188.74 | 215.11 |
| East | West Bengal, Bihar, Jharkhand, Orissa | 10.35 | 21.66 | 31.03 | 53.24 | 60.68 |
| West | Maharashtra, Gujarat, Goa | 102.8 | 165.13 | 191.78 | 207.5 | 236.5 |
| North East | Assam, Arunachal Pradesh, Manipur, Meghalaya, Nagaland, Tripura, Mizoram, Sikkim | 5.13 | 5.29 | 10.47 | 20.67 | 23.56 |
| South | Tamil Nadu, Kerala, Karnataka, Andhra Pradesh | 48.2 | 81.28 | 116.71 | 151.89 | 173.11 |
| Central | Madhya Pradesh, Chattisgarh | 13.21 | 16.29 | 22.33 | 32.52 | 37.07 |
| | Total demand | 242.67 | 378.05 | 516.98 | 654.56 | 746.03 |
| | Domestic supply | 101 | 156.7 | 182 | 211 | 230 |
| | Deficit | 141.67 | 221.35 | 334.98 | 443.56 | 516.03 |

*Source* PNGRB (2013)

**Table 13** End users of natural gas

| End user | Carbon molecule | Purpose | Substitute |
|---|---|---|---|
| Power | C1 | Used as a fuel in thermal power generation | Coal |
| Cement | C1 | Used as a fuel in gas fired boilers | Coal, LPG, Naphtha Furnace Oil and high-speed diesel (HSD) |
| Ceramic | C1 | Industrial fuel for spray dryers and is used for combustion in a kiln. | Diesel, Coal, Furnace Oil, Naphtha, C-nine and LPG, etc. |
| City gas | C1 | Used as a fuel for heating, cooking and cooling (domestic and commercial use) | LPG and electricity |
| Transport sector | C1 | Used in the form of CNG as a transportation fuel | Diesel, Petrol, and Auto LPG |

(continued)

**Table 13** (continued)

| End user | Carbon molecule | Purpose | Substitute |
|---|---|---|---|
| Fertilizers | C1 | Natural gas is the principal feedstock for the manufacturing of ammonia, an intermediate product primarily used in the manufacture of nitrogenous fertilizers such as urea, nitric acid, ammonium nitrate, and ammonium sulphate. | Naphtha and Fuel Oil |
| Petrochemicals | C2/C3 | Specific fractions in feedstock are used for manufacture of ethylene and propylene | Naphtha and Propane Gas |
| LPG | C3/C4 | Specific fractions are extracted to produce LPG | Crude Oil |
| Methanol | C1 | Feedstock | Naphtha and biomass |

*Source* Kar and Sahu (2012)

some of the industries such as power, cement, and ceramic use natural gas as a fuel. Other industries such as fertilizer, chemical, and petrochemical use natural gas as feedstock/raw material to produce derived products.

## *6.1 Gas Allocation Policy*

Domestic natural gas is considered green, clean, and premium source of fuel and feedstock, and with limited availability requires judicious and fair allocation to various demanding sectors. Considering the importance of fair allocation of domestic natural gas the government of India through Ministry of Petroleum and Natural Gas formulated “Natural gas use policy” in 1990 [Standing Committee on Petroleum & Natural Gas (SCPNG), 2013–2014]. Keeping in mind the potential demand of natural gas from various sectors, such as fertilizer, power, sponge Iron, LPG, industrial use, petrochemicals, an optimal allocation policy was desirable. In order to rationalize the allocation of natural gas from nominated blocks without any discrimination to any sector or region, the Government of India constituted the Gas Linkage Committee (GLC) of Secretaries in July 1991. The committee was well represented by the important stakeholders such as power, fertilizer, steel, chemical and petrochemicals and Planning Commission, Department of Economic Affairs, Department of Expenditure (Ministry of Finance), and three national oil and gas companies, namely GAIL, ONGC, and Oil India Limited. After giving due consideration to the demand, availability, and imputed economic value of natural gas in various sectors, GLC decided to allocate natural gas to various sectors on "firm basis" and "fall back basis". The concept of "fall back allocations" has been made to optimally use the temporary surplus gas in the system. As there was no further APM gas available for allocation to new consumers, GLC dismantled on 9 November 2005.

On 28 October 2010, Government of India formulated a policy on pricing and commercial utilization of non-APM gas produced by NOCs. As per the guidelines of the allocation of non-APM gas, the allocation should be done on the following priority basis:

(a) Gas-based fertilizer plants
(b) LPG plants
(c) Power plants supplying to the grid
(d) CGD systems for domestic and transport sectors
(e) Steel, refineries, and petrochemical plants for feedstock purposes,
(f) CGD systems for industrial and commercial customers, and
(g) Any other customers for captive and merchant power, feedstock or fuel purposes.

The gas producing companies are directed to follow the sector priority as indicated above and preference in allocation to be given to APM shortfall before meeting new demand. Within a sector, priority is accorded to the region where gas is produced.

Until 2012, the government did not develop any gas allocation policy for domestic gas produced from small/isolated fields. However, on 16 January 2012 the government came out with pricing and allocation policy for small/isolated fields similar to the policy developed on 28 October 2010.

The NOCs were given freedom to allocate gas from small discoveries whose peak production was less than 0.1 MMSCMD. Concerns were raised by various stakeholders about applying pricing and allocation policy of large and mainstream fields to small/isolated fields. Critical pricing and allocation issues related to small/isolated fields were actively deliberated, and the policies were revised. As per the revised policy guidelines notified on 8 July 2013, the sector priority has been lifted and the new customers to be treated on parity with existing customers for allocation of gas (Standing Committee on Petroleum & Natural Gas 2013–2014, p. 7). In case of additional availability of gas after providing for gas supplies to the existing customers, the additional gas has to be allocated through open competitive bidding process and the highest price bidder to be awarded.

Pre-NELP blocks are essentially the blocks which were awarded to national oil companies (NOCs) on nomination basis, but in some blocks the NOCs did not go beyond the discovery stage or did not reach commercial production stage due to financial or technology constraints. Such blocks or fields were auctioned to private companies for efficient and effective utilization of national resources. However, the government kept the provision of appointing a nominee for purchasing the gas from the producers and marketing it. For instance, GAIL has been appointed as the government nominee in PMT fields and Ravva fields for marketing under the directions of the government. The producers, in the rest of pre-NELP blocks, sell the gas as per the terms of production sharing contracts (PSCs) signed between the government and the operators.

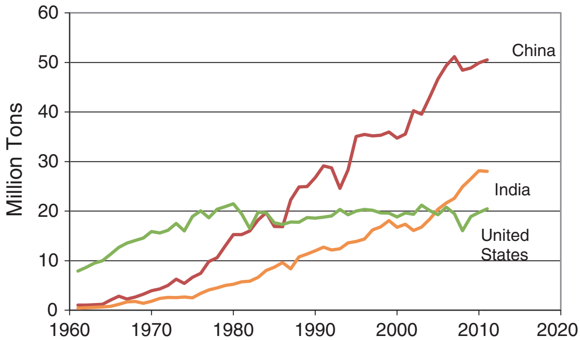
During the pre-NELP period, exploration and production policies were believed to be less transparent and heavily loaded in favour of national oil companies. In order to establish competitive parity, openness, and transparency under NELP, the Government auctioned blocks to private investors/NOCs/consortia. To ensure a level playing field, the government extended the same fiscal and contract terms to the investors under the NELP. Under the NELP contracts, certain amount of freedom has been allowed to the contractor to market gas within the framework of policy on the utilization of natural gas.

The government had constituted an Empowered Group of Ministers (EGoM) to take decisions on utilization of gas produced under NELP blocks (including KG-D6). The EGoM constituted for pricing, and commercial utilization of gas under the NELP has laid down following sector priority for allocation of gas from KG-D6 block (PIB 2014):

(i) Gas-based urea plants,
(ii) Gas-based LPG plants,
(iii) Gas-based power plants for supply of electricity to state distribution companies at regulated tariff for the period of power purchase agreement (PPA),
(iv) CGD entities for supplying to domestic and transport sectors, and
(v) Other sectors such as steel plants (only for feedstock and not for the captive power requirement), petrochemical plants (only for feedstock and not for the captive power requirement), refineries, CGD entities for supply to commercial and industrial sector customers consuming up to 50,000 SCMD (standard cubic meters per day), captive power plants

### 6.1.1 Fertilizer

India is the second largest consumer of fertilizers in the world, only after China (Graph 1). According to the Department of Fertilizers, India is almost completely dependent on import of supply of phosphatic and potassic fertilizers due




**Graph 1** Fertilizer consumption in China, India, and the USA, 1961–2011. *Source* http://www.earth-policy.org/data_highlights/2014/highlights43

to non-availability of resources within the country. Nitrogen is the only nutrient where the country can achieve near self-sufficiency. Out of our total requirement of about 30 MMTPA of urea, about 8 MMTPA (27 %) urea is imported. For cost-effective domestic urea production (22–23 MMTPA), natural gas remains to be the best possible source of feedstock. About 14 MMTPA of domestic urea is from domestic natural gas and the rest (8–9 MMTPA) is being produced from imported LNG/naphtha. There is no second thought to explain fertilizer industry plays a vital role in the development of the Indian agricultural sector and overall economy of the country. So the fertilizer sectors obviously and justifiably figure at the of gas allocation policy.

The fertilizer sector is the second largest demand driver of natural gas in India. Natural gas demand in this sector is projected to reach 106 MMSCMD by 2016–2017 from 55 MMSCMD in 2012–2013.

This sector is not only the second largest demand driver from a volume point of view, but also one of the most important sectors from socioeconomic progress view point. Also, fertilizer subsidy is another concern for the government. For example, the central government spent 74,569.85 crores ($12.428 billion[4]) as fertilizer subsidy in 2011–2012 and 70,592 crores ($11.765 billion) in 2012–2013 (DoF 2014). Considering the above fact the use of natural gas seems to be one of the key solutions to increase nitrogen self-sufficiency and reduce subsidy burden on the exchequer. Therefore, the government of India has been historically careful while allocating domestic gas to this sector. India is an agrarian economy, and Indian farmers are hugely dependant on fertilizers for higher agricultural productivity.

### 6.1.2 Domestic LPG (Used for Cooking)

In India, domestic LPG is considered to be a sensitive product and subsidized for the larger benefit of social strata under financial stress and hardship. The country is highly import dependant for meeting domestic LPG demand. Any disruption in supplies of LPG could lead to social disturbance and public outcry. In order to enhance public life and reduce import dependency the government promotes use of domestic natural gas for manufacturing LPG to meet domestic LPG demand. Further, the EGoM has also decided that higher fractions such as propane, butane and pentane should be extracted first and only the lean gas should thereafter be supplied to other sectors. Hence, high priority for the LPG sector sounds to be rational.

### 6.1.3 Power Sector

Currently gas-based power plants with a capacity of 21.3 GW (Table 14) constitute 9 % of total installed capacity of 237.7 GW. To achieve high economic growth, providing 24 × 7 electricity to all and seamless rural life could be viable

[4]Exchange rate of USD = INR 60 has been used.

**Table 14** All India installed electricity generation capacity (MW) as of 28 February 2014

| | Thermal | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Coal | Gas | Diesel | Thermal total | Nuclear | Hydro | RES | Grand total | Share (%) of gas |
| Northern | 35,283.5 | 5281.26 | 12.99 | 40,577.75 | 1620 | 15,994.75 | 5729.62 | 63,922.12 | 8.3 |
| Western | 54,069.51 | 9739.31 | 17.48 | 63,826.3 | 1840 | 7447.5 | 9925.19 | 83,038.99 | 11.7 |
| Southern | 26,582.5 | 4962.78 | 939.32 | 32,484.6 | 1320 | 11,398.03 | 13,127.33 | 58,329.96 | 8.5 |
| Eastern | 24,727.88 | 190 | 17.2 | 24,935.08 | 0 | 4113.12 | 417.41 | 29,465.61 | 0.6 |
| North–east | 60 | 1208 | 142.74 | 1410.74 | 0 | 1242 | 252.65 | 2905.39 | 41.6 |
| Islands | 0 | 0 | 70.02 | 70.02 | 0 | 0 | 10.35 | 80.37 | 0.0 |
| All India | 140,723.4 | 21,381.35 | 1199.75 | 163,304.5 | 4780 | 40,195.4 | 29,462.55 | 237,742.44 | 9.0 |
| Share (%) | 59.2 | 9.0 | 0.5 | 68.7 | 2.0 | 16.9 | 12.4 | 100.0 | |

*Source* GoI, CEA 2014

by additional production of power (electricity). Gas-based combined cycle power plants considered to be an efficient and greener option. Keeping in mind socio-economic prosperity, the gas allocation to power sector has been given the third top most priority. Apart from that, the power sector, especially coal-based power plants, found to be one of the biggest contributors to environmental pollution in India. Chen et al. (2011) suggest that "local" pollutant concentrations are exceedingly high in many developing countries and they impose substantial health costs, including shortened lives. A study conducted by Cesur et al. (2013) found evidence that air pollution severely impacts infant mortality and several illness and premature death (Greenpeace India 2014). The study estimates the monetary cost associated with these health impacts exceeds Rs. 16,000 to Rs. 23,000 crores (USD $3.3–4.6 billion) per year.

### 6.1.4 City Gas Distribution

CGD sector in India has been growing, and major important cities have been covered under CGD network. It is observed that the growth has been slower than the expected lines. The primary reason could be due to lack of domestic gas supply (Table 15), expensive imported gas, cancellation/delay in the bidding process, and policy bottlenecks. The most important objective of building CGD network is to

**Table 15** Domestic gas allocation for CGD network in India

| Entities and areas of operation | APM allocation | | | PMT allocation | RIL KG D6 allocation | | | Grand total allocation |
|---|---|---|---|---|---|---|---|---|
| | Firm | Fallback | Total | | Firm | Fallback | Total | |
| IGL, Delhi + Gautam Buddha Nagar + Faridabad and Gurgaon | 2.7 | 0 | 2.7 | | 0.31 | 0.3 | 0.61 | 3.31 |
| MGL, Thane-Navi Mumbai City Gas | 2 | | 2 | | 0.37 | | 0.37 | 2.37 |
| Bhagyanagar Gas Limited | 0.1 | | 0.1 | | 0.15 | 0.37 | 0.52 | 0.62 |
| TNGCL, Tripura | 0.13 | | 0.13 | | | | 0 | 0.13 |
| Green Gas Limited, Lucknow | 0.1 | 0 | 0.1 | | 0 | | 0 | 0.1 |
| Green Gas Limited, Agra | 0.04 | 0 | 0.04 | | 0.02 | 0.01 | 0.03 | 0.07 |
| Central UP Gas Limited, Kanpur | 0.1 | | 0.1 | | | 0.1 | 0.1 | 0.2 |
| CUGL, Bareilly | 0.05 | | 0.05 | | | 0.01 | 0.01 | 0.06 |
| MNGL, Pune City Gas | 0.4 | | 0.4 | | | 0.2 | 0.2 | 0.6 |
| AGCL | 0.01 | | 0.01 | | | | 0 | 0.01 |
| Gujarat Gas Company | 0.29 | 0.17 | 0.46 | 2.13 | | 0.6 | 0.6 | 3.19 |

(continued)

**Table 15** (continued)

| Entities and areas of operation | APM allocation | | | PMT allocation | RIL KG D6 allocation | | | Grand total allocation |
|---|---|---|---|---|---|---|---|---|
| | Firm | Fallback | Total | | Firm | Fallback | Total | |
| Vadodara Municipal Corporation | | 0.1 | 0.1 | | | | 0 | 0.1 |
| GAIL GAS | | | 0 | | 0.02 | | 0.02 | 0.02 |
| GAIL Agra Firozabad | | | | | | 0.3 | 0.3 | 0.3 |
| GAIL Vadodara | | | | | | 0.13 | 0.13 | 0.13 |
| Sabarmati Gas | | | | | 0.08 | 0.15 | 0.23 | 0.23 |
| HPCL | | | | | 0.05 | | 0.05 | 0.05 |
| Aavantika Gas | | | | | 0.01 | | 0.01 | 0.01 |
| Soumya DSM | | | | | 0.02 | | 0.02 | 0.02 |
| Adani Energy Ltd. | | | | | 0.2 | | 0.2 | 0.2 |
| Total | 5.92 | 0.27 | 6.19 | 2.13 | 1.22 | 2.17 | 3.39 | 11.71 |

*Source* Infraline energy

increase natural gas penetration and enhance accessibility of natural gas for the end users. Greater use of natural gas could reduce environmental pollution and improve quality of life. A recent study conducted by Cesur et al. (2013) indicates that the expansion of natural gas infrastructure has caused a significant decrease in the rate of infant mortality in Turkey. In particular, a one-percentage point increase in the rate of subscriptions to natural gas services would cause the infant mortality rate to decline by 4 %.

Important consuming segments under CGD are industrial, transport, commercial, domestic, and others. Use of natural gas in these segments could replace existing polluting fuels and help green growth in India.

### Industrial Customers

Natural gas has different industrial uses, including providing the base ingredients for wide varieties of products such as plastic, fertilizer, anti-freeze, chemicals, and fabrics. Also, industrial customers in ceramic, steel, and food processing, etc., use natural gas as a fuel for heating and cooling. Industrial segment is the largest consumer of natural gas under the CGD category. In states such as Gujarat, Maharashtra, and Andhra Pradesh, natural gas available for the industrial sector is helping industrial growth. For example, easy access to natural gas has been helpful in setting new industrial units in Morbi, Himmatnagar, Mehesana, Rajkot, and Vapi (Kar and Sahu 2012; Kar et al. Forthcoming). Their research findings suggest that industrial units in Gujarat are very happy to receive continuous and constant supplies of natural gas at the desired pressure. Natural gas found to be economical, safe, reliable, and eco-friendly, so many of the existing and new industrial units prefer natural gas as a fuel. On the other hand, the industrial segment is found to be the cash cows for the gas marketing entities. So natural gas offers win–win–win situation for customers–entities–environment. Gujarat is the leading state having well-developed natural gas infrastructure support leading to higher penetration and share of industrial connections (Table 16). The state has the highest share of about 69 % of industrial customers.

### Domestic Customers

While supplying natural gas, the domestic customers using natural gas for cooking should be treated with top most priority. The regulatory body very much acknowledges the emergency need and builds necessary measures to ensure a fair deal for the domestic customers. Any entity bidding for natural gas supply in a city needs to ensure supply of natural gas to a minimum number of domestic consumers. Regulatory body considers the domestic supply as mandatory, and the entities consider this as obligatory. Some entities operating in semi-urban and rural, or less developed markets consider serving domestic consumers as social service as the cost of serving the domestic customers is much higher than any other segment and margin from domestic customers is comparatively low. An average household consumes about 0.5 SCM/day of natural gas. Currently, in terms of volume this segment is not the most attractive segment for the gas marketing companies.

### Road Transport

The country transports nearly 57 % of the total goods by road, as compared to 22 % in China and 37 % in the USA (Planning Commission 2012, p. 196). The transport sector is one of the largest consumers of liquid hydrocarbon in India, a major contributor to greenhouse gases (GHGs), especially in the bigger cities due to the greater density of the vehicle population. To reduce GHGs emissions, the conversion of diesel and petrol-driven vehicles to compressed natural gas (CNG) fuel powered has been initiated. CNG drive was enforced through Supreme Court intervention in Delhi. As of 31 March 2013, close to 1.9 million vehicles were running on CNG and Delhi/NCR contributed the maximum number followed by Gujarat (Table 17). In terms of number of CNG stations Gujarat leads the way with above 300 CNG stations followed by Delhi/NCR, and Maharashtra. Bigger states such as Uttar Pradesh, Madhya Pradesh, Tamil Nadu, and Rajasthan are lagging behind and need to build better CNG infrastructure.

### Commercial

The commercial segment is one of the most important segments for the gas marketing companies. The commercial segment is not well developed in India as the use of natural gas has been limited to cooking and to some extent for cooling. Extensive use of natural gas for cooling and heating will have greater impact

**Table 16** PNG connection status in India (as of 31 March 2013)

| State | City covered | Company | Number of domestic PNG connections | Domestic PNG share (%) | Number of Comm. PNG connections | Comm. PNG share (%) | Number of Ind. PNG connections | Ind. PNG share (%) |
|---|---|---|---|---|---|---|---|---|
| Delhi | Delhi, NOIDA, Greater NOIDA, Ghaziabad | IGL | 410,000 | 18.14 | 1370 | 8.0 | 570 | 10.6 |
| Maharashtra | Mumbai, Thane, Mira-Bhayandar, Navi Mumbai, Pune, Kalyan, Ambernath, Panvel, Bhiwandi | MGL, MNGL | 647,790 | 28.67 | 1990 | 11.6 | 98 | 1.8 |
| Gujarat | Ahmedabad, Baroda, Surat, Ankeleswar | GSPC, Sabarmati Gas, Gujarat Gas, HPCL, VMSS, Adani Gas | 1,144,424 | 50.65 | 12,693 | 73.9 | 3686 | 68.5 |
| Uttar Pradesh | Agra, Kanpur, Bareilly, Lucknow | Green Gas Ltd. (Lucknow), CUGL(Kanpur) | 7090 | 0.31 | 55 | 0.3 | 430 | 8.0 |
| Tripura | Agartala | TNGCL | 11,431 | 0.51 | 256 | 1.5 | 41 | 0.8 |
| Madhya Pradesh | Dewas, Indore, Ujjain, Gwalior | GAIL Gas, AGL | 1775 | 0.08 | 6 | 0.0 | 49 | 0.9 |
| Rajasthan | Kota | GAIL Gas | 177 | 0.01 | 0 | 0.0 | 16 | 0.3 |
| Assam | Tinsukia, Dibrugarh, Sibsagar, Jorhat | Assam Gas Co. Ltd. | 23,632 | 1.05 | 759 | 4.4 | 366 | 6.8 |
| Andhra Pradesh | Kakinada, Hyderabad, Vijaywada, Rajmundry | BGL | 1802 | 0.08 | 15 | 0.1 | 1 | 0.0 |
| Haryana | Sonepat, Gurgaon, Faridabad | GAIL Gas, Adani Gas, Haryana City Gas | 11,508 | 0.51 | 43 | 0.3 | 123 | 2.3 |
| Total | | | 2,259,629 | 100 | 17,187 | 100 | 5380 | 100 |

*Source* Kar et al. (2015)

**Table 17** Status of CNG stations and vehicles (as of 31 March 2013)

| State | Entity | Number of CNG stations | Share (%) | Number of CNG vehicles | Share (%) |
|---|---|---|---|---|---|
| Gujarat | GAIL Gas/Adani Energy/Gujarat Gas, GSPC, GGCL, SGL, HPCL | 313 | 34.51 | 638,422 | 34.08 |
| Delhi/NOIDA, Gr. NOIDA/Ghaziabad | Indraprastha Gas (IGL) New Delhi | 290 | 31.97 | 720,000 | 38.43 |
| Maharashtra | Mahanagar Gas Ltd. (MGL) Mumbai, MNGL Pune | 203 | 22.38 | 334,810 | 17.87 |
| Andhra Pradesh | Bhagya Nagar Gas Ltd. (BGL) Hyderabad. | 29 | 3.20 | 19,958 | 1.07 |
| Rajasthan | GAIL Gas | 2 | 0.22 | 1085 | 0.06 |
| UP | Green Gas Ltd. (Lucknow), CUGL (Kanpur) | 30 | 3.31 | 56,857 | 3.03 |
| Tripura | Tripura Natural Gas Co. Ltd. (TNGCL) Agartala | 3 | 0.33 | 4682 | 0.25 |
| MP | Avantika Gas (Indore)/GAIL Gas Ltd. | 16 | 1.76 | 10,878 | 0.58 |
| Haryana | Haryana City Gas Ltd. | 14 | 1.54 | 85,560 | 4.57 |
| West Bengal | GEECL | 7 | 0.77 | 1201 | 0.06 |
| All India | | 907 | 100.00 | 1,873,453 | 100.00 |

*Source* Kar et al. (2015)

on the green environment in India. In the USA, natural gas currently accounts for 13 % of energy used in commercial cooling and this percentage is expected to increase due to technological innovations in commercial natural gas cooling techniques.

In India, use of natural beyond cooking should be pushed through. As per the existing economics of alternative fuels and availability of affordable electricity, viability of natural gas for wider use seems to be a distant dream. One of the ways to increase penetration of natural gas in the commercial sector is to promote tri-generation technologies to generate electricity, heating, or cooling.

Most promising areas of tri-generation application include hospitals, hotels, departmental stores, mall, data centres, industries, and large residential complexes. According to Trigen India Portal, it is estimated that there are several thousands of potential sites in India, where tri-generation could be applied economically within a range of 200 kWel to several MWel per installed system. Tri-generation technology working well in Jai Prakash Narayan Apex Trauma Center (JPNATC), AIIMS, New Delhi, and can be presented as a model case to promote the technology. Tri-generation technology offers benefits such as energy savings, economic savings, environmental savings, and increased reliability and interdependence from traditional forms of electricity supply.

Others

Research has been started in the USA to run locomotives on natural gas. Recently, CSX Corporation and GE transportation announced that natural gas-fuelled locomotives can travel longer distances without refuelling stops, as well as provide environmental and economic benefits. Adoption of natural gas-fuelled locomotives could make freight rail as a more attractive transportation solution (LNG Global 2013). Possibly an extensive Indian rail network could reduce load on the nation's highways in an environmentally efficient way.

Inland water transport seems to be another potential area where the use of natural gas/LNG/CNG could be very productive. According to the Planning Commission (2012, p. 231), the total external costs of inland navigation after accounting for all externalities, including accidents, congestion, noise emissions, air pollution and other environmental impacts are seven times lower than that of road transport. To reduce GHGs emissions, Indian coastal vessels could be converted to CNG/LNG fuel powered.

LNG-driven tugboats offer greater efficiency and less pollution could be better for external environment and even for the boat operators. The LNG tugboat is designed for the green future, so some of the countries in Europe and even Asian countries like China are developing LNG tugboat for preserving aquatic environment.So, LNG-driven tugboats may be tried in India.

## 7 Discussions

The position of India in Energy Sustainability Index Ranking (Table 18) is very uncomfortable and embarrassing one. Considering renewable resource richness, India should improve its score in the areas of energy security, energy equity, and environmental sustainability. The economic prosperity of the country is highly dependent on energy availability, and green development requires green energy. Natural gas along with other green forms of energy such as solar, wind, and biomass expected to play a crucial role. The areas where natural gas could contribute significantly are transport sector, cooling and heating, electricity generation, fertilizer production, green supply chain, petrochemical production, LPG production, and green production in industries such as chemical, steel, pharmaceutical, and ceramic. Various consuming industries such as fertilizer, chemical, and

**Table 18** India's energy sustainability index ranking

| | 2011 | 2012 | 2013 | Ranking |
|---|---|---|---|---|
| **Energy performance** | 124 | 124 | 124 | |
| Energy security | 87 | 86 | 76 | C |
| Energy equity | 110 | 110 | 110 | D |
| Environment sustainability | 123 | 123 | 121 | D |
| **Contextual performance** | 67 | 77 | 76 | |
| Political strength | 90 | 97 | 93 | |
| Societal strength | 76 | 80 | 80 | |
| Economic strength | 44 | 54 | 54 | |
| **Overall rank and balance score** | 115 | 117 | 115 | CDD |

*Source* World Energy Council (2013, p. 59)

pharmaceutical can produce derivatives from natural gas and contribute towards green developments in India. Similarly, the transport sector may gradually switch to green fuel such as natural gas to reduce impact on the environment.

The enabling factor for faster adoption of natural gas could be availability of gas, development of suitable cross-country gas pipeline with better spread for equitable distribution, and investor friendly policy for infrastructure development. Currently the western and northern states have the combined coverage of 60 % of total pipeline network in India. The eastern states such as Bihar, Jharkhand, Odisha, and West Bengal have almost no operational cross-country gas pipeline network. Therefore, gas distribution and consumption found to highly skewed. By 2030, all states in India will be connected through National Gas Grid and will have access to domestic or imported natural gas.

## 8 Conclusion

It is very clear that for green economy, clean energy would play the most important role. United Nations Millennium Development Goal and Climate Change initiatives are the prime drivers of clean energy policies across the globe. But due to financial and other constraints, many of the governments are not able to meet their own target. Therefore, public stakeholders encourage the private sector to come forward to participate in the cleaner and greener environment building measures. For green development, green manufacturing and production, transport, green supply chain, and green consumption need to be given priority.

Natural gas is considered as one of the important green fuels for driving green growth in India. By 2030, India will have a fully functional National Gas Grid and provide a green fuel option to industry, transport sector, residential and commercial buildings, and other consuming industries or individual consumers. Shale gas access to Indian companies at competitive price could prove as a game changer for green developments in India. Shale gas has already changed the global gas pricing dynamics and likely to push LNG price further down. This essentially means more LNG flowing to India leading to greater LNG infrastructure development in the country. Such developments could improve gas supply and availability in coastal states such as Tamil Nadu, Kerala, Andhra Pradesh, Odisha, and West Bengal. New gas corridor will be developed in some of these gas-starved states and driving green manufacturing, distribution, transport, and consumption.

Also, transmission of natural gas from Turkmenistan through TAPI is going to be a landmark achievement. This would enhance much needed supply security and enrich the gas sourcing mix of India. Availability of ready to feed in and use of dry gas could bring green growth revolution in India, especially in north Indian states such as Punjab, Haryana, Delhi, Uttar Pradesh, and Rajasthan.

Evolution of natural gas market in India is going to drive socio-economic transformation, green growth, and environmental preservation through reduction in GHGs, eradication of energy poverty, and reduction in death arising out of pollution.

