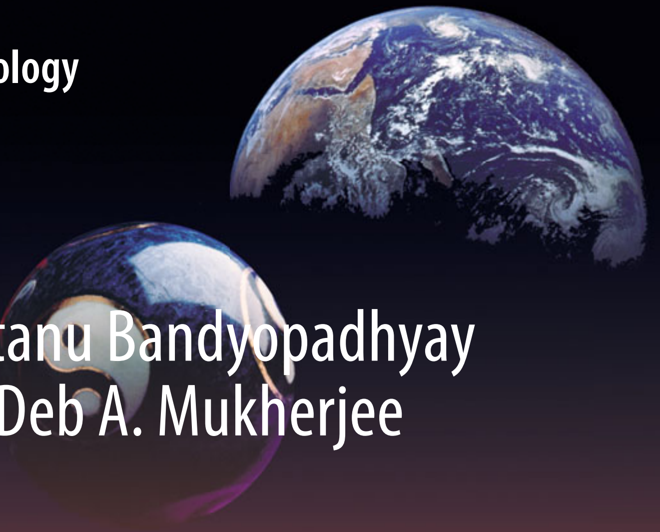
Green Energy and Technology



Sudipta De · Santanu Bandyopadhyay
Mohsen Assadi · Deb A. Mukherjee
Editors

Sustainable Energy Technology and Policies

A Transformational Journey, Volume 2

Springer

Green Energy and Technology

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Preface

Questions related to energy security, energy access, energy poverty, emissions related to energy usage, climate change, and above all issues related to overall sustainable development are forcing a rapid transformation in the energy sector worldwide. Existing energy scenario is primarily fossil fuel dominated. With the fast depletion of limited fossil fuel reserve, climate change problems due to emissions from fossil fuel sources, unavailability of fossil fuels in the remote corners of human settlements, and nonuniform distribution of the fossil fuel reserves making sustainable development a difficult proposition. Simultaneously, energy demand is always increasing with population growth and an increase of life standard of people over time. Transforming the present energy systems toward renewables is the most promising alternative. Meeting increasing energy demand and simultaneously increasing renewable share brings new challenges. Transformation to renewable-based energy system not only depends on the invention of new technology but is constrained by several socioeconomic and political constraints. For example, large capital is already locked in a large number of fossil fuel (mostly coal)-based power plants with matured technology over a long period. Phasing out of these plants must be properly planned to minimize social and economic impacts. Similarly, transport sector mostly depends on oil which is available mostly in some parts of the world. This has led to specific political issues all over the world. Thus, the issue of sustainable energy needs multidisciplinary analysis for possible future solution. Development of new technology is the key issue, but proper assessment of socioeconomic and political aspects is also critical for a sustainable energy solution. In two volumes of this book, these multidisciplinary aspects are reported and analyzed in several chapters by experts from all over the world.

In this volume 2 of the book, several aspects of transformation of sustainable energy are addressed in 18 chapters. Natural gas is expected to play a very critical role during transition from mostly coal-based power to renewable power as it can be used with better efficiency and lower environmental impacts than coal-based systems. Safari et al. discuss this future role of natural gas in two chapters. The first chapter explains the stimulus, enablers, and barriers of use of natural gas, and the second one explains these in more details with case studies. Carbon capture and storage is considered as the only feasible option of using reserve fossil fuels in the long run. Dutta discusses both the technology in brief and the current status of development worldwide. Distributed small-scale generation has several advantages as sustainable energy option. Somehsaraei and Assadi report the experimental performance of micro-turbine-based combined heat and power (CHP) plants. They also include better monitoring of these plants using artificial neural network tools. With several constraints, decision-making is complex, specifically for new technologies. The transportation sector is currently responsible for about a quarter of global energy demand and emissions. Managing transportation sector in a proper way is a big challenge for future energy sustainability. The next chapter by Lopez et al. discusses a life-cycle-based cost–benefit analysis framework for decision-making by policy-makers regarding low-carbon vehicle technology. Andiappan and Ng propose a framework for design operability and retrofit of energy systems through Disruption Scenario Analysis (DSA), Feasible Operating Range Analysis (FORA), and debottlenecking analysis. Geothermal energy is site-specific renewable energy. A systematic analysis using thermodynamic models of cogeneration using geothermal energy is reported by Parham and Assadi. Optimum energy conservation in batch plants using mathematical model is presented by Majozi. The perception of corporate sector about energy security of India is reported by Ghosh in the following chapter. It includes multidimensional socioeconomic and environmental perspectives of one of the largest industry groups of India, Mahindra. Finding alternative fuels for the transport sector is a big challenge of energy sustainability. It includes socioeconomic issues in addition to technology development. Ghosh and Roy report an overview of strategic niche management of national mission on bio-diesel in India. Rural electrification is a mission of India though the complete implementation is yet to achieve. A possible option with hybrid distributed generation using biomass and other local renewable resources is proposed by Palatel. Feasibility of producing oil and other value-added products from two nonedible oil seeds widely available in India as the feedstock is highlighted by Mishra and Mohanty. Shinde et al. present a study on possible sustainable renewable resources of India. They identify these resources as solar and biomass through technology and life-cycle assessments. Challenges and prospects of distributed electricity from renewable resources in India are discussed by Gon Choudhuri and Krishnan. These include both stand-alone and grid-connected options. Different aspects of “virtual power plants” with intermittent renewable resources in Indian context are reported by Mondal and Mukherjee. Use of new types of fuels needs modification of combustion devices to accommodate the new fuel. Bhattacharyya and Datta review the available literature on laminar burning velocity for fuels derived from biomass. They also explain the significance of it on combustion applications. Modeling of energy systems is useful to estimate expected performance and to obtain optimum design of the overall system. Sathisha and Dalal report an unsteady model of all all-vanadium redox flow battery to study effects of several important parameters. Electronics plays a critical role in any modern system including energy systems. Recent developments in electronics of strongly correlated electron systems are reported by Chanda et al.

This book in two volumes is for practicing professionals, policy-makers, and researchers in the field of sustainable energy with an interdisciplinary approach. This is developed in close collaboration with academia and industry under an ongoing Indo-Norwegian Cooperation Program (INCP-2014-10086). Editors acknowledge the support of their respective Institutes/organizations: Jadavpur University, Indian Institute of Technology Bombay, the Bengal Chamber of Commerce and Industry, and University of Stavanger of Norway. Thanks to the authors and reviewers from different parts of the globe for their contribution to this book. Editors also thankfully acknowledge the support of Springer throughout the editing and publishing process.

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Mohsen Assadi is Professor at Faculty of Science and Technology, University of Stavanger (UiS), Norway; Head of energy efficiency group for clean energy network at UiS; Head of monitoring and maintenance hub at CIAM, UiS; and Visiting Professor at Sheffield University and London City University. Developing methods and tools for identification of optimized instrumentation for cost-effective monitoring and control of various types of power plants have been one of the focus areas for the conducted R&D activities during the past years. Assadi has been project leader for several national and European-funded projects, dealing with performance monitoring and concept evaluation for conventional combined cycle plants using industrial gas turbines from various original equipment manufacturers (OEMs); a hybrid plant using combination of biomass-fueled steam cycle and natural gas-fired gas turbine with heat recovery steam generator (HRSG) delivering steam to a common steam turbine; an innovative cycle utilizing the humid air turbine concept, small-scale combined heat and power (CHP) units using mixtures of various gas fuels; an integrated gasification combined cycle plant, etc.

Deb A. Mukherjee is an entrepreneur, professionally qualified as a lawyer, with over 33 years of work experience in diverse business domains, engineering systems, information technology solutions, and later in energy services for the last 15 years. He was Executive Chairman of Eaga Energy India Pvt. Ltd. (subsidiary of Eaga plc UK FTSE 250 company) until 2012. Currently, he is an Investor and Country Director for Big Solar Ltd UK and also Managing Director of Cenergist Ltd UK—India Operations, an energy services business with operations in the UK, Spain, Germany, Italy, and now India. He is also incubating an IT start-up Teknowlegion Pvt. Ltd. in Kolkata, India. He has served on various trade committees in India and the UK and spoken at several international seminars on Sustainability Issues, Energy Efficiency, Renewables, Water Management, and Business Strategies. Currently, he is the Vice President of Bengal Chamber and Member of the Executive Board of the Chamber and the Chairperson of the Energy and Environment Committee of the Chamber.

Role of Gas-Fuelled Solutions in Support of Future Sustainable Energy World; Part I: Stimuluses, Enablers, and Barriers

Amir Safari, Soheil Jafari and Mohsen Assadi

Abstract Tackling the challenges of energy poverty and changing living conditions in line with the growing population, and doing so in a sustainable manner, is recognised as being of utmost importance for the world today. The main goal of this study is to illuminate the fact that providing energy to an ever-growing population of the globe during a period of transition, and so doing in a responsible manner, requires a sustainable energy mix of fossils and renewables. Given the fact that the energy solution of tomorrow has to combine various fuels and technologies, different solutions will be needed for different regions, as determined in line with various factors, including the availability of resources and specific needs. Consequently, the role of gas-fuelled solutions as part of the transition towards future sustainable energy world needs to be illuminated from a technical, economic, social, political and geographical point of view. The discussions and conclusions presented in the chapter support the expectation of the increased use of natural gas as a part of the global transition towards a low-carbon energy society. From a carbon-neutral energy perspective, however, the use of biogas and renewable-based hydrogen as replacement for natural gas, in the long-term perspective, could be expected. In this way, natural gas will be an important complement to renewable energy during the transition period. Infrastructure and energy conversion technologies developed for natural gas need to be designed in such a way so as to be able to cope with the transition towards biogas and renewable supported hydrogen. Moreover, small-scale combined heat- and electricity-production and distributed generation could be a potential gas-fuelled solution, providing an improved fuel utilisation factor and, as a result, reduced emissions of greenhouse gases. Taking into account the challenges of the increasing demand for reliable and affordable energy, as well as global climate change, it is concluded that common understanding needs to be established amongst all the players, including society,

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industries, strategists, decision-makers, politicians and environmentalists, so as to reach a new level of commitment and partnership.

1 Introduction

As a naturally replenished energy that can be found anywhere in the world, renewable energy is becoming more popular and useful in the modern-day world. The positive environmental impact of renewable energy makes them more important with regards the fact that fossil fuels, when burned, generate harmful greenhouse gas emissions that significantly contribute to the global warming phenomenon [1]. The growth of renewable energy contribution (19.2% of global energy consumption and 23.7% of electricity generation in 2014 and 2015, respectively) resulted in considerable investments worldwide (more than US $286 billion in 2015), the creation of job opportunities (estimated at 7.7 million) and overwhelming attention [2]. Although renewable energy resources are accessible across the globe, the question is whether or not it is possible to cover the world's energy needs solely through renewable sources, and whether there will be a single solution to the future energy needs of the world. In order to answer these questions, different aspects of the problem, i.e. social, technical, economic, environmental and political, etc., as well as different possible scenarios, need to be taken into account. However, the common understanding is that there will not be a unique solution, but rather a Pareto front answer for different locations and situations, which need to be pragmatically explained and discussed.

Undoubtedly, renewable energy is on a roll. As of the end of 2015, approximately 2000 GWs of renewable generation capacity existed globally, as noted by the International Renewable Energy Agency in a statement. In the following year, 2016, the largest-ever amount of new renewable energy capacity installation around the world was observed, with wind and solar energy driving the hike due, in large part, to a continued decline in technology costs, according to the annual update produced by the International Renewable Energy Agency (IRENA). Importantly, different growth of renewables has been witnessed in different regions—43% in Denmark, 25% in Germany, 13% in United States—meaning that the ambitious aims for the near future have been increased, amounting to 70% in Denmark by 2020, 55–60% in Germany by 2035, and an incredible 80% in China by 2050. Nevertheless, it seems that the transition to 100% renewable energy in the short- and mid-term is facing serious issues [3]; these will be discussed briefly here.

The foremost concern centred on the transition to a fully dominated renewable energy world is *energy poverty*. Currently, 1 in 5 people around the world (equal to almost 1.6 billion people) do not have access to modern energy services. For such individuals, having access to any kind of energy is fundamental to improving their quality of life, regardless of the energy resource. Figure 1 shows that billions of people remain without basic energy services.

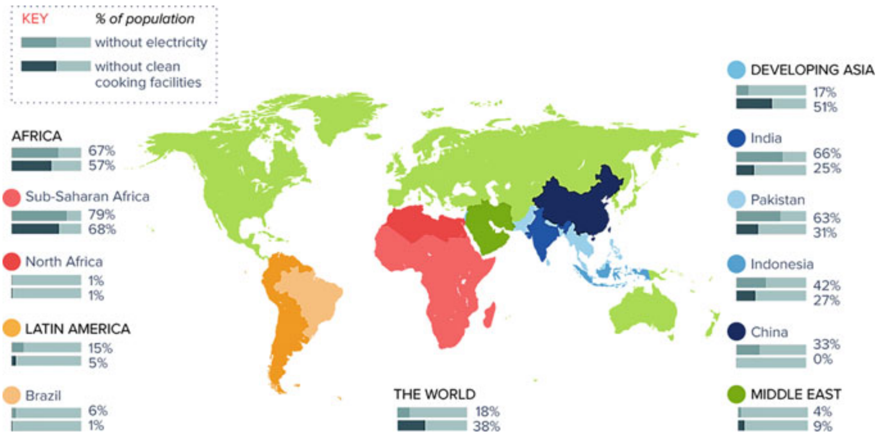

Fig. 1 Renewable energy is necessary but not enough: world energy poverty [4]

The second concern centres on *technical problems*. Availability and reliability are important parameters in the design and development of an energy network, which are not compatible with renewable sources' intermittent nature. In other words, although the topic of transition to renewable energy is very interesting, there remain some major technical issues in this path that act as limitations to achieving the goal. The most important ones include a lack of infrastructure, including large storage units, a lack of experts in the field, and a non-continuous source of renewable energy, meaning that the use of renewable energy is neither reliable nor affordable enough for most people [5]. In other words, it is difficult to generate the quantities of electricity needed solely through the use of renewable sources when comparing the volumes produced by traditional fossil fuel generators. Moreover, renewable energy often relies on the weather for its source of power: without enough rain, powerful wind or clear skies for sunshine, hydro generators, wind turbines and solar collectors, respectively, would not work properly and efficiently.

The third concern relates to *economic issues* in terms of fuel affordability and the possibility of using existing infrastructures, which result in more reasonable investment for non-renewable resources. At the same time, cost of infrastructure development for countries and regions with no/low infrastructure would be significant. Also, in terms of costs, renewable energy, today, does not seem to be cost-effective compared to traditional fossil fuel energy generation systems. In this regard, even if the most cost-effective choices of solar and/or wind power solutions could beat coal-based electricity-generation, it would be a different story for natural gas.

The fourth concern is that governments prefer to have a mature and stable regulatory framework in place. In addition, oil and gas (O&G)-rich countries prefer to rely on these resources as far as it is available and affordable for them. Lastly, though many countries have signed the COP21 agreement where its ratifications have a significant impact on their strategies, every country has its own pathway to devising a solution for a more sustainable world based on its own unique national

Table 1 Some facts about renewable/non-renewable energies

Type	Advantages	Disadvantages
Renewable	• Widely available • Lower cost outlay • Running cost generally low • Low pollution • Available for the foreseeable solution • Decentralized power production	• Unreliable supply • Usually produced in small quantities • Often very hard to store • Currently more costly per energy unit produced than most of other energy types
Non-renewable	• Addressing energy poverty • Highly concentrated • Easy to store • Reliable supply • Using existing infrastructures • Costs per unit energy are usually low as the technology is very mature	• Polluting • Occur in limited area • High capital cost • Significant running costs • Limited supply-will run out
Sustainable solution: Energy mix	We need to look at the future scenarios, short term, mid-term and long term. In mid-term, use of fossil fuel is dominant and mid-term (transition period) there will be mixed one where in fossil and renewable energy mix will be playing role However, what about long term? Actually, there are very different views on how the energy mix will be (between fossil and renewables), and also what it should be, and how fast the transition can occur	

and local circumstances. In this regard, Table 1 provides an overview of some of the merits and demerits of renewable and conventional energy resources.

In an effort to tackle the challenges and difficulties identified, one needs to solve a new energy equation system for the future, which does not have a unique solution. Through such an approach, fossil fuel-driven energies could be an excellent companion—and not competitor—for renewable energies (RE), thus enabling some of the most important challenges of tomorrow to be managed and circumvented. This would be a true proposition specifically with significant improvement in the energy efficiency (EE) of existing/future energy conversion systems.

Amongst all types of fossil fuel, however, it is recognised that demand for natural gas (NG), as the cleanest and most reliable fuel, will grow by 50% in 2035, according to IEA and Wood Mackenzie, and thereby will overtake the place of the coal in the global energy mix. Under the impulsion of various countries (e.g., China and the Middle East), where natural gas is making inroads in all consuming sectors, gas demand growth is expected to remain strong up until 2035 [6]. The international reports state that the Europe and Asia's increasing dependence on imports will drive the strong expansion of net inter-regional gas trade, expected to grow by 3.1% annually up till 2035. In this way, there are many enablers, openings and incentives (which would be briefly discussed in the current study), including but not limited to the possibility for distributed-generation (DG) as well as Combined Cooling, Heating and Power (CCHP) production, using Combined Cycle Gas Turbines (CCGTs) and other novel efficient cycles, existing mature technologies to make different types of gaseous fuel (from different states of natural gas, such as CNG, LPG and LNG, etc., through to biogas, syngas, and H2) effortlessly in operation, motivating reduced gas flaring (such as Global Gas Flaring Reduction—GGFR—international project), and addressing new challenges in the future electricity market, such as in terms of intermittent renewables, offshore/onshore green decommissioning in the petroleum sector industry, and so on.

For instance, Liquefied Natural Gas (LNG) trade growth will be stronger than that of pipeline, and its share of net inter-regional trade will increase from 46% in 2013 to 50% in 2035 [7]. Here, the most important is the easy and effective transportation of natural gas. LNG will be supplied from a growing number of sources, with new actors seen to emerge in North America, Oceania and East Africa. Furthermore, LNG will lead to the growing internationalisation of the gas markets, with flexible LNG and hub-pricing gradually expanding in Europe and Asia. The considerable infrastructures available will also help this growth rate.

However, there are some challenges and risks in the use of NG as a fossil fuel that should be considered. The most important one is the global climate change concern. The energy sector is in the spotlight as the Paris Agreement enters into force (though it is only a framework, meaning its impacts on the energy world depend on how the goals are translated into real governments' policy actions). The other important concern centres on technical considerations. In regards the nature of NG, the maintenance and regular inspection of the infrastructures and transportation facilities are vital. There is always the possibility of methane leakage, which is very risky considering greenhouse gas (GHG) emissions [6]. As a result, the world needs a new common understanding in order to achieve a new level of commitment to both energy supply and global warming from different energy demand and supply viewpoints (i.e. O&G companies, environmentalisms, renewable system developers and governments, etc.).

2 Energy Transition and a Mixture of Energy Resources: Barriers, Risks and Enablers

Many factors could contribute to the need for diversification amongst energy resources, e.g., a community that has relied heavily on coal, for instance, and is facing increasing demand as the energy use per capita rises. Some communities may broaden their energy generation diversity by adding different mixtures of such alternatives as solar and wind power. However, some countries like Norway basically rely on hydropower because of their abundance in natural water systems. Some other communities, still using renewable energies, supply their main proportion of their energy from more reliable resources as coal as well as hydropower. Economic and financial aspects as well as political strategies determine the ratio of each kind of renewable and fossil energy in use, in a country. Regions that rely heavily on coal or fuel oil/gas would also be affected by the price of fuel. The world map below demonstrates the global power plant fleet by technology, created using the power plant data source Platts UDI Database in 2012 [8].

2.1 World Energy Scenarios: More Energy, Less CO_2

Figure 2 shows a change in the total primary energy demands of the world, provided by different references, according to the different scenarios, mostly in petroleum-supporting organisations. Due to an increasing energy demand caused by a growing world population, however, low-carbon fuels and technologies, including both gas and renewables, play an important role in all energy scenarios for the maximum two-degree global temperature rise by 2050.

In particular, it is important to address that most of the electrical energy used by diverse end-users (residential, commercial and industrial sectors) comes from different types of resource, i.e. coal, natural gas, hydropower, solar power, wind power and nuclear, with the need to also determine the shares of different mixtures. According to IEA, for example, low-carbon resources would supply almost half of the increase in energy demand to 2040 (Figs. 3, 4, 5 and 6).

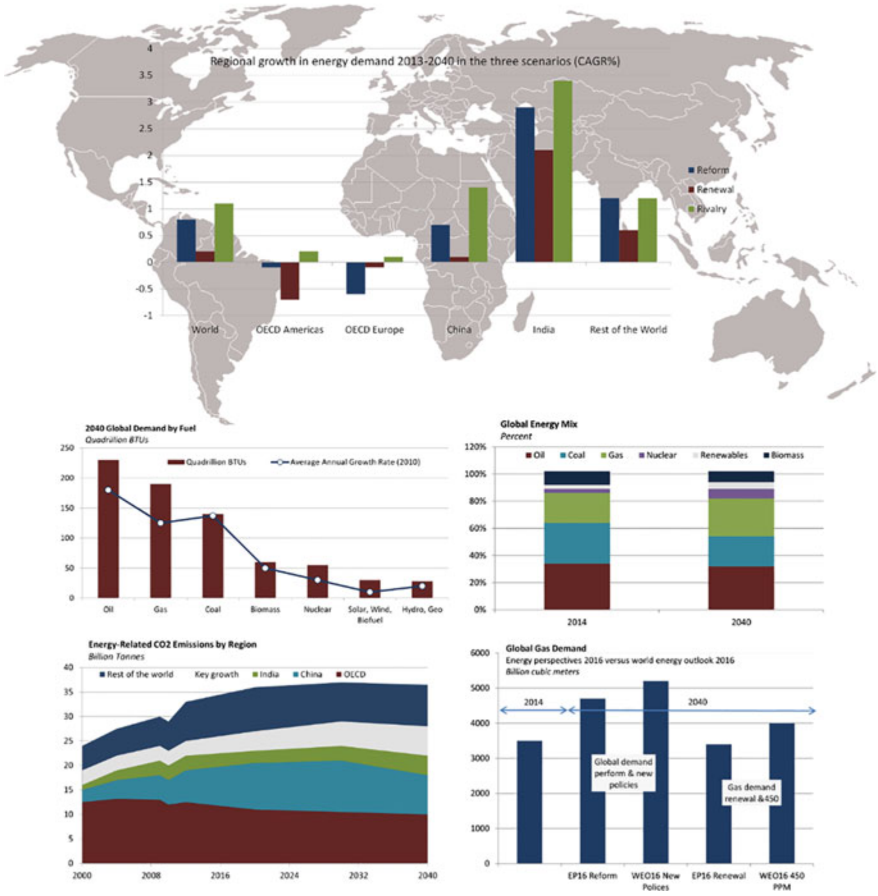

Fig. 2 A comparison of different scenarios presented by different sources [9]

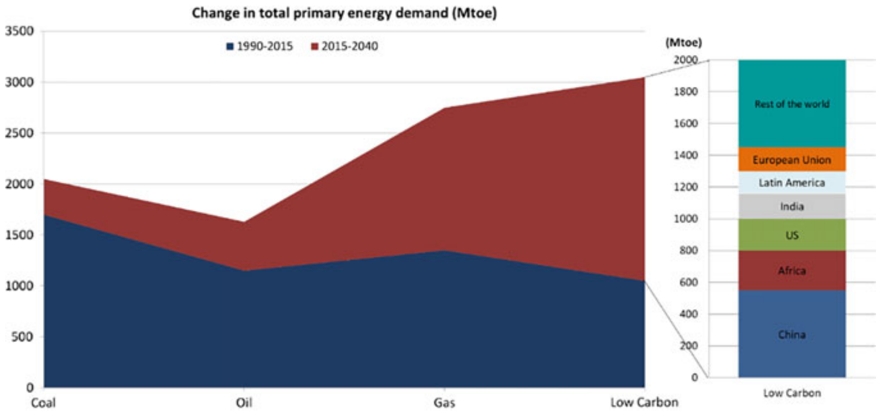

Fig. 3 Change in total primary energy demand [10]

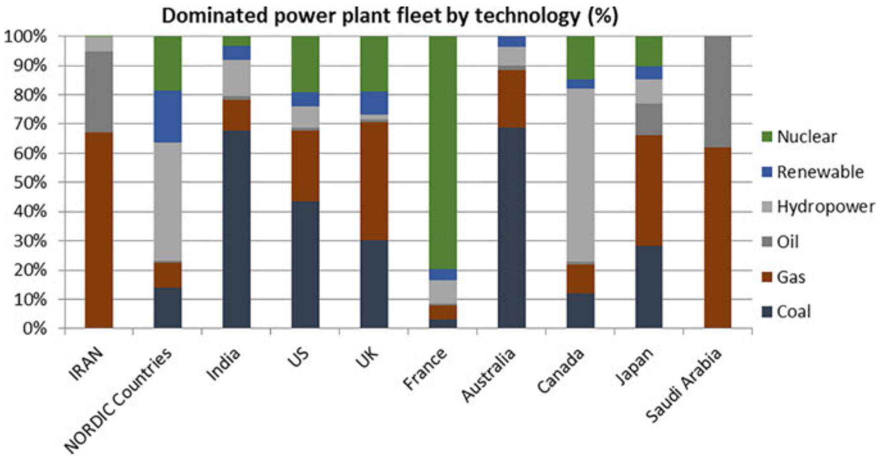

Fig. 4 Global power plant fleet by technology

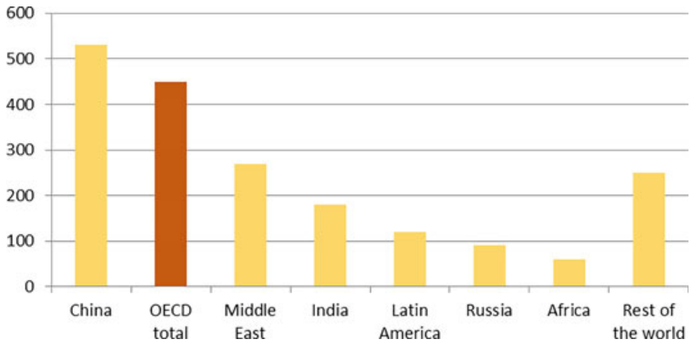

Fig. 5 The increase in natural gas consumption (bcm) in the GAS scenario, 2010–2035 [14]

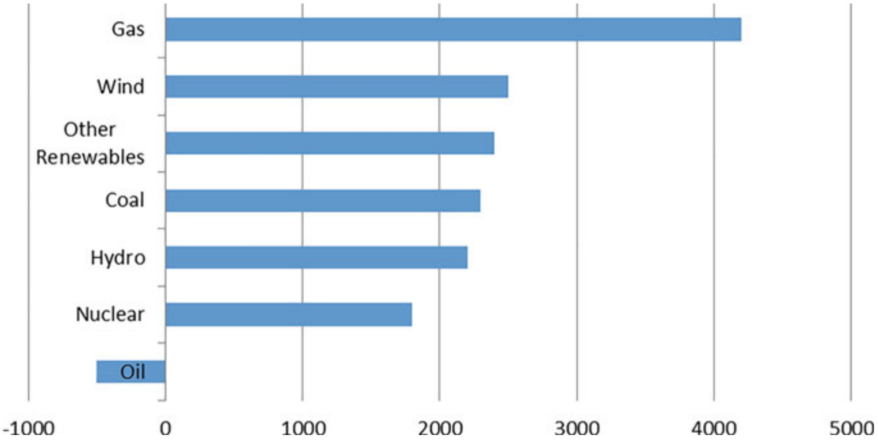

Fig. 6 Change in power generation by fuel (TWh) in the GAS scenario, 2010–2035 [14]

Generally speaking, most electricity is generated from a variety of energy resources, with the energy resources used recognised as varying from one place to another, depending on many different circumstances, such as those outlined below:

- Mentality: Psychologically, a community does not want to rely on just one energy resource for all its electricity/heat demands as this could induce insecurity in the event that the source is either temporarily or permanently unavailable.
- Quantity: The amount of energy that different people use per capita may vary significantly based on their socioeconomic status, the job they do, and where they live (i.e. political and social support for the energy resource).
- Combinatory: Using a mixture of resources supports availability, affordability and reliability.
- Energy efficiency: The effectiveness of converting an energy resource into electricity is a significant factor when deciding on the selection of a proper energy resource. As the efficiency of an energy generation system grows, less amount of fuel is needed for generating one unit of energy, comparing to older non-efficient systems. This also means that it will emit less carbon dioxide in the environment.
- Geography: The role of geography could affect which renewable and/or non-renewable energy resources are viable and cost-effective for a specific area.
- Proximity: Distance to the resources has an impact in determining the cost of energy. For example, a lot of natural gas is mined somewhere so that transportation costs to use this fuel would be lower for those areas than for others.
- Environmental concerns: Carbon dioxide emissions, according to local legislations and different CO_2 proxy/penalties, should be seriously considered. This could lead to health problems (usually, CO_2 is not connected to health, but NO_x and SO_x are), as well as long-term environmental impacts due to global climate

change. More specifically, when some resources are equally viable and costly in one area, eco-friendly options would be the key issue.

- Infrastructures: Existing assets and setups should be considered in terms of having more affordable resources for energy demands.
- Energy-saving: Energy conservation relates to the amount of energy consumed. The more energy conserved, the less needs to be consumed.

Accordingly, some communities need to rethink and accordingly redesign for an energy resources mixture plan that provides a good combination of high efficiency and low CO_2 emissions. The energy resources we use might have a negative impact on quality of life. Combinations that use an irrational high percentage of fossil fuels will increase air pollution; inefficient combinations, on the other hand, might cause a higher price of electricity or a shortage of energy.

The main challenge in reconciling the growth of the world's energy needs at lower GHG cannot be achieved by the sole use of renewables—at least in the short- and most probably medium-term. It can only be met by supporting renewables with other complementary strategies, such as the use of low carbon fuels, increased efficiency of fossil-fuel-based energy conversion systems, the implementation of Carbon Capture and Storage (CCS) technologies, emission reductions on large-scale transport, and waste heat recovery. As the IEA's 'Energy Technology Perspectives' 2015 report claims, amongst the technologies required to achieve the *2 Degrees Scenario*, renewables will be responsible for 30% of the CO_2 reduction in the power sector by 2050, CCS technologies for 13%, and nuclear energy for 8% of the cumulative reductions (data elaborated from [11]).

In general, it could be said that the market uncertainties in the context of world energy scenarios would create opportunities for natural gas. Regional energy security is in a safer side by more gas in use. In order to achieve this, the research and reports show that new supplies and trade routes emerge. Moreover, from a technical point of view, NG has a role to play in a low-carbon energy economy [12]. The recent studies and reports—which notably state that gas-fired power plants could reduce coal-dependence and greenhouse gas emissions significantly in the next 10 years—introduce natural gas as the key energy for a low-carbon future, with the replacement of coal with NG resulting in reduced CO_2 emissions, but not zero emissions. Therefore, NG is not a complete solution, but merely a bracket in time and part of the solution.

2.2 Natural Gas as Transition Fuel

Given the fact that 'green methane' from renewable electricity, i.e. hydrolysis and methanation, could be the destination fuel, the support of natural gas as transition fuel would be legitimised. Natural gas would provide large-scale power-generation capability during the transition, whilst green methane would replace NG, thereby supporting the future development of gas-based flexible energy-conversion technologies (such as gas turbines and gas turbine-based innovative power plants) as an investment in the realisation of the future's carbon-free energy system. From a global climate change point of view, however, there is no unique solution. All low-carbon energy (natural gas), carbon-neutral energy (biogas), carbon-free energy (renewables) and improved energy efficiency needs to be combined in order to control and manage climate change in the mid- and long-terms. Accordingly, the establishment of regulations, legislation and policies introduced by governments is an exigent need to support low-carbon intensity fuels, such as natural gas, in this transition period.

When discussing the role of natural gas in energy transition, there is a need to take different points of view into account. Various perspectives are considered in the following sub-sections.

2.2.1 Social Aspects

The main element in the social aspects of NG is the concept of energy. Currently, 1 in 5 people around the world do not have access to modern energy services. This changes the living conditions in many areas of the world. It is predicted that non-OECD countries account for 80% of all demand growth. China alone makes up almost 30% of the global growth, and is expected to use as much gas as the EU by 2035 [13].