## Annexure

**Table 19** Key task of PNGRB

| | Tasks | Details |
|---|---|---|
| 1 | To protect consumer interest by fostering fair trade and competition amongst entities by creating an environment for level playing field in downstream oil and the gas sector by: | Addressing issues of continuing anomalies in pricing and subsidies which affects the competitive positions of downstream sector |
| | | Addressing access to infrastructure on principles of contract carriage or common carrier to be applied on non-discriminatory principles. These principles include specifying pipeline access code. The PNGRB's task is to evolve an access code for non-discriminatory third party access to common infrastructure after meeting own genuine requirements |
| | | Facilitating creation of a trading platform for crude oil, petroleum products, natural gas and pipeline capacities |
| | | Ensuring competitive environment and transparent bidding process with selection criteria that incentivizes infrastructure (pipeline) investment |
| | | Ensure that the ownership of infrastructure by any CGD or any company does not become a barrier to competition and disincentivize creation of vertically integrated monopolies |
| 2 | Register entities so as to elicit serious participation from industry in all segments of downstream energy value chain on such terms which are fair, encourage competition and create adequate and efficient infrastructure. PNGRB registers entities to: | Market petroleum products and establish storage facilities. The storage facilities can be for storage of any petroleum product or for natural gas storage. Also, PNGRB ensures adequate availability, display of prices, equitable distribution of petroleum products along with enforcement of retail service obligations and continuous monitoring of transportation rates |
| | | Establish and operate Liquefied Natural Gas (LNG) terminals in order to receive LNG from ships and regasify the LNG to natural gas for further transmission through the pipeline |
| 3 | Authorize entities to: | Lay, build, and operate or expand a common carrier or contract carriage for optimal and efficient use of resources such as pipeline network |
| | | Lay, build, and operate or expand city gas distribution network for better utilization of pipeline networks and avoidance of duplicity of infrastructure |
| 4 | Regulate by regulations | Transportation rates for common carrier or contract carriage |
| | | Access to city gas distribution network would allow operators to optimally use the existing infrastructure and reduce additional investment leading higher return on investment |
| | | Tariffs to be reasonable and allowable. Also, tariffs have to eventually move from a "fixation regime" to a "traded regime". Fixation regime means that the tariff rates are fixed by the entity on a bidding basis and is fixed for any entity using that pipeline or CGD infrastructure. Traded regime includes the system followed in developed economies where the tariff for the pipelines is charged on an entry–exit model based on the total number of in and out pipelines located in a region |

*Source* Partially Adapted from Kar et al. (Forthcoming)

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# Scope for Small Hydro Projects in India

**A.K. Chaturvedi**

**Abstract** Energy is essential for the sustenance of life. Also **energy and the economic growth of a nation are interlinked**. Energy security of a country entails optimum utilization of indigenous and those sources of energy to which a nation can have access. Hydropower is an important and an economically competitive source of electricity. In India, hydro **projects up to 25 MW capacities have been categorized as small hydro power projects (SHPs)** and the Ministry of Non-Conventional Energy (MNRE) is responsible for their construction. The **technology for the SHP is fully indigenized**. SHPs though economical and less environmentally degrading, suffer from cascading due to a number of plants in tandem, may result into poorer quality of water and may have hydrology impacted at the sub-basin level. **India has a potential of about 20,000 MW through SHP,** and as such, it has been declared as one of the thrust areas. The Ministry is encouraging the development of small hydro projects both in the public and in private sector. There are about 25 equipment manufacturers of SHP turbine in the country with estimated capacity of about 400 MW per year.

**Keywords** Energy · Economic growth · Small hydro

## 1 Introduction

**Importance of Energy in the Growth of Nation**—Energy is essential for the sustenance of life and affects people in more than one ways. Also energy and the economic growth of a nation are highly interlinked. Growth or lack of it, in one

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case, affects the other directly. In fact, keeping in view its importance for the growth of a country, it is considered to be an important element in the evaluation of the comprehensive national power of that country, as it affects the growth of people on human development index (HDI) and exploitation of resources and economic development. Therefore, energy security of a country as defined by World Energy Assessment Report [United Nations Development Programme (UNDP)—1999] is, "**The continuous availability of energy in varied forms in sufficient quantities at reasonable prices.**"[1] In simple terms, it can be summed up as **the capacity of a nation to provide access to sustained and cost-effective supply of energy to its citizens**. In the case of India, it is further qualified and has been stated by the government of India (GOI) (Integrated Energy Policy—2006),[2] "**We are energy secure when we can supply lifeline energy to all our citizens irrespective of their ability to pay for it as well as meet their effective demand for safe and convenient energy to satisfy their various needs at competitive prices, at all times and with a prescribed confidence level considering shocks and disruptions that can be reasonably expected**". Thus, it is the commitment of the GOI that **the minimum essential energy will be supplied to its citizen irrespective of their capacity to pay for it**. Implication of such an understanding of the concept of energy security is that all possible sources of energy which are indigenously available or to which a nation can have access through outright acquisition or through arrangement of diplomatic/economic engagements with resource-rich countries at all times should be exploited optimally. It also means that the nation has adequate infrastructure to have strategic reserves to withstand disruption in supply due to geopolitical developments. To further add to this capacity, the country needs to constantly work to develop technologies to exploit all available/emerging indigenous resources optimally, and also it has its capacity built up in such a way that available resources are efficiently managed. Finally, the energy basket of the nation should, at any point of time, be diversified to the extent that disruption of one source does not affect the overall supply. Needless to add, that this basket will not be permanent in nature and will continuously evolve to factor in the ever changing; supply sources, technologies to leverage them and finally the measures to reduce the demand. Which also means a mechanism for the management of resources should be in place; which is capable of forecasting future requirements, future supply sources and be capable to establish a workable relationship between the two in an integrated manner. A holistic energy management entails provisioning/excavation of resources, generation, transmission, distribution, and finally utilization. Country's geography plays an important part in ensuring sustained availability of energy and its transportation.

[1]Group Captain AK Sachdev (2013) "India's Energy Security: Role of Offshore Helicopter Operations", published in Indian Defence Review, Issue: vol 28.3, July–Sep 2013 dated 13 Dec 2013.

[2]IEC-2013 Deloitte, "Securing Tomorrow's Energy Today: Policy and Regulations Long Term Energy Security" dated Feb 2013, uploaded on www.deloitte.com/in.


**Fig. 1** Geography of India *Source*: Wikipedia, "Geography of India", (illustrated in Section: Physiographic Regions) and uploaded on en.wikipedia.org/wiki/Geography_of_India

## 2 Geographical Peculiarities of India

Geography of India[3] has a bearing on the indigenous sources of energy, and therefore, there is a need to analyze the geography of India to get a reasonable picture of the availability of energy from indigenous sources. Figure (1) gives a vivid description of the geography of India. Northern frontiers of India are defined largely by the Himalayan mountain range. The Himalayas extend from Jammu & Kashmir in the north to Arunachal Pradesh in the east. Numerous Himalayan peaks rise over 7000 m, and most peaks in the Himalayas remain snowbound throughout the year. The Karakoram Range is situated further to the northwest in the state of Jammu & Kashmir. The range is about 500 km in length and is considered as the most heavily glaciated part of the world outside the polar regions. They feed a number of rivers such as Indus, Gilgit, and Shyok in the region. The Indo-Gangetic plains, also known as the Great Plains, are large alluvial plains dominated by three main rivers, the Indus, Ganges, and Brahmaputra. They run parallel to the Himalayas, from Jammu & Kashmir in the west to Assam in the east, and drain most of northern and eastern India. The main tributaries are Yamuna, Chambal, Gomti, Ghaghara, Kosi, Sutlej, Ravi, Beas, Chenab, and Teesta, as well as the rivers of the Ganges Delta, such as River Meghna. A feature, peculiar to Punjab and now even to certain areas of Rajasthan, is that the area is crisscrossed by a network of canals. Northeast is having a number of fast-flowing rivers. The

[3]Wikipedia, "Geography of India (Illustrated in Section on Physiographic Regions), uploaded on en.wikipedia.org/wiki/geography_of_India".

Central Highlands consists of three main plateaus—the Malwa Plateau in the west, the Deccan Plateau in the south (covering most of the Indian peninsula), and the Chota Nagpur Plateau in the east. The Malwa Plateau is spread across Rajasthan, Madhya Pradesh, and Gujarat. The average elevation of the Malwa Plateau is 500 m, and the landscape generally slopes toward the north. Most of the region is drained by the Chambal River and its tributaries; the western part is drained by the upper reaches of the Mahi River. The Deccan Plateau is a large triangular plateau, bounded by the Vindhya Range to the north and flanked by the Eastern and Western Ghats. The average elevation of the plateau is 610 m above the sea level. The surface slopes gently from west to east and gives rise to several peninsular rivers such as the Godavari, the Krishna, the Cauvery, and the Mahanadi which drain into the Bay of Bengal. The eastern coastal plain is a wide stretch of land lying between the Eastern Ghats and the Bay of Bengal. It stretches from Tamil Nadu in the south to West Bengal in the east. The Mahanadi, Godavari, Cauvery, and Krishna rivers drain these plains. The western coastal plain is a narrow strip of land sandwiched between the Western Ghats and the Arabian Sea. It extends from Gujarat in the north and extends through Maharashtra, Goa, Karnataka, and Kerala. Rivers originating in the Western Ghats are generally fast flowing, usually perennial, and empty into estuaries. Major rivers flowing into the sea are the Tapti, Narmada, Mandovi, and Zuari. India has around 14,500 km of inland navigable waterways.[4] There are twelve rivers which are classified as major rivers. All of these originate from one of the following three main watersheds:

- The Himalaya and the Karakoram ranges.
- Vindhya and Satpura ranges in the central India.
- Sahyadri or Western Ghats in the western India.

## 3 Energy Resources of India

India is well endowed with energy-bearing resources like coal: 298.94 billion tons[5] (fifth largest in the world), thorium (25 % of the world),[6] and renewable energy (RE) sources worth 191,000 MW.[7] India has a modest reserve of crude oil (5.7 billion bbl) and natural gas (47 trillion cubic feet) at the beginning of 2014.[8] However, presently India is the fourth largest importer of oil and gas in the world.[9]

[4]"Introduction to Inland Water Transport", Government of India uploaded on http://iwai.gov.in/introduction.htm.

[5]EIA Country Brief up dated up to June 26, 2014.

[6]BBC News, "US approves Indian nuclear deal" dated 09 Dec 2006.

[7]Sonali Mitra, "Small Hydro: Too Small for a National Mission," published by the Observer Research Foundation, New Delhi, as an Issue Brief-34 during Nov 2011.

[8]EIA Country Brief on India updated up to June 26, 2014, and uploaded on www.eia.gov/countries/cab.cfm?fips=IN.

[9]IBID-8.

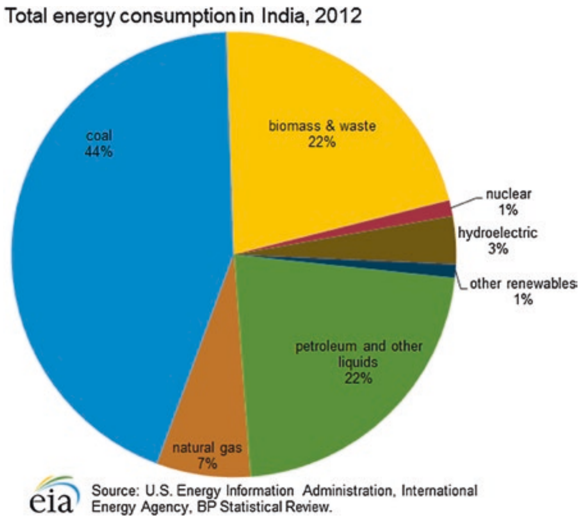


**Fig. 2** Total energy consumption in India, 2012

As far as solar energy is concerned, India is well endowed. With 200 days of yearly sunshine which amounts to a unit potential of 4 kWh per square meters, it is estimated that a total of 5000 trillion kWh of solar energy is incident on India per annum.[10] Besides being available for direct exploitation, this amount of energy gets transformed into energy-bearing resources which can be used for energy conversion.

It needs to be noted that these assessments do not take into account many other sources such as waste, geothermal, and tidal, for which cost-effective technologies have not yet been developed, and also new and emerging sources such as gas hydrates and gas shale, which are still in the research phase. In this context, aspect of the energy consumption growth in India is equally important. Primary energy consumption has doubled between 1980 and 2012,[11] and in 2011, India became the fourth largest consumer in the world.[12] However, per capita consumption in India is 1/3rd of the world average, which means that energy consumption growth in India is substantially driven by growing population. The lesson that emerges from the geography described above is that in India, besides grid-based supply, enough scope for the off-grid usage exists. The energy basket of India presently is as given in the Fig. 2, and evolving pattern of consumption of various forms of energy is given in the Fig. 3. An analysis of the two figures brings out that presently the energy basket is predominantly based on coal, biomass, and the petroleum. However, by 2030 while the consumption of coal, oil, and gas will grow

[10]Internet download: http://www.google.co.in/search?q=solar+energy+potential+in+India&tbm=isch&tbo=u&source=univ&sa=X&ei=dxvjU4KnJ4m9ugSB_oJo&sqi=2&ved=OCCUQsAQ.

[11]IBID-8.

[12]IBID-8.

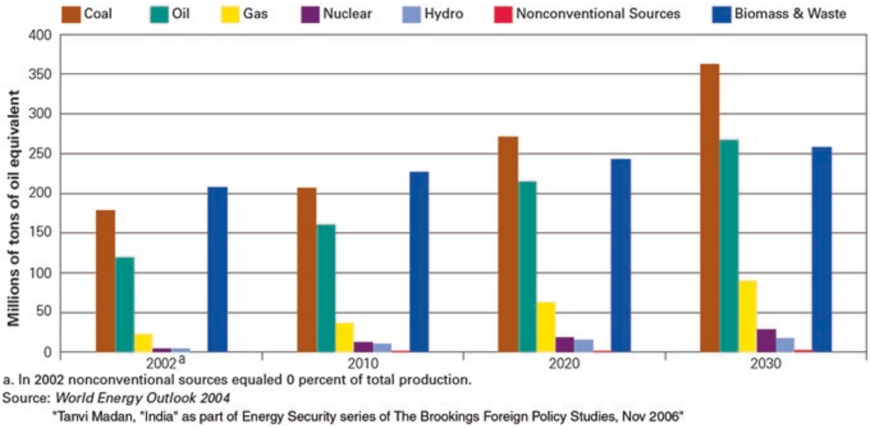


**Fig. 3** India's primary energy demand

steadily, the growth of hydro energy use will stagnate and the growth rate of the biomass would have started to retard. The question is whether India can afford to allow the use of hydropower to stagnate?

## 4 Hydro Energy

Hydropower uses the earth's water cycle to generate electricity. Water evaporates from the earth's surface, forms clouds, precipitates back to earth, and flows toward the ocean. The movement of water as it flows downstream creates kinetic energy that can be converted into electricity. The basic principle of operation of most major installations has remained the same since then. Plants depend on a large water-storage reservoir upstream of a dam where water flow can be controlled and a nearly constant water level can be assured. Water flows through conduits, called penstocks, and is controlled by valves or turbine gates to adjust the flow rate in line with the power demand. The water then enters the turbines and leaves them through the so-called tailrace. The power generators are mounted directly above the turbines on vertical shafts. The design of turbines depends on the available head of water, with so-called Francis turbines used for high heads and propeller turbines used for low heads. A total of 2700 TWH of power is generated throughout the world every year. Hydropower supplies at least 50 % of electricity production in 66 countries and at least 90 % in 24 countries.[13]

[13]"India Hydro energy" pub in EAI and uploaded on http://www.eai.in/ref/ae/hyd/hyd.html.

**Historical Perspective of Use of Hydro Energy**: The mechanical power of falling water is an age-old tool. It was used by the Greeks to turn water wheels for grinding wheat into flour and perform other tasks, more than 2000 years ago. During the "Middle Ages," large wooden waterwheels were developed with a maximum power output of about 50 HP. Modern large-scale water power owes its development to the British civil engineer John Smeaton, who first built large waterwheels out of cast iron.[14] In the mid-1770s, French engineer Bernard Forest de Bélidor published Architecture Hydraulique which described vertical and horizontal axis hydraulic machines. In the eighteenth century, Americans recognized the advantages of mechanical hydropower and used it extensively for milling and pumping. By the late nineteenth century, the electrical generator was developed and the same could be coupled with hydraulics.[15] The growing demand for power during the Industrial Revolution gave a boost to the development of technologies and the equipment to use them for power generation.[16] In 1878, the world's first hydroelectric power scheme was developed at Cragside in Northumberland, England, by William George Armstrong. It was used to power a single arc lamp in his art gallery.[17] The old Schoellkopf Power Station No. 1 near Niagara Falls in the USA side began to produce electricity in 1881. The first Edison hydroelectric power plant,[18] the Vulcan Street Plant,[19] began operating September 30, 1882, in Appleton, Wisconsin, with an output of about 12.5 kW.[20] By 1886, there were 45 hydroelectric power plants in the USA and Canada, and by 1889, there were 200 hydroelectric power plants in the USA alone.[21] Thus, by the early twentieth century, hydroelectric power accounted for more than 40 % of the United States' supply of electricity. During the fourth decade of the twentieth century, hydropower provided about 75 % of all the electricity consumed in the west and Pacific Northwest, and about one-third of the total United States' electrical energy.

At the beginning of the twentieth century, many small hydroelectric power plants were being constructed, by commercial companies in mountains and near metropolitan areas. Grenoble, France, held the International Exhibition of Hydropower and Tourism with over one million visitors. By 1920, as much as 40 % of the power produced in the United States was hydroelectric. This led to

[14]Internet upload on www.ieahydro.org/what_is_hydropower's_history.htm/, "IEA Hydro power".

[15]"History of Hydropower." U.S. Department of Energy.

[16]"Hydroelectric Power." Water Encyclopedia.

[17]"Boulder Canyon Project Act." 21 Dec 1928.

[18]From the pages of American History, "The World's First Hydroelectric Power Plant Began Operation 30 Sep 1882," uploaded on http://www.americaslibrary.gov/jb/gilded/jb_gilded_hydro_2.html.

[19]**Milestones: Vulcan Street Plant, 1882 Vulcan Street Plant, 1882, Appleton, WI Dedicated Sep 1977—IEEE Northeastern Wisconsin Section published in IEEE Global History Network and uploaded on** http://ieeeghn.org/wiki/index.php/Milestones:Vulcan_Street_Plant%2C_1882.

[20]The Evolution of the Flood Control Act of 1936, Joseph L. Arnold, United States Army Corps of Engineers, 1988.

[21]*The Book of Knowledge*. Vol. 9 (1945 ed.). p. 3220.

enactment of the Federal Power Act into law. The Act created the Federal Power Commission with the responsibility to regulate hydroelectric power plants on federal land and water. As the power plants became larger, their associated dams developed additional purposes to include flood control, irrigation, and navigation. Federal funding became necessary for large-scale development and federally owned corporations; for example, the Tennessee Valley Authority (1933) and the Bonneville Power Administration (1937) were created.[22] Additionally, the Bureau of Reclamation which had began a series of western U.S. irrigation projects in the early twentieth century was now constructing large hydroelectric projects such as the 1928 Hoover Dam.[23] The U.S. Army Corps of Engineers was also involved in hydroelectric development, completing the Bonneville Dam in 1937 and being recognized by the Flood Control Act of 1936 as the premier federal flood control agency.[24]

Hydroelectric power plants continued to become larger throughout the twentieth century. Hydropower was referred to as white coal for its potential to generate power.[25] Hoover Dam's initial 1345 MW power plant was the world's largest hydroelectric power plant in 1936; it was eclipsed by the 6809-MW Grand Coulee Dam in 1942.[26] The Itaipu Dam opened in 1984 in South America as the largest, producing 14,000 MW but was surpassed in 2008 by the Three Gorges Dam across River Yangtze by the town of Sandouping, located in Ying district, Yichang, Hubei province in China with a capacity of 22,500 MW.[27] Hydroelectricity has become popular and now meets over 85 % of the electricity demands in respect of a number of countries, including Norway, Democratic Republic of the Congo, Paraguay, and Brazil. The United States of America currently has over 2000 hydroelectric power plants that supply 6.4 % of its total electrical production output, which is 49 % of its renewable electricity.[28] The cost of hydroelectricity is relatively low, making it a competitive source of renewable electricity. The average cost of electricity from a hydro plant larger than 10 MW is 3–5 U.S. cents per kWh.[29]

**Hydro Energy Projects in India**: In India, history of water storage for subsequent use is quite old. In central India, the eleventh century Veeranam Dam once stretched for a full 10 miles. Two carved-rock slab dams from the same era created a 250-square mile lake in Madhya Pradesh. Near Bhopal, the Mudduk Maur Dam was the highest earth-filled embankment dam on earth for three centuries after its

[22]"Hoover Dam and Lake Mead." U.S. Bureau of Reclamation.

[23]IBID-22.

[24]IBID-20.

[25]IBID-21.

[26]IBID-22.

[27]"Three Gorges Project", a report by Chinese National Committee on Large Dams, retrieved on May 15, 2011.

[28]IBID-16.

[29]"Use and Capacity of Global Hydropower Increases", worked out by World Watch Institute during January 2012.

construction in 1500 AD. Outside Hyderabad, Meer Allum, built over 200 years ago, the first true multiple-arch buttress dam in history. Under the British Raj, dam building got a boost. But still power generation was not taken up on a large scale. However, after Independence, a number of multipurpose hydro energy projects have come up. Some of these are Damodar Valley Project in West Bengal and Jharkhand, Hirakud Project in Odisha, Bhakra Dam, stretched across a 1700-foot canyon on the Sutlej River to carry water and electricity to Punjab, Haryana, and Rajasthan, Sardar Sarovar in Gujarat, Tehri in Uttarakhand, and Indira Sagar in Madhya Pradesh. In fact, India remains one of the most active dam-building countries on earth.

**Types of Hydropower Plants**:

- **Conventional Dams**: Most hydroelectric power comes from the potential energy of dammed water driving a water turbine and generator. The power extracted from the water depends on the volume and on the difference in height between the source and the water's outflow. This height difference is called the head. The amount of potential energy in water is proportional to the head. A large pipe (the "penstock") delivers water to the turbine.
- **Pumped storage**: This method produces electricity to supply high peak demands by moving water between reservoirs at different elevations and level. At times of low electrical demand, excess generation capacity is used to pump water into the higher reservoir. When there is a higher demand, water is released back into the lower reservoir through a turbine. Pumped-storage schemes currently provide the most commercially important means of large-scale grid energy storage and improve the daily capacity factor of the generation system. Pumped storage is not an energy source and appears as a negative number in listings.
- **Run of the River (RoR)**: RoR hydroelectric stations are those with small or no reservoir capacity, so that the water coming from upstream must be used for generation at that moment or must be allowed to bypass the dam. In the United States, RoR hydropower could potentially provide 60,000 MW (about 13.7 % of total use in 2011 if continuously available).
- **Tide**: A tidal power plant makes use of the daily rise and fall of ocean water due to tides; such sources are highly predictable and, if conditions permit construction of reservoirs, can also be dispatchable to generate power during high demand periods. Less common types of hydro schemes use water's kinetic energy or undammed sources such as undershot waterwheels. Tidal power is viable in a relatively small number of locations around the world. In Great Britain, there are eight sites that could be developed, which have the potential to generate 20 % of the electricity used in 2012.
- **Underground**: An underground power station makes use of a large natural height difference between two waterways, such as a waterfall or a mountain lake. An underground tunnel is constructed to take water from the high reservoir to the generating hall built in an underground cavern near the lowest point of the water tunnel and a horizontal tailrace taking water away to the lower outlet waterway.

**Table 1** Classification of Hydro Projects in India

| Class | Station capacity in kW |
|---|---|
| Micro Hydro | Up to 100 |
| Mini Hydro | 101–2000 |
| Small Hydro | 2001–25,000 |
| Large Hydro | More than 25,000 |

*Source* MNRE, uploaded on Web site www.mnre.gov.in/schemes/grid-connected/small-hydro/

**Hydropower Projects Classification**: Hydropower projects are generally categorized in two segments, that is, small and large hydro. This classification actually is meant to classify projects as per their power generation capacity. In India, hydro projects up to 25 MW capacities have been categorized as small hydro power projects (SHPs). While Ministry of Power (MoP) of the GOI is responsible for the planning/construction/management of the large hydro projects, the mandate for the planning/construction/management of the SHPs (up to 25 MW) is given to the Ministry of New and Renewable Energy (MNRE) of the GOI. SHPs are further classified as per following categorization (Table 1):

**Issues with the Large Hydro projects**[30]: Some of the important relevant issues are as follows:

- Building a dam across a river floods the land upstream of the dam that would have otherwise been available for use. How a reservoir of a large hydro project affects the land availability will be quite clear from the following table (Table 2). It also raises a question as to how countries such as India and China which have such high population density can cope with the issue of displacement. Also the power generated for the surface area covered, particularly in plains, may not be able to justify these projects—with the population explosion availability of land for the dam and for reservoir increasingly becoming difficult to find.
- Such projects alter the landscape and affect the local community that would have lived and worked on the flooded land. A dam also alters the character of the river and prevents the free movement of fish—**case in point is drastic reduction in the availability of Hilsa fish in Ganges downstream of Farakka**.
- Diverting a river affects the nature of the countryside and does not lend itself to use on a large scale.
- Permanent, complete, or partial blockage of a river for energy conversion is adversely affected by variations in the flow.
- Building large-scale hydropower plants can be polluting and damaging to surrounding ecosystems. Changing the course of waterways can also have a detrimental effect on the affected human communities, agriculture of the region, and microecosystems prevailing in the areas, further downstream.

[30]IBID-13.

**Table 2** Large hydro project

| Name of the project | Surface area (in square kms) | Remarks |
|---|---|---|
| Balbina hydroelectric plant in Brazil[a] | 2360 | -The plant is located in plains<br>-It works out 2000 acres per MW. In contrast, a 10-MW plant in mountains may need just 2.5 acres per MW[b] |
| Aswan Dam, Egypt[c] | 5250 | -Dam is located in plains<br>-618 acres/MW |
| Bhakra Dam, Himachal Pradesh, India | 168.35 | -The plant is located in mountains<br>-31.4 acres per MW<br>-It validates that such projects are more suitable for mountains as they need less surface area |
| Tehri Dam, Uttarakhand, India | 52 | -Highest dam in India[d]<br>-13 acre per MW |
| Sardar Sarovar, Gujarat, India | 375.33 | -Plant is located in plains<br>-64 acres/MW<br>-This is a relatively new project, and it shows that the technology has improved to improve the systemic efficiency |

[a]Fernside, Philip, M., "Brazil's Balbina Dam: Environment versus the Legacy of the Pharaohs in Amazonia, Published in Environment Management Jul/Aug 1989, Vol-13, issue 4, pp 401-403
[b]Hand, M.M.; et al., "Renewable Electricity Futures Study", published under the aegis of National Renewable Energy Laboratory (NREL) during 2012
[c]www.en.wikipedia.org/wiki/Aswan_Dam
[d]http://en.wikipedia.org/wiki/Tehri_Dam

- In case of prolonged droughts and/or dry seasons when the rivers dry up or the volume of water gets reduced, the power output of the hydro projects gets reduced. Therefore, the effectiveness of the hydroelectric projects is a function of the sustained availability of water in the reservoir and in countries having extreme climatic condition (like India); this aspect, at best, can be described as unreliable.
- A particular problem, specific to rivers originating in Himalayas, is excessive accumulation of sediments in the reservoir, which reduces the water-holding capacity of the reservoir and as such affects the power generation capacity of the plant. Overall, also it adversely affects the environment.
- Displacement of large population as a consequence of the construction of large dams and with that attended resettlement problem of displaced persons makes such proposals less attractive**—it is generally seen that the life style of the displaced persons and also the communities gets affected, resulting in major social tensions**.

**Table 3** Major Projects since Independence

| Name of the Project | Construction time | | Power capacity (in MW) | Cost/estimated cost |
|---|---|---|---|---|
| | Date of commencement | Date of completion | | |
| Bhakra Project | 1948 | 1967–68[a] | 1325 | US $ 2680 million at the prices of 2001–2002[b] |
| Tehri Dam | 1978 | 2008 | 1000 | US $ 1000 billion[c] |
| Sardar Sarovar | 1979 | 2008 | 1450 | Rs. 28,613 crores in 2000–2001[d] |

*Note*
[a]Dam was completed in 1963
In all the cases, the cost at completion was substantially more than the estimated cost
[b]Edited by Ramesh Bhatia et al. and calculated by Bhakra Beas Management Board, "Indirect aspects of Dam-Case Studies from India Egypt and Brazil", published by Academic Foundation in 2008
[c]Internet upload: www.en.wikipedia/wiki/Tehri_Dam
[d]Internet upload: www.nvda.nic.in/pdf_files/ssp.pdf

- Construction of large hydro plants particularly in border areas may result into problems between upper riparian and lower riparian states, both within the country and also between the countries—**resolving such disputes prior to the commencement of the construction is necessary, but invariably such disputes delay the project; one such example is the case of Kishanganga hydroelectric project in J&K,[31] which was a cause of dispute between India and Pakistan due to perceptual incongruence between India on the interpretation of the Indus Water Treaty of 1960 which covers the Indo-Pak water relations**.
- Long gestation period will enhance the capital cost of the project and as such the cost of power per MW. This aspect is amply clear from comparing the cost of three major hydro projects in India (Table 3).
- In recent times due to prevailing geopolitical situation, **such projects are increasingly becoming huge security risk due to their vulnerability to sabotage and enemy action.**

[31]Kishanganga Hydroelectric Plant is a part of a run of the river hydroelectric scheme that is designed to divert water from Kishanganga to a power plant in the Jhelum River. It is located five km north of Bandipore in J&K and will have an installed capacity of 330 MW. Construction commenced in 2007 and was halted in October 2011 by Hague's Permanent Court of Arbitration based on a protest of Pakistan (lower riparian state) as she claimed such a disturbance will affect the availability of water for her Neelum Jhelum Project, which is coming up downstream of Indian project on Kishanganga River in Pakistan where Kishanganga is known as Neelum River. Permanent Court of Arbitration at Hague gave their final award in favor of India in December 2013. The project is likely to get completed by 2016.

## 5 Scope for Hydro Energy in India

**Power Potential of India's Hydro Resources**: India is blessed with immense amount of hydroelectric potential and ranks fifth in terms of exploitable hydro-potential on global scenario. As per assessment made by Central Electrical Authority (CEA), India is endowed with economically exploitable hydropower potential to the tune of 148,700 MW of installed capacity. Out of the total power generation installed capacity in India of 176,990 MW (June, 2011), hydropower contributed about 21.5 %, that is, 38,106 MW.[32] However, so far only 32 % of the capacity has either been developed or being developed.[33] Efforts are on to increase the contribution of hydro energy in the overall energy supply. It was 11.22 million tons of oil equivalent (Mtoe) during 11th Plan and targets for 12th and 13th Plans are 12.90 and 17 Mtoe, respectively.[34]

**The Hydro Resources of India**: The Himalayan river networks are snow-fed and have a perennial supply throughout the year. Rivers from other two river systems in India, originating in Vindhya ranges, Satpura ranges and Sahyadri ranges or Western Ghats, are dependent on the monsoons and shrink into rivulets during the dry season. The Himalayan rivers that flow westward into Pakistan are Rivers; Indus, Jhelum, Chenab, Ravi, Beas, and Sutlej. The Ganges originates from the Gangotri Glacier in Uttarakhand. It flows, southeast, draining into the Bay of Bengal. The Yamuna and Gomti rivers also rise in the western Himalayas and join the Ganges in the plains. River Brahmaputra originates in Tibet, China, where it is known as the Yarlung Tsangpo River (or "Tsangpo"). It enters India in the state of Arunachal Pradesh and then flows west through Assam. The Brahmaputra merges with the Ganges in Bangladesh, where it is known as the Jamuna River.[35] The Chambal River is a tributary of the Yamuna River in central India and forms part of the greater Gangetic drainage system. It originates from the Vindhya–Satpura watershed. The river flows eastward. Westward-flowing rivers from this watershed are Narmada and Tapti, which drain into the Arabian Sea in Gujarat. The Western Ghats are the source of all Deccan rivers, which include Godavari, Krishna and Cauvery, all draining into the Bay of Bengal. River Mahanadi, originating in Eastern Ghats, is another river which drains into the Bay of Bengal. These rivers constitute 20 % of India's total outflow.[36] The river network that flows from east to west constitutes 10 % of the total outflow. India's total renewable water resources are estimated at 1907.8 $km^3$/year.[37] Its annual supply of usable and replenishable

[32]IBID-8.

[33]12th Plan Document, Sec-14.13.

[34]IBID-10.

[35]Brahmaputra River, Encyclopedia Britannica.

[36]Manorama Yearbook.

[37]The Encyclopedia of Earth: water profile of India updated up to March 10, 2012, topic editor–Avanishpanikkar, Source—FAO.

groundwater amounts to 350 billion cubic meters (BCM).[38] Only 35 % of groundwater resources are being utilized.[39]

A study of the terrain relief of the country and the alignment/location of rivers/water bodies brings out clearly that in India, the availability of water is highly uneven, spatially as well as temporally. Prime source of water in the country, other than melted snow from the glaciers of Himalayas, is rainfall, which is restricted to three to four months of monsoon in a year. Rainfall is also quite uneven. The typical data for the current monsoon (2014) reveal variation from 15.2 cm in the western parts of Rajasthan to about 113.5 cm at Cherrapunji in Meghalaya.[40] A comparison of this variation will further accentuate if the rainfall data are combined with the rainfall data of Andaman and Nicobar Islands (annual average rainfall: 3000 mm[41]).

## 6 Small Hydropower (SHP) Programme

**Concept**:

- A SHP-based project is same as a large hydro project. It is different from a large hydro project only in terms of capacity. Like a large hydro plant, a SHP-based plant also develops hydroelectric power, although it will be on a scale which is smaller in size and serves either a small community or a small industrial unit.
- The definition of a small hydro project varies from country to country. In the USA, a plant having a capacity up to 30 MW is considered a SHP plant, but in Canada, this figure is 50 MW.[42] In India, plants having capacity up to 25 MW are considered SHP-based plants.
- The concept of SHP has caught the imagination of the world. During a period of three years, from 2005 to 2008, the number of SHPs in the world grew by a figure of 28 % over their number of 2005 and helped the capacity of small hydro to grow to 85 GW. Over 70 % of this was in China (with 65 GW), followed by Japan (3.5 GW), the USA (3 GW), and India (2 GW).[43] China plans to electrify further a large number of villages through SHP under their China Village Electrification Programme.

[38]JK Jain, et al., "India: underground water sources", published by The Philosophical transactions of Royal Society on May 03, 1977, and uploaded on http://rstb.royalsocietypublishing.org/content/278/962/507.

[39]IBID-7.

[40]Data for monsoon from June 01, 2014, to August 06, 2014, by Hydromet Division of IMD.

[41]Andaman Tourism, uploaded on http://www.andamantourism.in/andaman-climate-india.

[42]Internet Download—"Small hydro in Canada". Canmetenergy-canmetenergie.nrcan-rncan.gc.ca. dated 23 Mar 2009.

[43]Renewables Global Status Report 2006 Update, *REN21*, published in 2006.

**Principle**:

- In a SHP plant, the turbine converts the energy from falling water into rotating shaft power, which in turn gets converted into mechanical and electrical energy. In most of the cases, small hydro is “run of the river” (RoR); in other words, dam/barrage in SHPs is quite small, usually just a weir, and generally no water is stored.
- Regulation of small hydro generating units may require diversion of water around the turbine, since the project may have no reservoir to store unused water. Plants with either small storage reservoir or a small pumped-storage plants can contribute to distributed energy storage and decentralized peak and balancing electricity. Such plants can be built to integrate at the regional level as a source to provide intermittent RE.[44]
- Other small hydro schemes may use tidal energy or propeller-type turbines immersed in flowing water to extract energy. Tidal schemes may require water storage or electrical energy storage to level out the intermittent (although exactly predictable) flow of power.
- Since small hydro projects usually have minimal environmental and licensing procedures, and since the equipment is usually in serial production, standardized and simplified, and since the civil works construction is also small, small hydro projects may be developed very rapidly. The physically small size of equipment makes it easier to transport to remote areas without good road or rail access.

**Measures to Optimize the Cost**: Small hydro is often developed using existing dams or through the development of new dams whose primary purpose is river and lake water-level control, or irrigation. Occasionally old, abandoned hydro sites may also be considered for re-development. There are a number of companies which offer standardized turbine generator packages in the approximate size range of 200 kW to 10 MW. These “water to wire” packages simplify the planning and development of the site and reduce paper work related to dealing with multiple vendors besides getting involved with issues related to synchronization. Since in such a system non-recurring engineering costs are minimized and development cost is spread over multiple units, the cost of such systems is improved. While synchronous generators capable of isolated plant operation are often used, small hydro plants connected to an electrical grid system can use economical induction generators to further reduce installation cost and simplify control and operations. In many cases, salvaged substantial parts of the plant and equipment such as penstocks and turbines can also be used. For micro-hydro schemes feeding only a few loads, a resistor bank may be used to dissipate electrical energy as heat during periods of low demand. In a sense, this energy is wasted, but the incremental fuel cost is negligible so there is little economic loss. These cost-saving advantages can make the return on investment (ROI) for a small hydro site well worth the use of existing site infrastructure.

[44]Crettenand, N., “The facilitation of mini and small hydropower in Switzerland: shaping the institutional framework, with a particular focus on storage and pumped-storage schemes.” *Ecole Polytechnique Fédérale de Lausanne (EPFL). Ph.D. Thesis N*° 5356. Infoscience.epfl.c, during 2012.

**An Appreciation of Environmental Impact (EI)**: A SHP may get connected to a conventional electrical distribution networks as a source of low-cost RE or it may be built in a remote area not connected by the power grid. These plants have much smaller reservoirs, and their civil construction work also is not too elaborate, as such; it is considered that they have a relatively low EI as compared to a large hydro project. This, however, depends on the balance between stream flow and power production. The flow duration curve (FDC) is one of the many tools that help to evaluate the EI. The FDC is a Pareto curve of a stream's daily flow rate versus frequency. Reductions of diversions help the river's ecosystem, but they reduce the hydro system's ROI. It is therefore the responsibility of a hydro system designer and the site developer to strike a balance to maintain both the health of the stream and the economics.

**Advantages of SHP**:

- Clean energy is generated at a competitive price.
- These plants have features that make them suitable for peaking operations.
- These are less affected by problems of rehabilitation and resettlement of displaced/disaffected person's vis-à-vis large hydro plants.
- These plants can meet the power requirements of remote and isolated areas.
- Since technology has fully been indigenized and has matured over the years, it is not affected by geopolitical disturbances.

**Disadvantages**:

- A five-year study conducted in China's Nu River Basin by researchers at Oregon State University suggests that the cumulative effects of the SHP cause more economic damage per MW.[45]
- A research based on a study of 31 small dams (capacity less than 50 MW) and four large dams revealed that the small hydro plants were 100 % more detrimental to habitat diversity.
- The small projects were also more likely to disrupt network connectivity, cause lower quality of water, and are likely to impact hydrology more at the sub-basin level.

## 7 SHP in India

The use of SHP plant goes back into history. The first SHP-based plant in India came up in 1897. In India, the MNRE has been vested with the responsibility of developing SHP projects up to 25-MW station capacities. It has been declared as one of the thrust areas for power generation. It has been recognized that small

[45]Candace Pearson, "Small Hydro Projects in China have big impact," uploaded on file:///c:/users/99/Desktop/Small%20Projects%20in%20China%20Have%20Big%20 Impacts%20-%20BuildingGreen.htm.

hydropower projects can play a critical role in improving the overall energy scenario of the country and in particular for remote and inaccessible areas. With the strong thrust from the MNRE, the number of SHP-based plants has doubled in India between 2003 and 2013.[46]

**Potential**: An estimated potential of about 20,000 MW of SHPs exists in India.[47] MNRE has created a database of potential sites of small hydro, and 6474 potential sites with an aggregate capacity of 19,749.44 MW for projects up to 25 MW capacity have been identified.[48] Most of the potential is located in Himalayan states as river-based projects and in other states on irrigation canals. The statewise potential is tabulated below (Table 4).

**SHP Versus other forms of RE** (Table 5).

**Economic Analysis of SHP**: SHP is economically comparable, in fact slightly better than other RE sources such as wind and biogas and definitely far better than solar PV. The cost of power from small hydro is comparable to the cost of coal-generated power, which is around Rs. 2–3/kWh.[49] Also, a small hydro does not have any variable fuel cost as compared to conventional thermal power plant which relies on coal or natural gas. Primary costs such as depreciation, return on equity, and interests are derivatives of the capital cost. Even operation and maintenance costs are comparatively lower when determined as a percentage of the capital cost. It is relevant to note that while there is a national mission on solar energy,[50] which is still quite expensive, there is no national mission on early deployment of hydro/small hydro-based projects to exploit hydro-based resources of India. From the point of view of profitability, installation of SHPs for off-grid application in a mission mode will be a good strategy, more so as the RoR variety of SHP being highly successful in Indian context in Bundelkhand Region.[51] Such a strategy will also be able to address the environment impact (EI) and social impact (SI) issues related to the large hydro projects.

**Growth of SHP in India**: SHP is by far the oldest RE technology used to generate electricity in India. The Sidrapong Hydel Power Station was set up in 1897 in Darjeeling (West Bengal) with a total capacity of 135 kW.[52] This was closely followed by the Sivasamudaram project of 4500 KW in Mysore district of Karnataka in 1902, which supplied electricity to Kolar gold mines. Till independence in 1947,

[46]"Green Norms for Green Energy Small Hydro Power" edited by Souparno Banerjee and Sheeba Madan, published by Centre for Science and Environment during 2013.

[47]Download from MNRE site: http://www.mnre.gov.in/Small Hydro.

[48]IBID-13.

[49]Sonali Mitra, "Small Hydro: Too Small fora National Mission?", published ORF New Delhi during Nov 2011 and uploaded on www.orfonline.org Nov 2011.

[50]Jawaharlal Nehru National Solar Mission was launched on 11 Jan 2010 under the aegis of MNRE with the target of deploying 20,000 MW of grid-connected solar power by 2022.

[51]Private discussion with Dr. KD Sharma, former Additional Member Planning Commission (Water).

[52]Anon, "Sidrapong Hydel Power Station," Department of Power and Non-conventional Energy Sources, Government of West Bengal http://wbpower.nic.in/sidra.htm, as viewed on 2 Apr 2013.

**Table 4** The statewise potential

| S. No. | State | Number | Capacity (in MW) |
|---|---|---|---|
| 1 | Andhra Pradesh | 387 | 978.40 |
| 2 | Arunachal Pradesh | 677 | 1341.38 |
| 3 | Assam | 119 | 238.69 |
| 4 | Bihar | 93 | 223.05 |
| 5 | Chhattisgarh | 200 | 1107.15 |
| 6 | Goa | 6 | 6.50 |
| 7 | Gujarat | 292 | 201.97 |
| 8 | Haryana | 33 | 110.05 |
| 9 | Himachal Pradesh | 531 | 2397.91 |
| 10 | J&K | 245 | 1430.67 |
| 11 | Jharkhand | 103 | 208.95 |
| 12 | Karnataka | 834 | 4141.12 |
| 13 | Kerala | 245 | 704.10 |
| 14 | Madhya Pradesh | 299 | 820.44 |
| 15 | Maharashtra | 274 | 794.33 |
| 16 | Manipur | 114 | 109.13 |
| 17 | Meghalaya | 97 | 230.05 |
| 18 | Mizoram | 72 | 168.90 |
| 19 | Nagaland | 99 | 196.98 |
| 20 | Odisha | 222 | 295.47 |
| 21 | Punjab | 259 | 441.38 |
| 22 | Rajasthan | 66 | 57.17 |
| 23 | Sikkim | 88 | 266.64 |
| 24 | Tamil Nadu | 197 | 659.51 |
| 25 | Tripura | 13 | 46.86 |
| 26 | Uttar Pradesh | 251 | 460.75 |
| 27 | Uttarakhand | 448 | 1707.87 |
| 28 | West Bengal | 203 | 396.11 |
| 29 | A&N Islands | 7 | 7.91 |
| Total | | 6474 | 19,749.44 |

*Source SHP Potential as on 31 March, 2013,* "Green Norms for Green Energy Small Hydro Power" edited by Souparno Banerjee and Sheeba Madan, published by Centre for Science and Environment during 2013

the cumulative installed capacity of small hydropower in India had reached 532 MW.[53] After independence (and till very recently), India's main thrust had been on large hydropower dams. But with growing activism of anti-dam lobbies representing displaced people from areas which have already been inundated or are likely to come under inundation, as in the case of the Tehri Dam, the Sardar

[53]Sonali Mitra, "Small Hydro: Too Small for a National Mission?" published ORF New Delhi during Nov 2011 and uploaded on www.orfonline.org Nov 2011.

**Table 5** SHP versus other forms of renewable energy

| Renewable energy comparison | | | | |
|---|---|---|---|---|
| Source/Parameters | Biomass | Solar PV | Wind | Small hydro |
| Potential capacity MW | 61,000 | 50,000 | 45,000 | 15,000 |
| Grid-interactive installed capacity (MW) | 1083 | 46 | 14,989 | 3153 |
| Off-grid-interactive installed capacity (MW) | 122 MWeq | 2 MWp | | |
| Estimated capacity factor (%) | 70 | 20 | 14 | 50 |
| Electricity generation cost (Rs. /kWh) | 4–5 | 12–20 | 3.5–4.5 | 3–4 |

*Source* REN21 2009, Renewables Global Status Report: 2009 Update, RENI21 Secretariat, Paris

Sarovar Dam, and Indira Sagar Dam on Narmada River, the importance of smaller hydropower plants using RoR design as well as toward canal-based projects is getting center staged. It has been declared by the MNRE that the aim of the SHP programme is to enhance the installed capacity to about 7000 MW by the end of 12th Plan, and in absolute terms, it is estimated to grow by 2100 MW during 12th Plan. However, the total installed capacity of SHP projects in India has reached only 3632 MW in March 2013.[54] This capacity is spread over 950 projects; hence, the average SHP project capacity is 3.8 MW. It is further forecasted that at least 50 % of the potential in the country would be harnessed in the next 10 years.[55] The capacity is steadily increasing. During 10th Plan 536 MW and in the 11th Plan, a capacity of 1419 MW was added[56] against the target of 1400 MW.[57] A reality check reveals that so far 950 SHP projects with an aggregate capacity of 3632 MW have been set up and 348 projects aggregating to 1309 MW are under implementation.[58] The Ministry is encouraging development of small hydro projects both in the public and in private sector. Equal attention is being paid to grid-interactive and decentralized projects. MNRE ensures performance testing of all the plants for their functionality. The responsibility of setting up of the SHP comes under the purview of state governments.[59] Potential sites are either developed by the state or allotted to private developers for setting up of projects. The focus of the SHP programme is to lower the cost of equipment, increase its reliability, and set up projects in areas which give the maximum advantage in terms of capacity utilization. Financial support is also given to the state governments for the identification of new potential sites including survey and preparation of detailed project reports (DPRs) and renovation and modernization of old SHP projects. It also helps the

[54]Anon, "Achievements," Ministry of New and Renewable Energy, http://www.mnre.gov.in/mission-and-vision-2/achievements/website, as viewed on 25 Mar 2013.

[55]IBID-13.

[56]Farooq Abdullah's statement in Rajya Sabha during Question Hour as reported in "India Has Estimated Potential for 19,750 MW of Small Hydro Power Projects" published in CleanTech/Renewable Energy dated August 31, 2012.

[57]12th Plan Document, Table 14.43.

[58]IBID-13.

[59]IBID-13.

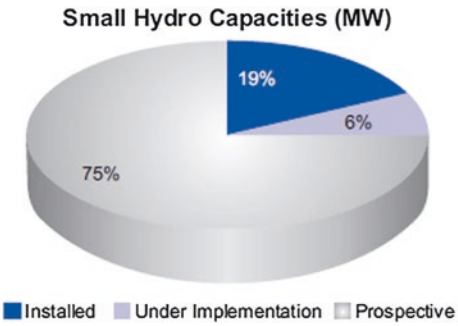


**Fig. 4** Current status for SHP prospects. MNRE 2011, ministry of new and renewable energy, small hydro. Available at: www.mnre.gov.in/prog-smallhydro.htm; accessed on October 19, 2011. *Source*: Sonali Mitra, "Small Hydro Too Small for a National Mission?", published by Observer Research Foundation (ORF) as issue Brief#34 dated November 2011

state governments in formulating their policies for the development of small hydro projects and exploitation of this potential. Twenty-four states have announced their policy to invite private sector players to set up SHP in their respective states. It may also be noted that India has adequate capabilities of setting up small hydro projects. Although the policies of the MNRE are encouraging the development of small hydro projects both in the public and in private sector, the SHP programme has now become an essentially private investment-driven programme. Most of the projects are proving to be economically viable, and as such, the private sector is showing lots of interest in investing in SHP projects. The viability of these projects will further improve with increase in the project capacity. Equal attention is being paid to grid-interactive and decentralized projects. In 2012, the SHP's share in the total installed RE capacity had gone up to 15 %.[60]

An analysis of Fig. 4 brings out that in Karnataka, India, having only 4.8 % of total potential capacity has been able to harness all its hydro potential. On the other hand, Himachal Pradesh, having highest potential, has shown only 28.3 % development. Given such huge gaps in the response of various states with respect to their respective potential and its realization, policies, regulations, incentives, and subsidy schemes need to be reviewed (Fig. 5).

**Manufacturing Status**: There are about 25 equipment manufacturers (As on 17 July 2014) of small hydro power turbine in the country who have over the years developed the capacity to fabricate almost the entire range of SHP equipment listed in MNRE Manual. The capacity of the industry in the country is presently estimated to be at about 400 MW per year.[61]

**Environmental Impact (EI)**: When compared to thermal coal power, SHP has no effect on climate change, its fuel source is inexhaustible, and it does not

[60]Anjan Ghosh et al., "Steady growth in small hydro power, however significant challenges" published in ICRA Rating Feature dated May 2012.

[61]IBID-13.

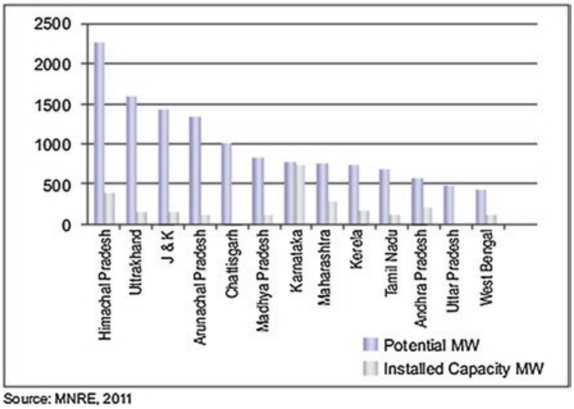


**Fig. 5** Potential and installed capacity of SHP in India. *Source* Sonali Mitra, "Small Hydro Too Small for a National Mission?", published by Observer Research Foundation (ORF) as issue Brief#34 dated November 2011

contribute to air pollution. Water pollution by a SHP is relatively low and happens mainly during the construction phase. Compared to large dams, it inundates much smaller area and causes little or no displacement of people. However, it needs to be noted that those projects, incorporating ROR design, do have multiple environmental and ecological impacts that can rival large hydro projects when measured against the actual generation of power from these plants. If measured according to impact per MW, SHP can—in certain scenarios—exert the same impact as a large hydropower project. Some of the relevant aspects are as follows:

- The impacts which are perceived to be of critical importance are ecological (on aquatic flora and fauna), physical (on water quality, sediment-carrying capacity, erosion, groundwater quality and recharge, climate, soil, and geology), and human induced (such as interference with drinking and agriculture water availability, solid waste generation, and socio-economic factors).
- Hydropower turbines, dams, and tunnels also have an impact on fish populations, as many fish species migrate for spawning; this migration is effectively barred by dam construction and dry river beds. "Fish ladders"—unblocked streams, either human-made or natural, running by the side of a project with "steps" low enough for the fish to travel—give fish an alternative means to move up and downstream. They can be used or created to improve migration; however, in most cases, this has not been done. On the other hand, the success rate of fish ladders is debatable,[62] especially in tropical areas, where there has been little research on how fish travel as opposed to studies on salmon migration in the northern latitudes.[63]

[62]Jed Brown et al. 2013, "Fish and hydropower on the U.S. Atlantic coast: failed fisheries policies from half-way technologies," *Conservation Letters,* 16 Jan 2013.

[63]Nachiket Kelkar, "Thirsty Rivers, Bygone Fishes, Hungry Societies', South Asia Network Dams, Rivers and People," http://sandrp.in/rivers/Thirsty_Rivers_Bygone_Fishes_Hungry_Societies_Nachiket_Kelkar_Dec2012.pdf.

- A single SHP plant has a relatively lesser impact on the surrounding area. However, since its output is also less, more plants are required to generate the same amount of electricity as one large hydropower plant would have done. Therefore, the cumulative impact of a number of SHP projects is more important. Four hundred SHP projects of 5 MW each have the potential to affect more tributaries directly compared to one large hydropower project of 2000 MW.
- The location of the dam site is also important. A large dam needs a greater flow which can only be possible on major rivers. The World Bank, one of the largest funding bodies for hydropower projects, admitted in 2003 that the impact of plants placed downstream on large rivers is more severe than that of projects, including those that are of small scale, placed upstream on smaller tributaries.[64]
- Technology used for constructing a SHP also contributes to EI. If SHP projects are designed with reservoirs (and not actual ROR), the area needed for these reservoirs is much larger per MW capacity as compared to large hydropower projects. Theoretically, the volume of a reservoir increases cubically with in terms of cubic units with an increase in surface area: A dam of double the size would hold four times more water and only then will be more efficient. Similarly, the storage volume would decrease multiple times if the surface area is cut in half.[65] In case project is canal based which does not has tunnels; no impact other than the change in the micro climate of the area due to the presence of the canal, will be experienced.

**Social Impact (SI) of SHP**: The fact that it is the most environmentally benign Renewable Energy (RE) resource, makes it even more lucrative for power generation. It is non-polluting and emits least amount of $CO_2$; it has least impact on flora, fauna, and biodiversity when compared with large hydropower projects. It does not even require deforestation, submergence of land, or rehabilitation.[66] Nine small hydro projects face fewer environmental clearance hurdles compared to large hydropower projects and therefore are generally not contested by social and environmental groups.

**Small versus Large Hydro Plants**: Although due to space constraint in India and long gestation period, the large hydro project in Indian context is increasingly becoming less and less relevant, there is a need to examine relative merit of large versus small hydro based on the comparison of the cost benefit in terms of economics, environment, and SI. Following two studies give a lot of clarity on the subject:

- **Bhagirathi Basin**: An analysis of diversion reach and head correlation of all ROR operational projects over Bhagirathi river basin reveals that the ratio of head in case of SHPs is approximately 18 times that of a large hydropower

[64]George Ledec and Juan David Quintero 2003, "Good Dams and Bad Dams: Environmental Criteria for Site Selection of Hydroelectric Projects," *Latin America and Caribbean Region Sustainable Development Working Paper 16,* World Bank, November 2003.

[65]Robert Goodland, "*How to distinguish better hydro's from worse*: *the environmental sustainability challenge for the hydro industry*," The World Bank 1995.

[66]Central Board of Irrigation and Power 2009; Manual on Development of Small Hydroelectric Projects, Publication no. 305, New Delhi-10. UNFCCC, 2004. Appendix B of the simplified modalities and procedures for small-scale CDM project activities; indicative simplified baseline and monitoring methodologies for selected small-scale CDM project activity categories, version 04. 22 Oct 2004.

**Table 6** Comparison of small and large hydro over Bhagirathi basin, Uttarakhand

| Parameter | Per MW for small hydro | Per MW for large hydro | Ratio of small/large |
|---|---|---|---|
| Diversion length (m) | 319.61 | 53.45 | 5.98 |
| Head (m) | 15.84 | 0.89 | 17.85 |
| Annual generation (MU) | 5.88 | 4.28 | 1.38 |

*Source* Analysis done by CSE
*m* meter, *MU* million units

project per MW of generation capacity. This leads to an increase in diversion length of the river by six times, whereas the annual generation is just 1.38 times. This shows that in case of a large number of SHP projects over a river basin, there are significant losses for the ecosystem; at the same time, the expected economic benefit is not commensurate to the investment. Thus, although SHP is said to have less ecological impact at the cost of economic benefit, in many cases, the decreased ecological impact (as compared to large projects) is not realized. The same aspects have been authenticated based on the live data about the Bhagirathi River in Uttarakhand (Table 6).

- **The Norwegian study**: In this study, a comparative analysis of environmental impacts from 27 SHP plants (less than 10 MW) with three large hydropower projects has been done. The results show that there is a slight tendency of a single large hydropower project to have lesser degree of environmental impact as compared to the accumulated impact of a number of small scale projects constructed in lieu. The results further show that the following impacts were on a higher scale in small hydro projects as comapared to large hydropower plants:
  - Sediment transportations and soil erosion.
  - Changes in local climate.
  - Impacts on fish migration and spawning.
  - Recreation.

**Cascading**: This is a common feature in case of small hydro plants and it entails, not leaving adequate distance between two projects, that is, head race of downstream project starting at tail race of upstream project. This kind of arrangement may lead to almost drying up of the natural channel of the stream during lean periods. According to Devadutta Das, emeritus professor, Department of Water Resources Development and Management, Indian Institute of Technology, Roorkee, cascade operation of small hydropower stations poses environmental concerns. Therefore, such cascade developments should preferably be planned, if there is no habitation along the river stretch with riparian use of water, and some smaller perennial streams join the river downstream of the diversion weir.[67]

[67]Planning and design of Asiganga-II and Asiganga-III small hydro power stations for tandem operation, http://2010.hidroenergia.eu/pdf/4B. 06.pdf, as viewed on 15 Apr 2013.

Reasons for cascading (on account of erection of unplanned SHPs) with attended adverse EI are as follows:

- Orientation of the concerned state's policy to generate revenue by levying taxes on project developers or selling the power which the state will get as part of the deal with the project developer—**there is a need to study the EI and the SI besides technical feasibility before a decision to implement a project is taken**.
- Ignorance on the part of those who are responsible for the management of the river basin. It may be noted that the river basin management entails addressing a number of issues having competing merits and necessity. The important issues with need to be considered include ascertaining the water requirements for irrigation, drinking, industry, and environmental needs. Historical data need to be maintained to establish the trend for future—**an integrated decision making through collegiate vetting to overcome the problem of dealing with multiple agencies is likely to help overcome this aspect**.
- **Multiplicity of planning agencies**: Two different ministries namely MoP and MNRE deal with policy formulation and implementation with respect to large and small hydro projects, and earlier funding was through the planning commission—**this issue, however, has substantially been addressed by new governance model introduced by the GOI**. **Now MoP and MNRE are under same minister, and probably the role of Planning Commission is also being curtailed**. Now the new funding model entails; funding from MNRE and through the nodal agencies of the concerned states.

**Constraints which inhibit the growth of SHP in India**:

- Construction risks due to remoteness of the location of the plant may add to the gestation period, and that adds to the capital cost—**one of the recommended solutions is flexible tariffs to cover the escalation in the capital cost may be able to address the issue**.
- Power tariff in India is a state subject and as such is different in different states. Reasons for such inconsistency are different orientations of the policy of each the state, and such inconsistency affects adversely investment because in many cases, differential tariffs are such either due to welfare orientation that the returns do not cover even the investment or due to remoteness of the area which enhances the capital as well as running cost of the project—**once again, a flexible tariff with a financial model which helps people to get power at affordable rates but not causing financial problems to the regulator**.
- One of the biggest fears is that the hydrological risks postcommissioning of the plant may make it defunct. The hydrological risks could be due to inadequate availability of water to generate power. These hydraulic risks could be on account of faulty estimates, environmental changes which were not envisaged earlier, or uncoordinated water diversion on upstream side—**center stages need an integrated approach to energy management**.
- Unchecked growth of SHPs may bring certain adverse EI-related problems—**this can be addressed by better and effective regulation**.

**Inhibitors to Construction of SHP**:

- Challenges in setting up plants in difficult and remote terrain—in such places.
- Delay in land acquisition and difficulty in getting statutory clearances fast—**land acquisition has post new Land Acquisition Act 2013 has become really difficult and may become one of the greatest inhibitors in future**.
- Inadequate grid connectivity and high wheeling and open access charges in some of the states—**this gives an approach that these SHPs will be more applicable to remote areas and planning of these SHPs should be done accordingly**.
- High capital cost of Rs. 7–8 crores/MW for a SHP is comparable to a large hydropower project.[68] This makes a SHP less attractive—**implementation of small hydro projects in mission mode (establishing a national mission on the lines of solar mission) with the component of subsidy incorporated into it for the agency executing it is probably the only way ahead**.

**Enablers for the Introduction of SHP in the Energy Matrix of India**:

- GOI's National Action Plan for Climate Control (NAPCC) has set the minimum share of RE in the overall energy matrix at 10 % by 2015 and 15 % by 2020. **With the share of the SHP having already reached 15 % of the RE component of the energy matrix of India, it is likely to go up significantly in next six years**.
- **The Central Electricity Regulatory Commission (CERC) has come out with several measures, including generic tariff norms for the SHP projects**, norms and pricing framework for RE Certificates (REC),[69] and an amended grid code to ensure smoother off take and transmission of power generated through RE sources, by the utilities.
- Under the control of the Central Financial Scheme (CFA) of the MNRE, capital subsidy is now provided to both, private and the state units/enterprises and for renovation and modernization of the SHP plants.
- Alternate Hydro energy Centre (AHEC), IIT Roorkee, is providing technical support for the establishment of SHP units, **which needs to be exploited**.

[68]Sonali Mitra, "Small Hydro: Too small for a National Mission", published by Observers Research Foundation as an ORF Issue Brief No 34 during Nov 2011.

[69]REC: The Electricity Act of 2003 as well as NAPCC provides a roadmap for increasing the share of renewables in the total generation capacity of the country. However, renewable sources are not evenly spread across the country. In this context, the concept of REC assumes significance. The concept seeks to address the mismatch between the availability of the RE resources and the requirement of the obligated entities to meet their renewable power purchase obligations (RPO). It is also expected to encourage the RE capacity accretion in the states where there is a potential for RE generation as the REC framework seeks to create a national-level market for such generators to recover their cost.