Between 2010 and 2035, global natural gas use in the GAS Scenario is expected to increase by more than 50% and accounts for more than 25% of the world energy demand in 2035. By growth of natural gas demand, reaching 5.1 tcm by 2035—1.8 tcm more than today, the share of coal in the energy mix is pushed into a decline. Accordingly, the gas share will overtake coal share by 2030.

In rapidly urbanizing areas as Middle East, China, and India, natural gas sounds more interesting for their growing energy demand. This demand determines the increase in natural gas consumption over the next 25 years (Some countries like India are very afraid of getting dependent on imports that leads to vulnerability in case of some political changes). Substituting other fossil fuels with natural gas will result in lower greenhouse and pollutants emission. Carbon emissions would lead to more than 3.5° temperature increase in accordance with the high gas scenario. Aiming at 2° of temperature increase demands much more effort as greater shift to low-carbon energy sources, boosting energy efficiency, new technologies such as CCS, which result in reduction of emissions.

2.2.2 Technical Aspects

Power-generation remains the dominant sector for natural gas demand in the IEA GAS Scenario, although there is a broad-based increase in gas demand spanning the industry, transport (specifically shipping) and building sectors. Natural gas is available when and where other sources of energy are not, which may be why studies show gas as overtaking coal before 2030 and as meeting one-quarter of global energy demands by 2035. Notably, demand grows 2% annually, compared with just 1.2% for total energy.

Natural gas could play an even greater role in the future global energy mix than that suggested by the current supply and demand trends owing to the fact it is easy to control through the use of efficient and matured NG-fuelled conversion technologies. According to the predictions provided by the IEA, it is expected that total electricity demand will increase by 70% by 2035, underpinned by the near-doubling of gas-fired generation.

Natural gas can be transported across the globe with a relatively low environmental impact. Natural gas can be transported safely and efficiently in its liquefied form (LNG) through the use of specially designed LNG tankers, incurring minimal fuel losses during transportation. LNG is an inexpensive and simple method of to transport in this regard. The share of LNG in global long-distance gas trade can be seen in Fig. 7, which is a promoter for another natural gas revolution. According to the IEA's central long-term scenario, LNG is expected to overtake pipeline.

Gas-fired plants have become crucial in the utilisation of large-scale intermittent RE sources due to their flexible operation. Although they are not currently flexible enough, since they were not designed for such purposes, there is, however, real potential to make new ones flexible. This would require significant investment in technology research and development. Natural gas also enables a move towards Distributed Generation (DG). Thanks to easy transportation and distribution using pipelines, natural gas could play a key role in DG. In addition, all gas-fired technologies could be adapted to use biogas/syngas/H2 in the future energy world; further development of combustor technologies would further enable gas-fuelled technologies to use the green gaseous fuels produced by excess power from renewables.

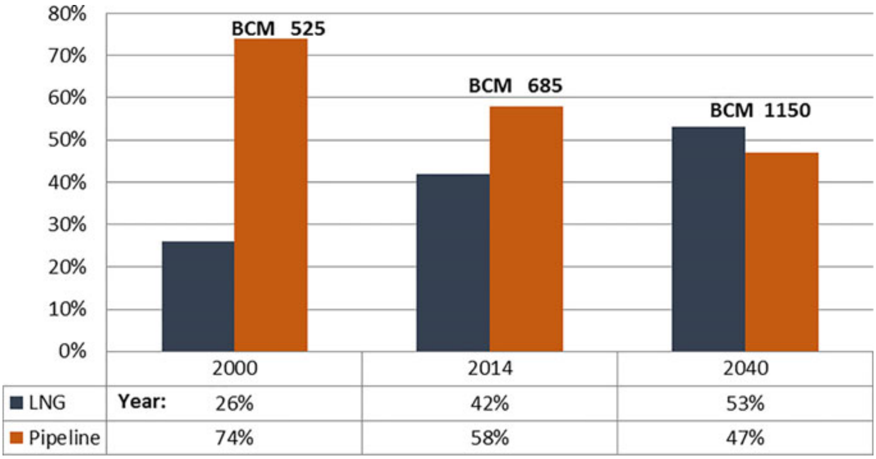

Fig. 7 Share of LNG in global long-distance gas trade [15]

2.2.3 Economical Aspects

In contrast to the WEO-2010 New Policies Scenario, the Golden Age of Gas Scenario (GAS Scenario) incorporates a combination of new assumptions that underpin a plausible but nonetheless more positive outlook for gas. China has implemented an interesting policy for gas usage, integrating lower nuclear power and more widespread use of natural gas in road transport. Abundance of natural gas, most of which being unconventional, has resulted in lower gas prices than what was assumed by WEO-2010. The GAS scenario also relies on government support of renewable energies. However, with respect to the infrastructures and facilities available, natural gas is an economic fuel, with existing gas networks/technologies not only needing to be maintained but also developed for both natural-gas and bio-gas, as well as storage applications (such as for power-to-gas technology). Figure 8 shows the 2030 levelised costs of electricity produced by different gas-based technologies.

2.2.4 Political/Governance Aspects

Being able to supply the world primary energy demand by NG predicted in the GAS Scenario, which is approximately 4000 Mtoe by 2030 [14], an increase in production equivalent to roughly three times the current production of Russia will be required. The largest existing gas-producers are expected to meet much of the increase in demand in the GAS Scenario; however, they will be joined by China as it becomes one of the world's largest gas-producers.

Natural gas supplies are identified as vital sources of energy and electricity for the next 250 years, which is before considered as the progress of power generation technologies efficiency. Therefore, whilst NG is considered reliable, abundant and accessible, with open markets in place, governments need to stabilise stable regulatory frameworks and/or improve existing ones so that a reduction in CO_2

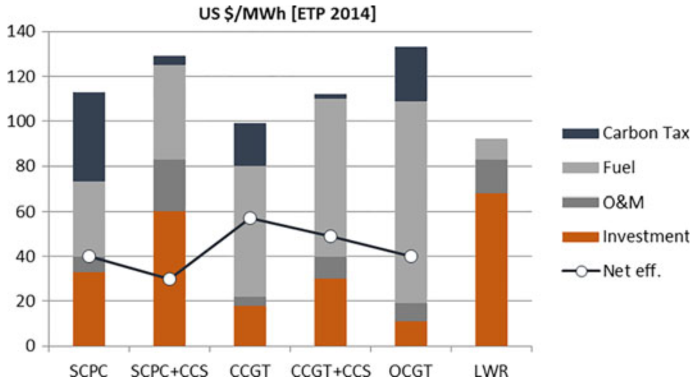

Fig. 8 2030 levelised cost of electricity [9]

emissions and global warming can be seriously considered as the core of strategic planning. Through such an approach, NG is a transition fuel towards a carbon-free energy system, i.e. NG a bracket in time and history.

From a legislation point of view, there remain many important issues that should be a point of focus, including, but not limited to, a long-term investment model for all related gas-based technologies, pricing models and the reformation of networks' tariff structures to take into account the increasing variability of generation, a modified model for the balancing and demand-side flexibility, the reinforcement of the governance framework for the higher penetration of distributed generation, storage and smart technologies, regulations centred on gas quality standards, including blending and bio-methane, certification systems for low-carbon gas in the industry, grid and mobility, contractual terms and pricing arrangements for natural gas, and the compatibility of gas-based solutions with market models.

2.2.5 Geographical Aspects

Any country has its own pathway to arriving at a solution for a more sustainable world, based on their unique national and local circumstances. The global proven reserves of natural gas, which amounted to 187.3 trillion cubic metres at the end of 2012 [16], shows a completely different pattern of natural resources, as well as transportation ways for diverse areas, as shown in Figs. 9 and 10. Based on data from The World Factbook [17], Iran has the world's second largest reserves after Russia.

Total recoverable resources could sustain today's production for more than 250 years, with all regions known to have recoverable resources equal to at least 75 years of current consumption. Unconventional gas[1] supplies 40% of the 1.8 tcm increase in gas demand to 2035, making up nearly one-quarter of total production. Not necessarily directly related to the global natural gas resource, which is vast and widely dispersed geographically, the large production of NG strongly depends on the drilling and exploitation technologies used (Fig. 11).

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[1] The term 'unconventional gas' refers to the method of extraction used for natural gas stored in low-permeability features, such as shale rock, sandstone, and coal seams. Generally, the difference between conventional (porous media) and unconventional (non-porous media) gas is the fact that for unconventional, gas is trapped in smaller volumes surrounded by tight formation, which needs to be cracked to establish connection between the volumes containing the gas to make the production economically interesting. The reservoirs of conventional type are connected since the reservoir is porous material.

Several methods and technologies are used to extract unconventional gas. The most economical methods are horizontal drilling and hydraulic fracturing. The American Energy Innovation Council (AEIC) states that the combination of these two methods is the most efficient technology for extraction of the unconventional gas [18].

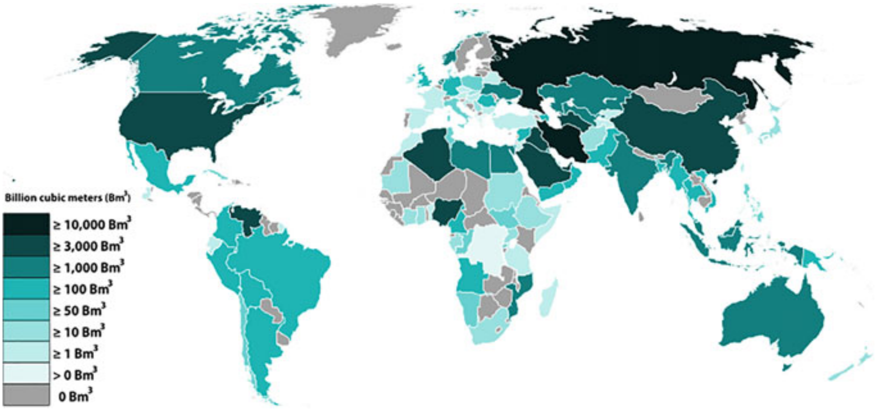

Fig. 9 Countries by natural gas proven reserves [17]

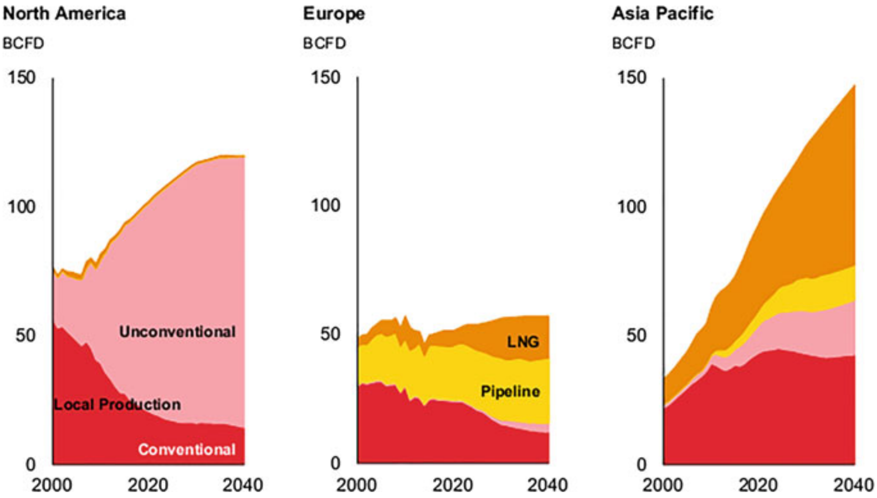

Fig. 10 Gas demand grows and supply diversifies [9]

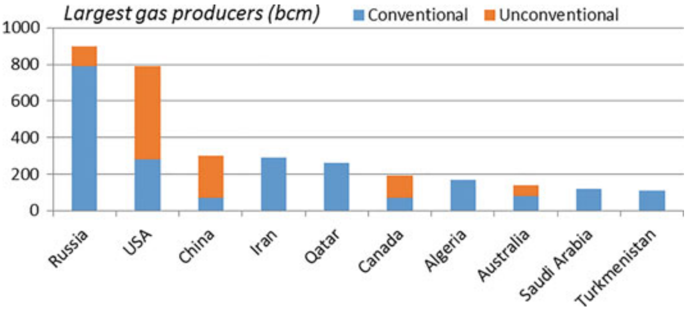

Fig. 11 Largest gas producers in the GAS scenario, 2035 [14]

2.2.6 Environmental Aspects

Natural gas is the cleanest fossil fuel. When NG is burned, it releases up to 50% less CO_2 than coal and 20–30% less than oil, taking the efficiency of electricity production into account (see Table 2). From power generation point of view, substituting natural gas with coal, and other fuels, will lead to decline the ratio of CO_2 (less than 50%), and eliminate of emissions of Sulphur Dioxide (SO_2), Nitrogen Oxide (NO_x), mercury (Hg) and other particulates. CCS technology (the capture and storage of CO_2) was the main target of current technologies, and reduction of emissions will be developments of natural gas based power generation systems. Higher air quality and public health are the benefits of the natural gas driven generation systems.

On the other hand, the methane leakage as a result of natural gas is an important environmental consideration, which comes from drilling sites and gas-processing plants (upstream emission), as well as pipelines and storage systems (downstream emission).

3 Approaches and Technologies: Gas-Fuelled Energy Systems and Scheme Integration

In this section, the key role of innovation in supporting the position of gaseous fuels in the decarbonisation of energy systems will be discussed in detail. These technologies and innovative solutions could be applied in different segments of the gas cycle, as shown in the Fig. 12.

3.1 Renewable Energy Systems (RES)' Backup and Grid Stability

It is accepted worldwide that increasing the share of renewables is a viable way of realising the decarbonisation of the energy sector; however, their inherent intermittency (and maybe also unpredictability) causes instability of the electric grid. Future sustainable energy systems, with a significant share of intermittent

Table 2 Natural gas; a far less pollution (tonnes per year per MWs)

Pollutant	Coal	Natural gas
CO_2	6352	2348
CO_2 with CCS capture	837	309
Carbon monoxide	4.62	1.64
Nitrous oxide (NO_x)	1.85	0.15
Sulphur dioxide (SO_2)	3.08	0.02
Mercury	2.0 oz	None

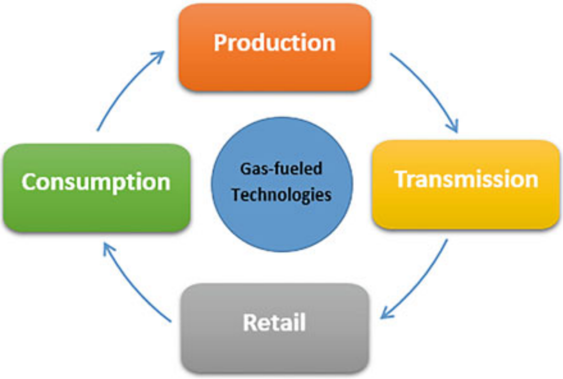

Fig. 12 To motivate gas-fuelled technologies, innovative and efficient solutions could be considered for different segments

renewable, such as wind and/or solar power, will require balancing power so as to maintain grid stability. This will be a growing challenge for all grid operators. A great deal of work should be undertaken by researchers to facilitate the integration of the variable power-generation into the grid. In this regard, the use of advanced power cycles, as well as existing gas-fired power plants, for backup and balancing could be considered feasible alternatives, although their flexibility needs to be improved. As a matter of fact, the significant growth of Renewable Energy Systems (RESs), such as wind power, will result in an increasing demand for flexible plants that can support integration by offering quick start-up and large load-changing capability. This could also be facilitated by various types of storage.

3.1.1 Grid Stability Challenges

Wind and solar energy being so much dependent on weather and time of the day have some intrinsic fluctuations. By the share of renewable power increases in the grid, the gas power plants transform from main power providers of the grid to the fluctuation balancers so as to overcome the shortages of the grid power. Such power plants should be capable of running in the lowest load possible and have high efficiencies. Due to probable sudden changes in the power generation and demand these power systems must be able to provide the grid with stabilized energy. High rate of power change may be needed even as fast as start/stop mode. These fast rate changes, though, impose wear to the power plant. Therefore, these power plant must have a good operational flexibility.

System stability during transient operation requires frequency control. Frequency drop as a consequence of varying shares of intermittent generation in the grid, is a major driving force for utilising existing infrastructure in GT-PPs, tagged as ‘must run power plants’. There are different combinations of GT-PP in contributing to control and balancing issues. For this purpose, a detailed model of a national power system is required for each region so that the load flow can be calculated and voltage and transmission limited for analysis (grid development will be needed):

- There is a significant impact of intermittent generation on system stability, such as frequency control (primary and secondary control) and voltage control, due to a reduced number of power plants (especially in Europe), therefor resulting in inertia in the grid.
- Increasing load flows can lead to increased voltage instability (losing reactive power). One of the contributions of the conventional gas-fired power plants to the grid is voltage control; however, their number is continuously reduced, resulting in increased grid instability. Accordingly, several actions are needed in order to maintain voltage stability.

The increasing share of renewable sources of energy [19], unpredictable and intermittent for their own nature (especially wind turbines, since wind day-ahead predictions are less reliable than solar ones), will result in more power fluctuations in the electricity grid. In such a scenario, gas-fired power plants will play an important role in electrical grid-balancing and back-up systems through compensating such fluctuations [20]. Thus, Gas Turbines (GT) for balancing and back-up power will be required so as to ensure loading and unloading phases are stabilised and carried out quicker than current ones, whilst still maintaining low pollutant emissions. At the same time, they will be required to be ‘parked’ at their minimum environmental load (with an increased turndown ratio), or even shut down when their power is not needed.

For example, in 2013, Spain and Germany experienced 13 and 25 GWs unpredictable daily load variations, respectively. National load ramps of more than 5 GWs/h are expected to be common. The required ramp rate will be approximately three times what is achieved today. Critical changes in the management of some power plants are already being experienced by users: as a matter of fact, the best available fossil-fuel technologies, i.e. Ultra-SuperCritical Pulverised Coal (U-SCPC), Integrated Gasification Combined Cycle (IGCC) and Combined Cycle Gas Turbine (CCGT), can be flexible but nonetheless have been found to suffer operational and reliability problems when used in this way. As a consequence, in 2013, 14% of the European installed capacity (corresponding to 24.7 GWs) was idled, closed or at risk. Following, in 2015/16, up to 50 GWs may be closed [21].

Although the intermittent operating mode of GT plants in Europe increased their CO_2, CO and NO_x emissions (e.g., the CO_2 emissions per MWh increased by 8% in 2014), it is remarkable to note that the global emissions of CO_2 did not rise for the first time in 40 years in the year 2014. This could mainly be related to a major shift from coal to natural gas, both in the USA and Asia, though the global economy grew by 3% [22].

3.2 *Carbon Capture and Storage (CCS)*

As previously stated, according to IEA, CCS technologies can be responsible for 13% of CO_2 reductions in the power sector in achieving the *2 Degrees Scenario*

[11]. However, it is observed that CCS deployment is occurring too slowly due to high costs and a lack of political and financial commitment. Importantly, although CCS technologies are considered technically feasible, they remain expensive and negatively impact load-flexibility; Open-Cycle Gas Turbines (OCGT) have greater load-flexibility when compared with other energy conversion systems, but the low concentration of CO_2 in exhausts makes CCS implementation on OCGT unattractive. Moreover, CCGTs have the highest efficiency, which makes them competitive concerning the cost of electricity, also in the carbon-free power-generation scenarios, but they have load-flexibility levels that fall lower than OCGT, and they further exhibit similar problems in regards CCS implementation. Furthermore, implementing CCS technologies in such plants results in significantly higher costs in electricity and further restricts their flexibility. As can be seen in Fig. 13, from the point of view of the final cost of electricity (assuming a carbon tax around 50 US$/t CO_2), CCGTs are more competitive than SCPC plants, with or without CCS [23], although the cost of CO_2 per captured tonne is lower for coal plants [24]. This remarkable result is explained in consideration to the fact that both the relative net efficiency penalty due to CCS (%) and the final net efficiency with capture (LHV, %) favour CCGT [23].

It is also important to note that, although advanced CO_2 capture concepts for power-generation are under development, they are designed in mind of base load. Such technologies should be rearranged for load flexibility, where possible, with unavoidable penalties both in terms of efficiency and costs. In other cases, some CO_2

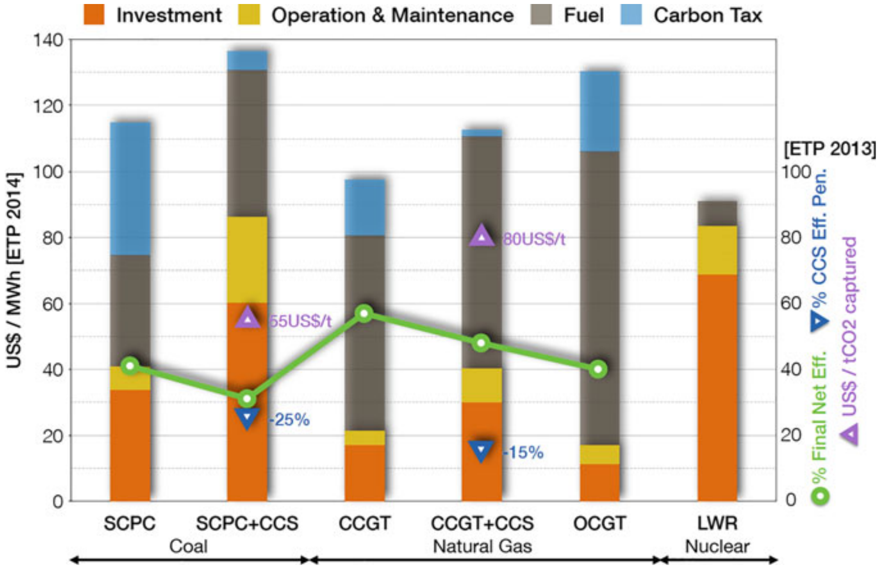

Fig. 13 CCS impact on the final cost of electricity for current power plants [11]. Final net efficiency with capture, relative net efficiency penalty due to CCS and the cost of CO_2 captured are also shown on the right axis [24]. In this analysis, the carbon tax is around 50 US$/ton [25]

capture concepts are not (or nearly not) compatible with the load flexibility requirements. Hence, plants with a simpler layout and fully integrated CO_2 capture processes offer a major step forward. The combination of high load change frequency and capture is not possible today, with more R&D needed in order to make it work.

3.3 Novel Cycles

Novel cycles should lead to innovative and cost-effective solutions centred on improving the ability of new and/or existing dispatchable gas-driven thermal power plants to meet fast load changes in order to better support the grid as a result of fluctuations in energy peak demands and power output from renewable sources, whilst achieving minimal fuel consumption and emissions, and similarly mitigating the effects of cycling operation so as to avoid excessive wear and service life expenditure—without impeding the potential CO_2-capture readiness of power plants.

3.3.1 Combined Cycle Gas Turbines (CCGTs)

Flexible CCGTs and gas-peaking units, as privileged technology for load variability in Europe, support the integration of RES on the grid in terms of fast start-up and ramp-up times and large load range. After the planned shutdown of coal-fired power plants, gas turbines, as energy conversion technology for mechanical drive and power-generation, can play an important role as a result of their specific characteristics, such as quick start-up and load change capability, as well as the possibility for fuel flexibility. Modern gas turbines, in combined cycle setup, reach very high efficiency. In addition, the increasing share of intermittent renewable energy in the energy system changes the pattern of energy-generation, requiring new innovative solutions. One arising question to be addressed centres on the role to be played by gas turbines in future energy systems, particularly where intermittent renewable energy will play a more dominant role.

The goal, however, is to produce as much as possible renewable green energy, minimising the contribution of the conventional power production needed to secure grid stability. Therefore, the gas turbine-based combined cycles will also have a role to play in tomorrow’s grid. The use of green methane from power to gas results in CO_2-free contribution from the CCGTs in the grid, providing grid services. This also provides an opportunity for heat-generation via CHP applications of CCGT plants, which also results in the decarbonisation of heat-generation.

3.3.2 Concentrating Solar Power (CSP)

Due to its dispatchable nature, notably a unique attribute amongst renewable energy technologies, Concentrating Solar Power (CSP) can be considered one of the more viable sources of renewable energy. However, the cost of electricity from contemporary CSP plants remains high, despite several decades of development. In order to drive down the costs, a step-change in technology is needed. Hybrid solar gas-turbine power plants (either natural gas or green methane) have been shown to be a promising alternative to conventional steam-cycle Concentrating Solar Power plants. Low water consumption and competitive electricity costs make hybrid solar gas turbines an attractive choice for deployment in high-insolation desert areas. By reducing water conflicts, new regions are opened up for the deployment of solar thermal power technology, leading to increased capacity, lower costs, and a reduction in our dependence on fossil-fuels.

Due to lack of established configurations, construction of the first commercial hybrid solar-gas turbine plant is so complicated. Some thermo-economic studies have been done over many different power plant configurations as simple- and combined-cycle power plants as well as an investigation of thermal energy storage to make decision making process easier [26]. Such studies have allowed identifying key issues for the future development of gas-turbine-based solar power systems:

- In order to maximise the degree of solar integration of gas turbines in CSP plants, the firing temperature of the gas turbine should be kept close to the solar receiver temperature, resulting in low temperatures and low thermal efficiencies. As such, hybrid combined cycle systems are a viable solution since the trade-off between high solar shares and high efficiency is less pronounced than for simple cycles. This allows the firing temperature to be reduced with less of a penalty to the overall power plant heat rate, and thereby allows more economical operation at higher nominal solar shares.
- In order to simultaneously reduce carbon emissions and keep the cost of electricity low, it is necessary to integrate both thermal energy storage and a bottoming-cycle into the hybrid solar gas-turbine power plant. With optimally designed gas turbines for this application, the performance of these power plants offers a significant advantage over a simple combination of conventional power plant designs, demonstrating both lower emissions and a lower cost of electricity than any combination of conventional power plant designs.

3.3.3 S-CO_2 Gas Turbine Plants

The authors, as well as other research and industrial groups in the world, hold the view that advanced gas turbine power cycles that use supercritical CO_2 (S-CO_2) as working fluid could be an effective answer to the power-generation needs of the 21st Century [27]. The idea of using supercritical CO_2 as working fluid is not new, going back to 60s of the previous century, when researchers were looking for new ways of improving the thermodynamic efficiency of closed Brayton-Joule power cycles [28]. Nowadays, such a technology could be exploited in different applications and sectors (power, oil & gas, transport).

Working with S-CO_2 will result in a highly cost-effective technology, with minimum environmental and space impacts compared with other fossil-fuel-based energy conversion systems with CO_2 capture. This will make deployment easier in a distributed fashion, closer to population centres (thereby reducing transmission costs), as well as a high value export to countries with growing energy demands. According to both the 2DS and 4DS (Degree Scenario) scenarios presented by the International Energy Agency (IEA) in its Energy Technology Perspective [23], conventional and unconventional natural gas will play an important role in power-generation until 2050. As a result, fully developed S-CO_2 gas turbine cycles can be expected to make significant contribution sin this period in terms of providing affordable and efficient power-generation with very low carbon footprint and in achieving sustainability in the increasing share of renewable energy sources.

The development and efficient implementation of this technology requires advancement in different fields, such as combustion, turbomachinery, heat exchangers, materials, oxygen production and CO_2 capture, as well as a high level of integration—not only between the specific solutions but also between different concepts, such as renewables, nuclear, Power2Gas, and the extraction of non-conventional natural gas.

Concerning S-CO_2 GT cycles, it is worthy to note that:

- It can be used to develop near-zero emissions and more load-flexible and compact gas turbine back-up power plants (to match non-programmable renewables).
- It can be adapted (semi-closed S-CO_2 gas turbine cycles using oxy-combustion as an internal heat source) to continuously work at its base-load with high efficiency (>50%), including a highly integrated and cost-effective CO_2 capture strategy, and with the ability to efficiently control the partial load operation by lowering both the fuel mass flow rate and operative pressures. It is remarkable to note that partial load operations are no longer related to environment constrains; hence, the system is also more efficient and flexible at partial loads.
- It can be easily adapted to efficiently use external heat sources, including Waste Heat Recovery (WHR) applications. For example, it can be used in nuclear, Concentrated Solar Power (CSP) and geothermal plants so as to increase efficiency or otherwise can replace the steam section of the present designs of Combined Cycle Gas Turbine plants to improve load flexibility and efficiency (as known, the steam power section makes the whole CCGT plant scarcely load-flexible).

Furthermore, such a plant can use external heat sources; it may be integrated with renewable sources of energy (concentrating solar power, geothermal) or designed for WHR applications so as to increase efficiency. As stated in [29], supercritical carbon dioxide (S-CO_2) operated in a closed-loop recompression Brayton cycle offers the potential of equivalent or higher cycle efficiency versus supercritical or superheated steam cycles at temperatures relevant for Concentrated Solar Power applications, thus bridging the gap of CSP plants in acting in fast-acting ‘peaker’ applications.

It is finally observed that S-CO_2 technology can be exploited in different applications and sectors so as to enhance their decarbonisation. Compactness and other features make such technology exploitable in power, oil and gas, and transport sectors (in the transport sector a reduction of at least 60% in GHGs is required by 2050, with respect to 1990). In particular, S-CO_2 cycles are exploitable in maritime transport. This is interesting since the GHG emissions of international maritime transport is increasing and accounts for approximately 4% of global man-made CO_2 emissions. Last but not least, such a technology can be exported to countries with growing energy demands.

In 2014–2016, the US Department of Energy has been funding 29 projects [30] on different strategic topics related to advanced S-CO_2 cycles. The DOE share is 44M US$ [31], whilst industry share is almost US$10 m. It is observed that there is already some thought centred on the design of an oxy-combustor with the ability to burn different fuels, from natural gas to hydrogen and syngas, thus resulting in gas fuel-flexible power plants [32, 33], which is very important in terms of assuring the role of gas in the future energy world.

3.4 Large-Scale Polygeneration/CCHP Plants

Using existing assets to provide grid services at low load can also contribute to power-generation at full load so as to provide backup for renewable energy using green gas. However, the availability of Combined Cooling, Heating and Power (CCHP) CCGT plants make it possible to reach a fuel utilisation factor of higher than 90%, i.e. the efficient use of the valuable green gas in the gas grid. 'Using the valuable gas to its maximum potential', which will be available at very low investment thanks to utilisation of existing assets. An additional fan might be needed to provide cooling air for turbine blades when running the engine at very low loads, which is a small investment. Smaller investments could also be needed to operate part of the burners only to maintain a necessary low load levels, making both OEMs happy, providing more components, with the operators able to make money providing grid services.

As a research area, however, CCHP plants can be considerably improved in mind of higher energy efficiency and being more environmentally friendly. In this framework, the polygeneration, as the simultaneous production of multiple energy vectors (electricity, heat and cooling), amongst other products (water, hydrogen, glycerin, etc.), is recognised as one of the most attractive novel concepts in the field of worldwide energy consumption [34]. The main aims of polygeneration are centred on increasing energy efficiency levels, using renewable and alternative sources, and reducing the environmental impact of energy-related technologies [35].

3.5 Small/Micro-Scale and Distributed Generation (DG)

Nowadays, small- and micro-scale Distributed Generation (DG) plays a key role in transforming the way in which energy is generated. This transformation is more well-documented in Europe and Japan, but is also happening elsewhere (the USA, Asia and the Middle East, etc.).

A gas-fuelled micro Combined Heat and Power (mCHP) system, as the most efficient, cost-effective and flexible low-carbon solution of DG, is the generation of electricity and useful heat from the same item of plant on-site. In most mCHP installations, electricity would be sold to the local supply network, with the heat generated able to be used on-site (maybe in combination with gas-fired boilers) and/or exported using district heating infrastructure. MCHP systems can also provide cooling through the use of absorption chillers that utilise heat as their energy source (i.e. CCHP). In this way, end-users from different sectors, including multi-family buildings, commercial and industrial applications, become partners sharing responsibility for greener and more sustainable energy supply. A mCHP system is also the most controllable DG alternative that can empower consumers by giving them control of their electricity and natural gas bills (i.e. becoming active participants in the energy market).

3.5.1 Benefits

As summarised in the schematic below, mCHP systems can deliver important benefits to energy consumers, as well as the wider energy system, in line with significant trends in regions with gas resources and/or distributed gas networks to reach their energy and climate objectives with some of these advantages outlined as follows:

- Considerable savings on total energy costs for the end-user (as a function of electricity and heat savings);
- Empowering energy consumers to transform consumers into energy prosumers, and giving them greater control over their energy bills;
- Improving the energy performance of buildings;
- Increasing the fuel utilisation factor of existing distributed infrastructure for gas network;
- Improved efficiency of natural gas use, i.e. better fuel utilisation factor (at least 25%);
- High levels of fuel flexibility (using all types of gaseous fuels), considering the new combustion technology, which is concluding the R&D phase and which might soon be available in the market;
- Reduced emissions and decarbonising of the heat sector (up to 33%);
- Independence and security of power supply, passive defence and privatisation;
- Reductions in the costs of transmission and distribution in the national electricity grid;

- Improvements in both the efficiency and overall reliability and peak shaving of the network;
- Support in the electricity grid and balance in the integration of intermittent renewables;
- The presentation of high-tech solutions to the national energy market, fostering economic growth and creating jobs (Fig. 14).