- Given the economic rationale, the relevance of the SHP increases manifold in its rural and remote area and off-grid application.[70] Besides sustainability, it fits into national priorities such as rural electrification, capacity building, and infrastructure.[71]

Need to exploit all possible sources of energy generation continues to remain the main driver for the continuous emphasis on the small hydro despite a number of factors which inhibit its use based on environmental and cost considerations.

## 8 SHP in the Future Energy Matrix of India

India is short of energy to meet its ever increasing needs to fuel its economy and meet the aspirations of its teeming millions. No respite from this state of being energy short is envisaged as the gap between the demand and supply is ever increasing. Presently to bridge this gap, import of energy-bearing resources is being resorted to. However, it needs to be appreciated that the dependence on the import of energy increases the vulnerability to international arms twisting besides being a big drain on the exchequer due to upward spiraling energy costs in the international market due to a number of geopolitical developments and increase in the demand itself. It is therefore essential that every indigenous source is exploited to the fullest, and this is where the importance of SHP lies.

SHP has its own limitation as far as its potential is concerned, but due to full indigenization of the technology and its effectiveness in off-grid/remote area usage, it can be a very useful element in the energy matrix especially in the near (less than five years) to middle term (less than 10 years) till technologies for other resources available indigenously get matured and become cost-effective.

However, a word of caution! Small hydro projects should be planned as a part of an integrated energy management mechanism wherein all locally available energy bearing resources are optimally exploited to meet the local energy/ power needs. These (SHPs) are particularly useful in remote and hilly areas which are not not connected by the power grid and extending the power grid is not cost effective. Cascading and other adverse environmental impacts caused by SHPs can to be addressed by better planning, regular maintenance (during operations) and continuous monitoring.

[70] Arun Kumar Tyagi, "Community Owned Small Hydro Projects-An Off grid Solution," Uttarakhand Renewable Energy Department (UREDA), presented in International Conference on Small Hydropower, Sri Lanka, during 2007.

[71] Ghosh, D., Shukla, P.R., Garg, A., Ramana, P.V., "Renewable Energy Technologies for Indian Power Sector: Mitigation Potential and Operational Strategies", published in Renewable and Sustainable Energy Review 6(6), pp 481–512 during 2002.

# Hydrogen and Fuel Cells

**Bahman Shabani and John Andrews**

**Abstract** Considering social (e.g. energy security), economic, and environmental issues associated with reliance on finite fossil fuel resources for energy generation, hydrogen (based on renewable energy and energy efficiency) is seen by many scientists and economists as a sustainable solution that can help the end users of energy meet their future supply requirements as well as greenhouse gas and other emission reduction targets. While diversity of renewable energy resources is the key advantage of these alternatives, their intermittency and unpredictability have to be addressed by complementing them with proper energy storage options such that these resources can be reliably employed to power stationary and mobile applications uninterruptedly as required. Hydrogen energy systems as reviewed in this chapter can play a strong energy storage role in conjunction with renewable energy resources, particularly in applications with long-term (e.g. in stand-alone stationary applications with highly variable seasonal input of renewables, central grids, or microgrids) and/or long-range (i.e. in automotive applications) energy storage requirements. The main components of a hydrogen energy system include hydrogen generation arrangement; hydrogen storage; distribution and delivery systems (long or short distance); and the means of converting the chemical energy of hydrogen into a desirable form of energy (e.g. electricity) for end consumers. Latest research and development related to these elements are discussed in this chapter.

**Keywords** Hydrogen · Electricity · Energy storage · Microgrids

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Green Energy and Technology, DOI 10.1007/978-81-322-2337-5_17

## 1 Introduction

Climate change, oil supply insecurity and price increase, rising population levels and per capita energy consumption, and air pollution are all seen to be major international challenges. Over 85 % of the ever-increasing global energy demand is supplied by fossil fuels. Hence, there is a strong connection between international economic development indices and the prices of these fossil fuels. The high dependence on oil-based fuels in some sectors is alarming. For example, more than 90 % of global transport relies on oil, and the ever-expanding transportation sector alone consumes around 49 % of the world's oil production, contributing 23 % of total global energy-related $CO_2$ emissions (2014). According to IEA (2013), the world is about a couple of decades away from 'peak oil' (i.e. 2035). For all these reasons, increasing global energy demand poses serious long-term challenges to maintaining security of energy supply at an economically affordable and environmentally sustainable level. It is therefore critically important to find an alternative to fossil fuels.

Hydrogen is seen by many scientists and economists as a strong alternative fuel that can help the automotive and stationary power supply sectors to meet future greenhouse gas and other emission reduction targets and provide energy security. Crucially, hydrogen offers a carrier and storage of inherently variable renewable energy sources such as solar and wind power. The role that hydrogen can play will thus become more pronounced in the foreseeable future as renewable energy supplies an increasing share of total energy supply (IEA 2013).

Hydrogen as an energy carrier offers the following key advantages:

- **Source flexibility**: Every region has some indigenous renewable resources that can be used to make hydrogen with zero greenhouse gas emissions, so that regional variations in traditional energy resources are no longer an issue
- **Energy security**: Hydrogen can replace imported petroleum as a transportation fuel
- **Improved urban air quality**: Water and heat are the only products when hydrogen is used in a fuel cell for power and heat generation. It is important to note that in combustion systems, in which air is used rather than pure oxygen, small amounts of $NO_x$ is also produced
- **Reduced greenhouse emissions and a contribution to mitigating global climate change**: Hydrogen produced from renewable energy can reduce greenhouse gas emissions, and hydrogen as a strong storage option for intermittent renewables can help penetrate these clean alternatives in the global energy mix. It is important to note that fossil-based production of hydrogen will require capture and sequestration of $CO_2$ to be a zero-emission system.

Hydrogen is not a primary energy source such as natural gas or crude oil. Rather it is just an energy carrier and storage medium that has to be manufactured using a primary energy input, such as solar or wind energy, fossil fuels (e.g. natural gas), and nuclear energy. Hydrogen as an energy storage option is particularly suited to longer term storage, that is, from weeks to months, and most notably from season to season as will be required by any renewable energy sources, since its energy content does not degrade over time. It is an energy carrier like electricity, but unlike electricity hydrogen has inbuilt energy storage. The energy stored in hydrogen can be regained through combustion (for example, in internal combustion engines) or electrochemical reaction (i.e. in fuel cells). The principal applications of hydrogen energy are as a portable fuel in the transport sector and for stationary power and heat supply. There is a wide range of applications in the latter area from large and smaller scale decentralised energy storage on the main electricity grids with increasing renewable energy input; stand-alone supply of heat and power to towns, islands, communities, and households remote from the grid; remote construction projects; remote telecommunication sites; power supply to remote industrial and agricultural facilities; and portable heat and power supply. These applications will be reviewed in this chapter.

## 2 Sustainable Hydrogen Systems: An Overview

The main components of a hydrogen energy system include hydrogen generation arrangements; hydrogen storage, distribution, and delivery systems (long or short distance); and the means of converting the chemical energy of hydrogen into a desirable form of energy (e.g. electricity) for end consumers. Hydrogen can be generated using chemical processes (e.g. chemical conversion of biomass or as by-product of some chemical processes) or by breaking water molecules using a primary source of energy (Fig. 1). The latter can be either renewables such as

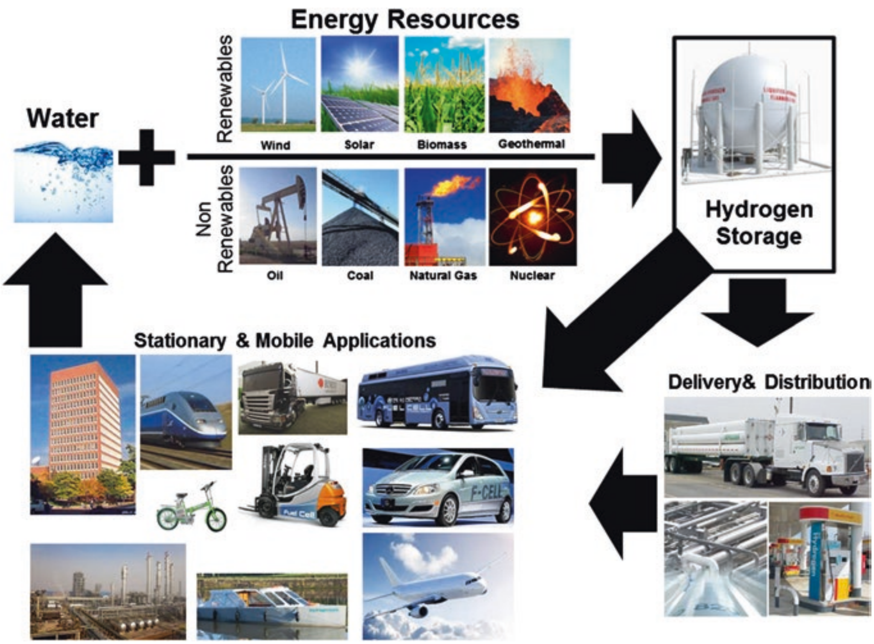


**Fig. 1** Hydrogen generation, storage, distribution and delivery, and consumption cycle

biomass, wind, hydro, and solar, or non-renewables such as oil, coal, natural gas, and arguably nuclear energy. In fact the non-renewable sources of energy do not support sustainability in long run, while some advocate using these resources in the shorter term in order to help introduce hydrogen into the energy mix.

Hydrogen can be generated close to the point of consumption using locally generated or transmitted electrical power; this minimises the size of the network required for distributing hydrogen. The water used in the first place to generate hydrogen is recycled to the nature when the end users consume the hydrogen. In this chapter, we will discuss the different components of hydrogen energy systems in more detail.

## 3 Hydrogen Production, Distribution, and Delivery

### *3.1 An Overview on Hydrogen Production Methods*

There are many different methods and sources for producing hydrogen, a diversity seen as a unique feature and advantage of this gas (Verhelst and Wallner 2009). Hydrogen can be produced by using biomass, solar thermal water splitting, waste water, thermochemical cycles, fossil fuels through carbon capturing (e.g. steam reforming of natural gas), water electrolysis using electricity generated by renewables, and nuclear fission (Hoffman 2012).

Nuclear fission technology is very expensive (Andrews and Shabani 2012a); moreover, previous disasters such as at Fujishima in Japan (WNA 2014), the siting of any new nuclear reactor is likely to generate strong local community opposition. There is still no proven safe method of disposing radioactive wastes, which can have irreversible environmental impacts and harmful effects on human health. Hence, nuclear fission technology is arguably not a sustainable solution for hydrogen production. Carbon capture and storage would allow zero-emission production of hydrogen from fossil fuels such as natural gas and coal. But it is as yet unproven on a commercial scale, is likely to be very expensive, and the containment of the carbon dioxide stored in geological formations cannot be guaranteed in perpetuity. In countries with abundant coal resources (e.g. Australia), where this fuel is widely used in coal-fired power plants, hydrogen extraction from coal might be considered as an immediately available and a feasible solution. However, the low hydrogen to carbon ratio (0.6–0.7) (Hoffman 2012) of coal would make the hydrogen production through this process challenging and expensive. Such a situation together with implications associated with finding sufficient and reliable geographical locations to store the captured carbon is likely to render the economics of coal-fired power stations with carbon capturing and storage (CCS) quite unfavourable (Jacobson et al. 2011). Hydrogen production from some fossil fuels with high hydrogen to carbon ratios, (i.e. natural gas) through steam reforming, has proven to be a relatively economical method of hydrogen production, while gas prices remain low. However, as also mentioned by Hoffman (2012), steam reforming of natural gas is generally regarded as simply a bridging technology to introduce hydrogen into the energy market, until hydrogen production from renewable energy can take over.

### 3.2 Hydrogen from Renewables

The four major renewable energy avenues to generate hydrogen are shown in Fig. 2. Heat generated through renewable energy sources (e.g. concentrating solar thermal collectors) can be directly used to break water molecules into oxygen and hydrogen at high temperatures (i.e. >2200 °C or 800–1200 °C with catalysts). This heat can also be used to generate electricity and the electricity is used to power water electrolysis. Electrolysers can also be power through other renewable electricity technologies such as PV, wind, and hydro. Biomass is also another avenue towards generation of hydrogen that is done through reforming biomass products (e.g. reforming biogas). And finally hydrogen can be directly generated through photolysis.

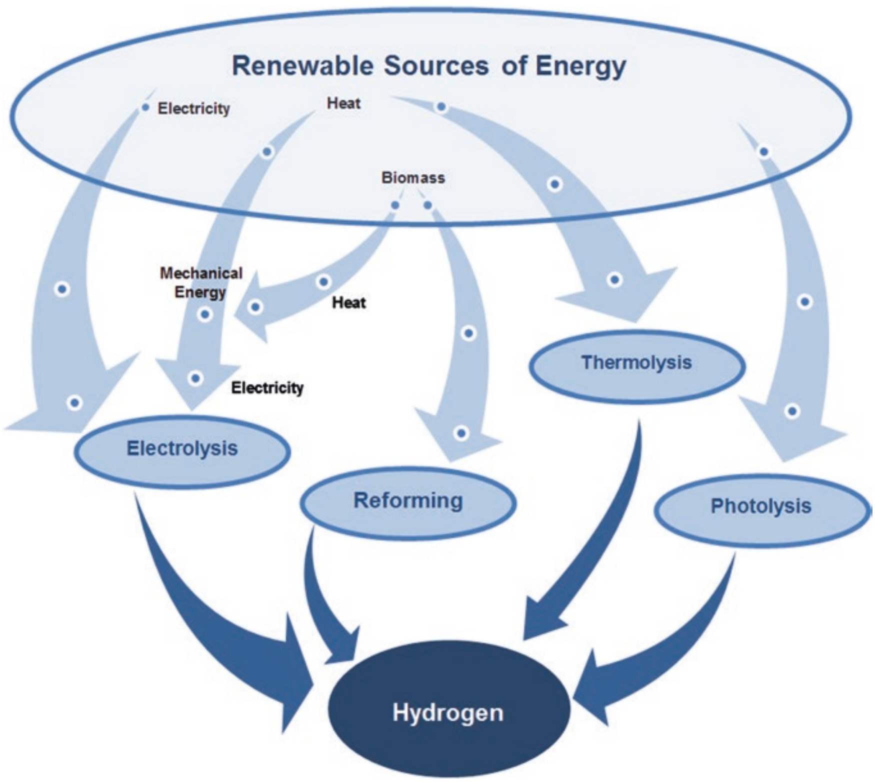


**Fig. 2** Hydrogen production routes through renewables

Zero-emission water electrolysis process powered by renewables can replace current economical methods such as steam reforming of natural gas if enough renewable energy sources are available and economically deployable (Andrews and Shabani 2012a). In estimating the availability of renewable energy resources for hydrogen production, the forecast growth in future energy demand, in particular to meet rises in material standards of living in developing countries, have to be taken into account (Kleijn et al. 2010).

The global primary energy demand is estimated to experience a considerable growth in the next few decades (IEA 2013). Hence, a massive growth in infrastructure is required to harvest additional renewable energy resources to meet this demand (Andrews and Shabani 2012a). Jacobson and Delucchi (2011) conducted studies to investigate the potential of main renewable energy resources, including wind, water, and sunlight in meeting the global energy demand. They showed in their study that the 2008 rate of energy consumption, 12.5 TW, which will increase to 16.9 TW in 2030 (without taking any energy efficiency measures), can be kept to about 11.5 TW (in 2030) by implementing cost-effective energy efficiency measures to their full potential. They showed that this lowered projected future demand can be entirely met by the electricity from renewables (mainly wind, water and sunlight), with hydrogen employed as an energy carrier and storage medium, by using only 1 % of the global land area. In the model developed by Jacobson and Delucchi (2011), wind turbines have the lion's share by potentially supplying 50 % of the total demand, concentrating solar thermal plants, and solar PV plants would supply 20 and 14 % of this total, respectively, followed by rooftop PV systems (6 %), hydroelectric and geothermal power (4 % each), and wave and tidal (1 % each).

## *3.3 Distribution and Delivery*

In the absence of extensive hydrogen distribution and delivery network, moving towards hydrogen as an alternative fuel may not seem to be viable. Different distribution methods have been taken into consideration such as using hydrogen pipelines (similar to what is currently practiced for natural gas) and bulk delivery of hydrogen using tube trailers (e.g. as compressed gas or liquid hydrogen) (Fig. 3). Hydrogen pipelines have been suggested by some to be an economic solution compared to other methods when it comes to transporting large quantities of hydrogen on continuous basis (Bockris 2013; DoE FY 2011). However, establishing national- or even state/provincial-wide hydrogen pipeline networks would require enormous capital. Special alloys for these pipelines to avoid hydrogen embrittlement must be employed, and there are significant technical challenges in keeping gas leakage to an acceptably low level. A blend of hydrogen and natural gas transferred through the existing natural gas network (i.e. 5–50 % hydrogen) is one of the interim solutions suggested (Melaina et al. 2013).

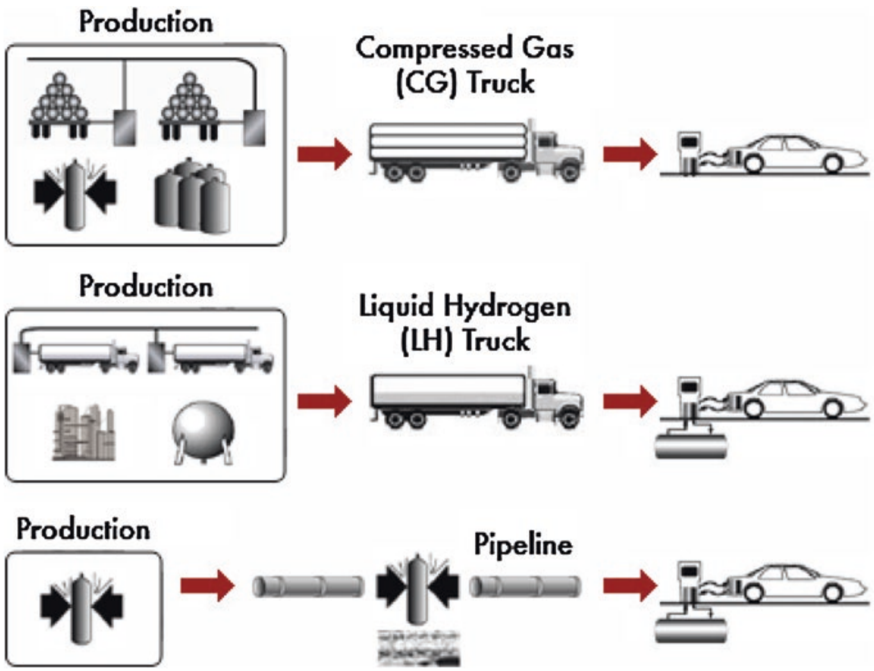


**Fig. 3** Hydrogen delivery pathways suggested by the US DoE (DoE 2014)

The cost and challenges associated with establishing an extensive hydrogen pipeline, storage, and distribution infrastructure form the basis of some policy-makers' opposition to hydrogen as an alternative transport fuel alternatively they favour battery electric cars charged using the existing grid. (Huétink et al. 2010), However, decentralised production of hydrogen and use of the existing electricity network can substantially shorten hydrogen distribution lines (Rifkin 2002; Sorensen 2005; McDowall and Eames et al. 2007; Dougherty et al. 2009; Andrews and Shabani 2012a) (Fig. 4). Potentially (and ideally), the only hydrogen distribution network required would be in major cities to transport hydrogen from bulk storage facilities to refuelling stations. In this scenario, hydrogen would be produced regionally and stored in medium-sized facilities for transport (e.g. by road tankers initially) to fuelling stations to refuel vehicles. Alternatively in some cases, hydrogen could be produced locally for direct use in refuelling stations. Major hydrogen production and storage facilities would be needed in major cities close to major ports and airports (for liquefied hydrogen). Further details about this approach have been discussed by Andrews and Shabani (2012a).

Investing in costly hydrogen refuelling stations is often seen as a high-financial risk until there are numerous hydrogen-fuelled vehicles on the roads. At the same time, the lack of refuelling infrastructure can make people reluctant to choose this

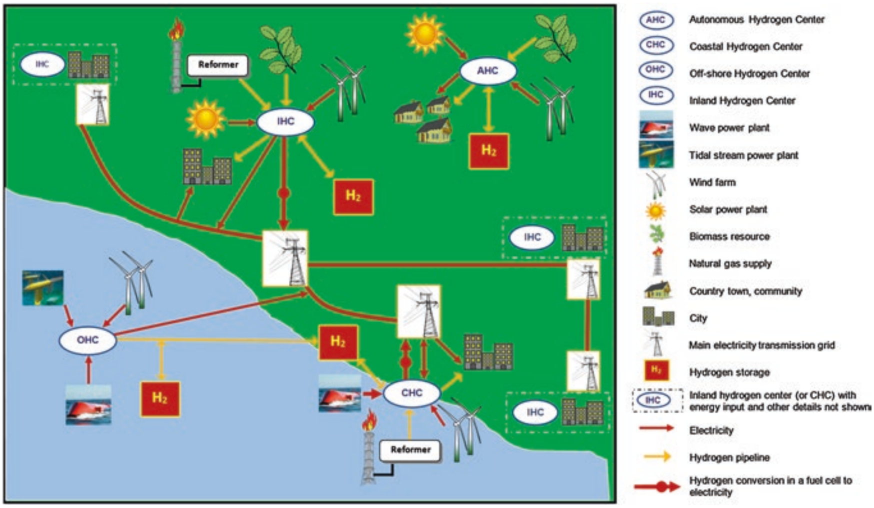


**Fig. 4** A schematic illustration of the proposed hierarchy of sustainable hydrogen centres showing the principal renewable energy inputs to each type of centre, the local hydrogen distribution system, and the interconnection of higher order centres via the main electricity grid (Andrews and Shabani 2012a)

technology (Farrell et al. 2003; Paolo 2007; Kim et al. 2008). This chicken-and-egg dilemma (which came first?) is one reason that car manufacturers have been reluctant to commercialise hydrogen vehicles (Paolo 2007; Zapata et al. 2010). Hydrogen fuelling stations supported by car manufacturers have been seen as one solution to this problem. For example, Daimler is now investing on building 100 hydrogen fuelling stations across Germany by 2017 with the plan to increase this number to 400 by 2023 (Braun 2013). Honda, whose hydrogen fuel call car the FCX Clarity is available for leasing, also offers a home-based hydrogen fuelling station in areas without access to larger scale fuelling stations (Fig. 5) (Blain 2007).


**Fig. 5** Home-based hydrogen refuelling solution supplied by HONDA

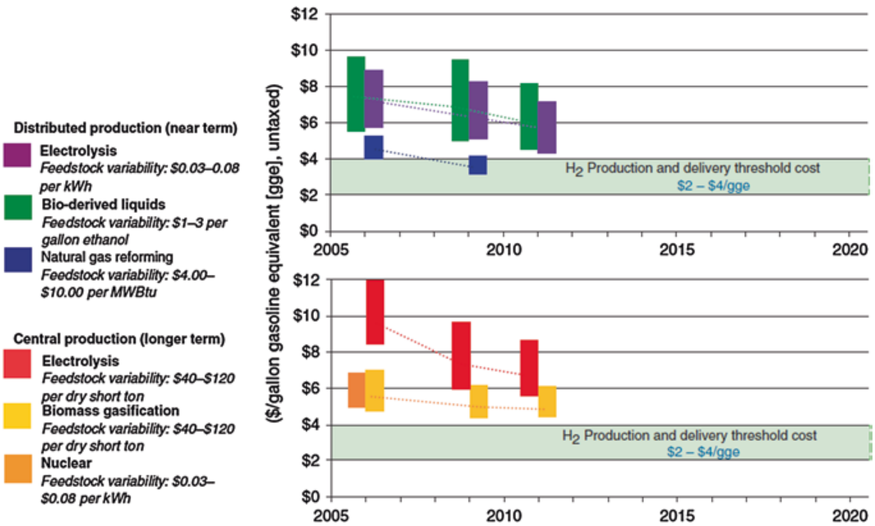


**Fig. 6** The estimated high-volume production and delivery costs for hydrogen produced from a range of distributed and centralised renewable energy, fossil fuel, and nuclear fission power sources (DoE 2013)

Some major questions remain unanswered about the economic competitiveness of hydrogen technologies, whether its production of hydrogen from renewables in a decentralised or centralised manner, bulk storage, transmission, and distribution of hydrogen, hydrogen fuel cell vehicles on land, sea, and in the air, and use of hydrogen storage on large-scale and smaller scale or micro grids for medium- to longer term storage to secure supply as the variable renewable energy contributions increase. Some evidence that hydrogen as a fuel is fast approaching economic competitiveness through technological development and economies of scale in production is provided in the US Department of Energy (DoE)'s report on its hydrogen research programme in the past (Dougherty et al. 2009) and more recently (DoE 2014). The US DoE's estimated ranges for the high-volume production and delivery costs for hydrogen produced from a variety of distributed and centralised renewable energy, fossil fuel, and nuclear fission power sources are provided in Fig. 6. These ranges are compared with what is called the 'hydrogen production and deliver costs range of 2–4 US$/gasoline gallon equivalent (gge), that is, 0.53–1.05 US$/L. However, in March 2013, the average US gasoline price was 0.93 US$/L, and the average European gasoline price was double this, that is, at about 2 US$/L. Hence, the threshold cost based on European petrol prices in Fig. 6 would be raised to around US$7/gge. On this basis, it can be seen that distributed production of hydrogen by electrolysis and biomass resources is close to being economic in the near term, and centralised production by electrolysis and biomass gasification will become clearly economic in the longer term. The IPCC7 report's reservations about the cost competitiveness of hydrogen produced by electrolysis using wind- or solar-generated electricity may therefore be quite readily addressed. The economics of hydrogen fuel cell vehicles and large-scale hydrogen-based energy storage systems from electricity grids will still need to be established as technology is further developed, commercialised, and deployed in high volumes.

# 4 Hydrogen Storage

## *4.1 Compressed Gas*

Storage of hydrogen as compressed gas remains the most common storage option, for both vehicular and stationary applications. Medium- to high-pressure vessels (~137 bar upwards) for stationary hydrogen storage have been used safely in industry for many decades. High-pressure hydrogen cylinders at pressures of between 350 and 700 bar are now the preferred on-board storage technology for hydrogen fuel cell vehicles. The Honda FCX Clarity, for example, uses a 170 l 350 bar (35 MPa) carbon–fibre composite tank to store around 4 kg of hydrogen, which gives the vehicle a driving range of between 450 and 600 km (HONDA 2014b). Existing 350 bar hydrogen gas tanks such as this have a gravimetric energy density of around 3.5 wt% (0.7 $kWh_e$/kg). Significantly, however, the new Toyota hydrogen fuel cell car to be released commercially in 2015 has a 700 bar carbon–fibre composite cylinders giving 5.7 wt% (1.135 $kWh_e$/kg) (Toyota 2014), which actually exceeds the 2017 US DoE target (Fig. 7). Research and development work is intensifying around the world to develop lighter weight and cheaper advanced composite 700 bar hydrogen storage tanks.

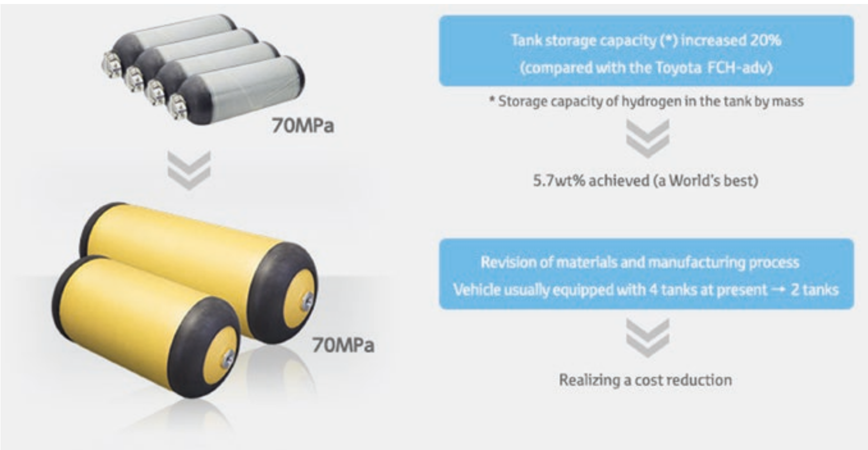


**Fig. 7** The new 700 bar compressed hydrogen tank, quoted as having a 5.7 wt% hydrogen storage capacity, to be installed in the new Toyota hydrogen fuel cell car (Toyota 2014)

The US DoE (2012) reported, for example, on achieving a lower cost compressed hydrogen tank through using carbonised fibre from low-cost textile-grade polyacrylonitrile blended with methyl acrylate co-monomer (Oak Ridge National Laboratory); and developing a pressure vessel design to achieve a 20 % reduction in carbon–fibre requirement.

There is growing interest in cryo-compressed hydrogen storage in sorbent materials such as metal organic frameworks (MOFs), synthesised composite metallic–organic materials with regular 3D structure and high porosity. Hydrogen is adsorbed on the extensive inner surfaces of the MOF when introduced as gas cooled to below 150 K and at a pressure in the order of 100 bar. The hydrogen is released on allowing the temperature of the vessel to rise towards ambient. Pacific Northwest National Laboratory in the USA has developed a relatively low-cost 135 cryo-sorbent type I vessel containing MOF-5 for hydrogen storage at 100 bar (DoE 2012). Northwestern University and NREL have been validating a hydrogen excess uptake of ~8 wt% at 50 bar and 77 K in a metal organic framework material (DoE 2012).

For stationary energy storage applications, the requirements for high gravimetric and volumetric energy densities for hydrogen storages are usually nowhere near so stringent as for vehicles. Often there is the space available for larger volume storages, and foundations that can support heavier storage systems, especially in many remote, stand-alone or backup power supplies where hydrogen storage is an excellent complement to a variable primary solar or wind energy supply system (Andrews and Shabani 2012a). Low to medium pressure, low-carbon steel or aluminium metal cylinders are commercially available for hydrogen storage at up to 100 bar. There is also the potential to use modified lightweight composite cylinders designed originally for LPG (mainly butane or propane) storage as hydrogen storages for stationary fuel cell supply systems. In such applications, it will generally be most practical and economic to employ a pressurising electrolyser so that hydrogen gas at up to 30 bar can be stored directly in such pressure vessels, without having to employ an electrically driven external compressor.