3.5.2 GHG Emissions

In terms of carbon emissions, they are reduced through generating electricity at the point of use so as to avoid the system losses associated with central power-production and distribution (which are the main losses). mCHP systems, in general, have the potential to reduce CO_2 emissions and reduce primary energy consumption when compared to a conventional boiler with electricity drawn from the grid. Depending on different scenarios, mCHPs can save approximately 240–300 PJ (1 PJ is 31.6×10^6 m^3 NG) primary energy per year (roughly 0.5–0.6% of the total energy used in the EU-27 in 2010). Based on this, greenhouse gases can be reduced by 13–14 [Mton of CO_2-eq/year] through the use of mCHP systems rather than gas boilers (equivalent to approximately 0.3% of the total EU-27 GHG emissions in 2010).

3.5.3 Technologies

As shown in Fig. 15, there are several types of technology able to be used in a mCHP system, whether fuel cell-driven or Stirling-based (external combustion engine) plants, and from reciprocating piston (internal combustion engine)-driven CHPs through to gas turbine-based ones.

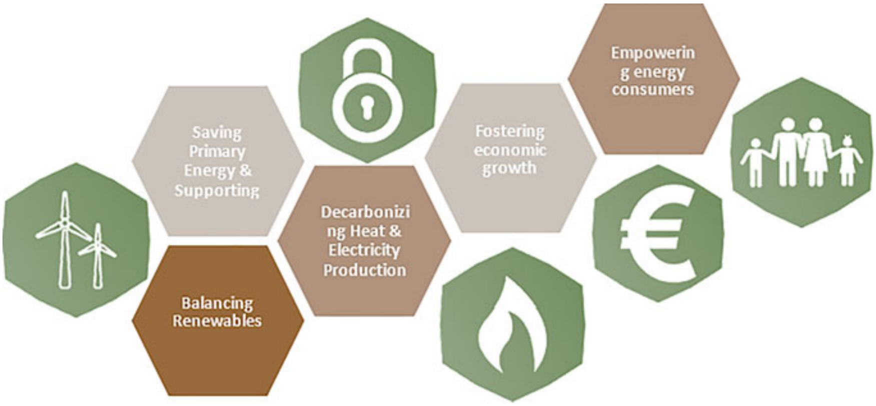

Fig. 14 mCHP systems can deliver important benefits [20]

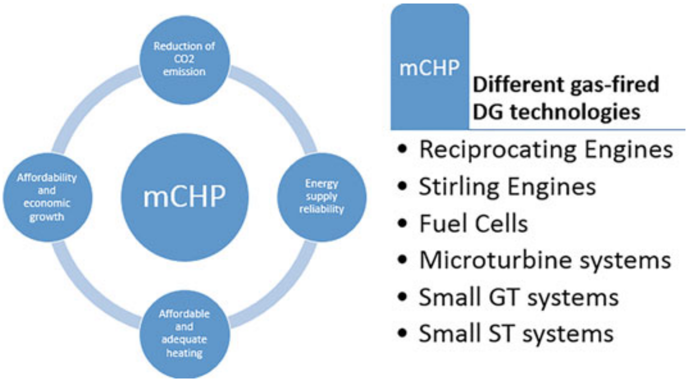

Fig. 15 Gas-driven micro CHP technologies, where each could be fuelled by any type of gas

Amongst the gas-fired CHP technologies, however, Micro Gas Turbine (MGT)-based CHPs are considered to be one of the most suitable solutions in terms of their size and volume, maintenance cost, reliability, operational flexibility, controllability, noise and vibration, and pollution and environmental impacts. MGTs, having only one moving part, are inherently more reliable than conventional reciprocating gas and diesel engines. Their maintenance cost also is less. This new system is also more regarding higher water temperature since its heat exchanger is not part of the engine cooling system. This system is also quieter and cleaner and it occupies less space. The emission of MGT-based CHP is much lower than the internal combustion based CHP. It can be directly injected to the greenhouses to boost the plant growth by its CO_2 content.

3.5.4 Operation and Performance

From an operational point of view, strong commercial potential, both in on-grid and off-grid segments, the unique ability to operate in a modular fashion in a shared environment, and the potential of coupling with heat pumps, are amongst the most significant characteristics of mCHPs. Both MGT- and ICE-based CHPs play a significant role for NG/green methane-fired electricity-generation in addressing renewable intermittency and/or nuclear inflexibility. On the other hand, for many countries, fossil fuels are dominant in supplying heat for buildings at least until 2030. Moreover, as the viability of the Carbon Capture and Storage (CCS) solution for decarbonisation targets remains in doubt, mCHPs is recognised as being able to play a leading role in decarbonisation targets at the domestic level. The schematic below shows where and how a mCHP unit can play a role in residential applications.

Depending on the technology used, the electrical efficiency of a mCHP unit could be in the range of 20% (for Rankine cycle and Stirling engine) and 50% (for solid oxide fuel cell). In terms of thermal efficiency (i.e. utilisation factor), it would be between 40 and 80% for different types of technology. However, an MGT-based

CHP produces electricity and heat, fuelled by natural gas, and accordingly achieves an overall efficiency of 80–90% (electrical efficiency of more than 30% with recuperator). Whether a mCHP is economically pragmatic or not is most basically dependent on the appropriate unit size of facility. It is highly necessary that during whole operation period of the unit, most of the electricity and heat being generated by the system be consumed (Fig. 16).

In Europe, Germany is the leading market for mCHPs; the reason for this is higher electricity prices, which means the self-generation of power is more attractive, which attracts supportive policy and a greater readiness of customers to test innovative solutions for their heating systems. Nevertheless, mCHP sales figures are marginal in the power-generation landscape. In 2005, worldwide mCHP installations amounted to some 31 MWs of installed capacity—up from 25 MW in 2004—with just a few companies offering products for the market. Manufacturers state that cost/price reductions are intensely coupled with the number of installations; in other words, this suggests that an economic cost-competitive product can be achieved if a strong political will exists to support mCHPs.

3.6 Smart Energy Hubs Supported by ICT

As we move towards a more sustainable energy economy, where the need to integrate more distributed generation is clear, smart energy hubs offer the highest potential for a deeper integration into an advanced energy system with ever-increasing shares of renewable energy for both existing (retrofitting) and new thermal power plants. In this way, Information and Communication Technology (ICT) considers the data dependency of the operational regimes, as well as the maintenance plans of complex energy systems, so as to identify reliable/cost-effective ways of integrating future DG systems into the public grid. ICT

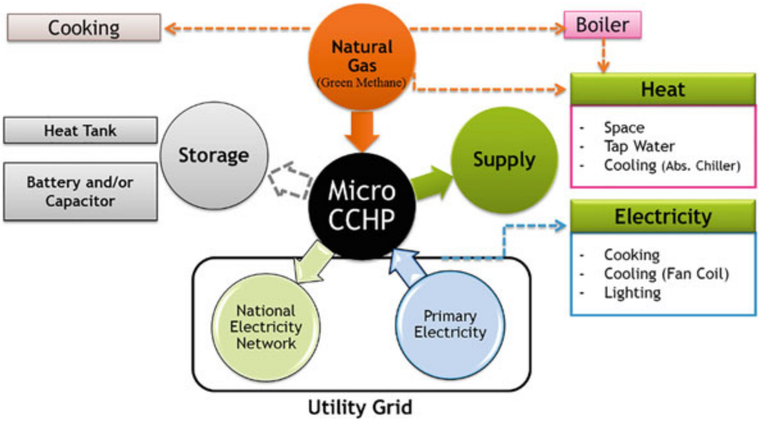

Fig. 16 mCCHP systems in residential applications

realises the integration of smart energy systems and smart networks/grids for the ‘more data, less energy’ concept (see the schematic below). When it comes to maintenance and operational management, significant data technologies enable a data-based and future-oriented prognostic strategy geared towards the better performance of any engineering arrangement, including energy systems, specifically for automated intelligent data-driven approach to the utilisation of distributed mCHP (Fig. 17).

The current trend associated with power generation is towards decentralization. Neighborhoods, buildings and private housings are generating their own power. Maturity of gas-fueled micro-generation technologies and the search for sustainability of energy are going parallel to each other. We are facing a shift from traditional power generation plants to diffuse bi-direction networks, capable of both supply and demand.

Market players (including energy companies, network operators and governments) will also take on new roles, where consumers will become ‘prosumers’ (producer–consumers) and new commercial/non-commercial actors will enter the market. The creation of such a ‘smart grid’ is possible through the use of sophisticated ICT. The most economical way for matching supply and demand can be management by ICT and intensive data analysis in the smart grids (Fig. 18).

3.7 Natural Gas and Fuel Cells

A fuel cell (FC) is an electrochemical device that converts the chemical energy (from the methane in natural gas or green methane) into electricity through a chemical reaction with oxygen. In general, fuel cells are quiet and reliable due to

Fig. 17 Cyber level and physical level in a smart energy hub

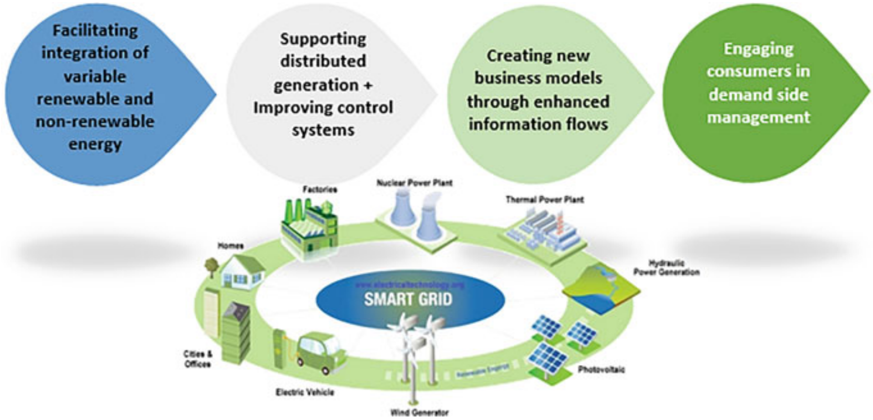

Fig. 18 Smart grids play an important role in the transition to a more sustainable energy mix (electricaltechnology.org)

their lack of moving parts. Fuel cells that can use methane, however, are high temperature cells and are usually sensitive to temperature variations. Most of the time, the cracking of solid parts due to thermal stresses prevents FC operation. Besides, they are also recognised as very expensive.

The working procedure of a fuel cell is as follows:

- Converting natural gas (or green methane) fuel to hydrogen in a fuel reformer (can also be internal reforming e.g., in SOFC)
- Generating DC power from hydrogen and air in the Stack and DC/AC converting in power conditioner
- Recovering useful thermal energy in an on-board heat exchanger.

The most important point relating to fuel cells is their high efficiency in comparison to other forms of power generation (Clear Edge Power Fuel Cells are 42% efficient in the generation of electrical power and, depending on the application, up to 90% efficient overall with full heat recovery).

Other advantages of fuel cells include the reduction of negative environmental impacts caused by conventional fossil fuel consumption (mostly due to the avoidance of combustion, where NO_x, etc. are formed), creating a clean alternative for on-site power, and low emissions of pollutants.

3.8 Bi-fuel (Gas–Gasoline) Vehicles

A bi-fuel system uses two types of fuel (not mixed together) with the capability of switching between the two in order to achieve the greatest efficiency for the vehicle. Sometimes, it is the price of the fuel that is the over-riding factor, rather than the efficiency: for example, gas or condensed gas is cheaper than gasoline, meaning the engine operates on that fuel as long as it is available. Of course, these vehicles are capable of using either fuel exclusively in the absence of the other fuel source, but will operate less efficiently when the right fuel is not available.

3.9 Power to Gas (P2G)

As stated earlier, growth in the share of intermittent renewable energy in the existing energy system has raised many issues, predominantly related to the need for large-scale storage and synchronisation of the generation and usage of electricity. Given the fact that the existing gas grid provides an efficient large-scale storage capacity, many key actors in the energy market are considering ‘power to gas’ (P2G) as an important contributor to large-scale storage of the renewable electricity. Not only IS the gas grid an asset for gas storage, but gas-based energy conversion technologies can ALSO be utilised to convert the ‘green methane’ or renewable gas to green electricity on demand (Fig. 19). In this way, unused wind/solar energy stored in the gas grids so that gas transport infrastructure can be used as an energy buffer for RES producers. P2G makes a more comprehensive connection between markets and energy sources.

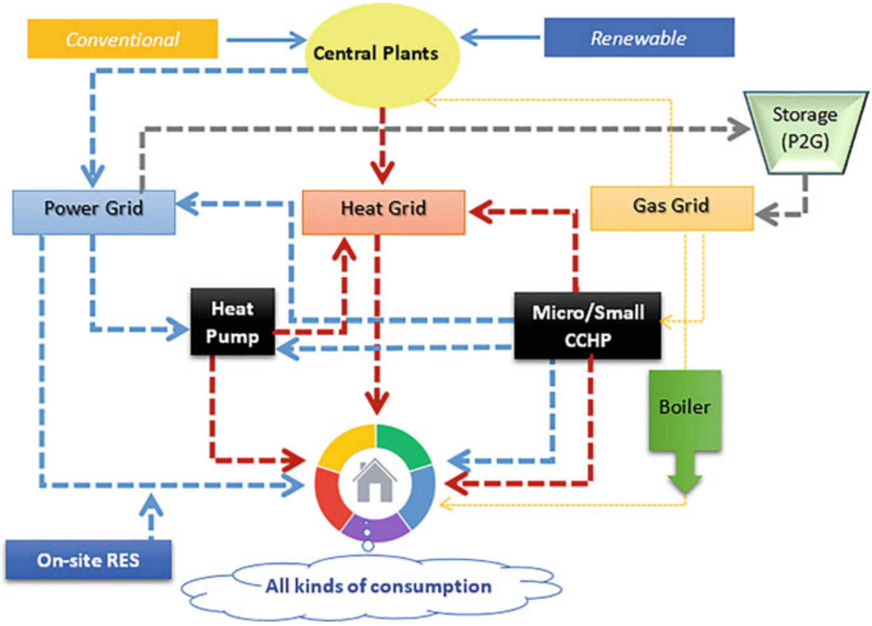

Fig. 19 Large-scale storages in an integrated energy system

Besides the need for quick-starting and flexible energy-conversion technologies, the need for large-scale energy storage systems for the synchronisation of power-generation and use is apparent. P2G is one of the enablers for storage technologies, identified for the storage of electricity generated by intermittent renewable, where surplus electricity is used to produce hydrogen through hydrolysis of water. In this case, the hydrogen can be converted to green methane via methanisation, which is then stored in the existing gas grid, utilising this important asset. There is a strong synergy between this process and biogas production, where the oxygen produced during hydrolysis can otherwise be used. The 'neutral' CO_2 produced during the combustion of biogas can then be used as carbon source for the methanisation process, ending up with a green energy system that requires efficient, flexible energy conversion technology, such as gas turbine, where the green methane is converted to electricity.

With the exception of storage, P2G can also be considered a transport option where gas pipelines can transport much higher energy volume than electricity transmission lines.

At the same time, the synergies between the use of fossil fuels, the P2G concept, methanisation and the S-CO_2 power plant technology with oxy-combustion can play an important role in terms of both energy backup and storage. In fact, such a plant may be designed to implement a highly integrated CO_2 capture strategy and thus to achieve a CO_2-free load-flexible technology not currently available in the market. The P2G concept can be easily integrated, adopting hydrogen and/or oxygen through the oxy-combustion, and making the CO_2 separation easier. In order to use the current gas transmission system, the methanisation process [36] can be used to convert the hydrogen from P2G to methane using the CO_2 already captured. When it is necessary to provide backup for the electrical grid, both the methane and oxygen obtained from P2G and methanisation can be used to feed S-CO_2 power plants with oxy-combustion.

Lastly, the research questions needing to be addressed centre on (but are not limited to) the following:

- Specification of the water quality needed
- Using pressurised electrolysis to produce hydrogen at high pressure
- Methanisation, i.e. the conversion of hydrogen to methane, which can be carried out using different methods. The selection of the most suitable method from both technical and techno-economic points of view is the key element.
- The storage of a certain part of the pressurised hydrogen directly in the gas grid, considering the WOBE index of the fuel gas.

4 Conclusion: Challenges and Proposals

The main goal of this chapter was to highlight the fact that providing energy to an ever-growing population of the globe during a transition period, and so doing in a responsible manner, will require a sustainable energy mix of fossils and renewables.

In order to achieve this purpose, the role of natural gas-fuelled solutions in support of a future sustainable energy world, along with its incentives, enablers and barriers, was discussed. As a result, this study clearly illuminated the important role gas-fuelled solutions can and will play in a future energy system, in which it is possible to establish a balance between different energy sources so as to facilitate a sustainable environment for the future population.

Most indications in this study suggest that gas has a place in the future energy mix. CCS could be the answer to counteracting climate changes as a natural gas asset, whilst non-fossil energy sources, combined with natural gas, could replace oil and coal in a transition period towards a future sustainable energy market. In this way, an immediate arising question to be addressed centres on the role of gas-fuelled technologies in the management of intermittent renewable energy, which is expected to play a more dominant role in the near future. This paper aimed at addressing this question in a holistic approach. Natural gas supports the shift to renewables (and does not hamper the transition or provide a locked-in natural gas future). There is a need to ensure a transition fuel if we are to stay within the carbon budget.

At the same time, energy security remains a major concern. The safety and overall stability of the electrical grid require a coordinated strategy of energy storage and grid backup that can be feasible using gas-fired power plants. Since the goal of the paper is to place emphasis on the role of natural gas (later on to be replaced by biogas and hydrogen), the conclusion is that natural gas can be an important complement to renewable energy during the transition period. The infrastructure and energy-conversion technologies developed for natural gas need to be designed in such a way so as to be able to cope with the transition towards biogas and renewable supported hydrogen, or something in this way.

Part II of this study will investigate different situations of various geographical regions by performing a number of case studies considering diverse solutions for the energy mix that would be required.

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Role of Gas-Fuelled Solutions in Support of Future Sustainable Energy World: Part II: Case Studies

Amir Safari, Nandini Das, Soheil Jafari, Oluf Langhelle, Joyashree Roy and Mohsen Assadi

Abstract Following Part I of this study, this chapter highlights each region in the world as having its own solution and approach to considering natural gas as a fuel of choice for smooth transition towards a sustainable energy world. Although energy sustainability is recognised as a global challenge, many of the issues inherent in this domain are site-specific. Therefore, it is necessary to identify suitable local solutions whilst taking into account resources, infrastructure, economic aspects, as well as the local/national energy policies. This means that there is not one solution that fits all cases; therefore, tailor-made solutions devised in mind of different circumstances need to be considered. The case study presented in this chapter compares different countries, i.e. industrial vs developing and those with national resources vs import dependent countries, with the aim of illuminating the fact that final choices and approaches that are seen to have a major impact on global warming due to CO_2 emissions from fossil fuels might look very different. In this part of the study, focus is centred on the utilisation of natural gas as the ideal partner complementary to renewables in a future sustainable energy mix, in support of different regions' policies. In this way, security of supply as a foundation for industrial development and the continued functioning of a modern society have to be maintained independent of the energy mix applied in each country. Different scenarios are presented and analysed in the case study, with attention paid towards discussing and illuminating the possible ways in which natural gas may be seen as a transition fuel from a global perspective so as to pave the way for the realisation of carbon-neutral or carbon-free energy solutions for the future. Since the examples presented cover four different categories of country (India, Iran, Norway and UK), combined characteristics may be recognised as representative for a large number of countries, thus making the generality of the conclusions rather strong.

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Keywords Natural gas · Sustainable development · Energy mix
Norway · India · Iran · UK

1 Introduction

Despite agreement on global goals, national autonomy will continue to have a dominant influence on deciding an individual country's energy mix. According to the International Energy Agency (IEA), energy from renewable will demonstrate the total greatest growth, whereas natural gas will also continue to grow, while coal (without carbon capturing) will be losing ground, and advanced nuclear power will see slow growth, although this remains uncertain [1]. Others, such as GreenPeace and CarbonTracker, adopt a more critical stance towards the role of natural gas as a transition fuel; in this vein, therefore, it is difficult to predict the future. Still, all indications point towards an increased energy need due to both population growth and economic development in different countries. There seems to be some agreement, however, to suggest that renewables will increase and that oil will most likely decrease, with coal expected to decrease whilst nuclear power will remain the same. Gas prospects, however, are more uncertain, depending on the time frames applied. The crucial question concerns the timing and how soon the transition to a low-carbon energy system will take, and whether the volume of renewable energy will be adequate to satisfy energy needs on a global scale. Thus, the future energy mix has to take into account both the global carbon budget and the energy needs of the world.

On the other hand, 'energy efficiency' provides hidden huge potential and, as such, is considered to be of great importance. By a systematic search through every energy-related project for energy-saving opportunities, considerable amounts of energy can be saved and energy efficiency improvement, combined with renewable power, could provide most of the power needed [1].

- Any country has its own pathway to a solution for a more sustainable world, based on their unique national and local circumstances. The global proven reserves of natural gas—which amount to 187.3 trillion cubic meters at the end of 2012—has a completely different pattern of natural resources and transportation ways for diverse areas, as shown in Part I of the same study [2].
- The global warming effect caused by CO_2 emissions to the atmosphere is recognised as this century's most threatening factor for life on Earth. As such, a substantial decarbonisation of the energy system, notably through the rapid growth of renewable energy technologies, is deemed necessary [3].
- The Paris agreement will be implemented via different means in different countries. For example, it is concerned with increasing NG-based thermal power plants' efficiency in Iran and also with replacing coal-based plants with NG-based ones in India. At the same time, national decarbonisation targets should be defined separately for each country, followed by stronger efforts to achieve such goals.

- All international O&G companies (Shell, Statoil, ExxonMobil, etc.) have their own energy scenarios, based on a variety of data sources, where the consequences of different prevailing geopolitical trends on energy demand, energy mix and greenhouse gas emissions are predicted. These usually adopt the stance, and accordingly argue, that, 'Gas and renewables will be frenemies, healthy competitors and allies', as stated by DNV GL Group President and CEO, Remi Eriksen [4].
- In addition, a large switch from coal to gas has been a growing theme in key energy-intensive markets, such as in the US, the UK, and China. More specifically in the developing world, replacing coal with gas is considered a baseload fuel to complement increasing renewable power. The gas transportation infrastructure can also be used for the renewable forms of gas (e.g., biomethane and hydrogen) produced by excess power from intermittent renewable electricity, such as wind and solar.

In the following sections, current status and development trends in the four selected countries for the case study will be presented.

2 India: A Net Oil- and Gas-Importing Developing Country

Secure and sustainable energy supply is one of the most important parameters of economy development. Sustainable energy supply, which is economically affordable, also needs to be socially and environmentally sustainable. One possible pathway for global energy transition is through the substitution of fossil fuel, although an alternative is also seen in low-carbon energy supply in the development of future sustainable energy systems. The smooth transition of a fossil-dominated economy to one less dependent on fossil-based energy sources can be achieved with an increasing use of natural gas in the medium-term. Natural gas can provide a mid-term support to a long-term solution as the carbon content of natural gas is 15.3 kg/GJ, which is recognised as much lower when compared to the carbon content of non-coking coal 26.2 kg/GJ [5], which, markedly, is more widely used in power-generation in the Indian context [6]. GHG emission from energy supply can be reduced significantly by replacing coal-fired power plants with natural gas Combined Cycle Gas Turbine (CCGT)-based power plants and/or Combined Cooling, Heating and Power (CCHP) [7]. Globally, the share of renewable energy is expected to be 37% of total power generation by 2040, compared to 23% in 2016 [8]. Natural gas-based power-generation with Carbon Capture and Storage (CCS) can act not only as a bridge to this transition but also as a part of the final solution.

In India at the present time, coal-based power-generation accounts for more than 60% of total generation [9]. India has devised a high ambition of achieving 56% of its installed capacity from non-fossil sources by 2030 [10]. Gas-fired power plants with the significant potential of load-balancing can have an important role to play in this regard. This will require 21 BCM of natural gas per annum [10]. The integration of natural gas with low-carbon energy supply technologies could prove crucial in the future mitigation pathways. CCS is one such technology option, which is expected to reduce 50–85% of GHGs globally by 2050 [11]. Aside from economic viability [12], other major barriers in the deployment of CCS at a commercial scale is that, as CCS involves a huge amount of investment risk, India strongly depends on the successful implementation of CCS technology in developed countries [13, 14]. A further impediment to CCS is the lack of storage capacity assessment, especially in India [13, 15].

CCHP production is the simultaneous generation of usable heat, cooling and electricity in a single process. For efficient electricity-generation, technologies such as gas-fired CCGT and CCHP can be important means of reducing emission with improved energy efficiency [16, 17]. Gas-based CCGT has a greater efficiency of around 55% when compared to coal based-plants [10]. Aside from CO_2 abatement, these technologies are also important means of primary energy savings [18, 19], and increase in energy efficiency up to 90% [20].

Projected peak demand for India at the end of 2022 is likely to be 235 GW [10]. The achievement of this target with only centralised generation is difficult. The efficient and economical design and operation of an individual small-scale distributed generation (DG) system with natural gas-fuelled micro turbines or fuel cells can be important. The cost of a natural gas-based DG system may become higher due to uneven transport and supply of natural gas in rural areas [21]. Comparing the use of local resources, such as small-scale solar, gas-based DG systems will require significant investment in infrastructure development [22].

The production and supply of natural gas had not been keeping pace with the growing demand of natural gas in the country, including the power sector. The gas provide for gas-based power stations in the country is insufficient, with the country recognised as facing huge generation loss [10]. High capital costs of CHP, CCGT equipment and infrastructure present further challenges in deployment. At the same time, a lack of research directed towards finance and investment needs for CCHP in India is also slowing down policy coordination. The environmental and economic benefits of CCHP, as well as other energy-efficient technologies, remain inadequately researched in the Indian context. India also lacks in technological expertise in energy-efficient technologies for the power sector; this will add to the complication of technology transfer.

2.1 Fossil Energy in India

2.1.1 Oil and Natural Gas Reserves

Oil and natural gas reserves in India are not significant. The proven reserves of crude oil in India, as of on March 2016, amounted to 621.11 million tonnes (MTs), of which 283.53 MTs is offshore. For natural gas, it is known to stand at

1227.20 billion cubic meters (BCMs), of which 745.41 BCMs is offshore [23]. This consists of only 0.3% of the world's total oil reserves and 0.8% of natural gas reserves [24].

In India, the number of explored oil fields totals 153, comprising 122 onshore oil fields and 31 offshore fields. The Western offshore fields contain maximum reserve equal to 333 million tonnes, totalling 43% of total reserves. Of the onshore oil fields, Cambay basin of Gujarat possesses 73 onshore fields.

The Indian oil reserves are significantly low in relation to the demand of the country; in the case of natural gas, on the other hand, this is not true. The total number of gas fields amounts to 134, of which 96 are onshore and 38 are offshore. The main onshore producing fields are in the states of Assam and Tripura in the northeast, Gujarat in the west, and Tamil Nadu and Andhra Pradesh in the south. Some of the most promising areas in terms of reserves are located offshore, including at the Krishna Godavari (KG) basin of the east coast and the Mumbai Offshore of the west coast [23, 25].

Reserves of oil in India are declining, and have been doing steadily since 2011, mainly due to the decline in onshore reserves. The onshore reserves of oil were seen to have declined by 2.7% in 2015 from the previous year, whereas the reserves of natural gas increased significantly during 2009–2015, as shown in Fig. 1 [23]. In the case of natural gas, an increase in estimated reserves in 2015 amounted to 3% from 2014. The maximum contribution in this increase has been from Eastern Offshore (77.5%), followed by Western Offshore (22.5%) [23].

The crude oil production during the year 2015–16 was seen to be at 36.95 MTs, showing a decrease of 1.36% when compared with the previous year. This decline in production is mainly owing to natural declines in the reserves of Mumbai Offshore, and less-than-expected production in newer fields. Natural gas production during the year 2015–16 was seen to be at 32.249 BCMs, which is 4.18% lower than the previous year. This was mainly as a result of natural decline in some of the fields, as well as the underperformance of wells, closure of wells for maintenance activities, the unplanned shutdown of the Gas Authority of India Limited (GAIL) gas line, and less off-take by consumers [23].

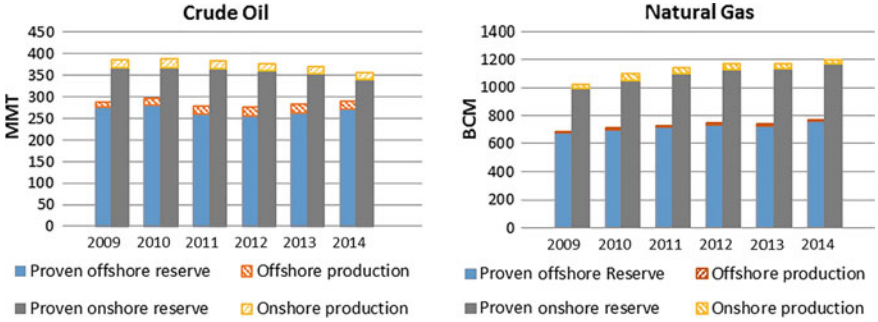

Fig. 1 Reserve and production of oil and natural gas in India

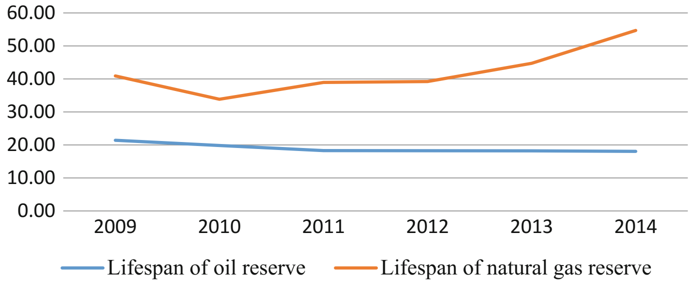

Fig. 2 Reserve-to-production ratio of oil and natural gas

The reserve-to-production ratio, which implies that, if the reserves remaining at the end of any year are divided by the production of that year, the result would be the length of time that those remaining reserves would last if production were to continue at that rate. This would increase for natural gas, as depicted in Fig. 2, owing to both increases in proven reserves by 15% and falls in production by 13% since 2009 [23].

India has a considerable amount of unexplored reserves of natural gas. The areas identified and prospective or potentially prospective is more than 1.1 million km^2 [25]. Since 2009, roughly 700 wells have been drilled in mind of exploration and development purposes, with an average meterage of 3 km per well in offshore cases, which is seen to be low intensity when compared to other offshore basins, such as the US Gulf of Mexico [25].

2.1.2 Oil and Natural Gas Trade

India is a net oil- and natural gas-importing country. The mismatch between domestic reserves and demand is a key contributory factor to the import dependency of India. Net imports of crude oil have increased from 99.41 MTs during 2009–10 to 159.25 MTs during 2014–15, with the increase for natural gas seen to be approximately 50% from 9.1 MTs in 2009–10 to 16.5 MTs in 2014–15 [26]. In the year 2014–15, on average, an 80% demand of oil and natural gas has been met by importing. Over the years, India has expanded a sufficient processing capacity to produce different type of petroleum products, so this country has become a net exporter of petroleum products [26]. In the year 2014–15, India has earned Rs. 213,936 crore as a net export value of petroleum products. India's trade deficit with OPEC Countries has shown a reduction of 42% from Rs. 491,660 crore in 2014–15 to Rs. 285,092 crore in 2015–16. Figure 3 shows that the reduction in trade deficit is mainly owing to the reduction in the OPEC import bill by 29.7% during the corresponding period [23].