### 4.1.1 Metal and Chemical Hydrides

Another option is to store hydrogen in solid-state form as a hydride, with metallic or other elements. To charge the storage material, usually in the form of a fine powder, it is exposed to hydrogen gas under pressure. In practical systems, the pressure required is very much lower than the 350 bar or higher pressures used in compressed gas storages, typically 50 bar or lower, and sometimes as low as 5 bar. Hydrogen gas molecules are split into atoms at the surface of the metal or other host particles to form H atoms that diffuse into the body of the particles and occupy interstitial sites within the crystal lattices of the host. The reaction between the hydrogen atoms and host metal or other atoms is exothermic, so heat must be removed to the surroundings or via a cooling system during the formation of the hydride in the charge mode. To release the hydrogen stored as a gas once more, the outlet of the storage container is exposed to a much lower pressure, 5 bar down to 1 bar typically. The heat required to break the hydrogen-host atom bonds is provided by the surrounding atmosphere or by some form of active heating if a faster rate of supply is required.

Metals that have been used in metal hydride hydrogen storage systems include Mg, Ni, Al, Ti, Fe, Zr, and V, often with the addition of rare earth elements such as La, Ce, and Y to form alloys with enhanced hydrogen storage capacities. Alloy structures including $AB_5$, $AB_3$, $AB_2$, AB, $A_2B$, and $A_2B_7$, where A is a rare earth element and B is a metal, have all been investigated for their hydrogen storage potential.

There are a number of commercial suppliers worldwide of metal hydride storage canisters in sizes typically ranging from 1 to 100 g of stored hydrogen. Individual canisters can be assembled in banks to provide the total storage capacity required in a particular application. $AB_2$ and $AB_5$ alloys are often used in these commercial systems, yielding gravimetric energy densities of the storage material itself up to 1.6 wt%, although this reduces to around 1 wt% for the whole system including the canister and fittings (that is, around 0.2 $kWh_e/L$). Their volumetric energy density is around 37 g/L, or 0.74 $kWh_e/L$. Their cost per unit mass of hydrogen stored is also usually very high, because mainly of the high cost of the rare earth elements used.

Research is continuing into developing hydrides with much higher energy densities. For example, a lot of work is focussing on alane ($AlH_3$), a colourless solid with a theoretical wt% of around 10. Aluminium is relatively abundant and inexpensive. The H release temperature of alane at just over 100 °C is acceptable, but producing this hydride from hydrogen and aluminium requires high temperatures and pressures, and/or complex electrochemistry. Currently there is no low-cost energy-efficient process available for regeneration of alane after use (discharge of hydrogen).

Interestingly, the US DoE hydrogen programme report (2012) indicated that work on metal hydride systems was being terminated due to the low probability of these materials meeting the required properties in the 2017 time frame.

A number of non-metallic compounds have high hydrogen content that can be released when on mixing with other chemicals, such as water, acids, or alkalis. These 'chemical' hydrides have also been extensively investigated as hydrogen storage materials. Two prime examples are listed below:

- Ammonia borane (AB), $NH_3BH_3$, a colourless solid with a theoretical maximum 19.4 wt% H storage capacity, which would be very attractive. Freiberg Technical University, Germany, has shown that AB can release up to 12 wt% hydrogen when heated between 370 and 470 K. The challenges are the high cost of making AB, since the precursor borate minerals are not abundant and expensive, and considerable energy is needed to regenerate AB after release of hydrogen so that the system is not readily reversible.

- Sodium borohydride, $NaBH_4$, a white powder theoretically capable so storing up to 10.6 wt% H. Adding water to this compound in the presence of a catalyst produces hydrogen. Horizon fuel cells (2014) have a commercial system available for portable power supply for military personnel. But it requires energy to produce sodium borohydride, and the reaction product ($NaBO_2$) cannot readily be converted back to $NaBH_4$, so it is essentially a one-way process.

### 4.1.2 Liquid Hydrogen

Liquid hydrogen requires cryogenic temperatures down to 20 K and associated expensive cryogenic insulation and storage tanks. Considerable energy is required to cool hydrogen gas to this very low temperature and hence liquefy it, in the order of 17 % of the energy content of the hydrogen. It is technically difficult to maintain this very low temperature in a cryogenic vessel, since any heat ingress leads to a pressure increase, and hence the requirement to vent some hydrogen gas. The rate of hydrogen loss for cryogenic-liquid hydrogen storage, if used in a vehicle application, can be as high as ~40 % during a typical use cycle, equivalent to about 20 g/h for every 1 kg of hydrogen stored (Ahluwalia et al. 2012). Yet liquid hydrogen does have a high gravimetric energy density (around 6.5 wt%) and volumetric energy density (~35 g/L), although the very high energy densities of the liquid itself are offset to some extent by the mass and volume of the associated cryogenic storage vessel and associated equipment to maintain this exceptionally low temperature. Densities in the order of those provided by liquid hydrogen are probably essential if hydrogen is to be used as a substitute jet fuel. The most energy and cost efficient ways to produce and store liquid for this application are the subject of continuing research. In other sectors, in particular road vehicles, it is likely that liquid hydrogen will be too expensive to become competitive with other hydrogen storage options.

### 4.1.3 Novel Hydrogen Flow Batteries

A number of research teams are investigating novel electrical energy storage systems based on hydrogen, but which also incorporate flow battery characteristics. For example, Andrews and Seif Mohammadi (2014) at RMIT University in Melbourne, Australia, proposed the concept of a ‘proton flow battery’, and provided an initial experimental proof of concept. In the proton flow battery, a metal hydride storage electrode is integrated into a reversible proton exchange membrane (PEM) fuel cell (Fig. 8). During charging, protons produced from splitting water on one electrode are directly combined with electrons and metal particles in the other electrode to form a solid-state metal hydride as the energy storage. To resupply electricity, this process is reversed. This system eliminates the need for the production, storage, and recovery of hydrogen gas, which limits the roundtrip

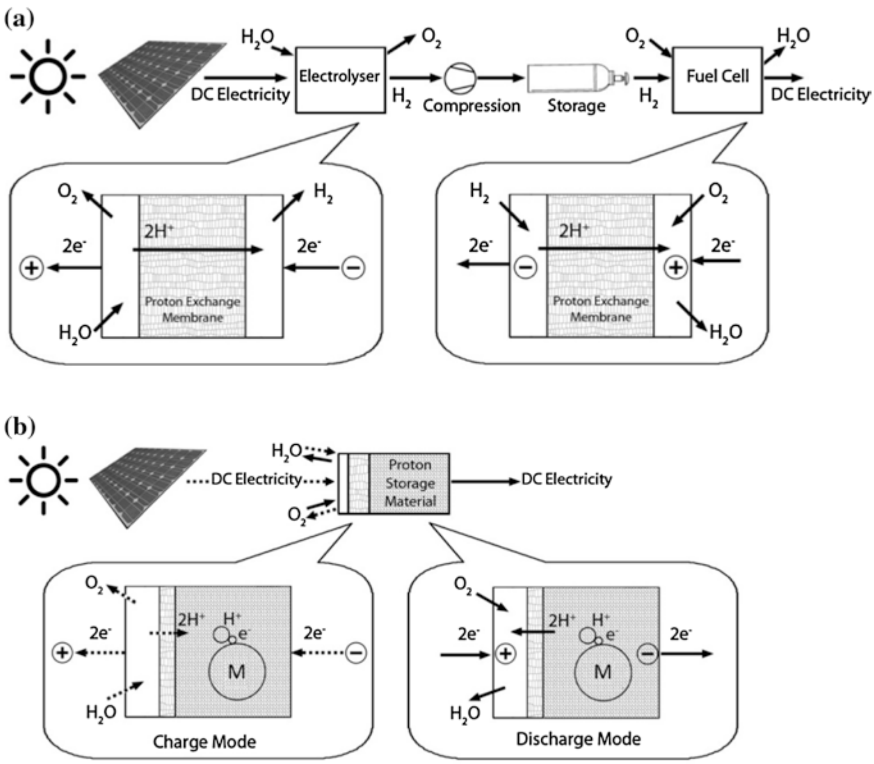


**Fig. 8** **a** The conventional system for storing electrical energy as hydrogen and then regenerating electricity, employing a separate electrolyser and fuel cell, and compression of hydrogen prior to storage. **b** The proposed new proton flow battery system employing a reversible fuel cell with integrated solid proton storage electrode. M represents a metal or carbon atom of the solid storage to which a hydrogen atom is bonded (Andrews and Seif Mohammadi 2014)

energy efficiency of conventional hydrogen-based electrical energy storage systems to below 45 % or less.

In principle, the proton flow battery combines the best aspects of hydrogen fuel cells and battery-based electrical power. It has the potential to have a higher energy density and be more economical than a lithium ion battery, since the source of protons—water—is much more abundant than lithium, which is produced from relatively scarce mineral, brine, or clay resources, and carbon for reversible hydrogen storage is widely available. The experimental results published to date are an exciting indicator of the promise of the concept, but a lot more research and development will be necessary to take it through to practical commercial application. The present research focus is on using porous carbon materials such as activated carbons, carbon nanotube, and graphene-based materials, as the hydrogen storage, rather than a metal hydride.

Yang et al. (2014) at the Loker Hydrocarbon Research Institute, University of Southern California, Los Angeles, USA, have developed and tested a novel Organic Redox Flow Battery (ORBAT) using two quinone-based water-soluble organic redox couples on the positive and negative side of a flow battery. During charging, protons from the oxidised form of the quinone move through a Nafion membrane as in a PEM electrolyser to be stored in the reduced form of another quinone passing through the other electrode. The authors claim that the properties of such redox couples make then very attractive for high-efficiency metal-free rechargeable batteries.

# 5 Hydrogen Fuel Cells

## 5.1 Operating Principles

A hydrogen fuel cell is a device that converts the chemical energy of hydrogen (using pure hydrogen or hydrogen-rich fuels such as natural gas) into DC electricity through an electrochemical reaction between hydrogen and oxygen leading to the formation of water. The DC electricity generated through this process can be used in a range of stationary and mobile applications. The electrochemical reaction in the fuel cell involves no combustion and needs no moving parts within the cell. This makes the process silent, efficient, and low maintenance. The maximum practical efficiency of fuel cells in electricity generation (up to ~50–60 % based on the high heating value of hydrogen) is much higher than that for internal combustion engines (~30–35 %). But still some heat is generated as by-product. If this heat is utilised as well as the electricity generated, the fuel cell can be used for combined heat and power applications with an overall efficiency of up to 80–90 %. Later in this chapter, we will further discuss how this efficiency is calculated.

The overall chemical reaction between hydrogen and oxygen in the fuel cells that leads to generation of electricity and heat can be described as below:

$$H_2 + 0.5O_2 \rightarrow H_2O \tag{1}$$

This core chemical reaction between hydrogen and oxygen in a fuel cell is expanded to take account of the real case when air is used instead of oxygen, and extra air and hydrogen, above the stoichiometric quantities, are fed into the fuel cell (Shabani et al. 2010a):

$$\lambda_{\text{hydrogen}} H_2 + \lambda_{\text{air}} \left( 0.5O_2 + \frac{3.76}{2} N_2 \right) \rightarrow H_2O + \frac{(\lambda_{\text{air}} - 1)}{2} O_2 + \frac{3.76}{2} \lambda_{\text{air}} \cdot N_2 + \left( \lambda_{\text{hydrogen}} - 1 \right) H_2 \tag{2}$$

where $\lambda_{\text{air}}$ and $\lambda_{\text{hydrogen}}$ are the air and hydrogen stoichiometric coefficients, respectively. The extra hydrogen and air (mainly nitrogen) leave the fuel cell

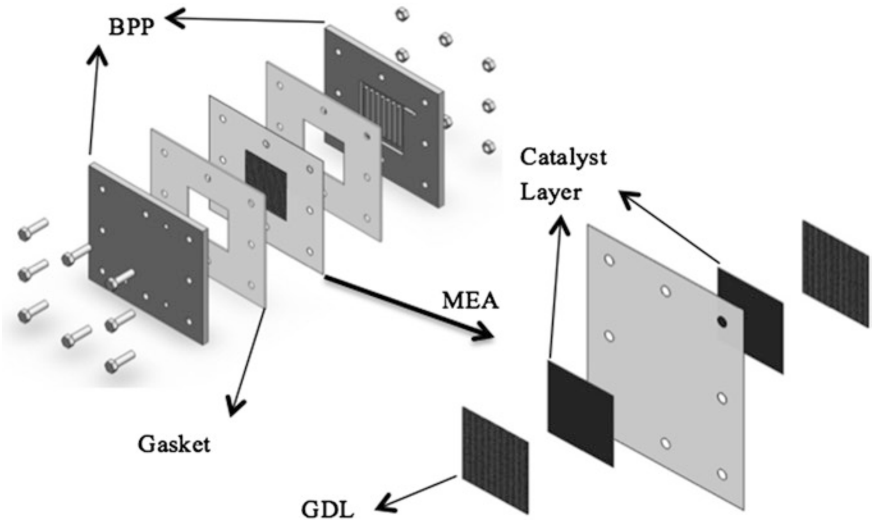


**Fig. 9** Schematic exploded view of a single fuel cell comprising membrane electrode assembly (MEA), gadgets, and bipolar plates

without taking part in the reaction. These gases just absorb heat and reject it the fuel cell (usually less than 5 % of the total heat generated by the fuel cell).

A fuel cell comprises four key components: cathode (air side or the positive pole), anode (hydrogen side or the negative pole), electrolyte that is a media for the mobile ions to travel between the electrodes, and bipolar plates that provide space for the gas flow channels for the supply of air (oxygen) and hydrogen to the electrodes as well as the circulation of a coolant in liquid-cooled fuel cells (Fig. 9).

Bipolar plates (Fig. 9) have important roles to play in a fuel cell stack. They collect the current and pass it through the individual cells. Accurate supply and uniform distribution of hydrogen and oxygen (air) gases are achieved through the gas flow channels created within inside the bipolar plates. Bipolar plates are also home for the coolant flow channels in liquid-cooled fuel cells. These plates are to be made from materials with high thermal and electrical conductivities to appropriately facilitate the thermal management of the stack and suggest minimum ohmic resistance against the flow of electrons. Bipolar plates are exposed to oxidation and hence their material should have a reasonable level of resistance against corrosion. These plates are responsible for about an average of 80 % of the total mass of fuel cell stacks. This gives the opportunity of using lighter materials while considering other properties required for their desirable performance. And last but not the least is the cost as another factor for consideration when choosing the materials for bipolar plates. Graphite is commonly used for making bipolar plates. However, this brittle material is always prone to physical failure. Their porous nature suggests that they have to be made thick to allow minimum permeation of reactants that could make the stack heavy. Graphite-based bipolar plates can be made by machining process only that suggests a high manufacturing cost. These days, composite materials and metal alloys receive more attention for use in bipolar plates (Wilkinson et al. 2009).

There are different types of fuel cell, depending on the electrolyte and the mobile ions used to create the reaction described by Eq. 1 (Larminie and Dicks 2003). Proton Exchange or Polymer Electrolyte Membrane Fuel Cell (PEMFC) is the most common type of fuel cell used in a range of applications. In this type of fuel cell, a Teflon-type solid polymer with a hydrophobic side chain (i.e. sulphonic acid, $HSO_3$) is used as electrolyte. PEM also stands for polymer electrolyte membrane since the electrolyte is a good proton conductor. The hydrophobic property of the Teflon helps repel the generated water while the hydrophilic property of the side chain creates a hydrated region and makes a diluted acid with weak attraction between $SO_3^-$ and $H^+$ ions, such that the $H^+$ ions can easily move ($H^+$ conductivity) through the membrane. Once the hydrogen molecules reach the membrane, only the $H^+$ ions can move through and the electrons should follow an external circuit to join the $H^+$ ions and oxygen molecules on the other side of the membrane. This is where water is generated while the movement of electrons through the external circuit is the very flow of electricity that the fuel cell generates. Most PEMFCs operate at relatively low temperatures (e.g. 50–100 °C), the reason for quick start-up of this type of fuel cell. By using solid electrolyte, this type of fuel cell is not sensitive to orientation with respect to gravity. Platinum catalysts are used on both electrodes of a PEMFC, a significant contributor to the total cost of the cell. Hence, platinum loadings have been reduced continuously, from 28 mg/$cm^2$ in the 1960s down to about 1 mg/$cm^2$ today, in an effort to reduce costs. The long-term target set by the US DoE for PEMFCs achieves a high-performing cell with only 0.2 mg/$cm^2$ by 2017 (DoE 2013). Platinum catalysts are very sensitive to impurities such as CO, which makes the use of fuel cells in polluted areas quite challenging technically, since incoming air has to be near perfectly filtered. In a separate line of research, there has been considerable progress in using low-cost metal-free catalysts (ScienceDaily 2013).

In phosphoric acid fuel cells (PAFCs), the anode and cathode reactions in PAFCs are very similar to those in PEMFCs with $H^+$ ions passing through the electrolyte. However, liquid phosphoric acid is used as electrolyte in this type of the fuel cell, which restricted the application of this type of fuel cell to mainly stationary applications. The maximum electrical and CHP efficiencies of PAFCs have been reported to be 42 and 85 %, respectively (Larminie and Dicks 2003).

Direct methanol fuel cells (DMFCs) can use methanol ($CH_3OH$) as a hydrogen-rich fuel rather than pure hydrogen. DMFCs suggest fewer challenges for storing and transporting of fuel, as methanol can be stored in liquid form at atmospheric pressure while its volumetric energy density is just more than 3.5 times higher than that for hydrogen when stored at 600 bar of pressure. DMFCs appear to be a possibly promising solution for portable applications such cellular phones and laptop computers, and a number of manufacturers are already introducing commercial versions of these applications. However, DMTCs are not zero-emission devices while in operation as they emit $CO_2$.

Alkaline fuel cells (AFCs) use a solution of potassium hydroxide (KOH) and water (alkaline) as electrolyte in this type of fuel cell. While the electrical efficiency of this type of fuel cell is quite high (up to 60 %), their lifetime is short, mainly due to their sensitivity to impurities such as carbon dioxide. This disadvantage has been the key barrier against the wide commercialisation of this type of fuel cell. The mobile ions in the type of fuel cell, moving from the oxygen side to the hydrogen side, are $OH^-$. The new generation of this type of fuel cell can operate at temperatures as low as just less than 30 °C while the earlier operated in the range 100–250 °C (Larminie and Dicks 2003).

Molten carbonate fuel cells (MCFCs) operate at relatively high temperatures of about 650 °C that gives them the capability of using hydrogen-rich fuels such as natural gas and coal without any need to external reformers. This ability also makes them suitable to be employed in natural gas and coal power plants where carbon capturing arrangement is in pace. The high operating temperature also provides the opportunity of employing non-precious materials and less sensitivity to CO impurities, although they are still sensitive to sulphur impurities of coal. The high operating temperature leads to a long start-up time, which is a reason that they are more suitable for stationary base-load power supply applications. The electrolyte used in this type of fuel cell is a molten carbonate salt mixture suspended in a porous, chemically inert ceramic lithium aluminium oxide ($LiAlO_2$) matrix. The mobile ions within the electrolyte in this type of fuel cell are ${CO_3}^{2-}$ groups. The electrical and CHP efficiency of MCFs are up to 60 and 85 %, respectively.

Finally, there are solid oxide fuel cells (SOFCs) that operate at high temperature of about 1000 °C, which gives this type of fuel cell; many of those characteristics already listed for MCFCs. The high operating temperature implies the use of specific safety measures such as employing thermal shields. The high quality of heat, generated by this fuel cell, makes it also suitable for a wide range of residential and industrial thermal applications when they are used as CHP units. The electrolyte of SOFCs is made of special type of ceramic to allow the movement of $O^{2-}$ ions.

The maximum theoretical open-circuit voltage (no load connected) of a single cell based on the high heating value (HHV) of hydrogen, and assuming that the entire energy content of hydrogen turns into electricity, is about 1.48 V (small variation is expected at different pressures and temperatures). However, the basic thermodynamics equations suggest some entropic heat generation even in an ideal reaction between hydrogen and oxygen with no irreversibilities. Considering this, the maximum theoretical open-circuit voltage is calculated to be about 1.23 V with small variations with pressure and temperature. In practice due to inherent irreversibilities associated with this reaction, the open-circuit voltage of a single cell is even less by being about 0.9–1 V. To achieve a higher level of voltage, singles cells are stacked together. It is important to note that the area of the cell has nothing to do with this voltage, while the capacity of the cell to pass the electrical current is determined by this area. A number of cells are stacked together in series in order to achieve a higher level of voltage and power (Fig. 10).

Different types of irreversibility occur as current is drawn from the fuel cell. These losses result in a lowering of the voltage that forms the V–I characteristic

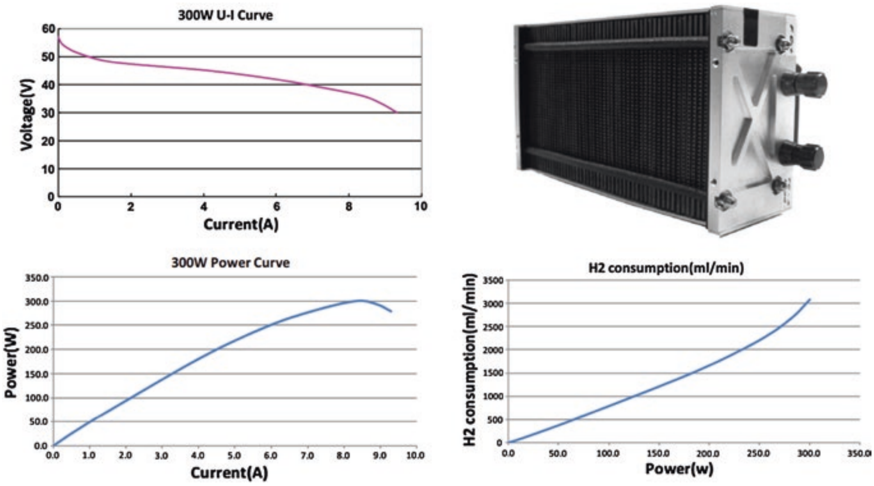


**Fig. 10** Performance curves of a 300 W PEM fuel cell (a stack of 72 cells in series) manufactured by Horizon Fuel Cell Technologies (Horizon 2014)

curve (also known as polarisation or overpotential curve) of the cell/stack similar to what is described in Fig. 10. This polarisation curve can be translated into a power versus current curve (Fig. 10) that is usually provided by the manufacturer. This curve together with the hydrogen consumption curve is used to evaluate the performance (i.e. efficiency) of a fuel cell (Fig. 10). The main reasons behind the fuel cell voltage drop include fuel crossover through the membrane (also called internal current); activation overpotential that is linked to the energy used to get the reaction going on one particular direction; ohmic losses are due to the resistance of the components against the flow of electrons (e.g. the cells interconnections) as well as the resistance of the membrane against the flow of $H^+$ ions; and finally, concentration losses happens due to the low concentration of oxygen supply at high currents. This type of loss is more pronounced when air is used rather than pure oxygen. Increasing the air supply can reduce the concentration losses; however, too much excessive air may not be recommended as it makes the membrane dry. A dry membrane does not provide an appropriate ground for the $H^+$ ions to travel between the electrodes. These irreversibilities determine the efficiency of the fuel cell at any operating points. The efficiency can be calculated by having the performance curves as shown in Fig. 10. For example, the efficiency of the fuel cell shown in this figure at 200-W operating can be calculated follows:

- Calculating the mass flow rate of hydrogen being consumed at this point: In this case, the volume flow rate at standard condition (273 k and 101.3 kPa) is given as ~1.75 standard litre per minute (SLPM). Using the idea gas low (PV = mRT) and using 4127 J/kg °K for the hydrogen gas constant, the mass flow rate can be calculated to be $9.4 \times 10^{-3}$ kg/h.

- Calculate the rate of energy supplied to the fuel cell through the inlet stream of hydrogen, by considering the HHV of hydrogen (~40 kWh/kg). It is calculated to be 376 W in this case.
- Now the efficiency of the stack can be calculated by dividing the power output (200 W) by the rate of input energy (376 W) that is worked out to be about 53 % in this case.

## *5.2 Examples of Applications*

### 5.2.1 Stand-alone and Backup Power Supply Applications

Recent advances in hydrogen-based technologies (e.g. fuel cell, electrolyser, and hydrogen storage) make hydrogen a suitable energy storage option for a wide range of stand-alone and grid-connected power supply systems (DoE 2010). The competitiveness of hydrogen storage is enhanced particularly where a longer term (i.e. season to season) and highly reliable storage solution with minimum environmental impact and maintenance needs is required. Hydrogen-based systems can obviate the need for bulky and expensive battery energy storage systems (Cotrell and Pratt 2003; Blanchard 2007; Gómez et al. 2009; Shabani et al. 2010a, b; Andrews and Shabani 2012b), normally used in remote power supply applications to store energy. Stand-alone and backup (e.g. in grid-connected areas with substantial power interruption periods) power supplies required by wireless stations such as Fire Contingency Network (FCN) and mobile network or power supply to isolated farms and households with poor (unreliable) to no connection to the main grid are examples of such applications. Hydrogen can be transferred to the site or generated onsite using the excess electricity generated by the renewables employed in the site (Cotrell and Pratt 2003; Shabani et al. 2010a, b, 2011; Andrews and Shabani 2012b). An example of the latter is given in Fig. 11, where a photovoltaic array supplies the load directly when primary solar energy is available, thus removing the dependence on transported fuel. Surplus electric power over the load is routed to a solid-state PEM electrolyser to generate hydrogen for storage and reuse at times when insufficient primary energy is available, such as at night and under cloud or smoke cover. The stored hydrogen is transformed back to electricity in a PEM fuel cell when needed to maintain a continuous power supply, such as during night-time, rainy, cloudy, or smoky conditions. Apparently, this arrangement can complement the battery storage used in the site as it mainly meets the long-term energy storage requirement of the site while the battery may only be efficient when used to store electrical energy for a shorter period (e.g. diurnal storage is required).

Hydrogen-based energy storage and supply arrangements can be preferred over conventional energy storage and power supply arrangements such as battery systems with or without diesel generator backup for the following reasons:

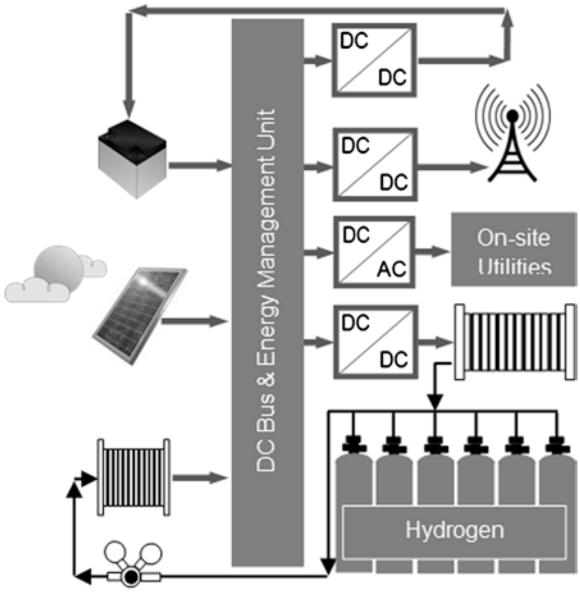


**Fig. 11** Schematic of an off-grid electricity supply based on photovoltaic primary energy with using hydrogen as long-term energy storage and battery to meet the short-term energy storage requirements and also acting as a buffer. The presence of a small battery bank may add to the overall cost of the system while offering additional reliability of supply (Shabani and Andrews 2015)

*Reliability*: Battery health status is always difficult to predict, particularly in harsh environments (too cold or too hot) (Dantherm 2009a, b). Diesel generators may be employed to backup batteries (Dantherm 2009a, b) and achieve a higher reliability; however, there are some degrees of unreliability associated with these technology as well, particularly in harsh climatic conditions or bush fires (Argumosa and Schucan http://www.ieahia.org/pdfs/FIRST.pdf; Varkaraki et al. 2003; Saathoff 2004; Dantherm 2009a, b; Saathoff 2010; Fosberg 2011; Bezmalinović et al. 2013).
*Operation and maintenance (O&M) costs*: Fewer moving parts, possibly no need for external supply of fuel (in case of onsite generation of hydrogen), and less maintenance visits (Varkaraki et al. 2003; Saathoff 2004; DOE 2010; Saathoff 2010; Bezmalinović et al. 2013; DoE 2014; Jiménez-Fernández et al. 2014) are seen as advantages for hydrogen systems. The low O&M costs lead to reducing the overall lifecycle costing of the system (Saathoff 2004, Saathoff 2010). This advantage is in particular more pronounced in relatively small systems (e.g. <5 kW telecommunication sites with few kWh of usage per day) located in hard-to-access areas (e.g. remote area power supply) over long duration of operation (i.e. >8 h per day) (Dantherm 2009a, b), since the long-term cost of system is more about the O&M costs rather than the initial capital cost of the system. Mainly due to the high capital and maintenance costs of batteries, using hydrogen-based energy storage arrangement provides opportunities for the whole power supply system to be cheaper than the alternative systems employing batteries as both long-term and short-term energy storage. The stand-alone remotely located sites

with no easy access have to be regularly visited for maintenance purposes if using batteries to store energy, disregarding the size of the load to be supplied. Diesel generators that often accompany the batteries to improve the reliability of the system and lower the size of the battery system; these generators add considerably to O&M costs since it is expensive to transport diesel fuel to the sites. Moreover, the supply of diesel fuel cannot be guaranteed at all times (e.g. under fire events), while more hydrogen can be produced if required.

*Lifetime*: Fuel cell power supply systems are usually designed to operate for approximately ten years while battery banks may need total replacement every three to five years (Dantherm 2009a, b, DOE 2010). Moreover, the hydrogen equipment lifetimes (i.e. fuel cell and electrolyser) are more predictable than batteries.

*Simplicity and scalability*: Considering the balance of the plant and the moving parts, the fuel cell systems are generally much simpler than diesel generators. Moreover, fuel cells are easily scalable (DoE 2014).