Most of India's natural gas import is done in the form of LNG. India has planned to import gas through pipeline and, for that, two major proposed pipeline projects are the Turkmenistan–Afghanistan–Pakistan–India (TAPI) pipeline and the Iran–

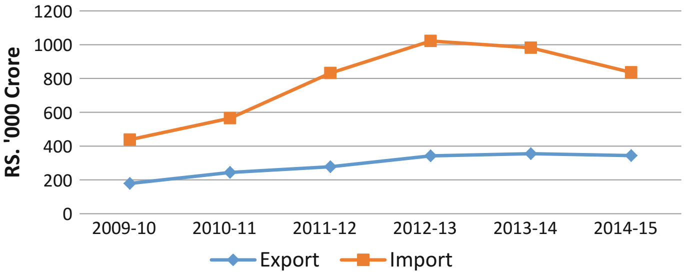

Fig. 3 India's trade with OPEC country

Pakistan–India (IPI) pipeline. The length of the TAPI pipeline is approximately 1680 km for transporting Caspian Sea natural gas from Turkmenistan, whilst the length of the IPI pipeline is estimated at 2700 km for Iran's South Pars fields in the Persian Gulf. However, both of these pipeline projects are yet be commissioned due to political instability in the region.

2.1.3 Oil and Natural Gas Network

The total pipeline length for oil and natural gas transportation in India has reached 42,486 km as of March 31, 2016. Furthermore, total crude oil pipelines have increased by 3.88% to reach 9853 km, as of March 31, 2016, as against 9,485 in 2015. Of this, 9365 km is onshore whilst 488 km is offshore. Pipelines for natural gas transportation in India stood at 17,658 km in March 2016 compared with 17,406 km in 2015, registering a growth of 2.55%. In line with this development, GAIL is contributing 11,077 km, accounting for around 63% of overall length [23]. India's longest pipeline for crude oil is the Salaya Mathura Pipeline, which belongs to Indian Oil Corporation Ltd. (IOCL), with a length of 2226 km and a capacity of 21 MTs. GAIL's pipeline for gas transportation is of a capacity of 82.5 BCM per annum.

2.1.4 Coal

India accounts for 7% of all global coal reserves [27]. The total proven reserves of coal and lignite at the end of 2015 were seen to amount to 137.8 billion tonnes [6] with a lifespan of more than 200 years given the current production level. Of these reserve, 95% are anthracite and bituminous, with the rest of lignite and sub-bituminous quality. The majority of Indian coal is seen to be coal with high ash content, with the average calorific value of this coal seen to be between 2500 and 5000 kcal/kg, which is considerably low when compared to that of the USA and China [28].

India's coal reserves are mainly located in the eastern and south central parts of the country. Around 99.08% of total coal reserves in India focuses in different states such as Jharkhand, Odisha, Chhattisgarh, West Bengal, Madhya Pradesh, Telangana and Maharashtra. The State of Jharkhand is acknowledged as having the maximum share, equating to 26.44%, in the overall reserves of coal in the country, followed by the State of Odisha with 24.72% [26].

Coal-production in the country during the year 2014–15 was 612.44 MTs, with a growth of 8.25% from the previous year [6]. As the average quality of Indian coal is not very high, the import of high-quality coal has become indispensable for India. Notably, the import of coal increased steadily from 38.59 MTs in 2005–06 to 212.1 MTs in 2014–2015 [26]. During this period, the export of coal was seen to be quite volatile: during 2005–06 through to 2008–09, there was a decline from 1.9 to 1.6 MTs, with a subsequent increase to 2.4 MTs in 2012–13, whilst in 2014–15 it was seen to be 1.2 MTs. Thus, the growth rate of gross import was seen to be 27.12% whilst net import was 28.05%.

As the coal mines in India are mainly located in the eastern part and as thermal power plants are located in a somewhat scattered manner, a large share of coal needs to be transported in order to reach to these power plants. Indian Railways is the prime mode of transportation for the movement of coal across long distances; this is also economical. Indian Railways accounted for 55% of the total coal transportation, and, in the year 2013–14, 42% of the railway's earnings came from coal transportation. In shorter distances, transport is carried out by road in trucks.

2.2 Renewable Energy in India

2.2.1 Biomass

Biomass energy constitutes approximately 18% of total primary energy use in the country, with more than 70% of the country's population depending on it [9]. The total potential for biomass-based power-generation in India is 4946 MWs as of March 2016, which is 11% of the country's renewable power-generation [29]. The southern states of Karnataka, Kerala and Tamilnadu and north-western states of Haryana, Punjab, Rajasthan, Gujarat and Maharashtra together generate 60% of total biomass power; these are mainly agro-based economy. Of the total installed generation capacity of biomass power 11.46% accounted for grid-connected. As of March 2015, the total number of biogas plants installed was seen to be 47.52 lakh (notably, a *lakh* is a unit in the Indian numbering system, equal to one hundred thousand), whilst Maharashtra accounts for the maximum number of plants, which was seen to be 8.56 lakh [26]. Moreover, of the total installed generation capacity of biomass power, 11.46% accounted for grid-connected. As was seen on March 31, 2015, of the total number of Biogas plants installed (47.52 lakh), a significant number of plants installed were in Maharashtra (8.56 lakh) [26]. It is envisaged to increase biomass installed capacity to 10 GWs by 2022 from its current capacity of

4.9 GWs, as biomass-based energy is known to have huge potential for the electrification of rural community. However, an uninterrupted supply of raw materials is a major challenge in biomass-based power-generation in India.

2.2.2 Hydropower

Hydropower contributes approximately 46.1 GWs to the current portfolio of installed capacity, of which 4.1 GWs is small hydro (up to 25 MWs) and 41.99 GWs is large hydro (more than 25 MWs) [9]. At the end of March 2015, installed capacity from hydro was seen to amount to 41,268 MWs, which comes second following thermal power, accounting for 13.04% of total installed power. The share of hydro in total capacity and also in generation began to decline in 1984–85 [29]. The hydro schemes under construction account for a capacity of 13,502 MWs, including Pumping Storage Scheme (PSS) of 1080 MWs. Capacity-wise, the northern part of the country has the most significant hydro potential of 18,302 MWs, as of 2015.

2.2.3 Wind Energy

Wind energy has been the predominant contributor to the renewable energy growth in India, accounting for 23.76 GWs, which is 65.2% of the renewable installed capacity in 2015 [9]. India ranks fourth in the world in terms of installed capacity of wind turbine-based power plants, mainly owing to its long coastline [29]. India aims at achieving a target of 60 GWs of wind power installed capacity by 2022. Achieved wind-based capacity addition for under the 12th plan (2012–2017) up to March 2016 is 9509 MWs, which is 53% of total renewable capacity addition. The total installed capacity of wind energy at the end of 12th plan is going to be 30,967 MW; this will contribute to 52% of total installed capacity from renewable sources.

2.2.4 Solar Energy

India's commitment to a growing role for low-carbon sources of energy is mainly led by solar. Solar power installed capacity has increased from only 3.7 MWs in 2005 to approximately 4060 MWs in 2015, with a CAGR of more than 100% in ten years [9].

In most part of India, more than 250 days of a year has a clear and sunny weather. The annual global radiation in India varies from 1600 to 2200 kWh/m^2, which is comparable with the radiation received in tropical and subtropical regions, where its energy potential is approximately 6000 million GWhs of energy every year. The highest annual global radiation is received in the two western states of Rajasthan and northern Gujarat [30].

In consideration to the total installed generation capacity of grid-connected renewable power share of solar, this is seen to be 12.5%. Likely capacity addition from solar at the end of 12th plan is expected to be 17,823 MWs, which is expected to be 51% of total renewable capacity addition [10].

2.2.5 Geothermal Energy

Geothermal energy has great potential as an environment-friendly and naturally occurring renewable source of energy. Studies on exploration and geothermal fields have been started in India since 1970. The Geological Survey of India identified 340 geothermal energy locations in the country, most of which are in the low-surface temperature range from 37 to 90 °C, which is recognised as suitable for direct heat applications. The estimated potential for geothermal energy in India is estimated as being approximately 10,000 MWs. India has seven geothermal provinces namely the Himalayas, Sohana, West coast, Cambay, Son-Narmada-Tapi (SONATA), Godavari and Mahanadi. Puga Valley of Ladakh is the most important one. In spring hot temperature in Puga Valley vary from 30 to 84 °C, discharging up to 300 l/min [31].

2.3 *Energy Policy in India*

The main objective of India's energy policy is to achieve three goals: energy access, energy security, and a lower environmental impact [9]. India has afforded special importance to the energy mix by promoting renewable sources, mainly power-generation through solar and wind, as well as Supercritical Technology in coal-based power plants [29].

2.3.1 Conventional Sources

To follow the low-carbon growth strategy, India is promoting Supercritical Technology for coal-based power plants, which is recognised as offering higher efficiency than conventional Subcritical Technology [10]. Capacity addition from Supercritical Technology-based coal power plants is likely to contribute approximately 39% of the total capacity addition from coal-fired plants at the end 12th Plan. Capacity addition from Supercritical Technology-based coal power plants are likely to contribute around 39% of the total capacity addition from coal-fired plants at the end of the 12th Plan [29]. India's crude oil and natural gas production has been stagnating in recent years. Furthermore, a gas-based power generation capacity of 4340 MWs is yet to be assigned a functional due to an inadequate supply of domestic natural gas [10]. Gas-based power-generation is expected to have the lowest capacity addition of 4340 MWs during 2016–17.

Although IEA's central scenario expects natural gas to overtake global coal use in the 2030s because gas-fuelled technologies for power-generation emit less carbon and air-polluting particulates thanks to the transportable LNG form, some nations, such as India, highlight an increasing demand for coal up to 2040 (Fig. 4).

2.3.2 Nuclear

Nuclear-based capacity is given the foremost priority in India due to its inherent advantages towards a low carbon growth strategy. The highest rate of annual growth from 2013–14 through to 2014–15 in installed capacity was for Nuclear power (20.92%) [26]. With a 2.2% share in current installed capacity, the total installed capacity of nuclear power in operation is 5780 MWs. In 2016–17, a further 1500 MWs of capacity addition was expected to be witnessed. Additionally, six reactors, complete with an installed capacity of 4300 MWs, are at different stages of construction. India aims to achieve 63 GWs installed capacity by the year 2032. Nevertheless, this is highly dependent on the supply of fuel [9].

2.3.3 Renewables

There has been a significant increase in renewable energy capacity in the country during the last decade. The share of renewables will continue to increase in coming years due to India's major thrust in promoting renewable energy sources. Aside from environmental benefits, another important factor behind the promotion of renewables in India is the reduction of import dependency for energy and the subsequent assurance of energy security [26]. India is running one of the largest renewable capacity expansion programmes in the world. One of the largest renewable capacity expansion plans in the world is in process in India. Between

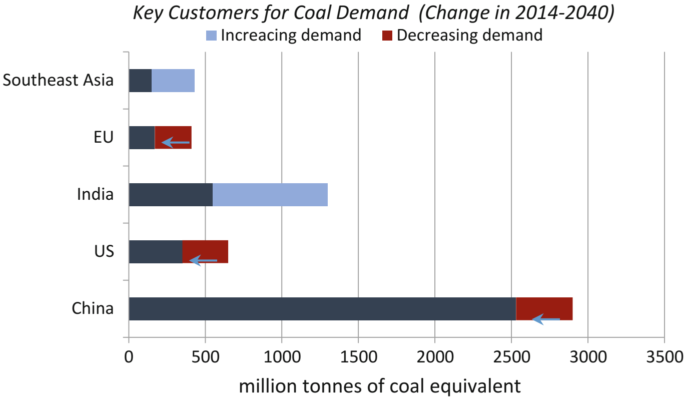

Fig. 4 IEA central scenario

2002 and 2015, the share of renewable grid capacity has increased more than 6 times, notably from 2% to around 13% during 2002–2015 [9]. This expansion of renewable energy is mainly driven by solar. The capacity of solar-based energy supply is expected to be 100 GWs by the end of 2022.

2.3.4 Future Policies

India's commitment towards achieving a low-carbon energy future is consistent with its energy policy. The share of non-fossil-based installed capacity comprises gas, hydro and nuclear, and is expected to increase to 46.8% by the end of 2021–2022 (Fig. 5) [26]. The deployment of low-carbon energy technologies, such as Carbon Capture Storage (CCS), has been initiated in mind of the more efficient use of coal in power-generation. In an effort to ensure an adequate domestic supply of natural gas, several policy initiatives have been adopted for the hydrocarbon sector. This includes the exploration of unconventional sources of natural gas, such as coal bed methane, natural gas hydrates, underground coal gasification [32], pricing freedom, and the marketing of natural gas [23].

India will continue to direct its efforts towards the expansion of renewable energy sources. At the end of the 13th Plan (2017–2022), the expected installed capacity of renewable sources is predicted to be 60 GWs, which will be 17.7% of the total installed capacity. This growth—in much the same way as in previous years—is going to be mainly through solar, which will be 30% of the total installed capacity and 63% of the renewable installed capacity [29].

2.4 A STEEP Analysis

If natural gas is to play mid-term support to a long-term solution for sustainable energy supply sources in India, several conditions need to be satisfied. In an effort to complete such an analysis in this section, the STEEP analysis is to be adopted,

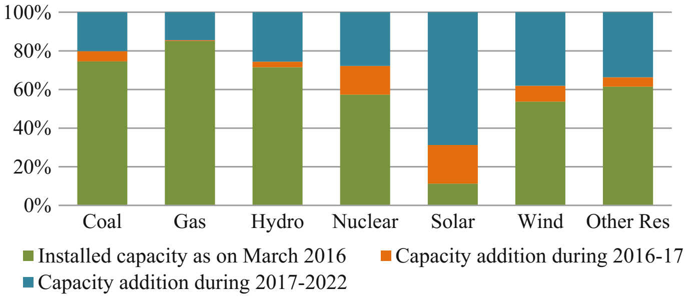

Fig. 5 Installed capacity and capacity addition of different energy sources under 12th and 13th Plan

which directs attention to all five dimensions, namely social (S), technological (T), economic (E), environmental (E), and political (P), inherent in sustainable development [33–35].

For each of these dimensions there are enablers and barriers with the capacity to indicate a move forward with natural gas as a future sustainable energy source in India, as a transition energy source, and the policy actions needing to be in place to facilitate such (Table 1).

2.4.1 Social Aspects

For the sustainability of any new technology, innovation or any other development strategy, there need to be roots in social needs and adoption in a particular societal context. In India, one of the social enablers centred on increasing the use of natural gas is increased access to modern fuel for cooking, especially in rural India, through the replacement of biomass burning. Although, India has one-sixth of the world's population, the usage of global energy is 6% in this country [25]. In India, energy for cooking is mainly dominated by biomass. A total of 67% of rural India still uses firewood as cooking fuel. Natural gas has huge potential in providing leapfrog access to modern fuel for cooking, especially in rural India, through the replacement of biomass burning in India.

Per capita energy use in India is recognised as 606.05 kgoe, which is comparatively lower than other developing nations, as shown in Fig. 6 [36]. India is the third largest producer of power in the world after China and the USA, with 1208.4 TWh of production in 2014, demonstrating 9.5% growth over the previous year [24]. Despite the increase in generation, the expansion of energy supply is required with more than 300 million Indian populations still deprived of this basic

Table 1 STEEP analysis for natural gas as a possible transition energy source for India

Term	Enabler	Barrier
Social	• Enhanced access to clean energy input for cooking and electricity	• Land acquisition and displacement for pipeline expansion
Technological	• Known proven technology • Flexible/peaking power supply	• Physical distance from the importing countries • Geological uncertainties
Economic	• Improved energy efficiency and energy intensity	• Supply bottleneck • Investment for infrastructure development • Price competitiveness
Environment	• Reduced GHG emission • Reduced urban/rural indoor pollution	• Fugitive methane emission • Upstream carbon emission • Water stress relative to renewables
Political	• Over compliance with Paris commitment by reducing share of coal use in energy mix	• Geo-political instability • Increase in import bill

infrastructural need. India's per capita electricity consumption is 765 Kwh against the world average of 3100 Kwh [36] (Fig. 6). Economic development without proportional expansion of carbon emissions has become one of the major challenges in today's development strategy in India. Accordingly, in order to achieve the target of universal energy access with low environmental emission, the promotion of gas-fired power plants can be viewed as an effective policy option for India.

Pipelines for the transmission and distribution of natural gas have been amongst the most significant infrastructure projects in developing countries, such as that of India. Almost 70% of the Indian population lives in villages with strong connections to the land. Land acquisition for any type of development activity has a social and political sensitivity in the country. Hence, there lie challenges in additional land acquisition for the expansion of natural gas network.

2.4.2 Technological Aspects

Available technology options for natural gas-based energy supply are well-researched and proven to be efficient in the Indian context. This technological advancement is a driving force for expanding the use of natural gas. Renewable power supplies in India are expected to be 175 GWs by 2030, which will account for 40% of total installed capacity [29], with natural gas able to work as a bridge fuel in this transition to renewable energy. Gas-fired power plants can provide flexible or peaking power to balance the intermittency of wind and solar energy into the power grid. However, domestic supply shortage, as a result of various unpredictable geological factors and the geographical distance from natural gas-importing countries, is adding to the technological barrier in promoting natural gas as an alternative energy source.

2.4.3 Economic Aspects

Growing urbanisation and the expansion of the manufacturing sector are the key drivers underpinning an increase in primary energy demands in the coming years in

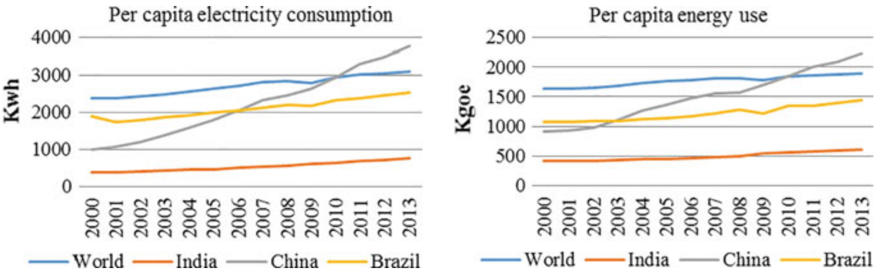

Fig. 6 Access to energy in India

India. Electricity demands are projected to be 2499 TWh by 2030, which is threefold the electricity demand of 2012 [9]. Should this increase in energy demand be supplied through natural gas—which is known to be a relatively cleaner[1] fossil fuel compared to oil and coal [5]—the energy intensity of Indian economy can be reduced significantly. The increased penetration of natural gas in the transport, power and industrial sectors also has a greater potential of improved energy efficiency [8].

The expansion of infrastructure for natural gas is involved with a huge investment requirement. India needs a clear policy and regulatory framework in order to attract the investments required for this purpose. In an effort to attract Foreign Direct Investment (FDI), the FDI policy has been liberalised for the petroleum and natural gas (P&NG) sector in 2013—despite the fact that, in 2015–16, the share of FDI in P&NG sector was only 3% of total FDI [23].

The production and supply of natural gas had not been keeping pace with the growing demand of natural gas in the country, including across the power sector; this is working as a major barrier. The gas supply for gas-based power stations in the country is inadequate, with the country facing considerable generation loss. Existing gas-based power plants are operating at very low PLF, equal to approximately 23% [10]. Gas-fired power-generation capacity of 4340 MWs is ready for commissioning; however, due to an unprecedented reduction in the supply of domestic natural gas in the country, these power plants are yet to be functional [29]. This is making the investment for the expansion of natural gas-based power generation even more critical.

The pricing of natural gas, both in the domestic market and internationally, creates a major barrier. As the price of both domestically produced and imported natural gas is steadily increasing over the years [23] (Fig. 7), the efficiency and economies of scale pertaining to the use of natural gas fall under question. Accordingly, in an effort to offset this price effect, more efficient technologies are needed, which essentially requires further investment. The development of a competitive natural gas market will be instrumental in setting the price of a natural gas at a reasonable level; this will also be favourable in attracting new investment for this sector.

2.4.4 Environmental Aspects

Approximately 60% of Indian electricity comes from coal-based thermal power plants. The coal-fired power plants' emissions in India are the main reason of environmental pollution [27, 28]. Switching from coal- to gas-fired power plants can be viewed as an effective GHG mitigation option in India as natural gas is a cleaner fossil fuel.

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[1] CO_2 emission factors for coal, oil and natural gas are 96,100, 73,300, 56,100 kg/TJ [5].

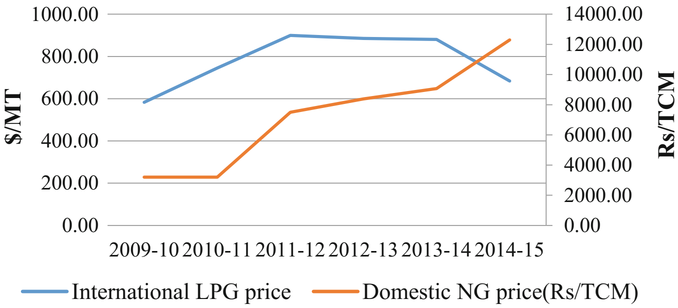

Fig. 7 Comparison of international and national gas prices

Degrading air quality in Indian urban centres is posing a significant threat to the environment, as well as to human health. Therefore, the abatement of air pollution in urban spaces across India has become a top priority in recent times. The penetration of natural gas in the urban transport sector and domestic sector in the form of LPG for cooking would contribute significantly to mitigating local air pollution.

However, fugitive emissions during extraction, transportation and distribution of natural gas are a major source of anthropogenic methane accumulation in the atmosphere. The leakage of methane from the natural gas sector is the highest contributing source for methane emission [37]. More research incorporating fugitive methane emission, upstream carbon emission and water use is required in an effort to develop further insight into the actual environmental benefit of natural gas.

2.4.5 Political Aspects

India has an abundance of in coal reserves. The use of domestic coal for energy purpose ensures national energy security; however, international consensus, which was made during the Paris Accord in December 2015, centred on arresting the global temperature rise within 1.5 °C, involves global energy transition by lesser use of fossil fuels. India is committed to reduce its emission intensity by 35% in 2030 [9]. Natural gas could play an important role in this transition. As India is far away from achieving self-reliance in natural gas-production, increasing dependence on natural gas will add to both import bills and consequent energy security risk.

India's import of natural gas faces challenges due to pipeline conflicts. India is set to import increasing volumes of natural gas from Iran and Turkmenistan. Due to various political uncertainties, this prospect is not able to show any desired outcome. Political facilitation, both at national and international level, is required for the further expansion of the natural gas sector.

3 Norway: An Oil- and Gas-Rich Developed Country

Norway is one of the wealthiest countries in the world and is recognised as a very special country in terms of the availability of energy resources. Further, Norway is 'one of the most energy secure and self-sufficient countries on the planet' [64]. Norway exports approximately eight times more energy than it consumes. Moreover, Norway's electricity production exceptional, recognised as almost 100% based on hydropower. In addition, Norway is a large exporter of oil and gas. In 2016, Norway produced approximately 145 bboe or 231 mill. Sm3 o.e. crude oil and gas—equal to approximately half of the volume of natural gas.

Nordic countries have a strong integrated electricity markets with considerable volumes for the day ahead, intra-day and balancing with the participation of producers and consumers. These countries have been informed ambitious goals towards decarbonising their energy systems till 2050 [38]. In this framework, case studies and reports have been developed in mind of objectively analysing such possibilities and ultimately prompting other countries to follow their lead. In the case scenarios performed in [39, 40], the need for gas-fuelled technologies in the future, notably as a consequence of choosing not to re-invest in nuclear energy, is highlighted. On the other hand, other scenarios (NETP) [41] state that the needed change is an increment of biomass-/biogas-generation technologies in an effort to cover the new demand and replace fossil fuels.

The real outcome is, of course, subject to the type of climate policies established in every region/country. One important aspect, however, is that any transition to a climate-neutral society in Nordic countries is somewhat dependent on the rate at which this is proceeding in the rest of the region.

3.1 *Fossil Energy in Norway*

Norway is one of the largest contributors to the European NG-market [43], which alone satisfies roughly 20% of the EUs natural gas demand [42]. The export value of crude oil, natural gas and pipeline transportation accounted for about 37% of the total value of Norway's overall exports. Investments in the petroleum sector accounted for approximately one-fifth of total investments in productive capital. Hence, for Norway, natural gas exports to Europe are a key economic interest. Norway's domestic consumption of natural gas is limited, with almost everything exported to other countries [42].

3.1.1 Oil and Natural Gas Reserves

By the end of 2016, it was assumed that a total of 3853 billion Sm^3 gas was left to be produced; nevertheless, gas reserves was estimated at 1782 billion Sm^3 [44].

The total amount of resources available since the start of the oil and gas adventure in Norway was up to 14.3 billion Sm3 oil equivalent, and by then only 48% had been produced/consumed [45]. This means that there remains 52% available for future consumption. In essence, there are four categories to divide the amount of gas on the Norwegian continental shelf: produced resources, reserves, contingent resources, and undiscovered resources.

Table 2 shows that entire 2388 billion Sm^3 gas are in reservoirs: most of it is planned to be produced with existing technology, although some is found in low-permeable or low-porosity reservoirs; this makes it more difficult to produce. Fortunately, the European market has a large amount of technology in constant development that can be used to find and produce more gas, maybe even from the trickiest reservoirs. New methods for improved recovery are estimated to produce up to 60 billion Sm^3 of gas [46].

3.1.2 Oil and Natural Gas Network

The start of the Norwegian gas transportation system happened in the early-1970s when the first large gas pipeline was laid. By 2017, it had been extended into a gigantic network consisting of approximately 8300 km of pipelines. Norwegian gas is delivered from the platforms standing on the Norwegian continental shelf. It can be processed offshore, in a separate construction, and sent directly to the receiver or otherwise can be sent to an onshore facility for processing before further transportation. Kollsnes, Kårstø, Nyhamna and Melkøya receive unprocessed well stream from the offshore platforms through an integrated pipeline system or otherwise by ships [47].

The integrated pipeline system on the Norwegian continental shelf can deliver approximately 120 billion Sm3 dry gas each year [42]. The three integrated facilities, namely Kollsnes, Kårstø and Nyhamna, are known to have the main credit for

Table 2 Norwegian oil and gas resources

Resource class	Oil (MSm^3)	Condensate (MSm^3)	NGL (Mill. tonnes)	Gas (GSm^3)	Sum (MSm^3 o.e.)	Change sum since 2015 (MSm^3 o.e.)
Produced	4169	116	190	2217	6863	232
Reserves	991	23	112	1782	3009	−119
Contingent resources in fields	351	3	21	246	640	45
Contingent resources in discoveries	367	3	14	299	697	−42
Production not evaluated (RC 7A)	145	0	0	60	205	−10
Undiscovered resources	1285	120	0	1465	2870	−50
Total	7308	264	337	6070	14,284	56

the huge amount of dry gas transported [47]. As an example, Kårstø gas and condensate processing plant has the Statpipe pipeline, transporting gas through Draupner, and their LNG is transported using ships. In addition, Europipe is allowing Kårstø to send gas directly to Europe [48].

Figure 8 shows different European destinations of Norwegian gas in 2016 [48]. The Norwegian gas delivered to these countries results in 20–40% of their total gas consumption [42] (see Fig. 9 for further details of the exporting lines).

3.1.3 Oil and Natural Gas Trade

Figure 10 (from Platts Analytics' Eclipse Energy) shows the Norwegian natural gas export to Europe. According to the former Minister of Energy, Tord Lien, talking to Platts in November 2016, Norway 'expects to export on average 100 Bcm/year'. Although it is less than the total of exports in 2015 as well as 2016 (i.e. approximately 115 Bcm), it remains a considerable amount and more than 20% of the EU's gas consumption. At the same time, it is in a situation with a surge in the supply of cheap US coal to Europe, meaning gas demand growth is estimated to be approximately only 1.5% per year from 2015 to 2021 [50].

The Norwegian transportation system is important for the exportation of gas. Pipelines and LNG boats can transport large amounts of gas inexpensively and in a shorter timeframe than what was possible a few decades ago. Almost 115 billion Sm^3 of gas is exported to other countries in Europe. This is a record high export amount for Norwegian gas, resulting in a total value of 160 million NOK [42].

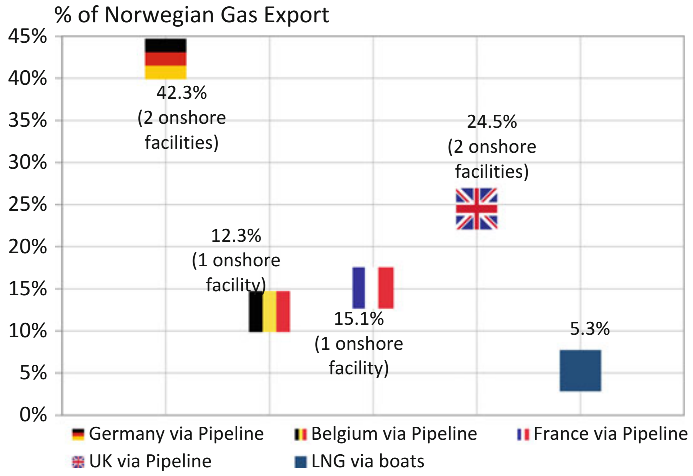

Fig. 8 Norwegian gas export

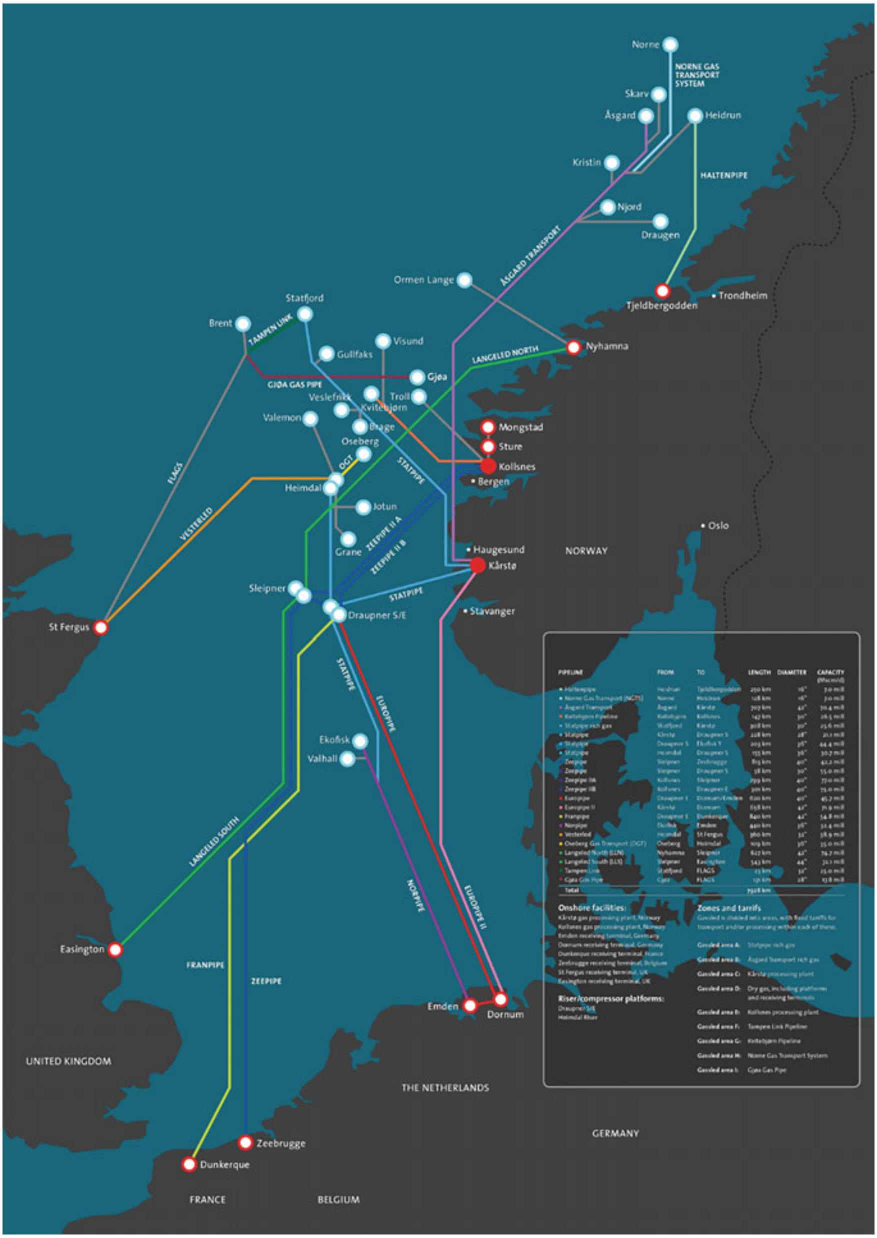

Fig. 9 Bringing Norwegian gas to Europe [49]

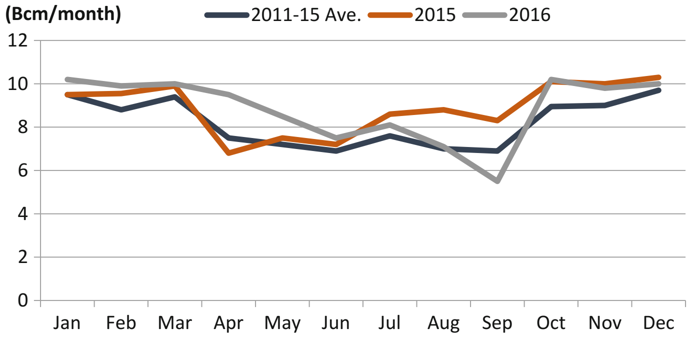

Fig. 10 2016 Norwegian exports to Europe at record high

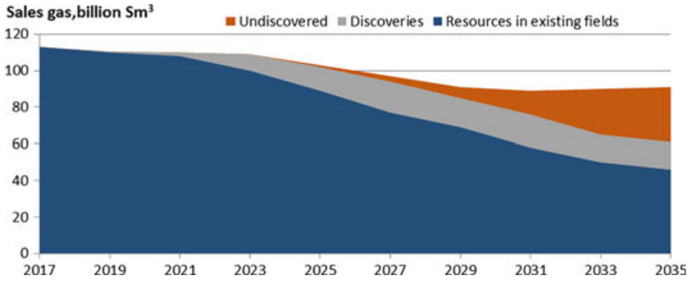

Fig. 11 Expected volumes of sales gas from Norwegian fields, 2017–2035

Finally, Fig. 11 shows the prognoses for future possible export opportunities, calculated by the Norwegian Petroleum Directorate [51]. For the next years, it is assumed that a sale of the resources will remain in reserves. From circa 2020, the use of discoveries has begun to be a part of the volume sold. Between 2020 and 2025, sales will be depending on what is now known as undiscovered resources to provide enough gas to keep levels at approximately the same as today's results.

In the long term, however, demand for Norwegian gas in Europe is also dependent on the energy and climate policies in the importing countries. Energy transition in Europe, with the growth of renewables and the ongoing efforts centred on improving energy efficiency, has made the longer-term demand for Norwegian NG more uncertain than before.

3.2 Renewable Energy in Norway

Power system and electricity use in Norway is different from most other countries, as a result specific challenges and opportunities will be occurred in this country.

3.2.1 Hydropower

The availability of significant hydropower resources and reservoirs that are fast and easy to control has resulted in more than 95% of Norway's electricity demand being covered by 1003 hydropower plants in 2015 [52]. Many reports highlight that, in the transition to a carbon-free future, the increased share of intermittent power will require regulating capacity of some sort in the power system, usually referred to as 'grid services', covering both balancing and backup [41]. Norway already plays a role in supporting intermittent renewables by providing hydro-based grid services via connectors to other countries, such as Denmark and Germany, for example. Two new interconnectors are planned with Germany and the United Kingdom. There is, however, an ongoing discussion in Norway concerning the role Norwegian hydro power resources can and should play in future European energy systems. Norway has notable potential for the installation of pump hydro storage, which could potentially provide mainland Europe with grid services since their reservoirs are at different heights, thereby enabling pumping water from a lower level to a higher level. Thus far, pumped storage has not been a priority for Norwegian authorities.

3.2.2 Biomass

Electricity from thermal power-production, including biomass, is equivalent to 2.5% of the total electricity use in Norway [52]. Fuel, such as transport fuels, from biomass was, in 2011, estimated to be 154 million litres in Norway [53]. Using biomass for electricity-generation has not yet been implemented on a large scale in the country.

3.2.3 Wind Energy

In 2015, 1.7% of total Norwegian electricity production was provided by 26 wind power plants [54]. Norway generally is known to have good wind resources compared with other countries. The average annual wind speed 50 m above ground can be 7–9 m/s in an exposed coastal area in Norway. At the start of 2014, Norway had 811 MWs of installed wind power, provided by 356 turbines in 20 registered wind farms. Another 9.1 TWh had been licenced; however, according to Norwegian Ministry of Petroleum and Energy (MoPE), it is 'unclear whether all this production capacity will be built' [55]. According to MoPE, wind power 'development in Norway has, so far, not been commercially profitable. and developments have depended on public funding' [55]. A 'Green Certificate Market' with Sweden, however, has made wind power more profitable in Norway. There are several large wind power plants that will be built before 2020. The largest wind power project in Norway is the Fosen wind project; this will produce approximately 3.4 TWh at the time of its completion in 2020. The project alone almost doubles the installed wind power capacity in Norway.

3.2.4 Solar Energy

Because of the large availability of energy from hydropower, amongst others, as well as owing to the geographic location, interest in solar energy production in Norway has not been overly high. The main use of solar power is in areas where electricity from the main grid are unreachable or otherwise in large industrial buildings. The cost of solar power in Norway is currently too high when compared to, for example, hydropower, which can be implemented on a large scale. The amount of direct sunlight, however, is comparable to Germany for the southern part of Norway. At the end of 2014, the total installed solar power capacity in Norway was seen to be 13 MWs [56]. The production capacity, however, increased sharply in 2016 (by a factor of 4), with solar expected to increase further.

3.2.5 Geothermal Energy

Some countries, such as the USA and Iceland, for example, have only short distances to hot mountains and can use the heat from the centre of the earth. The use of geothermal energy in Norway is limited to the use of heat from rocks and ground water in combination with heat pumps for space heating. The estimated amount of units installed is 26,000, capable of producing 3.5 TWh [56].

3.3 Energy Policy in Norway: Current Situation and Future Perspective

Will the need for Norwegian natural gas in Europe continue throughout the transition period towards a low-carbon energy future? And what are the prospects for natural gas consumption domestically in Norway? Exactly how the future energy mix will be composed is difficult to predict, but Norway is a special country in many respects. Norway is currently dependent on the income from fossil sources. Carbon Capture and Storage (CCS) has been advocated as a necessary in reaching the targets of the Paris Agreement and also when striving to continue with the use of fossil fuels within a carbon constrained world. Norwegian governments have been, and continue to be, actively advocating natural gas as a transition fuel in Europe. Within Norway, however, natural gas has been heavily disputed for a number of reasons, some of which are elaborated below.

3.3.1 The Norwegian Renewable Energy Sector

Norway is a country blessed with huge amounts of hydropower, making renewable energy targets easily accessible. Possibilities for wind power generation are also good in the country, both on the coastline, and onshore and offshore at the

Norwegian Continental Shelf (NCS). In addition, there is capital and good infrastructure available in principle, thereby enabling Norway to accomplish almost anything within this area.

The current energy situation in Norway is that approximately 95% of electricity comes from hydropower. There have been significant developments within the transport sector, moving from fossil to electricity on smaller vehicles, and from heavy oil to gas, and even to electricity on ferries and trucks, etc. Although Norway is a country with great fossil fuel resources, energy development at the national level is focused on moving towards non-fossil sources, energy efficiency, energy-saving, and smart cities in a sustainable society.

3.3.2 Balancing and Backup Power for Mainland Europe

The need for grid services, in terms of balancing and backup power, as a consequence of increased share of intermittent renewables, creates a new market for Norwegian renewable-based electricity. However, their excessive deployment also has an environmental concern with regards the carrying capacity of their respective ecosystems.

3.3.3 Norway's Export

Today, more than 95% of the gas produced in Norway is exported, with the Norwegian economy currently dependent on this income. Since a large amount of the oil and gas income is already saved for the future in *The Government Pension Fund Global* and as new money flow will also end up in the bank account, there is no immediate dependency compared to many other countries. However, the continuation of the use of natural gas as part of the energy solution in Europe is a key interest for Norway. It would be preferable to the Norwegian economy for natural gas to remain a part of the energy mix through the energy transition towards a renewable future. The most relevant countries for future Norwegian export destinations are those with a direct connection through the Utsirahøyden gas pipeline and NCS pipeline. Hence, Germany, France, UK and Belgium are already importing large amounts of Norwegian natural gas. Because of the flexibility of the Norwegian pipeline infrastructure, there are future possibilities for utilising this system in a low-carbon future.

LNG is the answer to the long-distance transportation of natural gas, although this depends on the receiver to have equipment for regasification. The new markets opening outside the pipeline infrastructure when liquefying the gas are exciting, but high costs of LNG-processing is an issue, causing slow progress in the global market. The Northern Sea Route north of Europe and Asia in the summer time are possible solutions to reducing the time consumption for LNG transport from Norway and Russia. Moreover, the Melkøya facility in Norway is recognised as well located for this LNG export route. From a long-term perspective, the reconstruction and expansion of LNG facilities at appropriate locations may, under certain scenarios, be a profitable investment for Norway.

3.3.4 Biogas Norway

From the long-term perspective, the same conventional energy conversion technologies (e.g., gas turbines) established for gaseous fuels would still be relevant, provided that a successful smooth transition to biogas and green gas, such as from power to gas route, can be achieved.

Biogas is an interesting option that can take advantage of the existing gas infrastructure. This solution is energy effective and has already been tested, implying promising future results.

3.3.5 CCS Development by Norwegian Authorities

Norway has actively contributed to the development of carbon capture and storage technologies, since a functioning CCS would pave the way for the use of natural gas in a low-carbon energy future.

3.3.6 Norwegian Transport Sector

In terms of transportation, Norway has been rapidly developing towards electrification to replace fossil fuels. The generous support system for Electric Vehicles (EVs) in Norway (i.e. tax and fee exemptions, being permitted to use public lanes, own EV license plates, and more), together with the decreased costs of electric vehicles, has resulted in electricity becoming a future fuel within the Norwegian small vehicle sector. There have also been some efforts directed towards creating an infrastructure for hydrogen fuel cell cars (based on electrolysis, not natural gas reformation), and the Lyse company in Norway (Rogaland region) is mixing upgraded biogas and NG for transportation usage. Nevertheless, attempts at making natural gas and biogas the fuel is not implemented on a large scale in Norway, and significant changes within a short-term perspective is unlikely. There are two main reasons for this: one is greenhouse gas emissions (GHGs); another is the fact that there is no gas distribution net in Norway, besides Rogaland. The infrastructure for charging EVs with renewable electricity from hydro is being expanded and home charging is already in place, meaning establishing a new infrastructure would not make sense.

Truck and marine transport, on the other hand, are areas in which it seems that natural gas could be part of the solution. The ‘blue corridors’ (www.lngbc.eu) is a positive development using natural gas as a solution for the transportation sector. Both truck and marine transport have the significant potential to reduce emissions, especially within the marine sector. Norway, however, is increasingly focusing on the electrification of transport heavy transport and the marine sector. The possibility of large GHG emission cuts in the transport sector has a high priority in the national climate policy and also on negotiations with the EU.

3.4 A STEEP Analysis

What then is the possible role of natural gas in the Norwegian context? How is natural gas viewed? And what are the visions for natural gas in a future of sustainable energy? In order to answer these questions, a STEEP analysis is adopted, which directs attention to all five dimensions, namely social (S), technological (T), economic (E), environmental (E) and political (P), in specific regards sustainable development [33–35]. For each of these dimensions, there are both enablers and barriers, which can indicate the role of natural gas as a future energy source in Norway, as well as the extent to which NG can contribute as a transition energy source. The framework makes it possible to link the factors and issues that affect the prospects for natural gas in a sustainable energy future (Table 3).

Table 3 STEEP analysis for natural gas as a possible transition energy source for Norway

Term	Enabler	Barrier
Social	• Population growth, but the demand for energy from mainland Norway has been declining slightly from 2010 and onwards. No energy (or fuel) poverty in Norway	• Availability of large hydro power resources, growth in other renewable energy resources together with national GHG emission targets and policies limits the use of natural gas domestically
Technological	• NG with CCS - high potential for emission reduction	• Domestic use of natural gas in large quantities requires a breakthrough for CCS technologies
Economic	• NG (and oil) exports important for economic growth and national income	• Investment in infrastructure development • Price competitiveness • Low electricity prices • Expected increase in carbon price
Environment	• Some potential for GHG emission reductions (with fuel switching from coal and oil to NG) in industries and marine transport	• Increased use of NG domestically will in many instances increase national GHG emissions
Political	• Some political will (among some political parties in Parliament) to increase the use of NG domestically	• Increased use of natural gas domestically disputed in Parliament • National GHG emission targets and policies limits the use of natural gas domestically

3.4.1 Social Factors: The Country of Energy Abundance

Compared to other countries, there is little energy (or fuel) poverty in Norway. Not only do Norwegians use less of their income on energy than average, but electricity prices in Norway are lower than in many other EU countries. Electricity consumption, however, is high. The average consumption of electricity in households in the EU is between 2500 and 5000 kWh a year, whilst in Norway, average consumption is 16,000 kWh. Electricity is used for heating, where others use natural gas or other heating sources. Very few households use natural gas for heating, and, with the lack of a natural gas infrastructure in most parts of the country and new policies potentially banning the use of natural gas for heating in new buildings, natural gas will play a very limited role. There is some natural gas use in district heating, but even in this regard the policies aim at phasing out fossil fuels as much as possible in order to reduce GHG emissions.

3.4.2 Technological Factors: The Quest for Carbon Capture an Storage (CCS)

In the mid-1990s, a new technological option highly relevant to the domestic use of natural gas gained increasing support Carbon Capture and Storage (CCS). The White Paper [57] following the release of the report from the World Commission on Environment and Development (WECD), *Our Common Future* in 1987 (led by the Norwegian Prime Minister Gro Harlem Brundtland), argued that climate change concerns could constrain the domestic use of natural gas [57]. The White Paper explicitly stated that ‘today, there exist no suitable technologies which can clean these (CO_2) emissions. To reduce these emissions, the use of fossil fuels has to be reduced’ (p. 84) [57]. For an oil- and gas-exporting country, this was a bleak future. The prospects of CCS radically changed that picture.

In the following years, the largest parties in Parliament—the Labour Party, the Conservatives and the Progress Party—advocated the increased domestic use of natural gas. CCS soon became one of the most important mitigation option advocated by ENGOs in Norway, most notably by Bellona and ZERO [58, 59]. In the summer of 1994, the company Naturkraft was established to develop and run two gas-fired power plants (without CCS) on the western coast of Norway at the locations Kårstø and Kollnes. Those power plants would increase domestic greenhouse gas emissions (GHGs) by approximately 6%. The owners were the petroleum company Statoil, power company Statkraft (both at that time fully owned by the Norwegian state), and the partially state-owned industrial conglomerate Norsk Hydro, which had operated power-intensive aluminium factories.

In April 1998, however, one of the Naturkraft owners, Norsk Hydro, took everyone by surprise and presented competing plans for a power plant with pre-combustion CCS. Since then, CCS has been high on the national agenda. The story of CCS in Norway, however, has remained rather bleak. The gas-fired power plant at Kollnes was never built and, although Kårstø began operating in 2007, it closed permanently in 2016. Furthermore, CCS (which was supposed to be in place in 2009) never materialised due to high costs, and, due to low electricity prices and high gas prices, the plant was uneconomic, even without CCS.

In 2006, the current Prime Minister declared a new project, a combined heat and power heating plant with CCS at Mongstad, Statoils and Norway's major industrial refinery at the West Coast of Norway. This was described as Norway's 'Moon landing', and Mongstad was described as 'one of the most important instruments in Norway's climate policy' [60]. The CCS part of the project at Mongstad never materialised due to high costs, but ended up as a European CO_2 Technology Centre. On February 15, 2017, Statoil issued a press release stating that it would close the plant by 2018 due to it being uneconomical. Presently, there are not any NG CCS projects in the program. Instead, the current government (a conservative, right-wing coalition) is focusing more on CCS in industrial processes. Three CCS projects were granted further funding in the 2017 budget: Norcem (cement), Yara (fertilisers) and the waste incineration plant in Oslo. The government is still hoping to have one industrial full-scale CCS project in place by 2020.

3.4.3 Economic Factors: Natural Gas Exports—Securing National Income

NG (and oil) exports are extremely important for economic growth, jobs and national income in Norway. This has led to a record high opening of new areas to be explored for oil and gas exploration in the Arctic in 2016 and 2017 in order to reduce the decline in petroleum production. From the mid-1990s, natural gas resources have also been seen as a promising opportunity to create new industries by increasing the utilisation of natural gas for industrial and commercial purposes from a domestic standpoint. This is still the official Norwegian policy, although it has been difficult to reconcile with national climate policies.

3.4.4 Environmental Factors: Is Natural Gas Environmentally Benign?

Natural gas has therefore at the centre of environmental controversies in Norway. The story of natural gas in Norway is actually two very different stories, one about natural gas exports from Norway to Europe and one about the domestic use of natural gas. Since climate change was put on the political agenda in the late 1980s, natural gas exports from Norway have been viewed as a way of mitigating climate change by providing the opportunity for coal-dependent nations in Europe to replace coal with natural gas. Every White Paper and all governments, since the early 1990s, have argued, and continue to argue, that Norwegian gas is good for the environment, which provides the primary justification (besides the economic revenues) for expanding oil and gas activities into the Arctic. Hence, natural gas exports align the economic (revenues), environmental (mitigation in Europe), social (the revenues finances the welfare state) and the technological (with the future prospect of CCS).

While the need for NG in the longer term in Europe—and also NG as a transition fuel—has been increasingly questioned by the smaller opposition parties in Parliament, the domestic the story remains very different. Norway is very different from most other countries in that it has the world's highest per capita hydropower production. Hence, most of Norway's domestic stationary energy consumption is based on hydropower. The environmental effects of using NG for stationary energy or electricity production (in an already emission free sector) are clear. As stated by the Ministry of Petroleum and Energy MoPE, 'Greenhouse gas emissions from domestic energy generation increased sharply in 2009 due to a high activity level at the Kårstø gas-fired power plant. Emissions rose further in 2010 and 2011 after the new combined heat and power heating plant at Mongstad came on stream' [55]. This illuminates the political struggles concerning the domestic use of natural gas and the importance of CCS in the national context.

3.4.5 Political Factors: The Struggle to Reconcile Domestic Use of NG and Climate Change Policies

The debate in Parliament, following the same White Paper [57] that argued that climate change concerns could constrain the domestic use of natural gas, resulted in Norway becoming the first country in the world to set a target for stabilising CO_2 emissions by 2000 at the 1989 level [61]. It soon became apparent, however, that the stabilisation target would be extremely difficult and also costly to achieve for Norway for several reasons. The fact that Norway's electricity demand is virtually 100% met by domestic hydroelectric power left Norway with few options to compensate for the growing emissions from the oil and gas sector [58, 62]. Thus, in 1995, the stabilisation target was officially abandoned by the Labour Government owing to the principle justification that petroleum production was much higher than expected, making it impossible to reach the stabilisation target [58, 59].

The possibility of CCS, however, fundamentally changed the prospects for domestic use of natural gas when it entered the political stage in a fierce political battle over the two aforementioned gas-fired power plants. The energy political cleavage that emerged cut across the traditional left–right axis in Norwegian politics and, in effect, energy and climate change issues became controversial for all likely government coalitions. When Norsk Hydro presented its plans for a power plant with pre-combustion CCS, the Norwegian Pollution Control Authority (SFT) issued an emissions permit in 1999 for the Kårstø plant, which demanded that Naturkraft reduced the CO_2 emissions from its project by 90% in an effort to comply with the demand that the best available technology (BAT) should be used [59]. Despite warnings that it might cause the Bondevik Government to resign, the majority in Parliament instructed the government to change the guidelines on CO_2 in the emissions permit for Naturkraft's power plants. As a consequence, Bondevik stepped down in March 2000 and was replaced by a short-lived Labour

Government, which soon gave the necessary permits for CO_2 emissions from the planned gas-fired power plants without CCS [58].

In 2005, a majority coalition Government consisting of the Labour, Socialist Left and Centre parties was established and re-elected in 2009. CCS was one of the most contentious issues in the negotiations between the parties both in 2005 and 2009, and the CCS component was crucial for the formation of the Government Coalition and for the 'Moon landing'. as such. The founding document of the coalition Government, the Soria Moria II declaration, stated that Norway should be a world leader in CCS, and accordingly upheld the principle of 'no new power plants without CCS' [63]. In effect, this meant that the future of natural gas for electricity production in Norway was made dependent upon the realisation of CCS.

3.4.6 Natural Gas Prospects

Natural gas consumption has increased somewhat in other sectors in Norway. The total use of natural gas for heat and power was 4.3 TWh in 2014. In addition, approximately 5 TWh natural gas was distributed as LNG or through the two natural gas pipelines that exist in the county Rogaland. What characterises Norwegian energy consumption, however, is that electricity (from hydro) is the dominant energy source. Hence, in order to reduce GHGs, natural gas only plays a role as long as it replaces other types of fossil fuel. Therefore, despite the government arguing that it will 'facilitate the use of natural gas' [64, 65], the prospect for increasing domestic use of natural gas is limited. Due to investments in new renewable energy (onshore wind power), small-scale hydro developments and the upgrading of some existing large hydro plants, Norway is about to receive a large surplus of emission-free electricity that can be used either domestically to replace natural gas (as in district heating) or exported to neighbouring countries. Hence, for the domestic use of natural gas, the economic, technological and environmental constraints continue to limit the use of natural gas in political terms. Thus, natural gas will most likely play a very limited domestic role in a sustainable energy future for Norway. How large a part Norwegian natural gas will play in a European sustainable energy future is a whole other issue. An increasing number of political actors are also questioning the role of natural gas as a transition fuel, and also the expansion of petroleum activities in the Arctic. Part of the coming political struggles will revolve precisely around these questions.

4 Iran: An Oil- and Gas-Rich Developing Country

Iran, located in the Middle East, has an area of approximately 1.648 million sq. km with more than 75 million populations. With its young population, high and growing energy demands per person, increasing urbanisation and economic development, Iran has been recognised as one of the growing power markets in the world. Iran is a significant energy-producing and -exporting country. Owing to the large gas reserves in the country and the advantage of gas versus oil, the energy policy in this country is based on an increase of gas/a decrease of oil usage in commercial as well as residential sectors. In Iran, the primary energy forms include fossil fuels (i.e. natural gas, fuel oil, gasoline and petroleum) [66].

This country has considerable energy sources. According to the US Energy Information Administration (EIA), the country holds the world's fourth largest proven crude oil reserves and the world's second-largest natural gas reserves.

Energy consumption has increased in Iran during the previous decades. According to the energy balance sheet of the country, total energy consumption was 325.3 million Barrels of Oil Equivalent (BOE) in 1988, whilst it shifted to 687 million BOE in 2001. Hence, total energy consumption has increased, with an annual growth rate of 5.9%, during this period. This consumption with a 5% increment, reached 1229.7 million BOE in 2013 (Energy Balance Sheet of Iran, 2006 and 2013) [67].

Iran also has a significant potential in renewable energy sources, namely solar, wind and geothermal, which is not being adequately harnessed. In terms of the installed capacity of renewable energy, it is the leader in the MENA region with 9612.3 MW. In the field of solar energy, Iran has the potential of almost 2800 h of sunshine on a yearly basis, and an average solar radiation of 2000 kWh/m^2 each year. Iran's first CSP plant started operation in 2010. The share of energy produced by wind power remains low. In 2013, wind capacity had increased to 93 MW [68].

In this part, focus is directed towards the importance of natural gas in Iran and the solutions in which this source of energy can be combined with renewable energy to solve the economic, environmental challenge in a secure and sustainable way.

4.1 Natural Gas in Iran

The use of natural gas as fossil fuel is only a part of the diverse role of this valuable natural resource. Other factors of key importance in the case of natural gas appear with its high added value and functionality to thousands of economically valuable products in the petrochemical industry.

In Iran, oil was firstly extracted only while a large amount of gas was produced at the same time. From 1910 to 1960, gas produced along with oil was mainly burned. In the early 1990s, the associated gas that was extracted was moved by pipeline to Russia and, in return, a steel mill was established in Iran by Russia. But then, whilst the export to Russia continued, the gas produced along with the oil was used in the Shiraz cement factory for the first time. In actual fact, Shiraz was the first city in Iran to be fuelled by natural gas; then, gradually, the gas network was distributed to other cities in Iran. Thus, the gases were burnt and wasted for more than 50 years and entered into factories, plants and people's homes.

Approximately 40 years ago, the NIOC made a techno-economy decision to gather associated gas for refinement, transmission and sale. After discussing the idea of selling gas abroad in 1344 SH, extensive studies were carried out and the project, so-called the first pipeline IGATI (IRAN Gas Trunk-line), was started and put into operation.

With the exploration of independent gas fields, such as Kangan and Pars, it was essential to separate the responsibilities between the National Iranian Oil Company (NIOC) and National Iranian Gas Company (NIGC). In this way, the NIOC was and continues to be recognised as responsible for the exploitation, production, trade and export of Iranian oil, with the NIGC responsible for exploitation, production, trade and export of Iranian gas.

4.1.1 Natural Gas Network

Gas can be utilised as feed stock in petrochemical plants and refineries, or otherwise exported through pipeline or LNG. Currently, Iran as second richest oil and gas reserves, supply approximately 133 billion barrels of oil and 24 thousand billion cubic meters of natural gas. It means that, Iran has 11.6% and 15.6% of the world's proven oil and gas reserves.

Iran has huge reserves of natural gas, and transportation from the fields of production through to Iranian end-users is carried out via pipeline. By the end of 2014, Iran's gas industry was recognised as responsible for the transmission and delivery of this clean fuel, employing 72 gas compressor stations, 36 operation centres, and more than 35 thousand kilometres of pipeline from 2 to 56 inches. The gas pipeline across Iran is known as the country's gas transmission network. These lines are scattered throughout the country in order to safely and effectively transfer natural gas from refinery locations through to gas stations, with subsequent distribution to consumers through these stations.

Iran's gas transmission system has 12 nationwide lines. The first country-wide pipeline starts from the Bidboland region, followed by Astara. The second country-wide pipeline begins at Kangan refinery and terminates in Ghazvin. The third pipeline route begins in Asaluyeh, southern Iran, and extends to Saveh. The recent pipeline has nine gas compressor stations so as to increase gas pressure along the way. The following table shows the Iranian gas network data (Table 4).

4.1.2 Natural Gas Reserves

As mentioned above, energy resources in Iran consist of the fourth largest oil reserves and the second largest natural gas reserves in the world with more than 33.6 trillion cubic meters (tcm) of natural gas as of 2013. Given the technology advances for exploration and energy production, Iran is planned to benefit its energy resources more effectively (Table 5).

Table 4 Iran Gas Trunk-line information [69]

Connection from/to	Length (miles)	Diameter (inches)
Asaluyeh/Lushan	734	33
Asaluyeh/Aghajari	313	56
Asaluyeh/Bid Boland	306	56
Asaluyeh/Iranshahr	560	56
Asaluyeh/Naeen	489	56
Asaluyeh/Saveh	712	56
Bid Boland/Qom/Qazvin/Rasht/Astara	685	42, 40
Kangan/Gazvin	646	56
Kangan/Pataveh	262	56
Saveh/Miandoab	292	40, 48
Tehran/Dasht-e-Shad	327	42, 48

Table 5 EIA global estimated natural gas reserves [70]

Country	Reserves (tcm[a])	Share of world total (%)
Russia	47.5	25
Iran	33.6	17.7
Qatar	25.2	13.3
US	8.6	4.5
Saudi Arabia	8.1	4.3

[a] Trillion cubic meters

Up to 2011, more than 42 gas fields and 92 gas reservoirs were registered in Iran. The South Pars gas field is the largest Iranian gas reservoir, which is along with Qatar's reserves of approximately 507 trillion cubic feet. This gas field is shared between Iran and Qatar, and has been named the North Dome Gas Field. Since the beginning of the harvest of this joint field of hydrocarbon resources, Iran and Qatar have been in competition for supremacy in the field. This is an area of 9700, 3700 km^2 in Iranian territorial waters and 6000 km^2 in the territorial waters of Qatar. The South Pars field supply approximately 40% of Iran's gross natural gas production in 2013 and is known to almost 40% of Iran's total proved natural gas reserves [71].

Given that natural gas is an important source of energy in the twenty-first century and in mind of the predictable demand growth expected by 2050, Iran is and will continue to be one of the most important energy suppliers in the world. According to the latest statistics from BP, the world's gas reserves were at 185.7 trillion cubic metres in 2013, where Iran, with its 33.8 trillion cubic metres, ranks first in the world ahead of Russia in terms of natural gas reserves. At the same time, Iran is the second-ranked country in the production of natural gas with 166.6 million cubic metres and taking third place in the world in terms of consumption with 162.2 million cubic metres in 2013. According to the NIGC, Iran's average natural gas production has been 552.81 million cubic metres per day in

1393 SH with about 10% increase over the previous year. The average natural gas production in the first months of 1394 SH has had approximately 9.15% increase compared with the same period in 1393 SH [72, 73].

4.1.3 Natural Gas Trade

With unlimited NG production, Iran is focusing on methods for export considerable volume of gas. Potential customers for Iranian gas exports include Turkey, Ukraine, Europe, India, Pakistan, Armenia, Azerbaijan, Taiwan, South Korea and China. Exports could be either via pipeline or by LNG tanker, with possible LNG export terminal at Asaluyeh or Kish Island [74].

Till 2012, Iran was the main exporter of NG via pipeline to three neighbouring countries, namely Turkey, Armenia, and Azerbaijan. More than 90% of Iranian exports went to Turkey in 2013. Iran provides 1% of global natural gas export and has no capability to export to global market via Liquefied Natural Gas (LNG) export terminals [75]. The NIGC is seeking funds from foreign investors to finance major pipelines that would allow Iran to export more gas; state officials have advised Natural Gas Daily as per Fig. 12. The main Iran gas trunk-line, which exports natural gas to Iraq, Pakistan and Oman, Europe, are IGAT 6, 7 and 9, respectively.

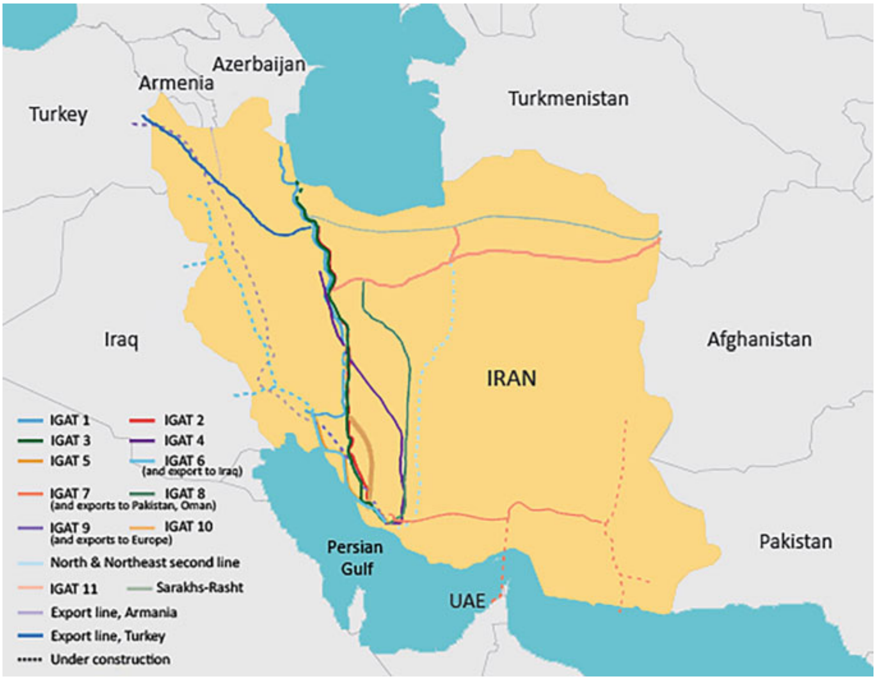

Fig. 12 Iran Gas Trunk-line

Table 6 shows the amount of Iranian import and export of natural gas to neighbouring countries and the amount of natural gas exports and imports from 2011 to 2015, as shown in Fig. 13 [69].

4.2 A STEEP Analysis

In order to review and determine the roles of natural gas in the future of sustainable energy in Iran, it is important to determine the social, technological, environmental, economic and political factors to be potentially accomplished through STEEP analysis. In this part, these factors investigated Iran as a country rich in natural gas resources (Table 7).

4.2.1 Social Aspects

Iran's energy combination is dominated by hydrocarbons, including natural gas and petroleum at approximately 98 and 2% a combination of hydropower, nuclear, biofuels and other renewable sources. Natural gas is also a very safe source of energy when transported, stored and used.