*Environmental impacts and risks: Both batteries and diesel generators are not regarded as environmentally friendly components due to issues with end-of-life waste management for batteries and of course exhaust emissions of diesel generators such as unburned hydrocarbons (HCs), CO and* $CO_2$, $SO_2$. *(Dantherm 2009a, b; Bezmalinović et al. 2013). Noise is another environmental impact for consideration; hence, the noiselessness of fuel cell systems can be regarded as another environmental advantage of this technology over diesel generators (DOE 2010; Bezmalinović et al. 2013). Also, high operating temperature of diesel generators and the explosion risk of batteries when overheated (e.g. during hot summer days) are other potential risks for consideration, especially in fire-prone areas where environmental and financial consequences of even a single fire incident are enormous (Dantherm 2009a, b; Bezmalinović et al. 2013).*

A range of factors must be considered when sizing of hydrogen-based energy storage systems. These factors include the site location and renewable energy input (or grid availability in case of using hydrogen for backup power supply in grid-connected areas); ambient conditions (e.g. temperature); electrical load profile; heating and cooling demands of the site; the performance of the individual components used in the system; and the level of reliability expected for the site (e.g. the number of days of autonomous operation). The energy storage behaviour (i.e. the variation of the hydrogen level in the tank or the batteries state of charge) is the best indicator to find out if the system operates sustainably. Figure 12 shows an example of the behaviour of a hydrogen and battery energy storage arrangement sized for a FCN site in Melbourne (Australia) area in which a solar PV array is used as the primary source of supply, and hydrogen and battery systems take care of the long-term and short-term energy requirements of the system, respectively. The system is designed for less than 0.5 kW of power requirement and a maximum daily demand of 1–4 kWh (low to high incident seasons) and maximum 10 days of autonomous operation (with no more than three days on batteries). The

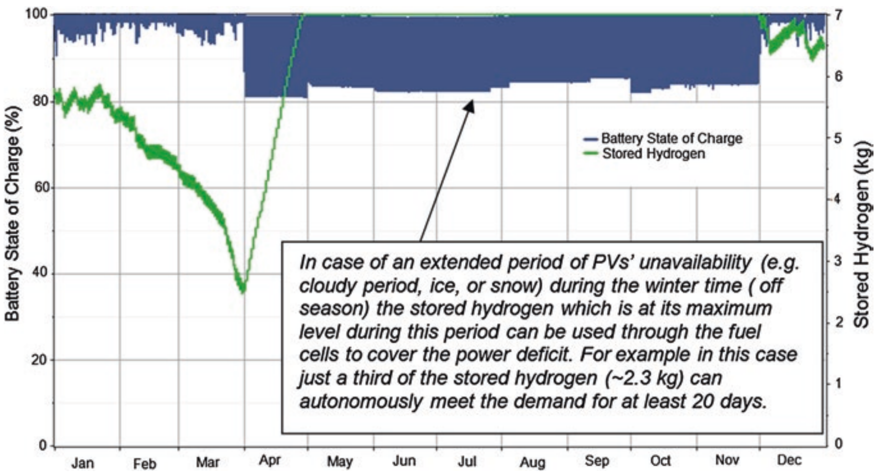


**Fig. 12** The variation of hydrogen level and battery state of charge in a solar-hydrogen-battery system sized for a FCN site (Shabani and Andrews 2015)

final levels of hydrogen in the tank, at the end of the year, are designed to be kept slightly above its initial level to allow for unexpected unavailability of the renewable source used in the system throughout the year. For the same reason (i.e. allowing for the system to operate autonomously if required), and also to maintain the supply pressure when the hydrogen level in the tank is low, the minimum level of hydrogen in the tank is kept reasonably (depending on the number of days of autonomous operation) above zero. The batteries come into play during the winter when the fire emergency system is rarely used and the system's energy demand is more short term. The minimum state of charge for batteries is kept to be above a certain level recommended by the manufacturer, even after a few days (e.g. three days) of autonomous operation.

If more than one solution satisfies the storage requirement of the system in terms of continuous supply of power, further optimisation is required by considering other factors such as the economic performance of the system, its social and environmental impacts, or the level of reliability expected. Future optimisation might be conducted on the selected system at an operational level (i.e. defending the best operational and controlling strategy). Methods such as artificial neural network (ANN) and genetic algorithms (GA) are used for system sizing and optimisation. There are commercially available computer simulation tools which are commonly used to evaluate performance of power supply and energy storage (e.g. hydrogen-based) systems. These tools can usually perform optimisation procedures to help users find the best possible power supply solutions and arrangements. HOMER, TRNSYS, hybrid power system simulation model (HYBRID2), general algebraic modelling system (GAMS), optimisation of renewable intermittent energies with hydrogen for autonomous electrification (ORIENTE), H2RES, hydrogen energy models (HYDROGEMS), remote area power supply simulator (RAPSIM), simulation and optimisation model for renewable energy systems (SOMES), and iHOGA are examples of computer simulation tools used for these purposes.

### 5.2.2 Combined Heat and Power Applications

As a consequence of the entropy change between products and reactants and the second law of thermodynamics, the efficiency of the fuel cell in converting the hydrogen energy into electricity is not 100 %. Part of the hydrogen's energy content appears in the form of heat rather than electricity. However, during a healthy operation for the fuel cell, part of this heat is used by the fuel cell internally to vaporise the water product. The rate of heat generation by the fuel cell, $Q^{\bullet}_{\text{total}}$, is calculated by using the difference between the electromotive force (EMF) of a fully efficient cell (e.g. about 1.48 V for a PEM fuel cell) and the actual voltage of a single cell at a particular current. The energy content of the hydrogen reacted inside the fuel cell ideally has to be converted to electrical energy. Any inefficiency in this conversion appears in the form of heat. In PEM fuel cells for example, the heat generated by the fuel cell stack can be calculated using the following equation:

$$Q^{\bullet}_{\text{total}} = n.S.j_{\text{cell}}\left(\text{EMF}_{(100\ \%\ \text{efficient cell liquit water})} - V_{\text{cell}}\right) = n.S.j_{\text{cell}}(1.48 - V_{\text{cell}}) \quad (3)$$

where $V_{\text{cell}}$ is the output voltage of a single cell with an effective area of $S$ at the current density of $j_{\text{cell}}$. The voltage of the fuel cell, $V_{\text{cell}}$, can be calculated theoretically, e.g. using the Butler–Volmer equations (Doddathimmaiah et al. 2009), or measured experimentally.

It is important to note that part of the fuel cell heat can be removed as sensible heat by the extra hydrogen and air (including its water content) in the exit stream of the fuel cell. This amount mainly depends on the air and hydrogen stoichiometry, although it is usually less than 5 % of the total heat generated for the normal ranges of stoichiometries used (Shabani et al. 2011). However, this form of heat removal can be considerable if higher stoichiometries of air are used for running the fuel cell. Considering the heat used internally by the fuel cell and the small portion that is removed by the extra reactants, the extractable hat from the fuel cell, is more or less about 30 % less than the total heat generated by the fuel cell (Shabani et al. 2011) (Fig. 13). Figure 14 shows the Sankey diagram of a 500-W PEM fuel cell (manufactured by BCS) (BCS 2009) obtained experimentally at its 5 A operating point (Shabani et al. 2011).

By capturing the fuel cell heat and using it in a heating application, the fuel cell becomes a combined heat and power (CHP) system with overall efficiencies in the range of 60–85 % (Gigliucci et al. 2004; Shabani et al. 2011). The heat collected from the fuel cell can be utilised for variety of applications such as space heating and cooling (i.e. through an absorption chiller) (Sossan et al. 2014), hot water supply (Shabani et al. 2010b), enhancing the release rate of hydrogen from

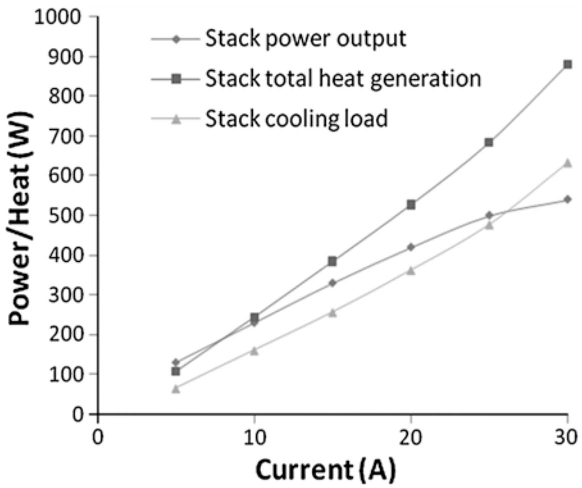


**Fig. 13** Theoretical investigation on a 500 W (540 W maximum power) PEM fuel cell stack manufactured by BCS

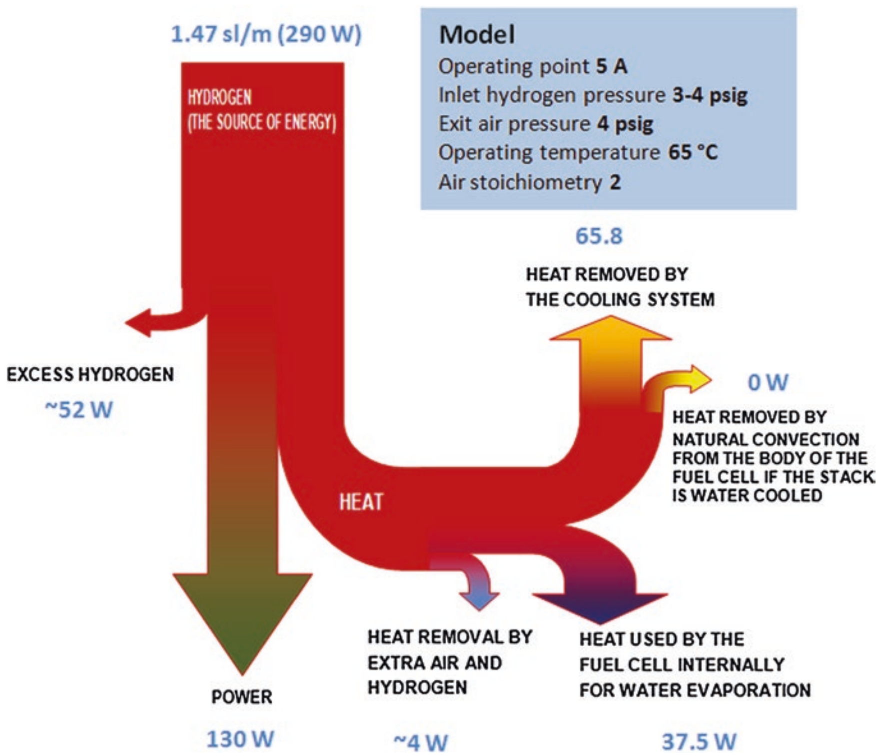


**Fig. 14** A Sankey diagram of a 500 W fuel cell (manufactured by BCS) at 5 A operating point, theoretical and experimental study

metal hydride hydrogen storage systems (Lee et al. 2013), preheating the fuel cell inlet air, particularly for applications in harsh climate conditions (e.g. remote telecommunication applications in extreme cold climate conditions), and etc. Fuel cell CHP systems range widely in terms of power output, i.e. from micro-CHP applications (usually 0.5–5 kW PEM fuel cells), used for small businesses or small-scale residential applications (Fig. 15), to large-scale CHP applications (electrical power output of 100 kW–2.8 MW) (e.g. 1 MW), used in apartment complex buildings, hotels, hospitals, or factories. Depending on the quality and the amount of the heat required (based on the range of the temperature—i.e. from less than 100 to 1000 °C), different types of fuel cells are used.

Fuel cell CHP systems also offer better flexibility for packaging than conventional gas engine or turbine cogeneration units, since fuel cells can be manufactured in almost any shapes (Panasonic 2011).

The fuel cell CHP market is growing rapidly (Carter et al. 2013); however, the share of this technology in the market is still smaller than that for conventional technologies. This is one of the key reasons behind the relatively high cost of this technology compared to conventional ones such as natural gas engines and gas turbines (Brooks et al. 2013).


**Fig. 15** 2011 model Panasonic micro-CHP unit (750 W) (Panasonic 2011)

### 5.2.3 Vehicles Applications

Globally, the future of road transportation will have a crucial bearing on efforts to move towards a sustainable energy strategy. Such a strategy must on the one hand address the severe constraints on greenhouse gas (GHG) emissions imposed by the imperative to avoid catastrophic climate change, and on the other guarantee energy security in the face of declining low-cost petroleum resources. On average, more than 90 % of the global transport sector relies on oil (van Vliet et al. 2011). Transportation alone consumes around 49 % of oil production and is the most rapidly growing consumer of the world's energy (1.5 % growth per year) (Amjad et al. 2010). The situation seems to be alarming when combined with even the most optimistic projections about the peak oil (Aftabuzzaman and Mazloumi 2011) predicting that the oil production would reach its peak of 106 mb/day in 2030. Moreover, according to recent IEA figures (IEA 2014), the transport sector is the second-largest source of GHG emissions at the global level, by emitting about 7000 Mt $CO_2$ (in 2011) into the atmosphere, representing 22 % of global $CO_2$-e emissions, with road transport as the largest contributor (about 5200 Mt $CO_2$-e).

Hydrogen is a carbon-free fuel that can be manufactured by using renewable sources of energy. This can address the concerns about the future supply of fossil fuels to the transportation sector and also the current and long-term impact of GHG emissions associated with excessive use of such fuels in this sector. There are two main approaches to employ hydrogen in transportation sector: internal combustion engines (ICEs) running on hydrogen and electrified vehicles with hydrogen fuel cell-based propulsion systems.

As discussed before, following the story of egg and chicken situation with hydrogen fuel cell technologies for vehicle applications, that is linked to uncertainties around the widespread availability of hydrogen refuelling infrastructure in a foreseeable future, the car manufacturers were generally hesitated to take risk by heavy investment on a massive shift towards hydrogen fuel cell technologies. That is why some of them (e.g. BMW and Ford) started put their focus on currently available, well-developed, established (at both manufacturing and maintenance levels), and cost-effective ICE technology, as a bridging technology to use hydrogen with the hope to encourage investments on hydrogen distribution and refuelling infrastructure (Fig. 16).

Although some properties of hydrogen (e.g. high octane number: +130) offer opportunities for improving the performance of Spark Ignition (SI) ICEs from the emission (i.e. GHGs), performance and energy point of view (Vancoillie et al. 2012), at the same time, some other properties of this fuel pose some technical challenges. Low power density and volumetric energy density (due to lean mixture); high level of $NO_x$ emission due to high combustion temperature; and abnormal combustion, surface ignition, and backfiring mainly due to wide flammability range, low ignition energy, and high-flame speeds are some of these technical challenges that researchers and car manufacturers (who started to look at this idea) faced with them (Verhelst and Wallner 2009).


**Fig. 16** One of the ICE-based hydrogen cars trialled by BMW in the past (HydrogenMotor 2007; TMR 2007)

Hydrogen fuel cell technology is another option being considered for powering future vehicles. The IPCC's 2012 special report on the role of renewable energy in climate change mitigation (IPCC 2014) included HFCVs in the mix of favoured options for lowering emission intensity in the road transport sector, along with biomass, hybrid petrol-electric, and battery electric vehicles (BEVs). Fuel cells are up to twice as efficient as an ICE in converting hydrogen energy to mechanical power (Mock and Schmid 2009; Hoffman 2012). That is why the range that can be provided by hydrogen fuel cell systems is roughly double compared to that can be achieved by hydrogen-based ICEs with the same amount of hydrogen stored on board (Sterling 2012). Since in a fuel cell the chemical energy content of hydrogen is converted to electricity, electrified power-train should be employed in hydrogen fuel cell vehicles (HFCVs). Feasibility of employing hydrogen fuel cell as a propulsion system has been studied and demonstrated in different transportation means including, two and three wheelers and scooters used for personal transport, passengers cars, vehicles used for public road transport (e.g. buses and taxis), heavy-duty trucks for goods transportation, boats, forklifts, and locomotives (Hoffman 2012; Shabani et al. 2012; Singh 2012; Sterling 2012). Most major automotive companies, manufacturing passenger cars, have shown their interest in hydrogen fuel cell cars by developing demonstration models of their popular products running on hydrogen (HydrogenCarsNow 2014a). HONDA FCX Clarity, the first publicly available fuel cell car since 2008, used to be leased in the USA for $600 per month under a 3-year leasing term (HONDA 2014a) with the successor model presented as a concept in 2013 and due to be available in the USA and Japan by 2015 (Fig. 17) (HONDA 2014b). The fuel cell car offered by HONDA can run for above 450 km on a full tank and the refuelling can be completed in less than 5 min. First hydrogen fuel cell car by Toyota is announced be available to hit the American market by 2015 (Toyota 2014) (Fig. 17). The Toyota fuel cell car has been announced to be sold in the USA and Europe for US$69,000 (IAHE 2014).


**Fig. 17** The commercial hydrogen fuel cell cars introduced by major car manufacturers such as Toyota, Hyundai, Honda, and GM

Hyundai is planning to offer its fuel cell Tucson model (over 450 km driving range per full tank of hydrogen) to the US market for leasing from $499 per month over a 36-month contract (Hyundai 2007) (Fig. 17). GM is also planning to join this market through collaborating with HONDA by 2020 (GM 2013).

The feasibility of using hydrogen fuel cell technology has also been demonstrated for short-haul buses (Fig. 18) in a number of projects and trials around the world (NREL 2014). Most of these projects focus on hybrid (battery/ultra-capacitor) fuel cell systems and liquid hydrogen delivery (with compressed gas stored on board the vehicles) as the main supply method with just a few of them using on-site electrolysis or reformer. Short-haul buses have many idle periods while their engines operate far from the rated power and hence at low efficiency (e.g. less than 10 %). That is why they produce more emissions than long-haul buses. It is notable that these short-haul buses are mainly operated within urban areas where the potential impact of their high emissions on the people can be considerable. Trials done around the world all demonstrated much higher fuel to transmission

**Fig. 18** Examples of hydrogen fuel cell bus and truck (INTECH 2014; Vision 2014)

efficiencies than the range usually expected in conventional diesel-based engines used in buses. For example, the trial of a hydrogen fuel cell/battery bus (2001–2003) (Folkesson et al. 2003), that was supported by Swedish National Research Programme for Green Car Research, showed that the bus (without using a regenerative breaking system) was up to about 30 % more efficient than conventional diesel-based buses of the same size and using regenerative breaking can extend the range of the bus by 24–28 % in the city duty cycles; or the measurements obtained from the bus trials in Perth, Australia (285,000 km), and nine European cities showed 47–57 % electrical energy efficiency for the fuel cells (based on LHV), while considering motor, inverters, and other losses as well as energy required by the bus' accessories; the hydrogen to transmission efficiency (LHV-based) was measured to be ~23 % (Cockroft 2008). An average electrical efficiency of 42 % (based on LHV) was reported by Bubna et al. (2010) for the hybrid fuel cell/battery minibus tested by the University of Delaware; and in ~20,000 km bus trial in China in 2008 (Li et al. 2010), the fuel cell efficiency was recorded to be above 50 % (LHV) most of the time. The hydrogen fuel cell buses were also found to be highly reliable. For example, in fuel cell bus trial in Perth, Australia, DSEWPC (2009) recorded an unavailability (for maintenance) rate of only 5–25 %, and an average rate of tow-backs to depot of only 3.9 per 100,000 km operation, which was actually better than that for conventional buses (at ~5 tow-backs per 100,000 km) (Cockroft 2008).

Heavy-duty trucks, used to transport goods, have also received attention to be powered by hydrogen fuel cell systems (Fig. 18). While not many demonstrations have been reported so far, one of the most notable and successful trials that is now commercialised, has been a class 8, 536-hp short-haul (covering 320 km range in an eight-hour shift) truck, called Tyrano. This truck has been developed by Vision Motor Corporation for use in ports in California (HydrogenCarsNow 2014b). Apart from the positive role of such hydrogen fuel cell trucks in reducing emissions associated with transportation of goods, the other key advantage has been reported to be the running cost of the truck, which is 30–40 % less than that for standard diesel trucks of the same size. The capital cost of this truck is 2.5 times higher than a same size diesel truck. However, this cost is expected to fall considerably with higher volume production.

PEM fuel cells are the most suitable fuel cell option for automotive applications. This is because of high power densities, relatively low operating temperature, response to dynamic loads, and quick start-up time (in the order of existing ICEs) of this type of fuel cell. PEM fuel cells advanced considerably since 50 years ago when used by NASA (NASA GEMINI-1960) for the first time (Larminie and Dicks 2003). The capacity of early fuel cells designed and manufactured for automotive applications was very low (e.g. 0.4 kW Ballard MK3 fuel cell). Today fuel cells of around 150 kW power are being manufactured (e.g. HD6 fuel cell modules by Ballard fuel cell) (Ballard 2014) for use in vehicles. The fuel cell used in Honda's FCX Clarity fuel cell car was 1900 W/l and 1500 W/kg, respectively, while the first PEM fuel cell used by NASA (NASA GEMINI-1960) had 20 W/l and 15 W/kg of stack volumetric and gravimetric power densities, respectively. Ballard then offered PEM fuel cells with a 2500 W/l volumetric power density (Mock and Schmid 2009) while recent reports are now talking about achieving gravimetric power densities of 3.7 kW/l and 2.5 kW/kg, respectively (BusinessWires 2014). Toyota used a fuel cell with volumetric power density of 3 kW/l in its recent hydrogen fuel cell and to be introduced to the market in 2015 (Toyota 2014). Such advancement offers possibilities to achieve better packaging configurations and performance.

The cost of PEM fuel cell used to be a big concern; however, an 80 % reduction between 2002 and 2014 with 30 % since 2009 are promising signs about the near future affordability of this technology. The current price of PEM fuel cells used in automotive applications (based on 500,000 units produced per year) is \$55/kW with an interim goal of \$40/kW by 2020 and an ultimate goal of \$30/kW (DoE 2013) to become competitive with ICEs priced almost stably at \$25–35/kW (Ahluwalia et al. 2011) (Fig. 19). Fuel cell durability, which has always been a key technical challenge against the development of this technology, is also improving rapidly. PEM fuel cell's durability needed to be proven through multiple real-world service trials and under conditions of rapidly changing loads, idle

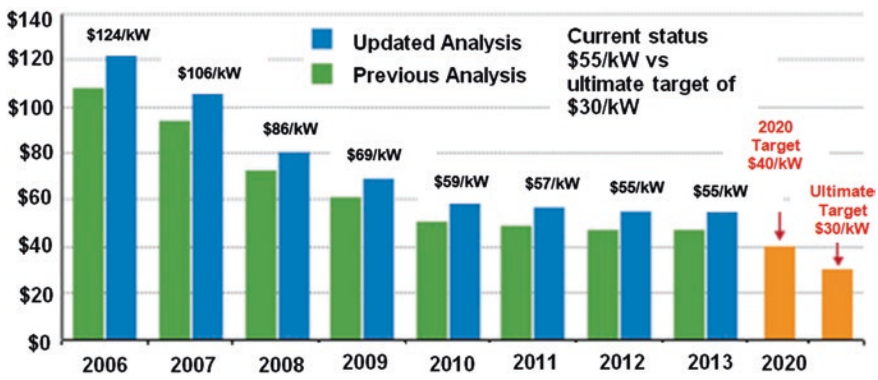


**Fig. 19** Projected transportation fuel cell system cost based on high-volume production of 500,000 units per year (DoE 2013)

conditions, and numerous start-ups and shutdowns similar to typical automotive duty cycles (Ahluwalia et al. 2011). 5000 h of operation (~250,000 km of driving) has been targeted by DoE (2013) for EPM fuel cell used in transport application in order to keep the technology competitive to the existing ICEs. Some exceptional records (e.g. bus trial by UTC Power, US: >10,000 h of operation) have achieved so far, but not repeated frequently (DoE 2011); however, most of the trials reported to date reported around 2500–3000 h of fuel cell lifetime.

Since the drive train of hydrogen fuel cell cars is electrified, it makes sense to compare the performance (e.g. deriving range and top speed) of HFCVs with BEVs. Driving range provided by hydrogen and also the quick refuelling time have always been regarded as the major advantages of hydrogen over batteries. Most of the HFCVs tried by major car manufacturer have reported to have ranges between 300–600 km (Fuelcells2000 2014). Toyota is claiming 700 km of range for its recent fuel cell car (Toyota 2014), which is even higher than current ranges normally suggested conventional ICE-based cars. The existing battery electric cars hardly achieve 100-150 km between two recharges (Fuelcells2000 2014). Top speed of HFCVs has improved considerably in the past two decades compared to when it was less than 100 km/h (Mock and Schmid 2009). Both BEVs and HFCVs have achieved top speeds of over 200 km/h in recent years. The examples of this are the 220 km/h for 2011 Mercedes-Benz F 125! Fuel cell car by Dimaler (Fuelcells2000 2014) and 210 km/h for the Tesla model S electric car by Tesla Motor (TeslaMotor 2014). Still the long time (in the range of a few hours) required for proper recharging batteries is a disadvantage associated with BEVs. Hydrogen cars can be refilled much quicker (in the order of a few minutes) particularly for high-pressure on-board hydrogen storage option. Cockroft reported (Cockroft 2007) 50 s needed to fill up one kg of hydrogen in a high-pressure hydrogen tank (e.g. 350 bar) (Perth hydrogen fuel cell bus trial 2004–2007), while recently Vision Motor Corporation reported the required time to fill 40 kg of gaseous hydrogen on board of their hydrogen fuel cell truck to be 4-7 min. This has to be noted that a passenger car needs 4-5 kg of hydrogen stored on board for having a range equivalent to today's passenger cars (~500 km).

It is important to note that not only the two technologies (hydrogen fuel cells and batteries) are not poles apart, but also they can play complementary roles in an electrified power train. As suggested by many researchers—e.g. Haraldsson et al. (2005), Ouyang et al. (2006), Wang et al. (2006), and Gao et al. (2008)—hybridisation of hydrogen fuel cell vehicles (e.g. by adding a small banks of batteries or super-capacitors) provides opportunities to use regenerative breaking system and also helps reduce the hydrogen consumption as well as the cost of the system. Batteries and/or super-capacitors can handle the peak of the demand and with them in the system, there would be no need size the fuel cell based such peaks. Moreover, in order to ensure a smoother supply of power to the load, the batteries and super-capacitors can buffer the power output of the fuel cell. In some applications with less acceleration (and hence sharp peaks) involved (e.g. road freight transport), particularly when some additional short-term energy storage is required, Li-ion batteries can be suitable options to act as buffer. Batteries usually

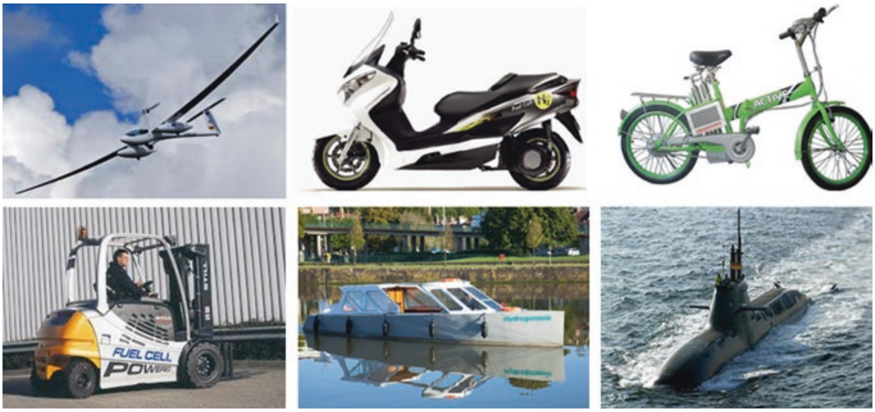


**Fig. 20** Examples of fuel cell applications in bikes, scooters, submarine, recreational boats, light aeroplanes, and forklifts (FuelCellToday 2012; AltusLift 2014; DW 2014)

are better options than ultra-capacitors in terms of energy storage capacity while the response time for quick discharge (to handle sharp peaks) might be slower than that can be achieved by using super-capacitors. However, for applications in which the buffer needs to be charged and discharged more frequently (e.g. to handle frequent sharp peaks), ultra-capacitors seem to be more feasible solutions (e.g. buses used in public transport sector in urban areas, or passenger cars). Lifetimes of ultra-capacitors (e.g. one million duty cycles) are far longer than batteries, and their round-trip energy efficiency (~95 %) is slightly better than that for batteries (~80–90 %). Unlike batteries, ultra-capacitors can be deep discharged without affecting their lifetime. Ultra-capacitors also show better gravimetric power densities than batteries (good to handle very sharp peaks), although their gravimetric energy densities are considerably lower than that achieved for Li-ion batteries (less storage capacity). Super-capacitors self-discharge quicker than batteries. It is notable that recently there has been lots of progress in battery technologies, particularly in terms of improving their lifetime, and power density.

There are many other examples of successful mobile/vehicle applications of PEM fuel cells at both commercial and trial levels. Scooters, light aeroplanes, mobility vehicles, bikes, boats, submarines, and forklifts are among these examples (Fig. 20).

## 6 Conclusions

Considering social (e.g. energy security), economic, and environmental issues associated with reliance on finite fossil fuel resources for energy generation shifting towards renewable energy resources makes sound sense. While diversity of renewable energy resources is the key advantage of these alternatives, their intermittency and unpredictability have to be addressed by complementing them with proper energy storage options such that these resources can be reliably employed to power stationary and mobile applications uninterruptedly as required. Hydrogen energy systems as reviewed in this chapter can play a strong energy storage role in conjunction with renewable energy resources, particularly in applications with long-term (i.e. in stationary applications) and/or long-range (i.e. in automotive applications) energy storage requirements.

Hydrogen energy systems are comprised of hydrogen generation arrangements, hydrogen storage, hydrogen distribution, and delivery systems (long or short distance), and finally the means of converting the chemical energy of hydrogen into a desirable form of energy (e.g. electricity) for end users. Latest research and development related to these elements have been discussed in this chapter.

Hydrogen can be produced from a wide range of renewable and non-renewable energy sources, but only hydrogen from renewables provides a totally zero-emission system and hence can contribute to tackling climate change. Renewable hydrogen (e.g. through electrolysis powered by wind or PVs) is the most sustainable option. Hydrogen distribution and delivery networks in place are crucial for hydrogen technologies to play a key role in energy markets. A range of options have been discussed for delivering and distributing renewable energy through hydrogen. Utilising local and national grids, while using large- and small-scale distributed hydrogen storage networks and limiting hydrogen pipelines (as much as possible) to short local distribution networks, is arguably the most practical and economic scenario.

Recent studies show that hydrogen production costs are dropping quite considerably (even using water electrolysis), so that hydrogen fuel cell systems are fast approaching competiveness with petrol and diesel, and gas and coal-fired power stations, particularly if a price on carbon pollution is imposed to reflect the very real economic costs of climate change. Large investments in hydrogen distribution and delivery (e.g. refuelling stations) infrastructures are reported everyday around the word, highlighting the growing attention globally towards this energy storage alternative.

Hydrogen storage is another essential component of hydrogen systems that should well accompany hydrogen generation, distribution, and delivery parts. There are already hydrogen storage technologies commercially available that are practical for on-board storage in hydrogen fuel cell vehicles, namely 350 or 700 bar compressed gas tanks made from lightweight advanced composite materials. In addition, low to medium temperature compressed gas tanks and metal hydride canisters suitable for stationary hydrogen storage applications can be purchased. Research and development work is continuing to enhance the gravimetric and volumetric energy densities of hydrogen storage systems and reduce their costs. Some novel flow-based hydrogen storage systems are being investigated which offer prospects for round-trip energy efficiency comparable to batteries, while maintaining hydrogen's advantages in terms of energy density.