Table 6 Iranian imports and exports of natural gas (bcm)[a] [76]

Country	Import	Export
Armenia	–	0.45
Azerbaijan	0.36	0.58
Turkey	–	6.92
Turkmenistan	7.95	–
Total	8.32	7.95

[a] Totals are estimates based on average per day trade

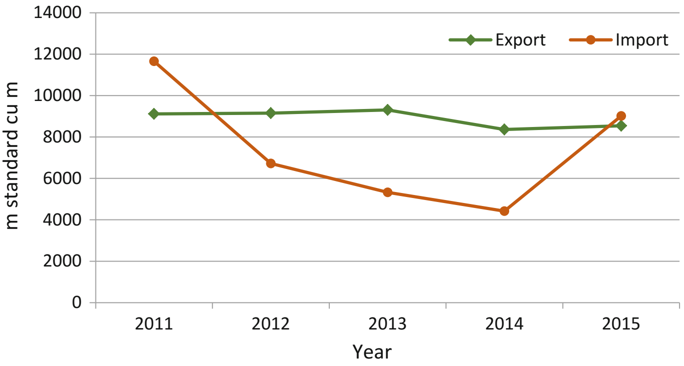

Fig. 13 Iranian natural gas export and import from 2011 to 2015

Table 7 STEEP analysis for natural gas as a possible transition energy source for Iran

Term	Enabler	Barrier
Social	• Largest growth in NG usage comes from petrochemical plants, power sectors and other huge industries	• Population growth and increasing demand for safe and clean energy
Technological	• CNG as a gas supply method to distant areas to increase the availability and environmental benefits • Mature technology of gas turbines and gas compressors	• Lack of modern technologies for growth in production of natural gas • Shortage of knowledge in direct conversion of NG to liquid (and other products) such as GTL technology • Lack of construction of new LNG terminals
Economic	• More export of natural gas based electric power will lead to high trade balance • Increasing investment and allocation credit for rural and urban natural gas network • Growth in natural gas revenue	• No specific comments
Environment	• Less in carbon content comparing crude oil • Increasing LNG allocation in natural gas trade and then less environmental impact • Export of wasted and burned natural gas as FLNG	• Overreliance on fossil fuel (like NG) resources leads to environmental concerns
Political	• Governmental incentive for growth of gas-based DG energy systems • Export of NG to European countries after signing the Joint Comprehensive Plan of Action (JCPOA)	• Problems in construction of new gas grid to Europe via the neighbours like Turkey

In Iran, people do not have access to modern energy system and services. In order to avoid overreliance on fossil fuel sources and environmental concerns in coming years, Iran has intended to develop renewables as an alternative. In Iran, natural gas is available and can be combined with renewable energy so as to reduce the amount of greenhouse gases produced in the country. As the main aspect of energy demand in Iran has been proven by fossil fuels, Iran has become one of the 20 countries to have a contribution in 75% of GHGs generation [77].

Iran, in respect to her geographical and political strategic situation, can play a leading role in global gas supply and, accordingly, can act in Europe and Asia. Natural gas still maintains the fastest consumption growth rate amongst the world's primary energies and is realised as having the greatest consumption growth amongst developing countries. Now, natural gas accounts for approximately 68% of Iranian domestic energy consumption. Figure 14 shows the annual natural gas consumption by different sectors in Iran [78].

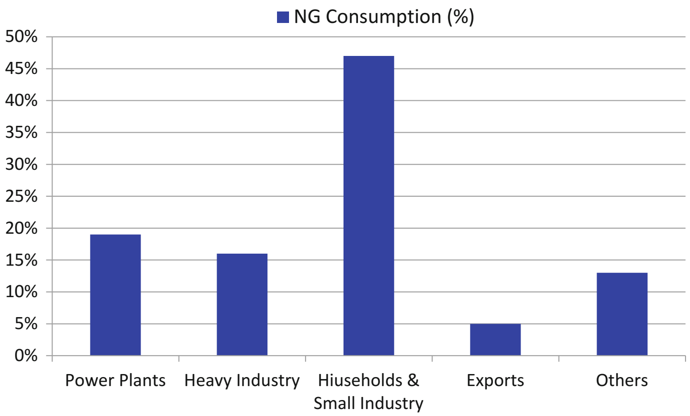

Fig. 14 The annual natural gas consumption by different sectors in Iran

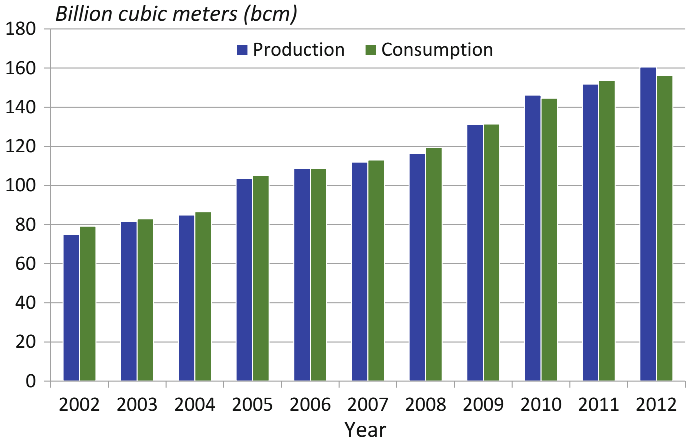

Fig. 15 Natural gas use in Iran 2002–2012 (billion cubic metres, bcm) [79]

As can be seen in Fig. 15, the total consumption of natural gas during 2002 until 2012 has increased.

4.2.2 Technical Aspects

As mentioned earlier, the growing importance of natural gas as a major energy source in Iran is shown by the amount of investment dedicated to the natural gas industry. Natural gas is the most efficient fossil fuel in conventional power-generation. Moreover, technologies with the capacity to operate with natural gas and reduce CO_2 emissions in Iran are not complicated technologies, and, as such, are more available.

On the other hand, natural gas is one of the multiple fuels on which combined cooling, heat and power systems based on gas turbines can operate. As Iran is ranked as the 4th greatest owner of oil reservoirs and has the second place from a gas reserves point of view, multiple storage options are possible, meaning this country has great potential capacity for CO_2 storage and, more specifically, remarkable pressure drop in its oil and gas reservoirs implies that enhanced oil recovery and enhanced gas recovery by carbon dioxide are prominent options [80].

Natural gas will continue to contribute to low carbon solutions in the very long-term. This solution can be reducing CO_2 emissions from gas-fired plants. As Iran is ranked the eighth greatest CO_2 emitter country in the world, Carbon Capture and Storage (CCS) technology as a dominated strategy should be implemented in this country to reduce CO_2 emissions. Growing carbon dioxide emission trends in Iran show a relative growth rate of 64.4% in 2009 compared to emissions in 2000 [80]. In 2014, the CO_2 emissions in Iran totalled 620 million tonnes. Furthermore, in terms of population, there was an increase in the country from 39% from 1990 through to 2014. In this period, changes in CO_2 per capita emissions amounted to 203% in the country [81]. Moreover, gas, as a new fuel, provides the modern technology of fuel cell construction for vehicles possible. In an effort to portray the enormity of Iran gas reserves, it is enough to consider that Iran's natural gas reserves alone exceeds the total volume of natural gas reserves in the USA, Canada, Europe, and the entire Asia pacific [82].

A combination of natural gas and renewable energies in a combined-cycle power plant is the other technology with the capacity to reduce the world's pollution levels. The first combined-cycle power plant with combination of solar, power and natural gas namely "Yazd power plant" was integrated in 2010 in Iran. This power plant is the eighth largest solar power plant in the world [77]. The capacity of installed and connected renewable energy power plants are shown in Table 8 for the end of the year in Iran.

4.2.3 Economical Aspects

The past and current state of natural gas in Iran, based on the economical factor, is related to the trade, tax, exchange rate, energy price and job opportunities, etc. As Iranian news agency Fars News said, since 10 years ago, Iran's power-generation capacity has grown by 7% annually. There are significant goals to further increase generation capacity in order to keep up with the domestic demand, but also to ensure that it continues exporting electric power. Amongst the countries, Iran exports to Armenia, Pakistan, Turkey, Iraq and Afghanistan. According to the Central Bank of the Islamic Republic of Iran, in 2013/14, approximately 68% of electricity exports were transported to Iraq [83].

Based on the OPEC annual statistical Bulletin 2016, the exchange rate national currency per US$ for Iran was 29011.50. The cost and economic justification are the fundamental questions on CCS. The answer to these questions is not simple

Table 8 Iran renewable energy power capacity—MWs

Sub technology	2008	2009	2010	2011	2012	2013	2014	2015
Large hydropower	7624	7656	8434	8684	9746	10,266	10,782	10,782
Onshore wind	90	90	93	98	98	98	117	117
Medium hydropower	46	47	51	60	60	62	65	65
Concentrated solar power	0	17	17	17	17	17	17	17
Small hydropower	3	2	3	3	3	3	3	3
Pumped storage and mixed plants								1040
Total	7763	7812	8598	8862	9924	10,446	10,984	12,024

since CCS costs depend on a variety of factors, such as energy price, which could differ from one country to the next, as well as investment costs and legal requirements.

4.2.4 Environmental Aspects

Nowadays, everyone in developed countries has become aware of the issue of climate change and the various methods centred on reducing the amount of greenhouse gases. Natural gas has the highest share of CO_2 emission because consumption of this fuel in power plants has priority over oil-based liquid fuels due to environmental considerations, easier handling, and lower maintenance and repair costs.

Iran was the 10th CO_2 emitter country in the world in 2008. The overall CO_2 emission in Iran is seen to be equal to 480 Mt per year. The major stationary sources to capture are power plants, the oil and gas industry, and large industries. Approximately 100 m tonnes CO_2 year are emitted from power plants in Iran.

Based on the global CO_2 emissions report of 2015, as provided by the PBL Netherlands Environmental Assessment Agency, the CO_2 emissions from gas flaring in Iran decreased 9% from 2005 to 2012. Iran shares 7.5% of the total CO_2 emissions from gas flaring. Available regulations, laws and treaties in Iran show the relevant aspects to the development of a legal system for CCS and in establishing the gaps for the secure and safe development of this country.

4.2.5 Political Aspects

Iran's high level of energy consumption and CO_2 emissions, combined with costly electricity-production by fossil fuels, which are highly subsidised by the government, are just some of the reasons underpinning Iran's policymakers being keen to utilise these natural conditions to attract private sector investments in the renewable energy market [83].

In order to avoid environmental concerns in the coming years due to the use of fossil fuels, Iran has planned to development of renewable energy sources with various polices towards increasing the share of renewables energies so as to improve energy security and reduce environmental pollution and create new job opportunities. These policies categorised into three groups, namely infrastructures and knowledge promotion, financial supports and funding, and power purchase agreement tariffs [84].

However natural gas is more environmentally friendly than other fossil fuels such as oil- and oil-based products, the absolute amounts of pollutants will continue to increase dramatically, with a soaring of CO_2 emissions results more global climate change. A policy of unbridled expansion of the fossil-based primary energy supply resulting from a rise in the share of natural gas supply would most likely cement the present consumption behaviour, restrict the rise in energy efficiencies and energy-savings measures, and extrapolate into the future the current transportation network in Iran, which has been geared towards expanding the road network and private transport, thereby defining the policy for decades to come [85, 86].

5 The UK: A Net Oil- and Gas-Importing Developed Country

In general, the UK has experienced strong energy security in Europe, being sure about ease of access of consumers to energy with a reasonable price. However, some risks, such as severe weather, technical failures, industrial action and various new changes, including decreases in fossil fuel reserves, will create new challenges for UK energy security in the years ahead [87].

5.1 Natural Gas in the UK

5.1.1 Natural Gas Trade

67 billion cubic metres of natural gas was used in the UK in 2015. Almost half of its value is produced by the UK from the North Sea and the East Irish Sea. In UK, 38% of required gas is provided by Europe and Norway via pipelines and 17% is imported into UK by tankers in the form of LNG [88]. Figure 16 shows from where the UK’s gas is sourced.

Natural gas is the most important source of energy in the UK because 80% of UK homes are powered by gas. Moreover, gas-fired power stations generate around 25% of the UK’s electricity. This provides an explanation as to why NG plays a vital role in the UK energy mix.

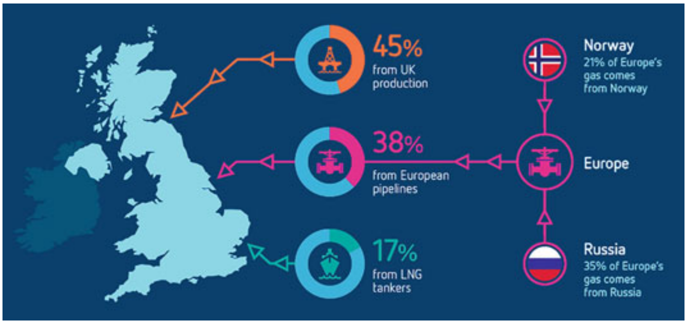

Fig. 16 The UK's gas sources [88]

5.1.2 Natural Gas Network

In terms of the NG network, various main parameters should be considered: Gas Pipelines, Gas Storages, and Liquefied Natural Gas (LNG). In regards the geographical situation of the UK, pipelines run under the sea. The four pipelines, which run from the European continent to the British mainland, are the UK–Belgium interconnector (IUK) with the import capacity of 25.5 billion cubic metres (bcm) a year, the UK–Netherlands pipeline (BBL) with the import capacity of 14.2 bcm a year, the Vesterled pipeline link connecting St Fergus in Scotland to a number of Norwegian gas fields and with the capacity of 14.2 bcm a year, and the Langeled pipeline, which runs from Nyhamna in Norway to Easington in Yorkshire, and which is recognised as the longest underwater gas pipeline in the world at 1200 km with 26.3 bcm capacity [89].

The UK has two main types of storage facility with more than 4 bcm of capacity to deal with the cold winters successfully. The first one is depleted gas fields, which alone can satisfy 10% of Britain's gas needs on a cold winter's day. The next one is created when water is pumped into the salt deposits created millions of years ago and which can be found hundreds or thousands of metres underground, which named salt caverns. In this second case, the water dissolves the salt before being pumped back to the surface. This procedure will be continue until the caverns are the right size and shape to store gas. As a result, a rapid response to short-term demand increases with mentioned facilities above.

Finally, Britain has three LNG import facilities (Dragon at Milford Haven, Pembrokeshire; Isle of Grain, Kent; and South Hook, Pembrokeshire), all of which are capable of meeting nearly 50% of annual demand together.

5.2 UK Renewable Energy

In recent years, interest in renewable energy in the UK has increased, resulting in a higher percentage of renewable electricity in the grid of the UK, as shown in

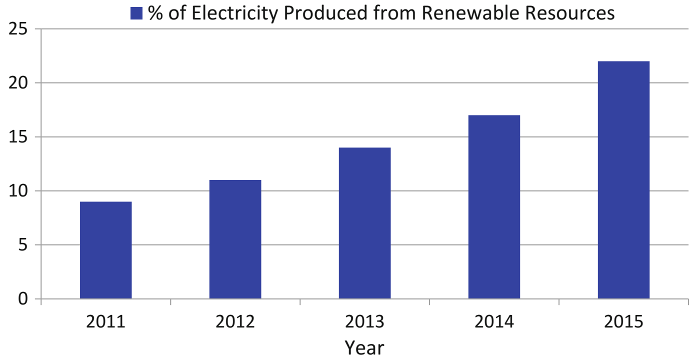

Fig. 17 Percentage of electricity produced from renewable sources in the UK, 2011–2015 [91]

Fig. 17. However, renewable heat and renewable energy use in the transport sector have also begun to become more widely considered in the last decade in the UK [90].

5.2.1 Wind Power

With respect to geographic and weather situations, the UK is considered to be the best location for wind power in Europe [92]. In 2015, electricity-generation in UK by wind power is 11% of other sources and 17% at the end of 2015 [93]. Onshore wind power is the cheapest form of energy in the United Kingdom, allowing for the costs of pollution [94]. In 2016, the UK supply more electricity form wind power than the coal [95].

5.2.2 Solar Power

In spite of cloudy weather, the United Kingdom is ranked sixth internationally in terms of total installed photovoltaic (PV) panel capacity, behind China, Germany, Japan, USA and Italy in 2015, thanks to the government's Feed-In Tariff (FIT) subsidy in 2010. In November 2016, there was a total installed capacity of 11.429 gigawatts (GWs) of solar power across the UK [96, 97].

5.2.3 Hydroelectricity

The interest in hydropower has been renewed in UK after the Renewable Obligation Certificate scheme (ROCs) and Feed in tariffs (FITs). Since 2012, hydroelectric power stations in the United Kingdom accounted for 1.65 GWs of installed electrical generating capacity, 1.8% of the UK's total generating capacity and 18% of the UK's renewable energy-generating capacity [98].

With respect to weather conditions, geographic situation and other economic impacts, other types of renewable energy in the UK (e.g., geothermal and biofuel) are negligible.

5.3 *Energy Scenarios in the UK*

The results and conclusions of the published reports show that, although achieving renewable energy growth, as described above, the UK continues to be mostly dependent on fossil fuels. The renewable energy only made up 25% of all UK electricity generated in 2015—this will rise as the UK aims to meet its EU target of generating 30% of its electricity from renewable sources by 2020, whereas most of the UK's electricity is produced by burning fossil fuels, mainly natural gas (30% in 2015) and coal (22%). Moreover, the National Grid will pay £122 m to keep coal and gas-fired plants on standby. Accordingly, it can be concluded that fossil energy will play a vital role in the future energy roadmap of the UK, even with its high rate of growth in regards renewable sources.

5.3.1 Short-Term Issues

A total of 39 billion barrels of oil and gas have been produced on the United Kingdom Continental Shelf (UKCS), with up to 25 billion barrels left. Therefore, the UK could continue to produce significant amounts of oil and gas. It is estimated that, in 2020, UK production could still meet 40% of the nation's demand for oil and gas in dealing with heating and electricity across the country [99].

In UK, the Electricity Market Reforming (EMR) is a short-lived policy to deliver low-carbon energy and reliable supplies, as needed by the UK with minimum costs to customers. The EMR uses two main mechanisms, including Contracts for Difference (CFD) and Capacity Market (CM). The former prepares long-term price stabilisation to low-carbon plants, permitting investment to come forward at a lower cost of capital and lower cost to consumers, whilst the latter provides a regular retainer payment to reliable forms of capacity, in return for such capacity being available when the system is tight [97].

5.3.2 Mid- and Long-Term Horizon

The upcoming challenges for energy and climate policy in the UK were reported by the Energy and Climate Change Select Committee on October 15, 2016. It recommended investment in energy storage on the supply side and efficient technologies that smooth-out demand peaks by switching devices off and running them at lower power during times of stress, for example [100, 101]. Many reports have been published on the future role of natural gas in the UK: the result makes it obvious that coal-to-gas replacement has already played a major role in reducing carbon emissions in the mid- and long-term in UK. In other words, in order to meet the commitment to reduce carbon emissions by 80% by 2050, the UK is already some way across the coal-to-gas ‘bridge’ [102, 103].

5.4 A STEEP Analysis

In this section, a STEEP analysis is performed in order to facilitate discussion on the political, economic, social, technological, environmental and legal aspects of natural gas in the UK in line with a sustainable energy future.

Regarding the energy overview in the UK, in regards the developed culture of optimised energy management and consumption and wide access to the modern energies, as well as the overall capability of the UK economy for expertise development in a wide range of renewable technologies due to the availability of facilities and manpower, the growth of the renewable energy as an alternative is predictable. However, there are a number of major barriers, such as strong population growth and an increasing demand for energy, as well as cold and unstable weather, that present gas-fired technology as the main source of energy in both short- and mid-terms. As such, when directing consideration to all of these factors, the main focus of the energy sector in the UK continues to be concentrated on oil and gas. However, due to a low number of available sources and global warming commitments, the UK should compete with potential markets and emerging economies, such as those of China and India, for oil and gas (Table 9).

5.4.1 Social Aspects

In order to achieve success in regards renewable energy as a solution to the world’s climate and environmental concerns, many infrastructures, social responsibilities, and the systematic corporation of people are required. With this noted, the construction and operation of the form of energy have many environmental and social implications. The greater the use of renewable energy, the greater the focus on sustainability credentials, which, in turn, results in sustainability and social responsibilities and increased renewable energy costs.

The other social factor that should be considered is the population and its associated factors, such as distribution, composition, dynamics and growth. The UK resident population is currently 65.3 million, which is seen to have grown by 6% compared with previous figures of 61.38 million in 2008 and 7.7% compared with 60.24 million in 2005. On the one hand, this strong population growth plays an important role in the increasing demand for renewable energy; on the other hand, a growing population can also act as a challenge for the industry to continue to provide a good service with the aim to reduce carbon emissions, and further highlights the active role of gas-fired energy in the UK future roadmap.

Table 9 STEEP analysis for natural gas as a possible transition energy source for UK

Term	Enabler	Barrier
Social	• Developed culture for optimised energy management and consumption • Wide access to modern energy	• Strong population growth and increasing demand for energy • Growing pressure for reducing emission from its own population
Technological	• The UK economy is capable of developing expertise in a wide range of renewable technologies due to the availability of facilities and manpower	• Lack of appropriate skills compatibility • The required infrastructures which needs a huge investment to come by
Economic	• The UK government is currently working on creation of interesting investment opportunities for the investors	• Unemployment which is a direct consequence of economic meltdown
Environment	• Target for the UK to reduce its greenhouse gas (GHG) emissions by at least 80% from 1990 levels by 2050	• Cold and unstable weather results in high consumption
Political	• To reduce import bill • Short- and mid-term, the main focus of the energy sector in the UK will be concentrated on oil and gas in the main	• Low available sources the global warming and commitment to reducing carbon gas emissions • UK should compete the potential markets with emerging economies like China and India for its oil and gas

5.4.2 Technological Aspects

When searching the current situation of renewable energy in UK, it is obvious that wind power consisted of 6546 wind turbines, with a total installed capacity of just under 12 GWs: 7950 MWs of onshore capacity and 4049 MWs of offshore capacity [104, 105]. In addition, solar power use has increased quickly in recent years as a result of reductions in the costs of photovoltaic (PV) panels combined with the introduction of a Feed-In Tariff (FIT) subsidy in April 2010 [106]. By February 2012, the installed capacity had reached 1000 MWs, and the government stated that 4 million homes across the UK would be powered by the sun within eight years, representing 22,000 MWs of installed solar power capacity by 2020 [107, 108].

The main technical issue in expanding the renewable energy sector is the ability to cope with a need for people and industries with appropriate skills compatible with renewable energy elements. For instance, there have been reports of shortages of turbine blades, meaning wind-farm development is restricted [109]. However, various skills from the oil and gas sectors can be readily transferred to the renewable energy sector. To clarify this, a brief SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis would be considered valuable.

In terms of strengths, renewable energy is one of the best alternatives for dealing with the issue of global warming so as to reduce carbon emissions to as low as possible. In this regard, renewable energy already benefits £485 million a year through the Renewable Obligation, and plans are in focus to offer further subsidies through amendments to electricity bills.

Regarding opportunities, the UK economy is capable of developing expertise in a wide range of renewable technologies due to the availability of facilities and manpower. This will drive the industry into maturity from which economy of scale can be achieved.

In terms of threats, recent reports state that some large energy companies have made the decision to curtail investment in renewable energy in certain regions and technologies, with more interesting opportunities (not necessarily in renewable energy) to be seen outside of the UK. However, other experts suggest that the replacement of the UK's ageing nuclear power stations with new nuclear power stations poses a serious threat to the future of renewable energy because they have very low carbon emissions and represent a perfect substitute to renewable energy in this respect.

Finally, in consideration to the weaknesses, the main issue is the infrastructure that would be required, which would necessitate significant investment. Investors are finding it very difficult to obtain much-needed funds from banks owing to the recession. Another point is that renewable energy is more expensive in the short-run when compared with other types of conventional energy source. This issue, combined with the shortage of equipment, such as in the wind farm power sector, for instance, also hinders the development of renewable energy.

5.4.3 Economic Factors

The Gross Domestic Product (GDP) in the UK has demonstrated an increase between 2005 and 2008, but a decline of 4.8% was seen in annual chain-linked GDP in 2009, which resulted in a below-the-growth GDP forecast for the period 2009–2013 (in other words, growth fell steeply to −4.2% in 2009, followed by a slow recovery to 2.6% in 2013). Lower GDP will affect renewable energy demand; however, in regards the point that the government has put in place several incentives to attract private investors in a bid, it is expected that the demand for renewable energy will continue to increase over the years to 2020 so as to facilitate the supply of the equivalent of nearly all 26 million homes in the UK. For this purpose, the UK government is currently working on creating interesting investment opportunities for investors in the renewable energy sector to implement its leas scenario to cover more than 30% of UK electricity needs with the use of renewable sources (mostly from wind power) by 2020. However, 70% of UK electricity needs will continue to rely on non-renewable sources, which provides clear confirmation as to the important role of gas-fired energy in the future of the energy policy in the UK.

The other important economic variable is unemployment, which is a direct consequence of economic meltdown. UK unemployment rose from 860,000 in 2005 to 910,000 in 2008, before suffering a huge rise of 68.1% to reach 1.5 million in 2009, and it will be expected to rise again in coming years [109]. Higher unemployment results in fewer people at work, which means lower energy consumption in the workplace and an increase of energy usage in domestic settings during periods of cold weather.

5.4.4 Environmental Aspects

Reduction of 80% of greenhouse gas (GHG) from 1990 by 2050 is a target of UK Climate Change Act 2008. Approximately 29% of GHG emission in UK was produced by energy supply sectors in 2015. This is a main result to switch fuels from coal to gas, with coal-fired power-generation demonstrating a decrease by 63% between 1990 and 2015. On the other hand, renewable generation in UK has played an important role in GHG emission reductions. In 2015, 23% of electricity supply mix in UK belongs to renewable sources [109].

5.4.5 Political Factors

With respect to the low available resources, the import of oil and gas in the UK is increasing. Currently, the UK should compete the potential markets with emerging economies, such as China and India, for its oil and gas. It could be a challenge for the UK to maintain a good relationship with such countries due to the different cultures and political structures. In other words, energy supply could prove to be a political issue for the UK in the future, which requires attention. This could be why the UK government is thinking of more political support on the renewable energy sector in the future as an alternative to heavy reliance on the importance of oil and gas [110].

Moreover, global warming and commitment to reducing carbon gas emissions is another important factor affecting the political decisions of the government. Although switching to renewable energy is vital for long-term strategic plans, renewable obligation requires providers to supply a specific amount of energy from renewable sources, which is not affordable at the present time, even with respect to the fact that the UK has almost 30 different low-carbon energy incentives in the form of tax credits and subsidies. As such, for the short- and mid-term, the main focus of the energy sector in the UK will be concentrated on oil and gas.

6 Concluding Remarks

The transition to a sustainable energy future is a global challenge, but needs to be nationally acted upon in order to achieve a necessary goal. Therefore, it is necessary to understand local challenges and sentiments so as to facilitate navigating through suitable local solutions, taking into account resource endowment, infrastructures, socio-economic aspects, as well as the local/national political choice for energy policies. It needs to be acknowledged that there is no one solution that fits all, and tailor-made solutions for different circumstances need to be considered.

The case studies presented in this article compare four different countries, i.e. industrially advanced vs developing economies, and being a net exporter or importer of oil and gas. The case studies illuminate the fact that final choices and approaches might look very different, but all, in essence, are targeting a long-term carbon free/carbon-neutral future energy solution through a mid-term low-carbon solution. Certain facts and figures were presented and compared with one another (in the form of tables or graphs), enabling a conclusion to be drawn that shows certain things as being general and in common, whilst also highlighting those elements that are specific to one or another country under study. Furthermore, a comparison table for each region under analysis was made in terms of Social, Technological, Economical, Environmental and Political issues. Discussions and studies indicated that the future of energy policies are case-dependent and should be defined separately and precisely for each region in respect to its own resources, current situation, and future goals. In other words, what the study has shown is that natural gas might play very different roles in different countries/regions. It will not be big in Norway, there are many challenges in India, more NG will be detrimental to climate change in Iran, and, finally, natural gas prospects are at least debatable given the new nuclear and rapid growth of renewables in the UK. More specifically:

- For Norway, having NG resources but very limited gas grid and no acceptance for increased gas use, hoping that other nations will continue using gas so that they can export their own gas, investing in CCS research, especially from gas-fired units, hoping to maintain their market share. Nevertheless, Norway's production has, on average, low GHG production emissions compared to other producing offshore fields [65].
- For India, gas network investments are a significant challenge, despite recognising the coal replacement opportunities and CO_2 reduction, but there are fears concerning becoming dependent on gas imports.
- For Iran, having large resources and well-developed infrastructure, improved efficiency is a major goal in the need to reduce consumption and emissions, with the installation of distributed power potentially contributing.
- For the UK, gas infrastructure in place but 'reduced own gas production', the potential for unconventional gas but no acceptance in place, aiming at policy measures to replace the current gas-based heating and thereby reduced CO_2 emissions.

Hence, the future energy mix is more open and uncertain than ever before. Unexpected movements could also be mentioned and discussed in conclusion so that national policies and strategies can be changed/adapted every 5–10 years.

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Role of Carbon Capture and Storage in Meeting the Climate Mitigation Target

Pratik Dutta

Abstract Scientific studies over the years have clearly indicated warming of global climate due to rising concentration of anthropogenic greenhouse gas emissions. Continued emissions are certain to lead to catastrophic consequence. Deliberating on this very important issue of sustainability of the entire earth for a long period, the global community finally reached consensus during the Paris Climate Agreement in 2015 to limit the temperature rise to 2 °C by 2050 and even try to achieve a lower temperature rise. Amongst other options like adoption of renewables on a much larger scale, fuel switching, and increasing power system efficiency; carbon capture and storage is perceived to be another feasible option for meeting this global climate mitigation target. Carbon capture and storage (CCS) essentially means chemically capturing CO_2 from power plants running on fossil fuels, especially coal, transport and then store it permanently in some geological formation beneath the earth. As per the estimate of International Energy Agency, 12% of the total greenhouse gas emissions totaling about 94 Gt of cumulative CO_2 emissions have to be stored into the subsurface geological formations up to 2050. Considerable research and development work backed by experience gained through demonstration and commercial projects, the technology is mature now. Although the first CCS project commenced operation more than twenty years back, the progress has been slow over the years due to many techno-economical factors and other policy issues. However, in the recent years, there has been significant progress in actual deployment of the technology with more than 21 large-scale running projects and projects under advanced construction. Furthermore, a number of projects are in the pipeline. The total installed capacity of all these projects is approximately 70 Mt of CO_2 per year. Although CCS is a proven technology now, notwithstanding the recent growth in deployment, the rate of adoption is still not in track to meet the global target set for 2050.

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1 Introduction

1.1 Global Warming and Rising CO_2 Concentration

A series of scientific studies over the last few decades have consistently pointed towards warming of the environment due to anthropogenic greenhouse gas (GHG) emissions. The major source of greenhouse gas is CO_2 emission from usage of fossil fuels. In the nineteenth century French physicist Joseph Fourier and Irish physicist John Tyndall first described the earth's natural "greenhouse effect" due to the existence of water vapor and a few other gases. A few years later, Swedish chemist Svante Arrhenius predicted that industrial-age coal burning would enhance this natural greenhouse effect. However, they said that this effect might be beneficial for future generations. The first evidence of rising global temperature came in 1938 when British engineer Guy Callendar collated records from 147 weather stations to show that the global temperature had risen over the previous century. He also showed a corresponding rise in CO_2 concentration over the same period and suggested that this rise in CO_2 concentration might be the cause of warming. However, Charles David Keeling gave the first unequivocal proof of rise in CO_2 concentration in 1958 when he systematically measured atmospheric CO_2 for four years at Mauna Loa in Hawaii and in Antarctica. Continued recordings at Mauna Loa indicated that half a century after the first recording, the CO_2 concentration had risen from 315 to 380 ppm in 2008 and then to over 400 ppm in 2012 [1]. Satellite images captured over the last few decades clearly show reduction in ice cover over the Arctic. A very disturbing trend emerged from the data collated by National Snow & Ice Data Center (NSIDC) on sea ice cover and depicted in Fig. 1, which shows that for the first time in the history of data recording since 1978, the sea ice cover did not grow during September–November in 2016.

1.2 Global Warming and International Actions

A US President's Advisory Committee panel in 1965 indicated that greenhouse effect is a matter of "real concern". But, the series of international environment conferences, starting from Stockholm in 1972 to Montreal in 1987, did not explicitly address the global climate change issue until the formation of Intergovernmental Panel on Climate Change (IPCC) in 1988. Following the first assessment report of IPCC released in 1990, which indicated a rise in global temperature by 0.3°–0.6 °C over the last century due to anthropogenic emission, the governments agreed on the United Nations Framework Convention on Climate Change (UNFCCC) during the Earth Summit at Rio in 1992 "stabilizations of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". Since then, IPCC have come up with a series of assessment reports. The latest one, the fifth

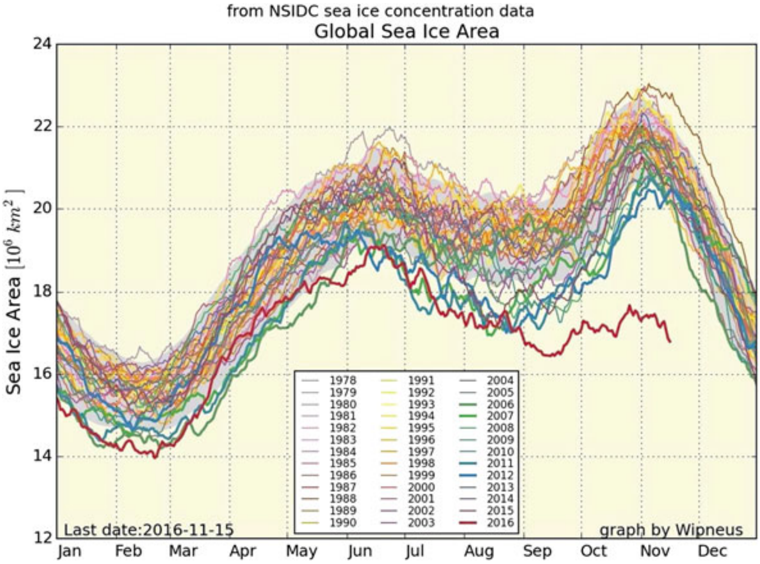

Fig. 1 Global sea ice variation statistics from 1978 to 2016 [2]

assessment report, was released in 2013. In between, a number of international negotiations took place starting from the Kyoto Protocol in 1997 to the UN Mexico summit in 2010 for reaching to a consensus on taking definitive actions for limiting global warming. Some positive actions were definitely observed but international politics and compulsions back home prevented some of the largest GHG emitting countries in the world in agreeing and coming to common platform, which might lead to result-oriented actions.

IPCC fifth assessment report (AR5), the latest in the series of IPCC reports, highlights the changes in earth's environment, trends in global greenhouse gas emissions, and the likely consequences of further warming. Following are some of the excerpts from the report [3]:

- Earth's surface was found to be successively warmer during the last three decades and the warmest 30-year period of the last 1400 years in the Northern Hemisphere was the period between 1883 and 2012. Based on globally averaged combined land and ocean surface temperature data, warming of 0.85 °C was recorded over the period 1880–2012.
- The rate of mass loss at the Greenland and Antarctic ice sheets is much larger over 2002–2011 compared to the corresponding 20-year period of 1992–2001. Glaciers have continued to shrink almost worldwide. In response to increased surface temperature and changing snow cover, it is very likely that permafrost temperatures have increased in most regions since the early 1980s.
- Between 1901 and 2010, the global mean sea level rose by 0.19 m.

- Large increases in the atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) have resulted due to anthropogenic GHG emissions between 1750 and 2011. Cumulative anthropogenic CO_2 emissions during the period to the atmosphere were 2040 ± 310 $GtCO_2$. Out of this, about 40% of the emissions have remained in the atmosphere (880 ± 35 $GtCO_2$). The rest was removed naturally from the atmosphere and stored in land and in the ocean. About 50% of the anthropogenic CO_2 emissions have occurred in the last 40 years.
- Despite a growing number of climate change mitigation policies total anthropogenic GHG emissions have continued to increase over the last three decades, which has reached 49 ± 4.5 $GtCO_2$-eq/year in 2010. Out of this, fossil fuel combustion and industrial processes contributed about 78% of the total GHG emissions increase from 1970 to 2010.
- Unless substantial efforts are undertaken to reduce GHG emissions beyond those in place, growth in global population and economic activities will lead to persistent growth in emissions, which may result in 3.7–4.8 °C global mean surface temperature increase in 2100 from compared to pre-industrial levels.
- To limit the rise in temperature to 2 °C relative to pre-industrial levels, the maximum allowable atmospheric concentrations is about 450 ppm CO_2 equivalent. For this to happen, cumulative CO_2 emissions from all anthropogenic sources since 1870 should remain below about 2900 $GtCO_{2.}$ Out of this, the cumulative emission by 2011 is about 1900 $GtCO_2$.

Under UNFCCC a landmark agreement was reached at the 21st conference of parties (COP21) in Paris in December 2015 between all the participating countries [4]. It could well be a turning point is fighting global climate change, which states "holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change." To achieve that goal, countries should "reach global peaking of greenhouse gas emissions as soon as possible, recognizing that peaking will take longer for developing country parties, and to undertake rapid reductions thereafter."

2 Carbon Capture and Storage Technology

2.1 Need for Carbon Capture and Storage

It is quite evident from the discussion in the last section that stabilizing the global climate would require large-scale effort to reduce anthropogenic GHG emissions. The most effective process to achieve this would be to completely stop burning of fossil fuels as soon as possible. Significant progress has been made towards adoption of alternate and renewable energy and the world will continue to strive for zero carbon emission. However, it is quite likely that fossil fuels will continue to burn for power generation and other industrial processes in the next decades to come. In this context, ‘carbon capture and storage’ (CCS) or carbon sequestration, a technology that prevents release of large amounts of CO_2 into the atmosphere generated through burning of fossil fuels, becomes important. CCS involves chemically capturing CO_2 from the flue gas of large industrial plants, compressing it for transportation, and then injecting into subsurface rock formations for permanent storage.

2.2 *Carbon Capture*

Capturing CO_2 is the first step in carbon capture and storage, which can be applied to large-scale emission sources like fossil fuel-fired power generation, natural gas processing, fertiliser production, manufacturing of industrial materials such as cement, iron and steel etc. Large-scale capture technologies have been operational at in the natural gas and fertiliser industries for quite some time and have recently been tried in the power sector. Three basic types of CO_2 capture; pre-combustion, post-combustion and oxyfuel with post-combustion have been practised. Pre-combustion capture process involves conversion of fuel into a gaseous mixture of hydrogen and CO_2. The hydrogen is then separated and burnt with no production of CO_2. The remaining CO_2 is compressed for transport and storage. The process is relatively more complex than post-combustion, which make the technology almost impossible to apply to existing power plants but is used in natural gas processing. Post-combustion capture process separates CO_2 from flue gas. CO_2 is captured using a liquid solvent or by employing other separation methods. In the absorption-based approach, the absorbed CO_2 in the solvent once absorbed by the solvent is released by heating to form a high purity CO_2 stream. This technology is widely used to capture CO_2 for subsequent use mainly in the food and beverage industry. In oxyfuel combustion process, oxygen is used in place of air for combustion of fuel. The combustion produces exhaust gas comprising primarily of water vapour and CO_2, can be easily separated to produce a high purity CO_2 stream.

2.3 *Geological CO_2 Storage*

Geological storage involves injection of captured CO_2 into deep subsurface rock formations, thereby preventing it from being released into the atmosphere. Many subsurface geological systems exist in the world, which can retain centuries’ worth of CO_2 captured from industrial processes. Based on the current status of technology, the following primary geological formations, as depicted in Fig. 2, can be the potential targets for storage.

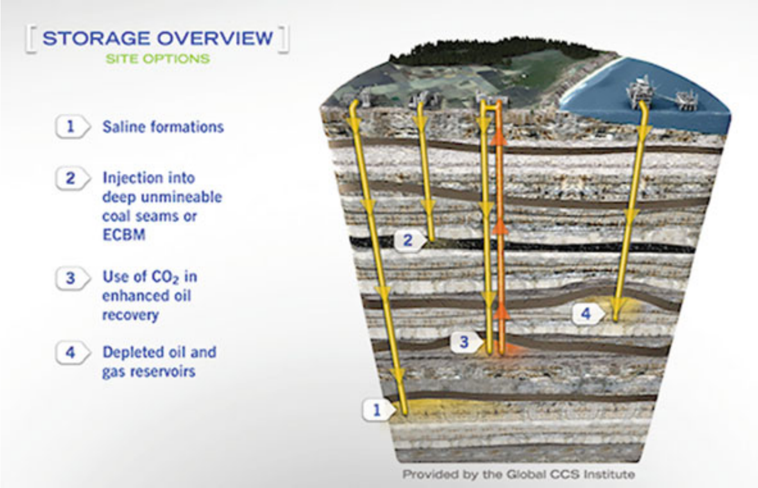

Fig. 2 Sites for geological CO_2 storage. *Source* www.globalccsinstitue.com

2.3.1 Saline Formations

Deep saline formations are the rock layers that bear non-potable saline water. The salinity of water may range from slightly brackish to a few times than the salinity of seawater. Only the formations, which are overlain by an impervious cap rock are suitable sites for permanent storage. Geological storage of CO_2 takes place through a combination of mechanisms, which include physical and chemical trapping. The process takes place over a large range of time and scale [5]. Physical trapping involves immobilization of CO_2 as free gas or supercritical fluid. There are two types of physical trapping mechanisms. The first one, known as static trapping, occurs in stratigraphic and structural traps. The other mechanism, known as residual trapping, takes place in the pores at residual gas saturation. When CO_2 dissolves in subsurface fluids, chemical trapping occurs, and finally the trapped CO_2 may induce chemical reactions with the rock matrix leading to mineral trapping. Under favorable circumstances, trapped CO_2 may continue migrating up within the subsurface at extremely low velocity. As a consequence, it would take tens of thousands to millions of years for the CO_2 to potentially reach the surface [6]. Theoretically, saline aquifers have the largest storage capacity of all geological sites and currently a number of CCS projects in saline aquifers are in operation.

2.3.2 Deep Unmineable Coal Beds

Methane gas is found abundantly in coal beds, where methane molecules are stored in the coal micropores in adsorbed form. This methane gas is extracted from the coal beds, known as coalbed methane (CBM), is an important source of natural gas worldwide. However, coal has much higher adsorption affinity to CO_2 than methane. When CO_2 is injected into coal beds that are too deep or uneconomic for mining presents distinct advantages. First, CO_2 is adsorbed into the coal leading to permanent storage. Second, adsorbed CO_2 molecules replace methane molecules from the adsorption site leading to additional methane release, the process known as enhanced coalbed methane (ECBM) recovery. Although methane is also a greenhouse has, it is much cleaner than coal and can be burnt in place of coal leading to much lower CO_2 emission. A number of pilot projects have been taken up for CCS in coal beds and ECBM recovery. This includes Alison unit in USA, Fenn Big Valley in Canada, Qinshui basin in China, Yubari in Japan, and Recopol in Poland. However, the general observation from these pilots is that CO_2 injection leads to lowering of permeability of coal, which seriously affects the gas flow process. The science of CO_2-coal interaction is yet to be adequately developed and the immediate scientific challenge for success of this process is to develop ways for overcoming this loss of permeability in coal beds. As a consequence, although regarded as a value-added option for CCS with the promise of additional methane recovery from the coal beds, no large-scale CCS projects in coal beds have been taken up till date.

2.3.3 Oil and Gas Reservoirs

Oil and gas reservoirs can store CO_2 under two different circumstances. There are many oil and gas fields, where major parts of the available hydrocarbon reserves have been extracted and the operations are no more viable. These depleted oil and gas reservoirs offer potential sites for CO_2 storage. The injected CO_2 gas can stay in the reservoir rock formation the same way the hydrocarbon has been staying there for millions of years. In the operating oil and gas fields, when the reservoir pressure becomes low to prevent free flow of oil into the well, injection of a miscible fluid like CO_2 can alter density and viscosity of the fluid resulting in easier flow of fluid from the reservoir to the well. This process is known as enhanced oil recovery (EOR). EOR has been practiced for several decades in the petroleum industry. But with increasing focus on combating climate change and CCS coming to the forefront as an emission mitigation option, greater attention is being paid to the potential for CO_2-EOR as a tool to support geological CO_2 storage. CO_2-EOR practices can be modified to deliver significant capacity for long-term CO_2 storage.

2.3.4 Bio-CCS

A more recent addition to CCS technology is bio-CCS, where a CCS project is combined with an industrial facility burning biomass for energy generation or consuming biomass as part of the process (e.g., Ethanol plants). In bio-sequestration, which is a part of natural carbon cycle, plants absorb CO_2 from the atmosphere and use this CO_2 for growth. In the industrial facilities burning or processing biomass the CO_2 is released back into the atmosphere. Therefore, energy production from biomass can be treated as 'carbon neutral', as it absorbs the CO_2 but then releases it back into the atmosphere upon combustion or processing. However, when CO_2 from the combustion or processing of the biomass is captured and then stored in geological formations instead of being released into the atmosphere, there may be net removal of CO_2 from the atmosphere, resulting in negative emission.

2.4 Global CO_2 Storage Capacity

Both onshore and offshore sedimentary basins with potential for CO_2 storage exist throughout the world. The estimates of the technical potential for different geological storage options are given in Table 1 [5]. These estimates and the associated uncertainties are based on assessment of literature and include both of regional bottom-up and global top-down estimates. Needless to say that in the absence of detailed assessment, these overall estimates vary widely with high degree of uncertainty. This is mainly due to the fact that detailed knowledge of saline formations is quite limited in most parts of the world. For oil and gas reservoirs, however, uncertainty is the estimate is relatively less, as this is based on the calculation involving replacement of original hydrocarbon volumes with CO_2 volumes. It should be noted that, with the exception of EOR, all these reservoirs would not be available for CO_2 storage until the depletion of hydrocarbons. Furthermore, pressure changes and geomechanical effects due to hydrocarbon production in the reservoir may reduce available capacity.

3 Status of CCS Deployment

The concepts of capture of anthropogenic CO_2 and geological storage as a greenhouse gas mitigation option first came in the seventies, but the idea gained credibility in the nineties through a series of research projects. The subsurface disposal of acid gas (a by-product of oil production with up to 98% CO_2) in some oilfields of North America provided additional useful experience. By the late 1990s, a number of privately and publicly funded research programs were underway in North

Table 1 Storage capacity of various geological storage options [5]

Sink type	Lower estimate (Gt CO_2)	Upper estimate (Gt CO_2)
Oil and gas reservoirs	675	900
Deep unmineable coal seams	3–15	200
Saline formations	1000	Possibly 10^4

America, Japan, Europe, and Australia. Consequently, a few oil companies exploring geological storage as a mitigation option in gas fields with high natural CO_2 content. The projects included Natuna in Indonesia, In Salah in Algeria, and Gorgon in Australia. The world's first large-scale CO_2 storage project (1 $MtCO_2$ per year) was initiated in 1996 by Statoil at the Sleipner Gas Field in the North Sea. Since then, as the level of confidence in the technology increased through successful operation of demonstration and full-scale projects, geological storage of CO_2 has grown from a novel concept to one that is increasingly regarded as a potentially important and practically implementable mitigation option.

Currently, there are 21 large-scale CCS projects in operation or under construction throughout the globe [7]. The list of these projects is given in Table 2 and location of some key CCS projects is shown in Fig. 3 [8]. These 21 projects have capacity to capture around 37 million tonnes of CO_2 per annum (Mtpa). Furthermore, as given in Table 2, there are seven more projects in the advanced deployment stage with a total CO_2 capture capacity of around 8 Mtpa. The growth from 10 large-scale operational projects to the current 21 has taken place over the last decade. A further 11 large-scale CCS projects, shown in Table 3, are in early stages of development planning (the Evaluate and Identify stages) with a total CO_2 capture capacity of around 21 Mtpa [8]. Highlights of some key CCS projects are as follows.

- The Sleipner CO_2 Storage facility was the first in the world to inject CO_2 into a dedicated geological storage setting. The Sleipner facility, located offshore Norway, has captured CO_2 as part of the Sleipner area gas development since 1996. The captured CO_2 is directly injected into an offshore sandstone reservoir. Approximately 0.85 million tonnes of CO_2 is injected per annum and over 16.5 million tonnes have been injected since inception to January 2017.
- The Great Plains Synfuels plant, located in North Dakota, produces high purity CO_2 as part of its coal gasification process. Carbon dioxide capture capacity of the plant is approximately 3 Mtpa. The captured CO_2 is transported via pipeline to the Weyburn and Midale Oil Units in Saskatchewan, Canada, for use in enhanced oil recovery. Around 35 million tonnes of CO_2 has been captured and transported to date.
- Petra Nova Carbon Capture, operational since January 2017, is the world's largest post-combustion CO_2 capture system presently in operation. Production unit 8 of the W. A. Parish power plant near Houston, Texas, was retrofitted with a 1.4 Mtpa post-combustion CO_2 capture facility. The captured CO_2 is transported via pipeline to an oil field near Houston for enhanced oil recovery.
- Abu Dhabi CCS Project, the world's first application of CCS to iron and steel production, was launched on 5 November 2016. The project captures approximately 0.8 Mtpa of CO_2 from ESI plant in Abu Dhabi and used for enhanced oil recovery.
- Illinois Industrial Carbon Capture and Storage Project is the world's first large-scale bio-CCS project with capacity of 1 Mpta. This is also the first CCS project in the US with storage of CO_2 into deep saline formation.

Table 2 Large scale CCS projects under operation, construction, and advanced deployment

Project name	Country	Operation date	Capacity (Mtpa)	Storage type
In operation				
Terrel Natural Gas Processing Plant	US	1972	0.4-0.5	EOR
Enid Fertlizer	US	1982	0.7	EOR
Shute Creek Gas Processing Plant	US	1988	7.0	EOR
Sleipner CO_2 Storage	Norway	1996	1.0	Dedicated geological storage
Great Plains Synfuels Plant and WeyburnMidale	Canada	2000	3.0	EOR
Snohvit CO_2 Storage	Norway	2008	0.7	Dedicated geological storage
Century Plant	US	2010	8.4	EOR
Air Products Steam Methane Reformer	US	2013	1.0	EOR
Coffyville Gasification Plant	US	2013	1.0	EOR
Lost Cabin Gas Plant	US	2013	0.9	EOR
Petrobas Santos Basin Pre-Salt Oil Field CCS	Brazil	2013	1.0	EOR
Boundary Dam CCS	Canada	2014	1.0	EOR
Quest	Canada	2015	1.0	Dedicated geological storage
Uthmaniyah CO_2-EOR Demonstration	Saudi Arabia	2015	0.8	EOR
Abu Dhabi CCS	UAE	2016	0.8	EOR
Illinois Industrial CCS	US	2017	1.0	Dedicated geological storage
Petro Nova Carbon Capture	US	2017	1.4	EOR
In construction				
Gorgon CO_2 Injection	Australia	2017	3.4–4.0	Dedicated geological storage
Alberta Carbon Trunk Line with Agrium CO_2 Stream	Canada	2018	0.3–0.6	EOR
Alberta Carbon Trunk Line with North West Strugeon Refinery CO_2 Stream	Canada	2018	1.2–1.4	EOR
Yanchang Integrated CCS Demonstration	China	2018	0.4	EOR

(continued)

Table 2 (continued)

Project name	Country	Operation date	Capacity (Mtpa)	Storage type
Advanced deployment				
Sinopec Qilu Petrochemical CCS	China	2019	0.5	EOR
Rotterdam Opslag en Afsvang Demonstration Project	Netherlands	2019–20	1.1	Dedicated geological storage
CarbonNet	Australia	2020s	1.0–5.0	Dedicated geological storage
Sinopec Shengli Power Plant CCS	China	2020s	1.0	EOR
Lake Charles Methanol	US	2021	4.2	EOR
Texas Clean Energy Project	US	2021	1.5–2.0	EOR
Norway Full Chain CCS	Norway	2022	1.3	Dedicated geological storage

- Quest, located in Alberta, Canada, retrofitted CO_2 capture facilities to three steam methane reformers at the existing Scotford Upgrader. Launched in 2015, Quest has the capacity to capture approximately 1 Mtpa of CO_2. The captured CO_2 is transported via pipeline to the storage site for dedicated geological storage.
- Yanchang Integrated CCS is an industrial CCS development located in Yulin City, Shaanxi Province, China. Yanchang Petroleum, through affiliates, is developing CO_2 capture facilities at two coal-to-chemicals plants. The smaller scale capture source of 0.05 Mtpa CO_2 capture capacity has been in operation since 2012, while the larger CO_2 source of 0.36 Mtpa CO_2 is currently in construction and may be operational by the end of 2018. Captured CO_2 would be used for enhanced oil recovery in oil fields in the Ordos Basin in central China.
- CarbonNet is working on the potential to establish a commercial scale CCS network. It would involve bringing together multiple CO_2 capture projects in Victoria's Latrobe Valley, transporting the CO_2 via pipeline and injecting deep into offshore underground storage sites in the Gippsland region. It plans an initial capacity to capture, transport and store in the range of 1–5 Mtpa of CO_2 during the 2020s.

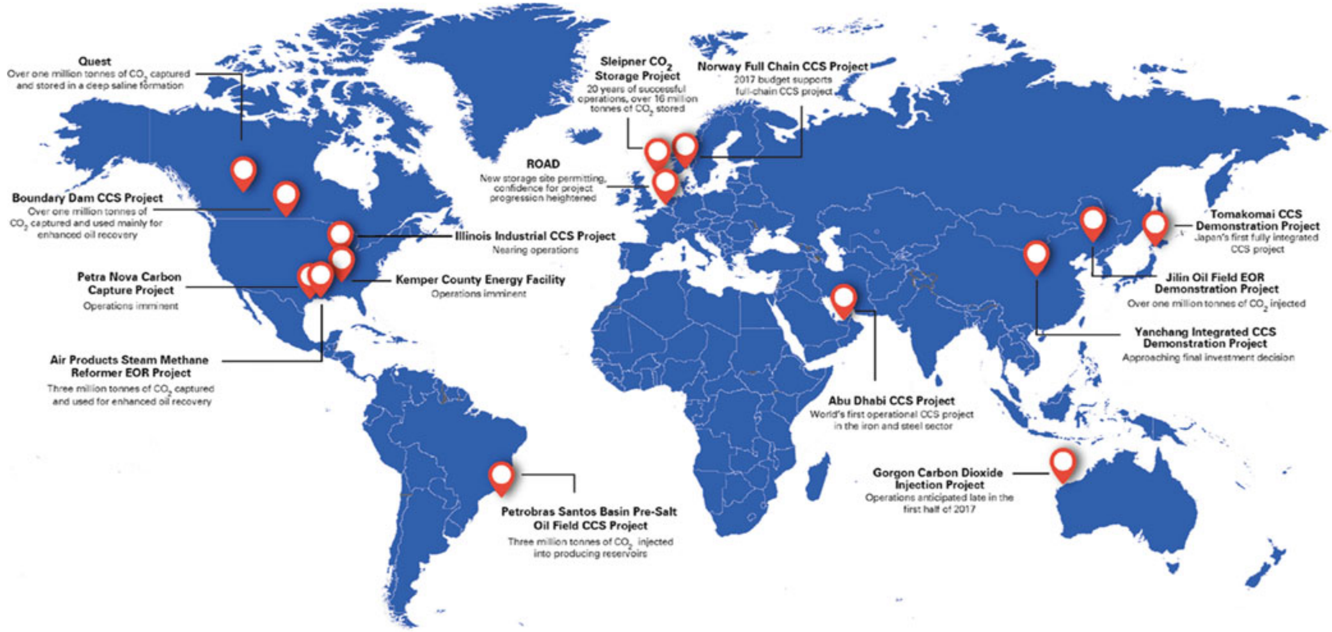

Fig. 3 Location of some key CCS projects [7]

Table 3 CCS projects under early deployment

Project name	Country	Operation date	Capacity (Mtpa)	Storage type
Riley Ridge Gas Plant	US	2020	2.5	EOR
Sinopec Eastern China CCS	China	2020	0.5	EOR
China Resources Power Integrated CCS Demonstration Project	China	2020s	1.0	Dedicated geological storage
HuanengGreenGen IGCC Large-Scale System	China	2020s	2.0	EOR
Korea CCS-1	South Korea	2020s	1.0	Dedicated geological storage
Korea CCS-2	South Korea	2020s	1.0	Dedicated geological storage
Shanxi International Energy Group CCS	China	2020s	2.0	Not specified
Shenhua Ningxia CTL	China	2020s	2.0	Not specified
Teesside Collective	UK	2020s	0.8	Dedicated geological storage
Caledona Clean Energy	UK	2022	3.8	Dedicated geological storage
South West Hub	Australia	2025	2.5	Dedicated geological storage

4 Future of CCS

4.1 Estimated Future Contribution of CCS

As detailed in Sect. 1.2, as per the Paris agreement, an ambitious target was set to keep the temperature rise to “well below 2 °C” and also to continue efforts towards 1.5 °C. Substantial efforts will be required to deploy all low-emissions technologies as rapidly and extensively as possible, which would include adoption of large-scale CCS projects. So far the use of fossil fuels in power generation and industrial processes is concerned, CCS remains the only technology solution capable of delivering significant emissions reduction from these sources. In the 2005 IPCC Special Report on CCS the climate experts recognized the role of CCS in constraining future temperature increase [5]. This recognition continued to gather support and subsequently, the IPCC Fifth Assessment Report (AR5), published in 2014, highlighted that the availability of CCS and bioenergy with CCS (BECCS) will be “critical in the context of the timing of emissions reductions” [3]. The AR5 also indicated that it would be difficult to limit atmospheric concentrations to about 450 parts per million (ppm) CO_2-equivalent, which corresponds to the temperature increases of around 2 °C, with limited deployment of CCS.

The role of different options for limiting the temperature rise to 2 °C (2DS) from the "no action" scenario of 6 °C (6 DS) temperature rise, as assessed by the International Energy Agency (IEA), are shown in Figs. 4 and 5 [9]. A portfolio of technologies need to deployed for meeting the target. This will include renewables, increased efficiency, nuclear, fuel switching, and CCS. In the 2 °C scenario (2DS), CCS including negative emissions from BECCS needs to deliver 94 Gt of cumulative CO_2 emission reduction during the period 2013 to 2050. CO_2 reduction through CCS amounts to 12% of the required cumulative CO_2 emission reductions compared to 32% by renewables, 10% by fuel switching, and 38% by increasing end-use efficiency. The 94 Gt of CO_2 captured and stored by CCS through 2050 under the 2DS comprises, shown in Fig. 5, include emissions from all sources. Out of this total capture, power sector needs to account for the majority, which stands at 52 $GtCO_2$ or 55% of the total CO_2 capture. Roughly 29 $GtCO_2$ or 31% of the total needs to be captured from the industries like production of chemicals (38%), iron and steel (33%) and cement (29%). The remainder (about 13 $GtCO_2$) would need to be captured from biofuel production and gas processing [9].

As the net balance of emissions during the later half of the century is warranted, negative emissions from bio-CCS (BECCS) would assume increased importance. The role of negative emissions in achieving more ambitious climate targets was analysed in the IPCC AR5 and is now receiving more attention following Paris. BECCS is the most mature of the negative emission technology options and could generate as much as 10 $GtCO_2$ of negative emissions per year [9]. The world's first large-scale BECCS project, the Illinois Basin Decatur Project in the United States,

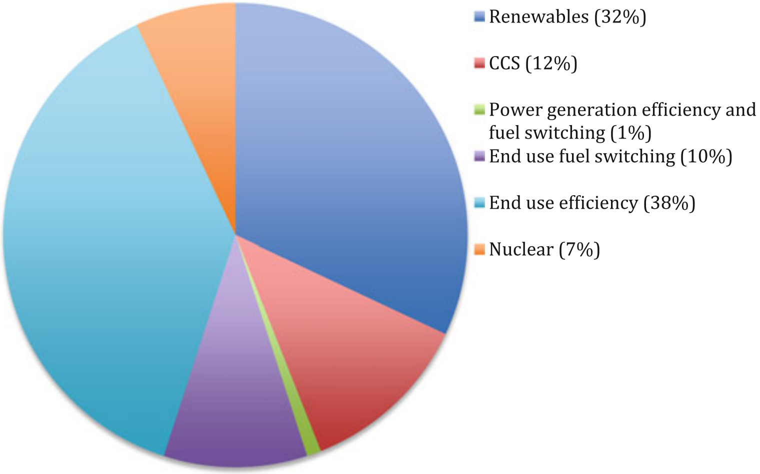

Fig. 4 Contribution of different low emission technologies to global emission reduction

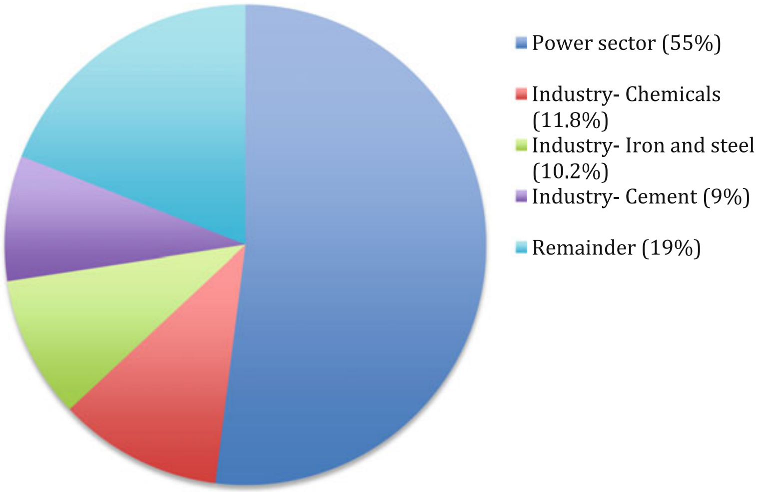

Fig. 5 Sources of CO_2 capture under 2 DS scenario

is in the process of commissioning, which is designed to capture 1 $MtCO_2$ per year from a bio-ethanol plant. However, there are many technical, economic and social challenges associated with the technology that needs to be addressed for wider scale deployment of BECCS. Of particular importance are the availability of sustainable biomass and access to CO_2 storage sites in the vicinity.

Although the global portfolio of CCS projects continue to rise with a current capacity including the existing and planned projects is around 70 Mt of CO_2 capture per year, the task ahead is huge. Being on course to a 2 °C reduction path would require significant acceleration and a few fold order increase in current CCS deployment from the current level to around 6.1 $GtCO_2$ in 2050, requiring average growth of more than 15% per year [9].

Significant advancements have been made through dedicated research and development over the last 20 years on capture, transport and storage technologies. The costs have come down and the technologies are now being applied on a commercial scale. While research and development efforts will continue to be crucial in further refinement and improvement in the technologies, major breakthroughs and reduction in cost can only be achieved through actual deployment at large scales.

4.2 Role of Policy—Past and Future

Although recognition of CCS by climate experts has increased over time, CCS deployment has been hampered by fluctuations in policy and levels of financial support. Prior to the release of the IPCC Special Report on CCS in 2005, considerable interests and activities built up starting from the first ministerial-level meeting of the Carbon Sequestration Leadership Forum (CSLF) in 2003. Subsequently, the plans and activities momentum continued to build. In 2008, European Union (EU) released its CCS directive. The first IEA technology roadmap for CCS was released in 2009 and G8 leaders committed to launch twenty large-scale CCS projects by 2010. However, the global financial crisis put brakes on many of these ambitious projects. Between 2010 and 2016 a number of large-scale CCS projects were cancelled and the announced commitments for funding were either scaled down or withdrawn across Europe, the United States and Australia. United Kingdom's GBP 1 billion CCS commercialization program was cancelled in 2015. In a major blow to CCS, two highly prospective and important projects—White Rose and Peterhead were cancelled in 2015. The Peterhead CCS project proposed to apply CCS to gas-fired power station while the White Rose was planned for demonstration of oxy-fuel capture technology at higher scale. Shale gas revolution leading to cheap availability of natural gas in the US led to the cancellation of many CCS projects. Recently, Kemper County project, which was a major clean-coal technology project with power generation from lignite gasification and concomitant CCS was cancelled in favor of power generation through natural gas. Prevailing global low price of crude provided threat to CO_2-EOR and CCS investments.

Amongst all these gloomy developments, however, there have been a few encouraging developments as well in the recent years. In 2015, China and United States announced a bilateral CCS initiative. China also released its CCS Roadmap developed by the Asian Development Bank and the National Development and Reform Commission. As stated in Sect. 3, six large-scale projects are expected to commence operation within the next two years, including two further projects in power generation. The Paris negotiations have also provided required fillip to global climate policy and accelerate the transition to near zero net emissions. It is expected that the post-Paris period would offer sufficient impetus towards regaining momentum in CCS deployment and adopting new approaches.