Stationary and mobile applications of hydrogen have also been reviewed. Hydrogen can be a technically viable solution for decentralised power supply arrangements (e.g. within microgrids) with or without connection to a main grid (e.g. a wider national grid). Remote applications with needs for long-term, low O&M cost, and reliable power supply solutions can be the best candidates for practicing hydrogen solutions (e.g. remote isolated households, and isolated telecommunication towers). Fuel cells also generate heat while producing power, making the system suitable for a range of isolated or grid-connected combined heat and power applications (e.g. electrical power and hot water supply for remote households) with enhanced overall efficiency (i.e. ~85 %). Fuel cell CHP systems are gaining further economic attractiveness with considerably increasing sales record in the past five years. In terms of automotive applications, many major car manufacturers around the world (e.g. Toyota, GM, Hyundai, Honda, etc.) are now having hydrogen fuel cell cars in their agenda with some being already available commercially. This is while the availability of hydrogen infrastructure (i.e. production, distribution, and delivery) is being dealt with as a major challenge against further development of this technology. This challenge is currently addressed by some policy makers, investors, and car manufacturers themselves (e.g. in the USA, Germany, and Japan).

Slowly but surely, hydrogen energy is coming back into consideration as a significant contributor to future sustainable energy strategies based on renewable energy and energy efficiency that can guarantee energy security and avoid catastrophic climate change. Gone are the heady days of the hydrogen economy in which hydrogen was to be one and only fuel. Yet some major roles for hydrogen in the transport sector and for energy storage on central grids, microgrids, and for remote applications are now opening up as the performance of hydrogen technologies is improving as their costs fall rapidly. Hydrogen thus deserves more attention from those policy makers and scientists who are still leaving it off their agendas.

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# Combined Cooling, Heating, and Power (CCHP) or Trigeneration Technology: An Approach Toward Higher Energy Efficiency, Emission Reduction Potential and Policy

**Anant Shukla**

**Abstract** The energy demand in India is growing at a very fast rate, the present energy generation could not be able to keep pace with this increasing demand with energy shortage of 6.2 % and peak shortage of 2.3 %. To address the increasing gap between demand and supply, there is an urgent need to bridge the gap through energy efficiency and integration of renewable energy in the energy mix of the country. This paper presents a new concept in Indian building sector which addresses the energy efficiency through Trigeneration technology. A gas engine with natural gas is used to produce power, and the waste heat for producing cooling and heating through Vapor Absorption Machine (VAM) and hot water recovery from low temperature (LT) jacket water respectively. This increases the efficiency up to 85 % or even more as compared to the conventional methods of power production. The present paper discusses one such case study on a pilot project implemented under the Indo-German Energy Program. The pilot project is funded by the German Federal Ministry of Environment, Nature Conservation, Building and Nuclear Safety (BMUB) and is the first project completed successfully under International Climate Initiative (IKI) of BMUB in India. This paper presents the information on the techno-economics of the pilot project at New Delhi.

**Keywords** Trigeneration · Combined Cooling, Heating, and Power (CCHP) · Energy efficiency · Waste heat recovery · Decentralized reliable power generation

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## 1 Background

Combined cooling, heating, and power (CCHP) or Trigeneration plays an important role in efficiently meeting growing energy demands while reducing environmental impacts amid growing concerns about energy security, GHG emissions, energy prices, and economic competitiveness. The viability of the technology depends on the actual value proposition in terms of GHG emission reduction, fuel savings, and the return on investment. An experience on the technology in the given scenario through a pilot project pays an important role in defining value proposition of the technology solution. Until the implementation of the Trigeneration project, there was very less or no awareness about the technology and its advantages. Trigeneration technology utilizes the primary fuel and quantifies the three outputs of Trigeneration systems and compares the fuel use with that of the conventional mode of energy generation.

The energy demand in India is growing at a very fast rate with energy shortage of 6.2 % and peak shortage of 2.3 % (Central Electricity Authority, Govt. of India); the present energy generation will not be able to keep pace with the growing demand. To address the increasing gap between demand and supply, there is an urgent need to bridge the gap through energy efficiency and integration of renewable energy in the energy mix of the country. This chapter introduces a highly efficient concept in Indian building sector addressing the need of energy efficiency through Trigeneration technology. In this chapter, Trigeneration technology and an overview of the Indian market potential for Trigeneration are discussed.

Trigeneration technology or combined cooling, heating, and power (CCHP) is the simultaneous production of three forms of energy, viz. power, heating, and cooling. The technology recovers the waste heat from an engine/turbine to meet energy needs of a building, thereby increasing the efficiency from 36 % in case of conventional methods of power production to 80 % or even more. It is suitable for buildings which need simultaneously all the three forms of energy.

To demonstrate the technology and its advantages, a project was set up in an existing building in New Delhi. The demonstration project can achieve an efficiency of 70 % or more during peak summer season.

## 2 Introduction

India is the world's fourth largest consumer of energy and fifth largest in power generation capacity. According to an estimate, the energy demand could increase by at least four times by 2032 compared to present level. Electricity production is mainly based on the burning of fossil fuels, since they are widely available and easy to utilize. Table 1 (Ministry of Power, Govt. of India) shows the present energy generation mix in Indian power sector. In the table shown, the gas-based technology covers ca. 9 % of the total power generated in the country, the total gas required for power generation more than 70 % of gas is imported. With 25 % imported energy, the energy demand in India is growing at a very fast rate;

**Table 1** Indian electricity scenario—power generation (as on 20 September 2014)

| S No. | Fuel | MW | Share (%) |
|---|---|---|---|
| 1 | Total thermal | 155968.99 | 68.19 |
| a | Coal | 134388.39 | 58.75 |
| b | Gas | 20380.85 | 8.91 |
| c | Oil | 1199.75 | 0.52 |
| 2 | Hydro energy | 39788.40 | 17.39 |
| 3 | Nuclear energy | 4780.00 | 2.08 |
| 4 | Renewable energy | 28184.35 | 12.32 |
| | Total | 228721.73 | 100 |

to address the demand, the present energy generation could not be able to keep pace resulting in energy shortage of 6.2 % and peak shortage of 2.3 % (Central Electricity Authority, Govt. of India) (Fig. 1).

It has been demonstrated all over the world that energy efficiency can provide significant benefits to develop and developing countries alike. Industrial and commercial enterprises, government agencies, and households that improve their energy efficiency reduce their energy costs. For government agencies, it increases the availability of tax revenues for productive uses. The Government of India's initiatives in this direction began in 1990 with the power sector reform program aimed at restoring financial viability of state power utilities. Subsequently, the Electricity Act, 2003, and the Energy Conservation Act of 2001 have provided a framework for promoting energy efficiency (EE) in the country. Bureau of Energy Efficiency (BEE) has been set up to facilitate implementation of the provision of the Act.

Due to the gap between demand and supply, frequent power failure occurs; the energy supply is then met through alternative energy sources like diesel generators and battery stored power (invertors). According to a rough estimate, the capital

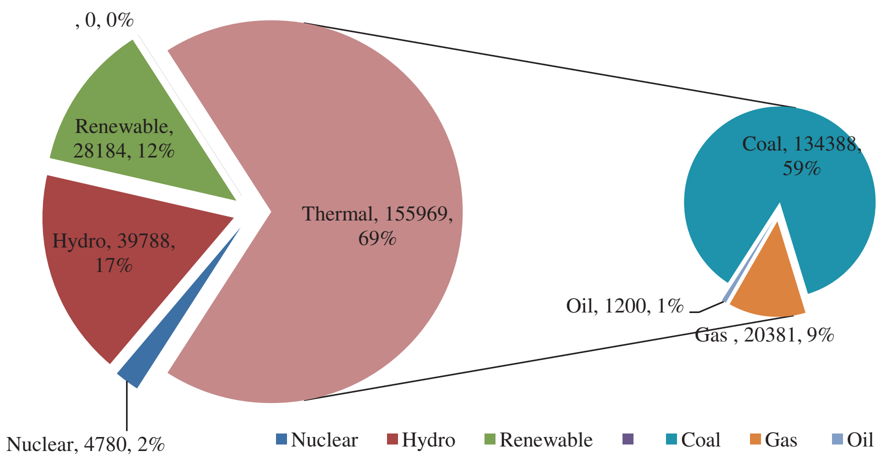


**Fig. 1** Indian power generation scenario (September 2014)

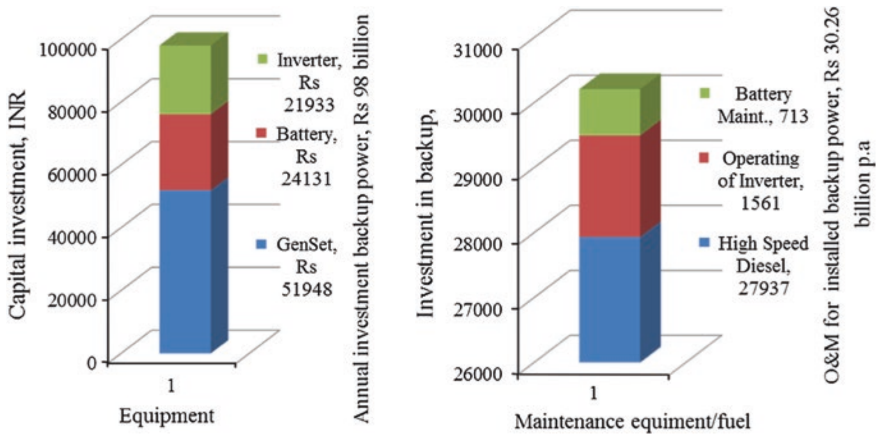


**Fig. 2** Investment in backup power and its O&M

investment in purchasing backup investment roughly comes out to be 98 billion rupees and ca. 32 billion rupees for its operation and maintenance (Wartsila 2009, Fig. 2). This contributes to already energy starved and polluted city by the presence of industries and transportation sector in the vicinity of the national capital that use conventional fuel to meet energy demands. The downsides of this practice have become more and more obvious; among them, GHG emission, substances with ODP, power reliability, quality, and shortages, etc., are a major concern. The diesel generator sets contribute to the pollution in cities facing frequent power cuts due to unplanned development and geographical locations, etc. The diesel generators in this case can be replaced by an energy-efficient Trigen technology in applications which has simultaneous use of power, heating, and cooling requirement.

## 3 Trigeneration Technology

The most common air-conditioning of buildings in India is done by air-conditioning units using vapor compression chillers (Fig. 3), e.g., split, cassette, window, electrical chiller. This technology has a high share in the energy performance of buildings because of low efficiency and high outside temperatures reaching over 40 °C during peak summer. One potential measure for increasing energy efficiency is a combined cooling, heating, and power (CCHP) system. Trigeneration technology stands for simultaneous production of electricity, cooling, and heating, which is unknown in India and not sufficiently demonstrated yet.

The Trigeneration technology (Fig. 4) utilizes primary fuel (e.g., natural gas) as fuel to produce power and the waste heat recovered from the exhaust gases from the gas engine for cooling through absorption chillers in summer, and low temperature (LT) heat for heating purpose or electricity and heating in winter. Trigen technology

**Fig. 3** Picture showing multiple electrical air conditioners installed at a typical building

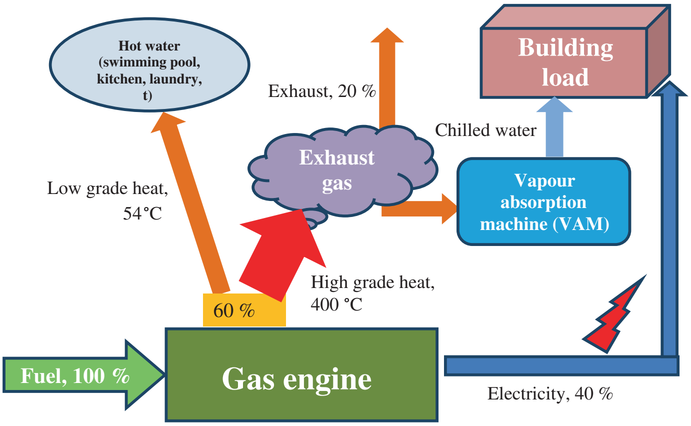


**Fig. 4** A schematic of typical Trigeneration system

is by and large unknown in India and is not sufficiently tested. In the most common type of Trigen system, fuel is used by a prime mover to drive a generator to produce electricity. The waste heat from the prime mover is recovered to provide useful thermal energy for cooling and heating. This arrangement is called topping cycle. The common toping cycle Trigeneration configurations are given below:

Type I: An engine/turbine burns fuel to generate electricity, and the heat recovered from the exhaust gases and jacket water is utilized for heating and/or cooling.
Type II: A steam/gas turbine uses high-pressure steam to drive a generator to produce electricity. Low-pressure steam extracted is used for heating and/or cooling.

In bottoming cycle, the fuel is used to produce thermal energy in an industrial process and heat from the process otherwise wasted is used to generate power.

An ideal combustion of gas and air is illustrated in the following equation:

$$CH_4 + 2O_2 + 7.52N_2 = 2H_2O + CO_2 + 7.52N_2$$

The above equation is for pure methane; typical gas fuels practically used are comprised of other constituents which require different combustion equations in the real scenario with small amounts of oxides of nitrogen ($NO_x$), carbon monoxide (CO), and unburnt or partially burnt hydrocarbons are emitted from the exhaust. However, the amount of $NO_x$, CO, and partially burnt hydrocarbons vary depending upon engine design, application, operation, and maintenance.

The operating conditions for the best performance of an engine include right combustion temperature, appropriate air to fuel ratio of the inlet charge, minimum engine loading, maintaining the design parameters (e.g., piston, spark plug, charge turbulence, jacket water, and operating temperature), and control system capability (ignition timing, inlet charge, mixture control, etc.).

## 4 Preliminary Selection Criteria

There exists a huge energy saving potential in India among various sectors identified for replication of Trigen on the basis of developed criteria suited to Indian building sector. The basic parameters used for selection of a building suitable for Trigen are as follows:

1. 24 h operational building
2. Simultaneous requirement of electricity, heating, and cooling
3. Operation of backup arrangements at site
4. Power supply, failure, fluctuations, etc.
5. Space availability for installing the system
6. Centralized heating and cooling system
7. Availability of fuel (natural gas, etc.)
8. Favorable regulatory environment

## 5 Vapor Absorption Machines (VAM)

In the Trigeneration technology, the main factor is the utilization of waste heat recovery. The waste heat is recovered either to produce air-conditioning or electricity. In former type where waste heat is used for air-conditioning, vapor absorption machines are used. VAM can be classified into direct fired and indirect fired depending on its thermal energy input. An indirect fired VAM was used in the demonstration plant to recover the waste heat from the engine.

**Table 2** Refrigerants used in absorption technology has minimal ODP and GWP compared to compression technology

| Refrigerant | Boiling point °C | ODP | GWP |
|---|---|---|---|
| R-32 | −51.7 | 0 | 675 |
| R-11 | −23.82 | 1 | 4000 |
| R-134A | −26.30 | 0 | 1300 |
| R-12 | −29.79 | 1 | 10,900 |
| $NH_3$ | −33.30 | 0 | 0 |
| R-22 | −40.76 | 0.05 | 1700 |
| R-502 | −45.40 | 0.283 | 4.1 |
| LiBr + Water | – | **0** | **0** |

The main advantages of a VAM are as follows:

1. Lower electrical requirements for chiller operation
2. Lower sound and vibration levels during operation due to non-mechanical parts
3. Conversion capacity from heat to cool
4. Refrigerants do not have adverse impact on the environment (Table 2)

The refrigerants used in VAM have minimal ozone depletion potential (ODP) and global warming potential (GWP) as compared to that used in vapor compression technology.

The vapor absorption machines used in the demonstration plant can operate on both heating and cooling mode in winters and summer season, respectively.

## 6 Case Study: Trigeneration at Jai Prakash Narayan Apex Trauma Center, AIIMS

Jai Prakash Narayan Apex Trauma Center (JPNATC), All India Institute of Medical Studies (AIIMS) (Fig. 5), is a premier government hospital built to cater the accidental and casualties who require immediate attention. The hospital building for the demonstration of the Trigeneration technology is a seven storey building situated in New Delhi. The demonstration site has a total energy consumption of 1.2 MW of electricity and installed cooling capacity of 800 TR achieved through screw chillers. The hot water requirement for kitchen, laundry, and sterilization was met through diesel fired boilers, and at present, the fuel used is piped natural gas (PNG). The hospital has two separate grid lines as emergency backup power supply used during main grid failures. If the two grid backups fail, three diesel generators of capacity of 1 MW each supply energy to the building.

To meet the requirements of the hospital, a small demonstration plant was set up without disturbing the critical areas, e.g., operating theater, sterilization. The demonstration plant consists of three main components (Table 3) gas engine, VAM, and electrical chiller. The gas engine (utilizes natural gas as fuel) (Fig. 6) was used to produce power up to 347 kW, and the exhaust gas from the gas engine


**Fig. 5** Demonstration site JPNATC, AIIMS in New Delhi

**Table 3** Installed components of Trigeneration plant installed at JPNATC

| Equipment | Make | Size | Parameter |
|---|---|---|---|
| Gas engine | Schmitt Enertec | 347 kW | 37 % elec. eff. |
| VAM | Thermax | 105 TR | COP 0.7 |
| Chiller | York | 250 TR | COP 4 |
| Cooling tower | Mihir | 400 TR (340 $m^3$/h) | 1800 kCal/h |

**Fig. 6** An inside view of the Trigeneration demonstration pilot plant at JPNATC

released at a temperature of 420 °C was then fed into a VAM of capacity 105 TR. The single-effect VAM installed at site utilizes the heat from the exhaust gas and high-temperature (HT) water from the engine to produce chilled water at 7 °C. LiBr and water are used for absorbent and as refrigerant and an electrical chiller for additional cooling demand.

The low temperature (LT) water at 54 C from the LT jacket water recovery from the engine is used as pre-heated water in boiler and finally utilized for application in kitchen and laundry.

## 7 Trigeneration Project Baseline

With the gas prices at Rs. 19/scm, electricity prices at 9.10 Rs./kWh, and diesel prices (15 Rs./kWh) at 50 Rs./liter, the baseline revealed that the estimated payback period of the project was 3.2 years. However, during the last three years since the demo plant was commissioned, the natural gas prices have gone up drastically with marginal increase in diesel and grid prices. Table 4 presents the baseline energy consumption at the hospital (estimate year 2010).

## 8 Trigen Project Payback Estimated During Project Period

Table 5 presents the various costs taken into consideration in estimating the baseline of the hospital assessed in the year 2010.

**Table 4** Estimation of baseline energy consumption at JPNATC (year 2010)

| Energy type | Cost per annum | | Electricity/Fuel consumption |
|---|---|---|---|
| | Million Rs | € (×1000) | kWh/l |
| Power | 26.5 | 311.8 | 3 million kWh |
| Cooling | 14.6 | 171.8 | 1.6 million kWh |
| Heating | 1.5 | 17.6 | 43,800 l/annum |
| Project baseline | 426 | 501.2 | – |

**Table 5** Savings estimated from Trigeneration plant during the year 2012

| Parameters | Value | | Energy costs/Savings |
|---|---|---|---|
| | Million Rs | Million € | |
| Equipment cost | 35 | 0.6 | Power (347 kW)—Rs. 15.1 million |
| Additional project cost | 6.2 | 0.103 | Cooling (VAM 105 TR) Rs. 9.8 million |
| Total project investment | 41.2 | 0.69 | Heating (20 kW) Rs. 1.3 million |
| Annual savings from Trigen | 13.0 | 0.22 | |
| Project payback | 3.2 Years | | |

## 9 Energy Savings

As compared to the overall efficiency of 25 and 36 % of the primary energy used in thermal power plants and diesel generators reaching the end user, the overall efficiency of the Trigeneration plant comes out to be 67 %. The efficiency can further be increased by increased utilization of LT hot water presently being used only 20 kW from LT circuit.

The plant covers about one-third of the energy demand of the hospital and has resulted in energy saving up to 660,000 kWh per annum and GHG emission reduction of 1700 $tCO_2$ per annum due to the utilization of waste heat in VAM, energy-efficient centrifugal chiller and diesel savings in the boiler. The plant was commissioned in October 2012; since then, the gas prices have risen from 19 to 45 Rs./scm and have also impacted the project payback from 3.2 years to more than 5 years.

After commissioning of the plant, it is being monitored for the performance and the data gathered will be made online on www.trigenindia.com from June 2014 onwards.

## 10 Market Potential of Trigen Technology (GTZ, DESL, 2010)

To identify the potential and attractive sectors for replication of Trigen, a market study was conducted. According to the study, the potential of Trigeneration is more than 10,000 MW in the Indian building sector (DSCL Energy Services Company Limited 2010). The building sector can be divided into the following categories according to building bylaws as shown in Fig. 7.

Industries are selected from the building categories to explore the Trigeneration attractiveness. A detailed study was conducted in selected industrial sectors on the basis of market attractiveness and financial attractiveness. The internal rate of return (IRR) was calculated on the basis of the following parameters:

1. Electricity tariff of €0.089 per kWh
2. Tariff for sale of surplus power to grid €0.074 per kWh
3. Average heat to power ratio of the building category

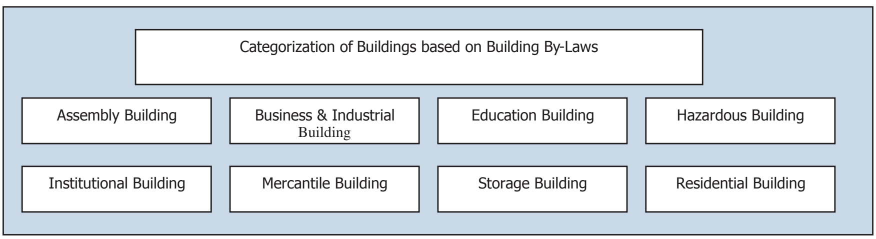


**Fig. 7** Categorization of building types based on building bylaws

4. Capacity utilization was considered constant for all building category
5. Price of gas at €0.18 per $m^3$
6. Operating hours of cogeneration/Trigeneration plant per annum as 8000 h
7. Weather conditions of Delhi (composite climate) for all building types

Operating hours of each building type used in estimation were considered as given below:

1. Private/Government office: 2340 h/annum
2. Retail: 5040 h/annum
3. Hotel: 8760 h/annum
4. Hospital: 8760 h/annum
5. Airport: 8760 h/annum

The values for project IRR and operating hours per annum for each of the building were normalized to a maximum score of 10 and rated accordingly. The score for financial attractiveness was given a weightage of 60 %, and the annual operating hours were given a weightage of 40 %, to arrive at the final score for the market attractiveness. The Fig. 6 shows the sector wise ranking on the basis of the above criteria. According to the study, hotel industry is the most attractive market followed by airport, hospitals, etc. The size of the bubble denotes the replication potential in the sector. A sector wise potential is shown in Table 6 (Fig. 8).

**Table 6** Potential of Trigen in select industrial sectors

| Industry | Potential MW |
|---|---|
| Alumina | 59 |
| Caustic Soda | 394 |
| Cement | 78 |
| Cotton Textile | 506 |
| Iron and Steel | 362 |
| Man-made fiber | 144 |
| Paper | 594 |
| Refineries | 232 |
| Sugar | 5131 |
| Sulfuric acid | 74 |
| Total | 7574 |

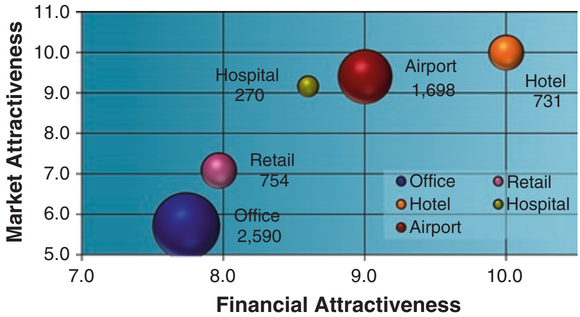


**Fig. 8** Market attractiveness of various sectors identified for replication

## 11 Trigeneration Map: Potential Cities with Trigeneration Potential

In an effort to assess the potential for Trigeneration applications in major Indian cities, a map (Fig. 9, Indo-German Energy Forum Sub-Office 2014) highlighting the current status of the most important parameters to assess the deployment of Trigeneration technologies was prepared under the Indo-German Energy Forum

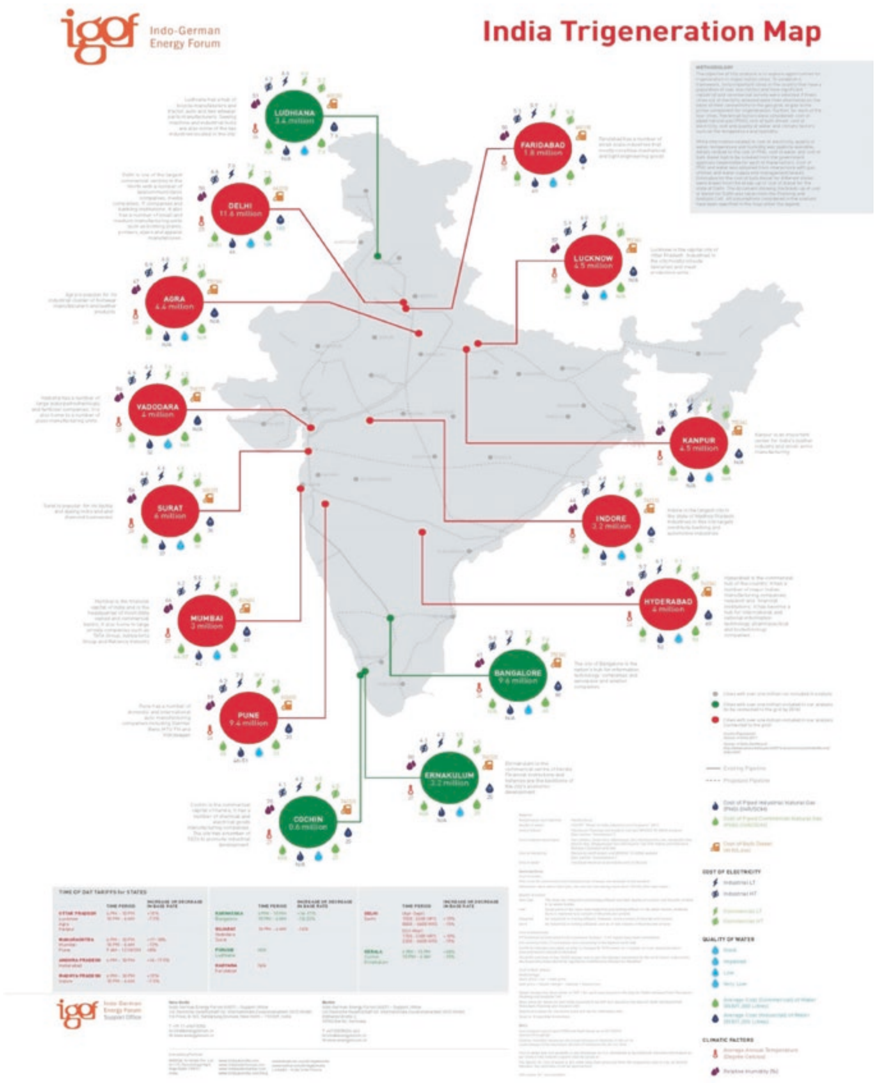


Fig. 9 A map showing cities with potential of Trigeneration with gas network available and proposed

(IGEF). In the present version, cities with PNG supply or planned in next one year are covered. Some of the parameters shown in this version of the map are as given below:

(i) Availability/cost of piped natural gas
(ii) Availability/cost of electricity
(iii) Cost of water and the need for processing of the water for use
(iv) Cost of diesel
(v) Environmental factors (annual temperatures, humidity, irradiation)
(vi) For typical customers—hospitals/hotels/offices/commercial buildings/etc.
(vii) For the top Indian cities (Delhi, Mumbai, Bangalore, Hyderabad, Pune, Cochin, Ludhiana etc.)—including basic city data.

The map is available on the project Web site for further feedback and suggestions to further improve the quality. The next upcoming version seeks the following improvements:

(i) Include cities with PNG supply anticipated within the next 2–3 years
(ii) Indicate parameters such as the number of airports, hotels, commercial buildings, hospitals, luxury apartment societies
(iii) Indicate the cities that fall in the Green Energy Corridor
(iv) Parameter to indicate the growth of the air-conditioning market in each city
(v) Indication of information needed to setting up Trigeneration plant

## 12 Enabling Favorable Policies for Trigeneration Technology

Since there are no regulations defined for transportation of chilled water to nearby users, there is an urgent need to provide support for such installations through favorable policies. Policies favoring energy-efficient Trigeneration are required in the Indian building sector with incentivizing such installations. Fuel allocation to plants with higher overall efficiency when compared to the large gas-based power plants must be given priority; Trigeneration not only have higher efficiency but also have no or very less emissions and transmission and distribution losses. This also curbs issues like theft, and user can control the power factor to reduce GHG emissions. To provide a level playing field to gas based Trigen project, a policy support is recommended. There exists a Cogeneration Act (energytransition.de) in Germany in order to promote Trigeneration; there exists a similar law in Indian energy sector to prioritize energy efficiency.

## 13 Conclusion

Natural gas-based Trigen technology has many fold advantages as compared to the conventional way of power generation. The efficiency of gas-based Trigen plant achieved is 67 %, and it can be as high as 85 %, even more as compared to 25 % of energy received from centralized power plants. Apart from efficiency benefits, the advantages are even higher, viz. higher reliability, low carbon footprint, environmental benefits, GHG reduction, fuel flexibility, diesel abatement, to name a few.

The pilot project demonstrates the success achieved in implementing a plant in an operational building showcasing the possibilities of integration in the existing and operating plant. However, there is an urgent need to frame policies and incentive schemes in order to promote the efficient utilization of primary energy.

Unit conversions

1 MJ/Year = 3.6 kWh/Year
kWh = kVAh × Power Factor
1 kWh = 860 kCal
1 Foot = 0.3048 m
1 TR = 3024 kCal/h
1 TR = 1200 BTU/h
Energy Efficiency Ratio = 12/(kW/TR)

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# Energy Sustainability Through Nuclear Energy

**A. Shukla**

**Abstract** Energy sustainability is one of the most vital factors for the growth of any nation as well as global mankind. With exponentially increasing energy demand and concerns for carbon emission/climate change, it is inevitable to pave a pathway for energy production, which takes care of ever-increasing energy requirements as well as provides clean energy resources. Though there are concerns related to the safety of nuclear reactors and safe treatment of the nuclear waste, nuclear energy is still one of the most clean energy sources in terms of carbon emission with large availability of fuels to run nuclear power plants. Thus, nuclear energy has strong potential to fill the present gap between need and supply and to provide energy sustainability. This chapter explores the possibility of achieving energy sustainability through nuclear energy along with the possible challenges in this direction.

**Keywords** Energy · Sustainability · Nuclear · Treatment · Carbon emission

## 1 Introduction

In the present era, when energy demand is increasing day by day and is likely to increase even with faster pace (International Energy Agency 2010), with increase in proportion of population supplied by electricity, nuclear energy remains on top agenda for all concerned stakeholders. Along with the primary question—how to cope up with ever-increasing energy demand and achieve energy sustainability—there are secondary questions too, such as whether the electricity demand will

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continue to be served predominantly by extensive grid systems, whether there will be a strong trend to distributed generation (close to the points of use), and whether increase in energy production will keep on increasing carbon emission or we can have enough clean energy resources. These are important technological-cum-policy questions interwoven with the major question of exploring possible resource itself. Either way, it will not obviate the need for more large-scale grid-supplied power, especially in urbanized areas having domestic as well as industrial requirements, over the next several decades. Currently, much demand is for continuous, reliable supply of electricity on a large scale, and this will continue to dominate.

Currently, our energy requirements are mainly fulfilled through fossil fuels. There are three major forms of *fossil fuels*: coal, oil, and natural gas. It is predicted that these resources may reach on the verge of depletion after about six decades. Moreover, the carbon emission from these resources is so high that it has already started affecting biosphere and can be seen in terms of climate change and global warming which may put serious threats to mankind. In such a scenario, it is of paramount importance not only to achieve energy sustainability but energy sustainability through clean energy resources. However, there are many channels to produce clean energy, namely solar, wind, and geothermal. On the basis of bulk requirement versus fuel availability, impact on climate, land use, costs, and technology transfer, nuclear power is the only energy option that can help globally in achieving energy sustainability. Hence, to achieve energy sustainability along with reduced carbon emission, nuclear energy production is bound to contribute heavily (Grimes and Nuttall 2010).

| Nuclear energy: facts at a glance | |
|---|---|
| Total power production through nuclear energy | About **370,000 MWe** |
| Number of operational commercial nuclear power reactors | 430 in 31 countries |
| Largest nuclear power plant | Bruce Nuclear Generating Station, Canada |
| Worldwide electricity production through nuclear energy (in %) | Approximately 12 % |
| Country which has largest share of nuclear energy | France |
| Cost of nuclear power production | (60–80) USD/MWh |

At present, all the nuclear power plants producing electricity are based on the process of nuclear fission. Nuclear fission is a nuclear process where a heavy nucleus fragments into lighter nuclei along with producing energy. When a neutron passes near to a heavy nucleus, for example, uranium-235 (U-235), the neutron may be captured by the nucleus and this may or may not be followed by fission. Capture involves the addition of the neutron to the uranium nucleus to form a new compound nucleus, which further breaks into lighter nuclei along with emission of neutrons and energy. These emitted neutrons give rise to further process of nuclear fission, and hence, chain reaction takes place, which could be controlled for producing desirable amount of energy. Currently, nuclear fission-based reactor technology is in quite advanced stage and is being used considerably for power production. There is one another possibility to produce energy via nuclear fusion—the process through which Sun and other stars generate energy. This process has its own benefits in terms of fuel and nuclear waste in comparison with nuclear fission-based power plants. Consider this to be ideal for energy production; attempts are on to develop power plants based on nuclear fusion.

Nuclear fusion is a process whereby two hydrogen nuclei collide and join together to form a heavier atom, usually deuterium and tritium. When this happens, a considerable amount of energy gets released at extremely high temperatures: nearly 150 million °C. At extreme temperatures, electrons are separated from nuclei and a gas becomes plasma—a hot, electrically charged gas. A plant producing electricity from a nuclear fusion reaction could well replace nuclear fission plants. The fuel for nuclear fusion is abundant (deuterium, lithium, and tritium), with very little radioactivity and low radioactivity of the components with a short half-life, no need for underground storage, and no environmental risk in case of accident, as plasma cannot exist without being confined in a chamber under high pressure. Fusion is arguably one of the major research challenges of the twenty-first century. It is an option to provide environmentally benign energy for the future without depleting natural resources for next generations. Therefore, fusion scientists from the European Union, India, China, Japan, Korea, Russia, and the United States are proceeding with the construction of a 500-MW (thermal power) experimental plant (ITER—the International Thermonuclear Experimental Reactor). Although further research and development work needs to be done on materials and on concept improvements, ITER is expected to be the last major step between today's experiments and a demonstration power plant. The Fusion Power Coordinating Committee (FPCC) provides a platform to share results of fusion activities worldwide: the ITER project, the International Atomic Energy Agency, the European Commission (EURATOM), the International Tokamak Physics Activity (ITPA), and the Nuclear Energy Agency. The FPCC also coordinates and oversees the activities of fusion-related multilateral technology initiatives, or Implementing Agreements, that carry out R&D on the physics, technology, materials, safety, environmental and economic aspects, and social acceptance of fusion power (Intergovernmental Panel on Climate Change 2007).

## 2 Current Status

The generation of electricity using nuclear energy started in early 1950s, and the first commercial nuclear power plants started operation in the early 1960s. Electricity production through nuclear power grew rapidly in the 1970s and 1980s as countries sought to reduce dependence on fossil fuels, especially after the oil crisis of the 1970s. By 1990s, nuclear power emerged a strong contributor in the field of energy supply, though the growth stagnated slightly due to increasing concerns about safety operations following accidents in the Three Mile Island (1979) and Chernobyl (1986) (Talbott et al. 1979). The delays along

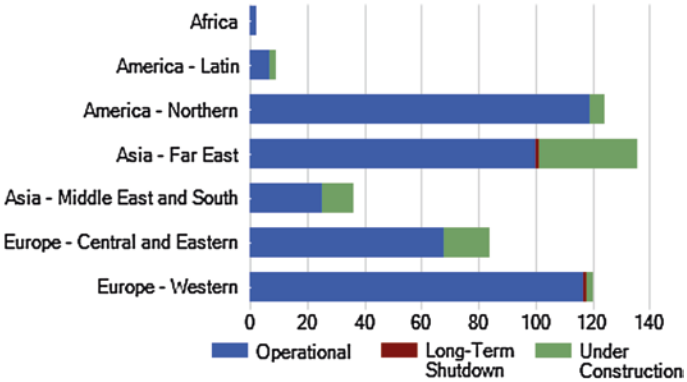


**Fig. 1** Geographical distribution of operational/long-term shutdown/under construction nuclear power plants (Talbott et al. 1979; http://www.nei.org/Knowledge-Center/Nuclear-Statistics/World-Statistics)

with higher-than-expected construction costs at some nuclear plants, and a return to lower fossil fuel prices, also contributed to the stagnation of nuclear energy growth chart. However, from 2000, there was a renewed interest in nuclear power, and the pace of construction accelerated after 2005. At the end of 2010, there were 65 reactors under construction, and 60 new countries had expressed interest in launching a nuclear program to the International Atomic Energy Agency (IAEA). As of May 2014, 30 countries worldwide are operating 438 nuclear reactors for electricity generation and 72 new nuclear plants are under construction in 15 countries. Figure 1 shows the geographical distribution of nuclear power plants which are either operational or under construction. It is evident that Asia overall has chosen nuclear power plants for its energy supply in considerable fashion. Moreover, Africa is on the lowest side to adopt nuclear technology and certainly has big opportunity due to large energy requirements. The USA and Europe are undoubtedly leading the nuclear energy production, but their future plans to enhance nuclear capacity are under question due to raising concerns over treatment of nuclear waste disposal and safety operations. Nuclear power plants provided about 375,504 MWe of power which is about 12.3 % of the world's electricity production in 2012 (http://www.nei.org/Knowledge-Center/Nuclear-Statistics/World-Statistics). In total, 13 countries relied on nuclear energy to supply at least one-quarter of their total electricity. Tokyo Electric Power Co.'s (TEPCO) Kashiwazaki-Kariwa plant in Japan is currently the world's largest nuclear power plant, with a net capacity of 7,965 MW but is operating only at 48 % of capacity due to earthquake damage and decommissioning. Hence, currently Bruce Nuclear Generating Station, located in Canada, is the largest nuclear facility in the world with a net capacity of 6232 MWe. As of now, there are more than 400 nuclear reactors which are operational in about 30 countries. Countrywise list of same is given in Fig. 2 along with number of operational reactors. France is one among the leaders in energy production through nuclear energy having more than 50 operational nuclear reactors and relying mainly on nuclear

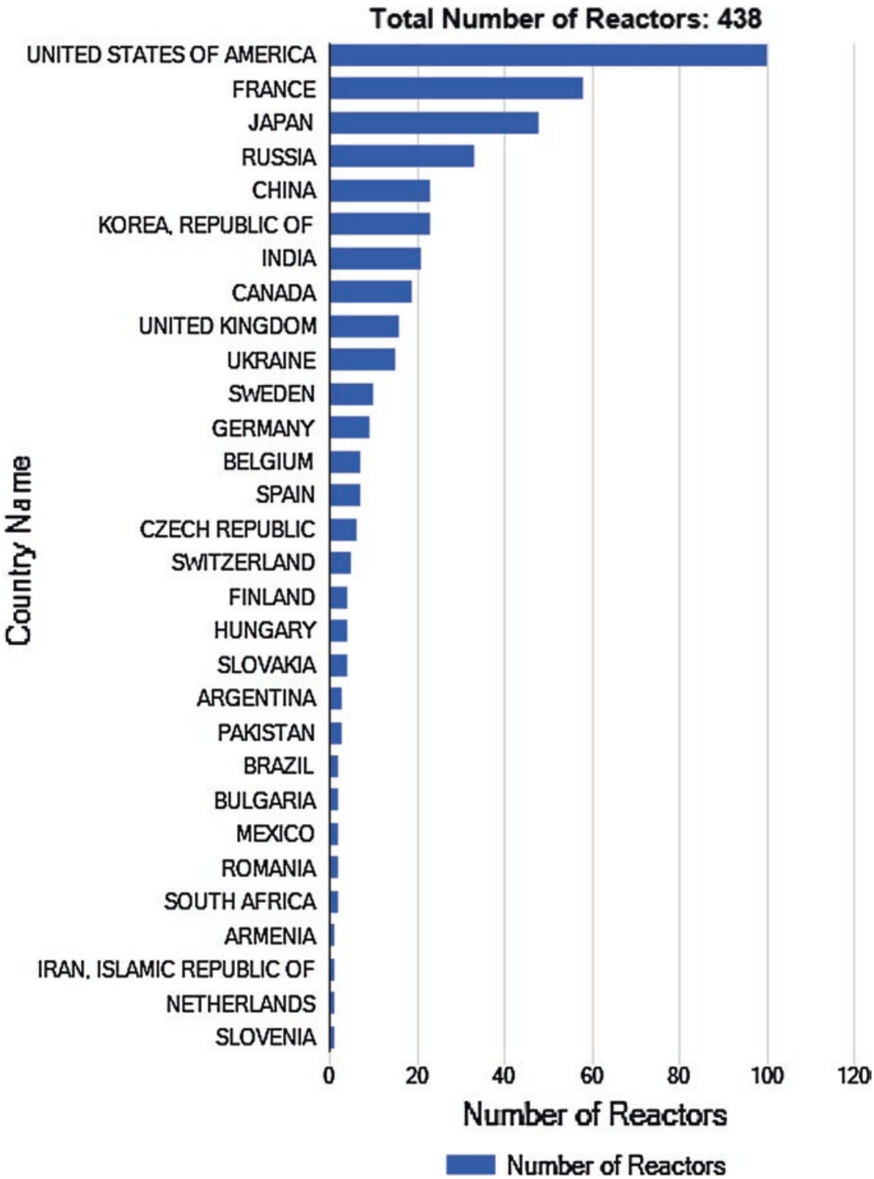


**Fig. 2** List of countries along with number of operational nuclear reactors (Talbott et al. 1979; http://www.nei.org/Knowledge-Center/Nuclear-Statistics/World-Statistics)

power only for major part of its energy needs (ref. to Figs. 2 and 3). The situation of countrywise share of power production through nuclear energy is expected to enhance in Asia phenomenally, with number of reactors under construction (http://www.nei.org/Knowledge-Center/Nuclear-Statistics/World-Statistics, http://www.eia.gov). As evident from Fig. 3, currently European countries are

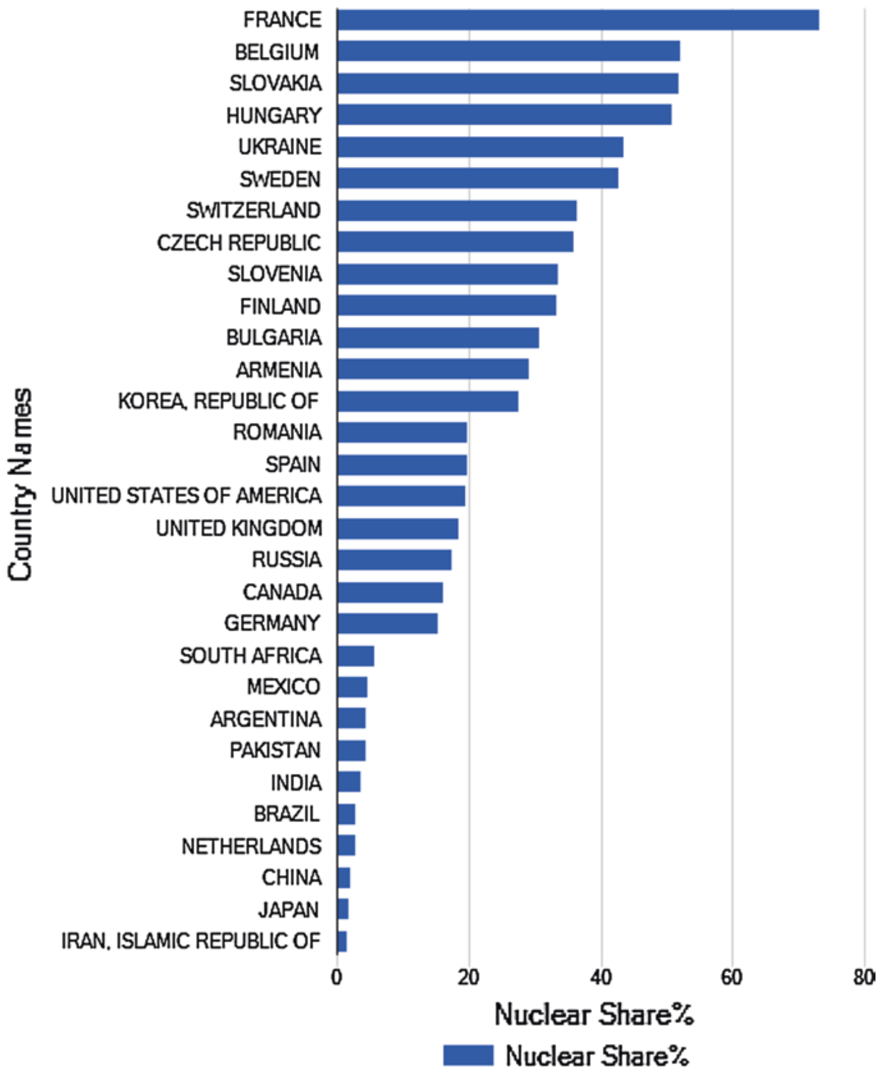


**Fig. 3** Countrywise share of power production through nuclear energy (in %) (Talbott et al. 1979; http://www.nei.org/Knowledge-Center/Nuclear-Statistics/World-Statistics)

utilizing nuclear power as major energy resource. Earlier Lithuania was global leader among the countries utilizing nuclear energy, fulfilling more than 80 % of its requirements through nuclear power. By the end of 2009, Lithuania closed its last nuclear reactor, which had been generating 70 % of its electricity.

In March 2011, a major earthquake and tsunami ravaged the Pacific coast of northern Japan and damaged the cooling system at the Fukushima Daiichi nuclear power plant, resulting in a severe accident. No deaths have been attributed to the accident (while the tsunami and the earthquake killed about 20,000 people), but serious releases of radioactive material resulted in contamination of the surrounding environment and led to the evacuation of several thousand inhabitants from neighborhood. This accident forced to rethink about the safety concerns related to nuclear power plants. In reaction, most nuclear countries announced safety reviews of their nuclear reactors and the revision/improvement of their plans to address similar emergency situations.

One of the advantages enjoyed by nuclear power plant operators is the abundance of fuel. Uranium, the main material for fueling nuclear power plants, is plentiful and available in many parts of the world. Although, at present, annual uranium production provides only some 60 % of reactor consumption, secondary sources, such as inventories of producers, utilities and governments, and ex-military materials, are sufficient to cover demand. The current global demand for uranium is about 68,500 tU/year (tons uranium per year). The vast majority is consumed by the power sector with a small amount also being used for medical and research purposes, and some for naval propulsion. At present, about 53 % of uranium comes from conventional mines (open pit and underground), about 41 % from in situ leach, and 5 % is recovered as a by-product from other mineral extraction. Kazakhstan produces the largest share of uranium from mines (38 % of world supply from mines in 2013), followed by Canada (which long held the lead) (16 %), and Australia (11 %) as shown in Table 1. Thus, the world's present measured resources of uranium (5.4 Mt) in the cost category a bit above present spot prices and used only in conventional reactors are enough to operate nuclear power plants for more than a century

**Table 1** Production of uranium through mines in last five years (in tons U per year)

| Country | 2009 | 2010 | 2011 | 2012 | 2013 |
|---|---|---|---|---|---|
| Kazakhstan | 14,020 | 17,803 | 19,451 | 21,317 | 22,451 |
| Canada | 10,173 | 9783 | 9145 | 8999 | 9331 |
| Australia | 7982 | 5900 | 5983 | 6991 | 6350 |
| Niger (EST) | 3243 | 4198 | 4351 | 4667 | 4518 |
| Namibia | 4626 | 4496 | 3258 | 4495 | 4323 |
| Russia | 3564 | 3562 | 2993 | 2872 | 3135 |
| Uzbekistan (EST) | 2429 | 2400 | 2500 | 2400 | 2400 |
| USA | 1453 | 1660 | 1537 | 1596 | 1792 |
| China (EST) | 750 | 827 | 885 | 1500 | 1500 |
| Malawi | 104 | 670 | 846 | 1101 | 1132 |
| Ukraine | 840 | 850 | 890 | 960 | 922 |
| South Africa | 563 | 583 | 582 | 465 | 531 |
| India (EST) | 290 | 400 | 400 | 385 | 385 |
| Brazil | 345 | 148 | 265 | 231 | 231 |
| Czech Republic | 258 | 254 | 229 | 228 | 215 |
| Romania (EST) | 75 | 77 | 77 | 90 | 77 |
| Pakistan (EST) | 50 | 45 | 45 | 45 | 45 |
| Germany | 0 | 8 | 51 | 50 | 27 |
| France | 8 | 7 | 6 | 3 | 5 |
| Percentage of world demand (%) | 78 | 78 | 85 | 86 | 92 |

http://www.eia.gov

(http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Mining-of-Uranium/World-Uranium-Mining-Production/). This represents a higher level of assured resources than is normal for most minerals. Other resources are known to exist and could be made available with further exploration and development efforts. Moreover, the introduction of advanced reactors and fuel cycles could multiply the lifetime of those resources by 30 or more and allow for a sharp rise in demand. Indeed, breeder reactors could eventually make nuclear energy a quasi-renewable source. Further exploration and higher prices will certainly, on the basis of present geological knowledge, yield further resources as present ones are used up. In the long term, we are confident that ample natural resources and progress in technology can ensure nuclear fuel supply, whatever the development of nuclear energy may be.

## 3 Challenges

Like any other energy source and technology, nuclear energy has advantages and drawbacks in each of the three dimensions of sustainable development: environmental, social, and economic. Policymakers must have authoritative facts, figures, and analyses to support their decisions on energy choices. The Nuclear Energy Agency can provide expertise and help governments to assess nuclear energy on a level playing field, with alternatives. While the economic sense of nuclear energy is no longer an issue, financing the building of nuclear power plants and fuel cycle facilities remains a challenge. Recent decisions in Europe to build new plants suggest greater interest from investors, but they remain cautious about the long-term financial risks. To reassure them, governments must at least provide stable regulatory frameworks in the field of nuclear safety and radiation protection, and back this up with clear policies to limit greenhouse gas emissions.

In parallel with technical improvements, addressing public concerns about nuclear risks is a high priority. Nuclear power plants generate large quantities of highly radioactive material. This is due to the leftover isotopes (atoms) from the splitting of the atom and the creation of heavier atoms, such as plutonium, which the nuclear power plant does not utilize. It is called nuclear waste. It is necessary to isolate the waste from humans and environment for about 100,000 years before it decays to safe levels. The consensus among the nuclear power industry is that radioactive waste should be isolated by multiple barriers and placed deep underground. However, other strategies involving waste transmutation are being investigated. Another main concern to address is that of waste management and disposal. Although radioactive waste management, including final disposal, does not raise any significant technical or economic problems—it is essential to note in this regard that the cost of waste management and disposal is already integrated in the price paid by consumers of nuclear electricity—establishing repositories to hold all waste types for a considerable time has proven to be a challenge. However, experts agree that the safe disposal of radioactive waste is feasible, with due respect being given to health and environmental regulations protecting present and future generations. Advanced studies and demonstration projects have been carried out on the treatment, packaging, and disposal of the waste in deep geological formations. These provide confidence that the successive natural and engineered barriers will satisfactorily isolate waste from the biosphere for as long as its level of radioactivity requires. Several countries, such as Finland, Sweden, and the United States, are in the process of developing repositories that should be opened within a decade or so (Elliot 2007).

Safety is of paramount importance in this regard. The excellent safety records of nuclear power plants and fuel cycle facilities in operation in OECD countries demonstrate the effectiveness of stringent regulations in place and of the efforts by industry and regulators to implement a robust safety culture. As a result of these efforts and progress in technology, the impacts of nuclear energy facilities on human health and the environment are well below the levels imposed by regulators and accepted by society in general for industrial activities. Going beyond mere compliance, the radiation doses received by workers in nuclear installations have been more than halved over the past 20 years. Meanwhile, the strictly monitored radioactive releases surrounding nuclear power plant sites remain extremely low (typically between a tenth and a hundredth of natural background radioactivity) and are decreasing further still.

## 4 Nuclear Power: Is It Really a Sustainable Energy Source?

With all said and done, it is important to examine the question, "If nuclear power can be termed as sustainable energy source? Does nuclear power meet our current energy needs and has potential for future too without compromising the living conditions of next generations?" Let us try to answer the same in terms of some specific criteria (Pearce 2012).

### *4.1 Greenhouse Gases and Carbon Emission*

Nuclear power complies with the international standards of carbon emission as nuclear power plants do not produce greenhouse gases. In fact, they have helped several nations to reduce their greenhouse gas emissions significantly. Moreover, it is possible only by the use of nuclear energy for all nations to meet the demand for increased energy while still reducing emissions of greenhouse gases.

### *4.2 Land Requirements*

Compared to other non-carbon-based and carbon-neutral energy options, nuclear power plants require far less land area. For a 1000-MW plant, site requirements are estimated as follows: nuclear, 1–4 $km^2$; solar or photovoltaic park, 20–50 $km^2$; a wind field, 50–150 $km^2$; and biomass, 4000–6000 $km^2$. Estimates about urban civilization suggest that by 2050, half of the world's population will live in large cities (Hondo 2005). This will require concentrated energy production systems in proximity to those population masses. The use of large land areas for energy production will be impractical.

### 4.3 Long-lasting Reserves of Fuels

Estimates about known fuel resources suggest that nuclear power plants can easily provide for more than 250 years of consumption using current "once through" commercial reactor technology. The technology exists (though it is not yet significantly deployed), with multiphase fuel usage and fast reactors, to utilize even more energy from each fuel sample. Recycling of uranium and plutonium could extend the fuel supply for by order of magnitude of estimated years of consumption. Abundance of uranium is spread all around the globe in relatively politically stable countries. These known resources clearly provide for many future generations with strong edge over limited fossil fuel materials.

### 4.4 Nuclear Waste Disposal, Environmental Impact, and Personal Safety

Rather than disperse massive quantities of waste products over wide areas, as is the case with emissions from fossil fuel plants (sulfur oxides, nitrogen oxides, carbon dioxide, and toxic metals such as arsenic and mercury contained in the fly ash), nuclear power plant operators are able to consolidate the waste and sequester it safely while its radiation level drops. By comparison, some of the waste dispersed into the air from fossil fuel plants is toxic and will remain so forever. The record of the civilian nuclear power industry in safely isolating both low-level and high-level nuclear wastes has been excellent. There have been no significant releases of nuclear waste to the environment, and improved repositories such as the recently licensed Waste Isolation Pilot Plant (WIPP) in the USA offer promise of an even more secure future. Potential environmental impacts from nuclear power operations are carefully controlled and regulated. Presently, nuclear plant operations are quite standardized and are operated according to stringent safety standards, posing no threat to workers, society, or to the environment. Over the long term, the fission of nuclear fuel resources and safe isolation of the radioactive wastes generated in the plant operation process actually reduce the exposure of the biosphere to nuclear radiation through naturally occurring radioactive elements. Moreover, the quantity of fossil fuel, such as coal, required to provide equivalent amounts of energy would release chemical elements and gases which are much more contaminated resulting in greater exposure to hazardous materials than would be the case using nuclear power.

### *4.5 Preservation of Fossil Resources*

Controlled fission of small amounts of uranium fuel can be used to generate large amounts of electricity without burning carbon-based fuel sources. The amount of fuel (mass and volume) required for nuclear power is significantly less than that required for a fossil-fueled plant. Energy produced by one ton of uranium is equivalent to 17,000 tons of coal. Nuclear power plants utilize resources of fissionable heavy metal (uranium) which has no other major use. Thus, the use of nuclear power slows the depletion rate of fossil resources significantly and helps in preserving fossil fuel resources to meet future developmental needs. Further, it frees fossil resources, so they can be used for other critical applications, such as feedstocks for chemical processes, personal transportation, and residential heating and cooking. Lowering the demand for fossil fuels in developed countries contributes to environmental equity by allowing developing countries to have vital energy supplies at lower cost (Goswami 2008).

### *4.6 Nonproliferation of Nuclear Weapons*

From the early days of nuclear power development, there has been widespread concern that increased use of nuclear power would lead to the diversion of nuclear materials to clandestine weapon production. The system of international safeguards implemented by the IAEA, however, has been effective in preventing diversions of nuclear materials from commercial power reactors or reprocessing plants. The effectiveness of the safeguard program is aided by the extreme technical difficulties inherent in converting nuclear material produced in power reactors to weapons-grade material.

### *4.7 Technology Transfer*

Transfer of technology to developing countries has made a major contribution to energy production in developing countries, such as Brazil, China, India, Korea, Argentina, and South Africa. This ongoing technology transfer continues to build technical capacities to manage nuclear material and the ability to regulate, oversee, and ensure its safety. As a result, the foundation is being built in the developing world for additional use of nuclear energy and promotion of the beneficial uses of nuclear science and technology in the future. Hence, overall nuclear energy can be undoubtedly termed as reliable sustainable energy source.

## 5 Future Prospects

Recent studies have shown that new nuclear power plants can compete favorably with alternatives, generally gas- and/or coal-fired plants, in most countries. The main factors that contribute to the competitiveness of nuclear power plants, based on new designs that may be ordered today, include cost-effectiveness of the concepts, and enhanced technical performance such as longer lifetimes, higher energy availability, and better fuel utilization. The advanced light water reactors currently available on the market are designed for 60 years of operation at an average availability factor above 90 %. They are designed to make better use of the energy content of natural uranium and to generate some 15 % less waste. Obviously, rising prices of fossil fuels and concerns for clean energy reinforce the competitiveness of nuclear-generated electricity. Furthermore, the pricing of carbon emissions in the costs of fossil fuel burning, through tradable permits and taxation for instance, will increase the competitive margin of energy sources that emit no or very little carbon.

Fast reactors, closed fuel cycles, and re-using of nuclear fuel are some of the key options in enhancing the sustainability of future nuclear systems. Fast reactors can reduce waste streams and improve efficient use of uranium. To enhance the sustainability of nuclear power globally, thorium can be used as an alternative fuel. Technology development is diversifying to meet a wide range of conditions for the deployment of new reactor designs, including small- and medium-sized reactors. These reactors may allow for expanded use of nuclear power—including on smaller grids and in remote settings, as well as for nonelectrical applications—and improve the access to nuclear energy, including for developing countries.

## 6 Summary and Conclusion

Nuclear energy is no more a new term to the present civilization. Today, worldwide, 68 % of total energy production comes from fossil fuels (41 % coal, 21 % gas, and 5.5 % oil), 13.4 % from nuclear fission, and 19 % from hydro and other renewable sources. In such a scenario, it is very less likely to reduce the usage of fossil fuels drastically at present; however, the impact of the usage of fossil fuels vis-a-vis the growth of nuclear generating capacity will become fully clear only in the coming years. A majority of countries have confirmed their construction plans (including China, the Emirates, France, Poland, the United Kingdom, and the United States), while a limited number of others (essentially Germany and Italy) have decided to eventually phase out nuclear power or to abandon their nuclear plant projects due to public outrage against safety concerns.

These challenges also point to the attraction of nuclear energy and demonstrate the opportunities involved. Nuclear power is a nearly carbon-free electricity generation source, with a large and diversified fuel resource base. Nuclear energy may be considered as essential part of the complete solution to energy sustainability, together with renewable energy sources. Today, nuclear energy has become a proven, mature technology benefiting from broad industrial experience. State-of-the-art nuclear energy systems in operation worldwide have demonstrated highly satisfactory technical and economic performance. Moreover, extensive R&D programs are under way in many countries, often as part of international endeavors, and aim to make even more progress to enhance safety and proliferation resistance, to reduce uranium consumption and waste, and to increase the competitiveness of nuclear energy. Construction of nuclear fusion-based reactor tokamak will be major breakthrough in this direction.

To summarize, nuclear energy complies strongly on the scale of safety, reliability, competitiveness, and efficient use of natural resources, as well as health and environmental protection, to become a part of sustainable energy solution, provided governments, industry, and civil society work together to lay out a robust policymaking framework for all options to be assessed and developed according to their respective costs and benefits for society. This also includes cooperation across the globe, so as to ensure the continuous supply of fuel, technology transfer with highest possible standards in the fields of safety and reliability, health and environmental protection, proliferation resistance and physical protection, and economics. Thus, nuclear energy could make a very unique contribution to diversification, security of energy supply, and the reduction of greenhouse gas emissions in a cost-effective way globally. Energy efficiency and savings, carbon sequestration, renewable sources, and nuclear energy are to be looked together meet the demand of growing populations and economic development while protecting the environment.

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