The future for CCS will ultimately depend on efforts required for strengthening and expansion of the climate response globally. The Paris Agreement provided an extremely significant milestone with the potential to influence future CCS deployment. It is clear that the world is not on track for achieving the Paris ambitions and significant gap exists between the actions needed and the actions currently planned for emission reduction. Bridging this gap will require high levels of political commitment. The pace, purpose, and intensity with which various countries and their governments now undertake this task will ultimately determine the future of CCS deployment.

5 Conclusion

Twenty years of research, development and demonstration has increased the confidence in CCS technology. Although detailed site characterization is required before employing this technology to a particular site, it can be concluded with reasonable certainty that sufficient geological sites are available across the globe for storage of the captured CO_2. One major concern of CCS is substantial cost addition to the industrial process. However, in the existing scenario, complete switching to other low-carbon technologies is not only feasible but costly as well. CCS is vital for meeting the 2 °C global temperature rise targeted and mandated in Paris agreement. It is calculated that about 12% of the total GHG reduction will come from CCS by 2050. The pace of development in adoption of CCS has gained momentum in the recent years. However, given the quantum of CO_2 reduction, achieved so far, appears to be a big challenge.

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Micro-Scale Combined Heat and Power: Contributor to Sustainable Energy Solution

Homam Nikpey Somehsaraei and Mohsen Assadi

Abstract Researchers investigate the performance of a micro-scale combined heat and power (CHP) system in bioenergy application. The focus has been on the micro gas turbine (MGT) technology as a high-efficient and fuel-flexible distributed generation (DG) system. The combination of MGT and bioenergy seems to be a bridge solution into a sustainable energy future. A wide-ranging performance analysis was conducted to assess the technical limitations and opportunities of micro gas turbines operating with biomass-derived gaseous fuels. For realization of the distributed CHP, tools for monitoring and diagnostics that are easy to apply would be needed. For this purpose, the application of artificial neural network (ANN) for monitoring of a MGT was investigated using the extensive data obtained from an existing test rig. The prediction results showed that the ANN model could serve as an accurate baseline model for monitoring applications.

Keywords Combined heat and power · Distributed generation
Micro gas turbine · Biomass-derived gases · Artificial neural network
Monitoring

1 Introduction

It is projected that by the year 2040 the global energy demand increases up to around 35% from 2010 level [1]. The increasing demand for energy will contribute to a significant increase in greenhouse gas emissions, mostly CO_2, which sets the world on a path that is not consistent with the environmental goal of keeping the rise in global average temperatures below 2 °C. Therefore, deployment of high-efficient technologies as well as utilization of renewable energies are both vital for the transition from an unsustainable energy path to a sustainable one. In this respect, there is a growing trend towards greater use of distributed generation (DG),

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especially in combined heat and power (CHP) application. Micro gas turbines (MGTs) are considered as a promising DG technology, thanks to their high overall efficiency (i.e. about 80%), low emissions and high fuel flexibility. MGT fueled by gaseous biofuels produced from anaerobic digestion or thermal gasification represents potentially a lucrative alternative to bridge between the energy efficiency and renewables to realize a sustainable future.

Tools for condition monitoring which are easy to apply would be needed to enhance the DG operation, particularly in remote and rural areas where maintenance resources are not always accessible. One suitable tool is a data-driven method based on artificial neural network (ANN) for accurate prediction of the system's performance and thus detection of degradation or impending failure before it develops to a major damage, leading to avoid an unexpected stoppage and thus achieve a higher reliability.

2 Micro Gas Turbine

Benefiting from a growing interest in distributed generation, it is anticipated that MGTs will take an increasing share in the future energy market [2–4]. Micro gas turbine technology, which is usually defined as a small gas turbine up to a few hundred kilowatts, benefits from the advantages of both gas turbine technology and small-scale CHP application. This technology provides electrical efficiency of about 30%, high fuel flexibility, low emissions, high power density, low vibration level, heat recovery potential, and low maintenance costs. When it comes to CHP applications, it also offers a high overall efficiency of about 80% [4–6]. In addition to natural gas, other fuel types such as diesel, landfill gas, ethanol, and other bio-based liquid and gas fuels can be used in MGTs. The combination of MGT and gaseous biofuels seems a profitable match, especially for distributed power generation, enabling costly large national grids to be avoided. This mainly contributes to reductions in greenhouse gas emissions and fossil fuel consumption.

2.1 Micro Gas Turbine Technology Background

MGT technology is not new and its development dates back to the 1960s, when it received attention from the automotive industry as a source of power for vehicles [7]. The use of MGTs as small-scale gas turbines accelerated in the 1980s, when the demand for distributed electricity generation increased due to the deregulation of the electricity market. MGT technology with its current definition was finally developed in the late 1990s, but it was not commercialized until the early 2000s [8]. So far, a few companies in the US, Sweden and UK, as Capstone, Turbec and Power Works respectively, have introduced their commercial MGTs, ranging from 30 to 200 kW, into the market. Due to their fuel flexibility, ability to operate in parallel-to-grid or stand-alone modes, ability to operate collectively for higher power demand, quick start-up and shut-down, stable and reliable operation, high ramp rate, and low emissions, they are considered appropriate for applications including peak shaving, backup power, CHP and resource recovery applications. MGTs are also used in the oil and gas, mining and other industries like food and paper production, which may be located in remote areas where reliable operation is very important, allowing them to reduce costly downtime due to unexpected failure of the power supply. Moreover, the products, byproducts and waste from these industries are available as a free source of fuel [4, 9].

There are two designs of MGTs, namely single-shaft and two-shaft. In the single-shaft design, the compressor, turbine and generator are mounted on the same shaft, and the turbine drives both the compressor and the generator, which is located on the cold compressor side (i.e. compressor inlet). On the other hand, in the two-shaft design, the first turbine drives the compressor on one shaft, and the second turbine drives a gearbox and the generator on another shaft, which produces power at commercial use frequency. The single-shaft MGTs operate at a very high rotational speed (i.e. 70,000–100,000 rpm) and produce high frequency power. The high frequency power is converted to grid quality using a power electronics, instead of a gearbox. Compared to the two-shaft design, single-shaft MGTs use fewer moving parts and thus have the potential to reduce maintenance cost and increase reliability [10].

Figure 1 shows the schematic of a typical single-shaft MGT for CHP application. MGTs feature a centrifugal compressor, a radial flow turbine and a recuperator. Unlike large-scale gas turbines, they are equipped with single-stage radial turbomachinery rather than multi-stage axial ones to achieve a compact size and lower manufacturing cost. Since the single-stage turbomachinery does not provide high pressure ratios, MGTs use internal heat exchangers called recuperators to preheat the combustion air in order to obtain a satisfactory level of electrical efficiency. Using a recuperator can double electrical efficiency and reduce fuel consumption by 30–40% [10].

MGTs operate on Brayton cycle basis. Figure 1 shows that the intake air coming from the ambient is compressed by the compressor. The compressed air passes a recuperator where it is preheated by exhaust gas coming from the turbine. The compressed and preheated air is then mixed with fuel and burned inside the combustion chamber. The combustion gases expand through the turbine. The turbine exhaust gas enters the recuperator and transfers heat to the colder compressed air. This increases the temperature of the incoming air to the combustion chamber and thus less fuel is required to reach the operating temperature, resulting in increased efficiency. Given the still high recuperator outlet temperature, the MGT is also equipped with a gas-water heat exchanger, which recovers the exhaust gas heat after the recuperator for heating purposes.

MGTs include other systems, namely fueling, lubricating, cooling and control systems. The fueling system includes the pipes, fuel valves and injectors, which regulates the amount of fuel that should be fed to the combustion chamber. If the fuel inlet pressure reduces below the required injection pressure, a compressor is also used to raise the pressure. The fuel pressure needs to be well above the

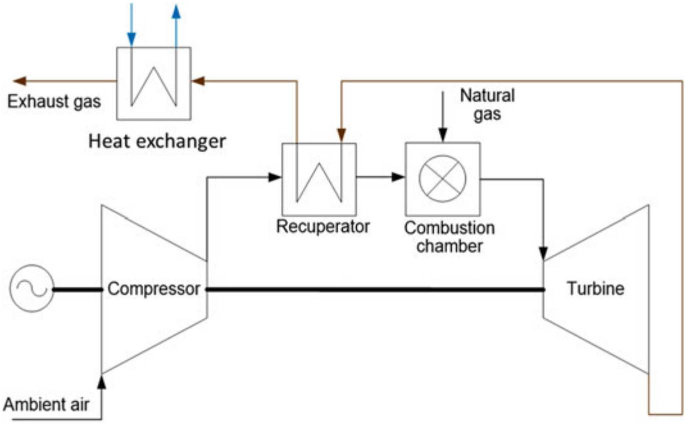

Fig. 1 The schematic of a typical CHP MGT

compressor outlet pressure. The purpose of the lubricating system is to circulate the oil to lubricate the bearings such as the bearing supports of the shaft. The cooling system circulates cooling agents such as air and water around the system to keep the temperature of the components within the desired ranges. The function of the control system is to ensure stable operation of the system by monitoring the performance parameters and adjusting the control signals, mainly fuel flow rate, accordingly.

A significant improvement in MGT efficiency can be achieved at higher pressure ratios and temperatures. The limiting factor here is the material that is utilized in the MGT design. Most components are made of metallic alloy without air cooling. Therefore, a higher pressure ratio, which leads to higher operating temperatures, results in shortened lifetime. Though this issue can be dealt with by the development of high-temperature material, higher efficiency at higher temperatures increases the potential for higher NOx emissions, which need a more sophisticated combustion chamber [4].

One of the critical components in the design of MGTs is the recuperator. The two main performance parameters of the recuperator are effectiveness (i.e. the ratio of the actual heat transfer to the maximum possible heat transfer) and pressure drop. An increase in effectiveness requires a larger surface area, which results in a higher pressure drop as well as higher cost. The increased pressure loss causes the power output to reduce. However, as can be seen in Fig. 2, the cycle efficiency considerably improves as the recuperator effectiveness increases. The recuperator design is therefore made by a trade-off between MGT performance and cost. This means obtaining an optimal design point, in which the recuperator effectiveness satisfactorily increases the cycle efficiency, while power drop and cost are acceptably low [9, 10].

Basically, there are two types of design for the recuperator in an MGT package, namely, the cube shaped (i.e. the conventional type) and the annular shaped recuperator. The first one is installed in line with turbomachinery right after the

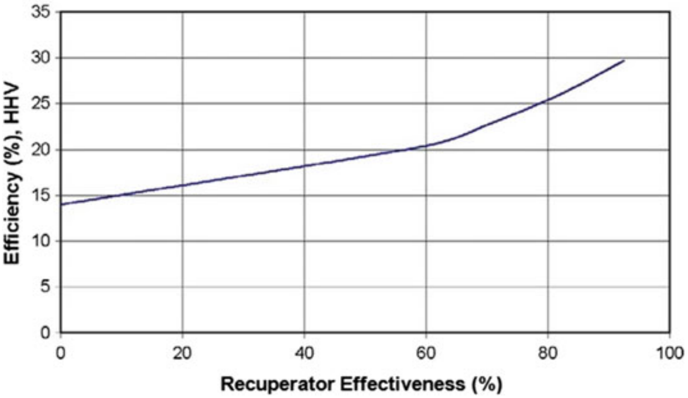

Fig. 2 Variation of MGT efficiency as a function of recuperator effectiveness [9]

turbine. The main advantage of this recuperator is the possibility of partially bypassing the recuperator when the demand for thermal power is higher than that could be recovered from the exhaust. The second type, which is wrapped around the MGT, eliminates the additional connections and thus includes the advantages of low pressure losses and low level of noise [11].

The electrical efficiency of the MGT decreases at part load operational conditions due to the reduction in the mass flow rate (i.e. via the reduced rotational speed) and the decrease in the turbine inlet temperature. Figure 3 shows the variation in the electrical efficiency at different load levels for a 100 kW MGT. The performance of the MGT is also affected by the ambient conditions, particularly temperature. As the ambient temperature increases, the air density is decreased, resulting in less air mass flow and thus lower power output could be expected at constant rotational speed. Figure 4 shows the variation in power output and electrical efficiency as a function of the ambient temperature. The efficiency decreases with increasing the ambient temperature. This is because the compressor needs more power to compress the air with a higher temperature. Both power and efficiency decrease with decreasing ambient pressure and increasing altitude for the same reason.

MGTs have the potential for low emissions levels, and they are designed to achieve lower emissions at full load operation. The main exhaust gas emissions from the MGTs are NO_x, CO, unburned hydrocarbon (UHC) and CO_2. NO_x is formed by three mechanisms, namely, thermal NO_x, prompt NO_x and fuel-bound NO_x [10]. The main NO_x formation in MGTs is due to thermal NO_x, which is affected by flame temperature and residence time. Lower flame temperature and also lower residence time of fluid in the combustion chamber are favorable effects for NO_x reduction [5]. Prompt NO_x is formed by early reaction of the nitrogen content in air with hydrocarbon radicals in the fuel. The fuel-bound NO_x is usually produced when the fuel composition contains nitrogen. Since natural gas has a very small amount of nitrogen, MGTs produce a negligible amount of fuel-bound NO_x. The CO and UHC are the products of incomplete combustion. Lower residence

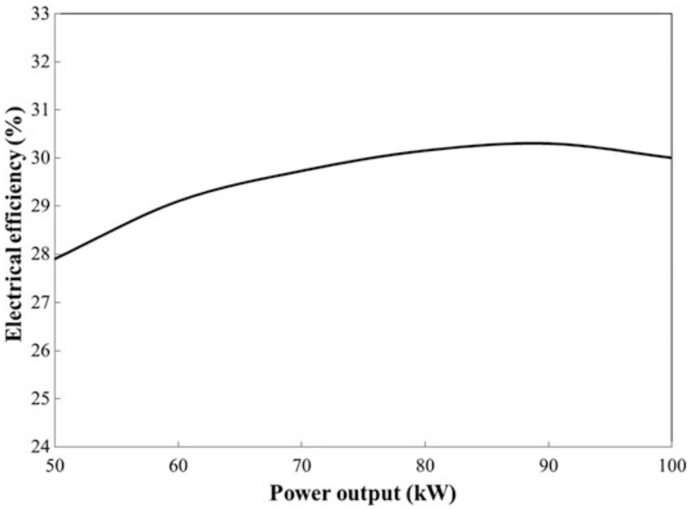

Fig. 3 The efficiency variation of a typical MGT as a function of load [9, 12]

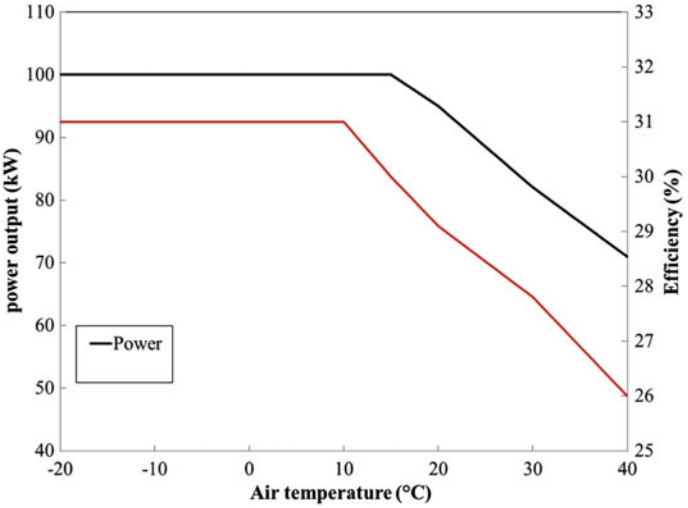

Fig. 4 Effects of ambient temperature on the performance of MGT [9, 12]

time contributes to incomplete combustion and thus higher CO and UHC [5]. MGTs tend to have incomplete combustion at low power loads. Figure 5 shows the variation of CO and NO_x emissions for a 100 kW MGT. The CO concentration sharply decreases as the power load increases, and its concentration becomes very low from 70 to 100 kW load. The NO_x concentration is very low for all power loads. CO_2 concentration is also of concern due to its impact on greenhouse gas emissions. By burning natural gas, the carbon content of the fuel is present in

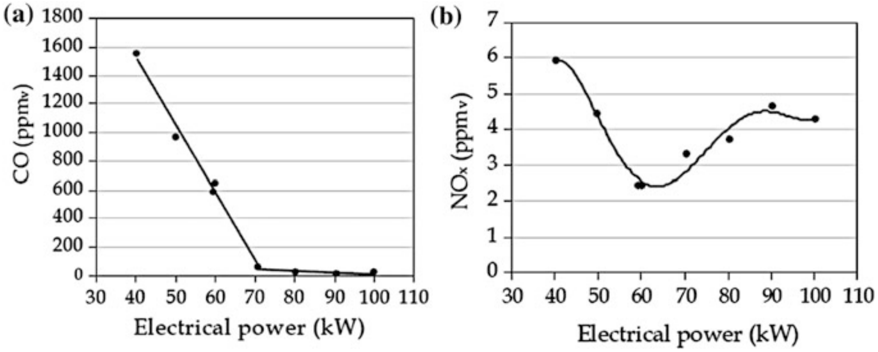

Fig. 5 Variation of CO and NO_x concentration with respect to power load [13]

combustion products as CO, UHC and CO_2. As the CO and UHC concentration in the exhaust gas decreases by increasing the power loads due to improved combustion, the CO_2 (i.e. product of complete combustion) concentration must in return increase. In CHP application, MGTs have the potential for even lower emissions' levels. Since the overall efficiency of fuel utilization in CHP systems is higher than the efficiency of conventional systems, the emissions' level per unit of useful energy produced (both in electrical and thermal power) is lower than that of conventional systems [10].

3 An Overview of Biomass-Derived Gaseous Fuels

The continuously increasing request for reduced greenhouse gas emissions incorporates the requirement to reduce the consumption of fossil fuel. One option, besides the improvement of energy efficiency, is to replace fossil fuels with those based on renewable sources [14]. Biomass is the unique source of renewable energy today, which can be provided as solid, gaseous or liquid fuel and utilized for generating electricity and heat, as well as for transportation purposes. Gaseous biofuels can be categorized into two groups, namely, producer gas and biogas. Producer gas is produced through the thermal gasification process, which mainly consists of CO, H_2 and N_2. The process requires a complex plant arrangement, which operates at high temperatures. Therefore, this technology is more suitable for large-scale production, with specifically trained operators on site. Biogas is generated through an anaerobic digestion process, consisting of mainly CH_4 and CO_2. This is currently the most-used technology for decentralized small-scale application.

3.1 Biomass Feedstocks

Feedstocks can be split into first, second and third generation. These categories are closely connected to the type of feedstock used and will be described in the following.

First generation feedstock refers to the biomass that have been derived from sources like starch, sugar and vegetable oil. Here, the main issue has been that the required area for growing the biomass crops would compete with food production. In the long term, this could raise food prices and thus affect the security of food production. Therefore, an accurate assessment of the available farming land that could be used for growing biomass crops is required for sustainable biomass production. Second generation of biomass feedstock is made from lignocellulosic biomass or woody crops, and agricultural residues or organic waste. Unlike first generation, this feedstock production does not compete with food production. Lignocellulosic biomass, as the most abundantly available organic material on earth, is a promising raw material for biofuel production. It is difficult to degrade lignocellulosic biomass and thus a pre-treatment process is required to improve biogas formation out of lignocellulosic biomass [15, 16]. Agricultural residues or organic waste is another group of material within the second generation of biomass sources. This group covers manure, organic waste from farming as well as organic waste from food. When it comes to waste from food, the composition of the feedstock varies in a wide range, resulting in challenges to optimize the gas production process. Two possible feedstocks of third generation biomass are microalgae (pond scum) and macroalgae (seaweed). There are two major advantages of using these sources as feedstock. First, the growth of algae does not usually compete with food production and second, the growth rate of algae is continuously high, and therefore the quantity of resulting biomass is much higher than that of first or second generation feedstock [17].

3.2 Anaerobic Digestion Process

Anaerobic digestion is a series of decomposition processes of organic matters in the absence of oxygen. Biogas and digested material are the main products of this process. Through the anaerobic digestion process, the initial feedstock is successively broken down into smaller compounds. The four main steps involved in the digestion process are hydrolysis, acidogenesis, acetogenesis, and methanogenesis [18]. Figure 6 shows a schematic of the successive occurrence of these steps.

Hydrolysis is the first step, in which the large polymers like carbohydrates, proteins and fats are decomposed into smaller and soluble compounds such as glucose, glycerol, fatty acids and amino acids. During acidogenesis (fermentation), the products of the hydrolysis are broken down by fermentative bacteria to methanogenic substrates like acetate, hydrogen, and CO_2, along with volatile fatty acids and alcohols. Since volatile fatty acids and alcohols cannot directly be converted into methane, they convert into the methanogenic substrate like acetate and hydrogen during acetogenesis. The resulted acetate, hydrogen and CO_2 are then converted into methane, CO_2 and water during the methanogenesis.

The biogas production rate and the methane content of the biogas depend on several parameters such as temperature stability, pH-value of the substrate, concentration of nutrients, amount of inhibitors (e.g. ammonia) and substrate feed

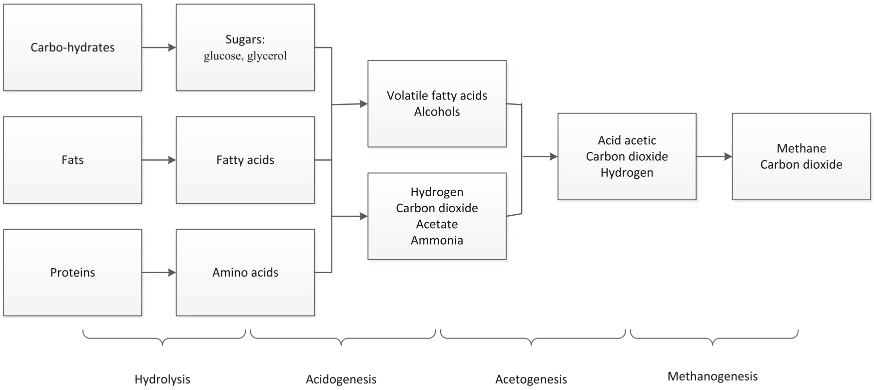

Fig. 6 A schematic of main steps of anaerobic digestion process

[18, 19]. These parameters indeed define the environmental conditions for the microorganisms.

3.3 Gasification Process

In thermal gasification, the hydrocarbons inside the biomass material are heated and they breakdown into gases, liquids and char due to pyrolysis. The gases with lower ignition temperature starts to burn, thus generating more heat. By increasing the temperature, carbon char freed by the pyrolysis also begins to react with oxygen i.e. an exothermic process, which leads to increasing of the heat. The produced gases, which are not fully combusted because of low amount of oxygen, are collected, cooled and cleaned.

The burnable components are carbon monoxide, hydrogen and methane with minor amounts of other hydrocarbons such as propane and ethane. The non-combustible components of the gas are mainly carbon dioxide, nitrogen and water vapour. The gas obtained from gasification is so-called producer gas or syngas. Since these gases exist the gasification reaction at elevated temperatures, some of the energy of the reaction can be used to further enhance the energy density of the produced gas. The water gas shift reaction is one of these enhancements. This reaction uses the heat of the gasification process to break down water molecules into hydrogen and oxygen, increasing the hydrogen content of the produced gas. The carbon monoxide content is also reduced by the presence of the added oxygen, but the overall energy density is increased. The enhancement using the thermal energy from the gasification reaction, which would otherwise be lost as the producer gas is cooled, improves the overall energy efficiency of the plant. The entire process is rather complex. The producer gas also contains tar, which should be removed from the gas stream for downstream applications. There are different types of gasifiers and also different gasification technologies on the market, which are described in more details in [20].

Table 1 Examples of biogas composition from anaerobic digestion [21]

Component	Unit	Biogas plant	Sewage plant	Landfill
CH_4	vol.%	60–70	55–65	45–55
CO_2	vol.%	30–40	35–45	30–40
N_2	vol.%	<1	<1	5–15
H_2S	ppm	10–2000	10–40	50–300

Table 2 Examples of composition of gases from-commercial wood and charcoal gasification [21]

Component	Unit	Wood gas	Charcoal gas
N_2	vol.%	50–54	55–65
CO	vol.%	17–22	28–32
CO_2	vol.%	9–15	1–3
H_2	vol.%	12–20	4–10
CH_4	vol.%	2–3	0–2

3.4 Composition of Biomass-Derived Gases

Tables 1 and 2 show typical biomass-derived gas compositions obtained from anaerobic digestion and gasification, respectively. As demonstrated in these Tables, biogas from the anaerobic digestion process mainly consists of methane and CO_2 while CO, hydrogen and methane are the main combustible components of producer gas from gasification process. Depending on the type of feedstock, product gases may contain small amounts of impurities such as hydrogen sulfide and organic silicon compounds.

4 Micro Gas Turbine Fuelled by Biomass-Derived Gases

When the fuel is changed from natural gas to low calorific fuels such as biogas and/or producer gas in an MGT system, a larger quantity of fuel needs to be injected into the combustor because of the lower heating value of the fuel, which impacts the performance and the operating conditions of the MGT. The turbomachinery, such as the compressor, needs to operate at conditions that deviate from the original design. Compressor surge is a particular concern when firing low heating value fuels. However, in contrast to large-scale gas turbines, the surge problem in MGT systems does not seem to be very critical when fed by gaseous biofuels. This is due to the utilization of centrifugal compressors and the much lower fuel flow rate relative to the air flow [22]. Moreover, MGTs have a variable speed engine, which gives them additional freedom in operation.

Since the biogas and producer gas characteristics such as lower heating value and Wobbe Index differ from those of natural gas, it is not practically possible to directly burn these low calorific fuels in a combustion chamber originally designated for natural gas. Therefore, MGTs need to be modified, taking into account the increased fuel flow rate and changes in fuel characteristics. The modifications include redesign of combustion chamber and/or minor modifications of fueling system i.e. fuel injectors, fuel valve, fuel path, and control system [23–27].

Biogas from anaerobic digestion is a tar-free gas and hence it could be fed as fuel to the gas turbines without a major cleaning process. However, depending on the type of feedstock, it may contain small amounts of impurities such as hydrogen sulfide, water (moisture), organic silicon compounds and ammonia. Therefore, some cleaning actions might be needed before burning biogas. The major impact of the impurities is on material degradation, corrosion and aging of the components. This depends to a large degree, however, on their concentration. Hydrogen sulfide is generated if the feedstock contains sulfide. Hydrogen sulfide can result in a highly corrosive effect and thus reduced lifetime at high temperature [21, 28]. Biogas should also be dried or dehumidified before feeding to the gas turbine. Otherwise, it can cause the fuel systems to foul as well as a cavitation problem [11]. Ammonia concentration is usually too low to be filtered out [21]. Organic silicon compounds exist occasionally in biogas; they convert to silicon oxides during the combustion and can form deposits on the combustion chamber walls. They can also build up as a deposit on the recuperator, resulting in reduced heat recovery and thus reduced efficiency [11]. This also might require cleaning and therefore higher service and maintenance costs.

Unlike biogas from anaerobic digestion, produced gas from a gasification process contains tar as well as other contaminants such as particulates, alkali compounds, sulfur and nitrogen that need to be processed properly before using in gas turbines. Tar removal is considered as one of the biggest challenges in gasification technology. If the produced gas from biomass gasification is intended to be utilized, tar needs to be removed. Otherwise, it condenses on the wall of the equipment and create tar deposits that can result in fouling. Together with tar, particulates consisting of ash, char and material of the gasifier can cause fouling and abrasion. Alkali, sulfur and nitrogen compounds in gas leaving the gasification process can result in various technical issues such as corrosion and thus it is desirable to remove them for gas to power applications. These upgrading processes are rather expensive and complex which make the biomass gasification challenging and rather inefficient for small-scale applications [29–31].

A case study to investigate the fuel flexibility and the performance of an existing MGT system operating with low heating value fuels obtained from biomass is presented and discussed in the following sections. In this study, a Turbec T100 MGT is considered as the reference case and the engine performance when fed with biogas and producer gas instead of natural gas, is analyzed for a wide range of operating conditions. For this purpose, a steady state thermodynamic model of the standard configuration, running on natural gas, has been developed and validated against experimental data obtained from an existing test rig in Norway [32, 33].

4.1 Micro Gas Turbine Test Rig

The test rig is based on a commercial Turbec T100 MGT which was installed at a test facility in Stavanger, Norway. The T100 is a single shaft recuperative gas turbine which mainly comprises a centrifugal compressor, a radial turbine, a high speed generator, a combustion chamber and a recuperator. The contribution of the recuperator is to reduce the fuel consumption and thus, increase the efficiency [34]. At ISO condition, T100 generates 100 kW electricity with an electrical efficiency of approximately 30%. Table 3 summarizes the engine nominal performance data at ISO condition.

Besides the standard instrumentation, the test rig was equipped with additional sensors to allow supervision of additional performance parameters. The instrumented MGT test rig is shown in Fig. 7. A probe containing pressure and temperature measurement sensors was placed in front of the compressor inlet. In order to measure the gas condition at the compressor exit, three temperature and three pressure sensors were installed circumferentially, providing the possibility of obtaining an average value of the flow field. Pressure and temperature sensors were also installed at the combustor head to measure the pressure and temperature of the incoming air preheated by the recuperator. Moreover, an additional pressure sensor was located at the turbine exit to measure turbine outlet pressure. A schematic illustration of the engine with measuring points is shown in Fig. 8. Further details of the instrumentation have been presented in [35].

4.2 Performance Analysis of MGT Fueled by Biomass-Derived Gases

The performance of the MGT when fed with biogas instead of natural gas is evaluated based on a validated thermodynamic model. The MGT model has been validated against real-life data obtained from the test rig, with setup as described in the preceding section.

Table 3 Engine performance data at ISO condition [12]

Parameter	Unit	Nominal value
Power output	kW	100
Electrical efficiency	%	30
Fuel consumption	kW	333
Compression ratio	–	4.5
Shaft speed	rpm	70,000
Turbine inlet temperature	°C	950
Turbine outlet temperature	°C	650
Recuperator outlet temperature	°C	270

Fig. 7 The MGT test rig

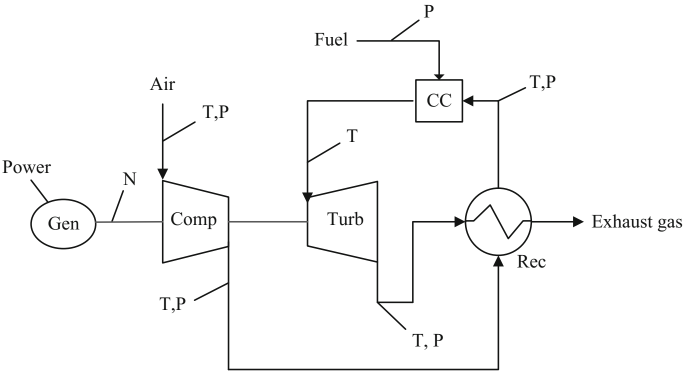

Fig. 8 The MGT layout and measurement points

Table 4 shows the fuel compositions assumed for the analysis. Since biogas obtained from the digestion process consists of the two major components, namely, CO_2 and methane, other minor constituents do not significantly affect the gas properties. Therefore, for thermodynamic calculations, only CO_2 and methane were considered for the simulation purposes. A biogas with 45% methane was assumed for the analysis, taking into account the minimum content of the methane of biogas in typical digestion processes. The remaining content, i.e. 55%, accounted for CO_2 fraction. For the producer gas from gasification, the gas composition was obtained from the agricultural waste gasification at atmospheric pressure studied in India [36]. The rice straw is the input to the system as the biomass feedstock. Moreover, the

Table 4 Fuel gas compositions

Component	Unit	Natural gas	Biogas	Producer gas
CH_4	mol%	78.73	45.00	0.09
C_2H_6	mol%	12.13	–	–
C_3H_8	mol%	1.95	–	–
CO_2	mol%	6.00	55.00	11.14
CO	mol%	–	–	21.33
N_2	mol%	1.19	–	42.35
H_2	mol%	–	–	18.52
H_2O	mol%	–	–	6.57
LHV	MJ/kg	46.2	11.5	4.3

composition of natural gas is based on a laboratory analysis (gas chromatography) of the gas sample that was taken from the fuel supply pipe during the experimental activities carried out in Norway [35].

The operational condition of the MGT changes with power load demand set by the user and engine inlet condition, especially ambient temperature. Therefore, the impact of product gases from both anaerobic digestion and gasification process on the engine performance is investigated for different power load demands with an ambient temperature of 15 °C as well as for changing ambient conditions at 100 kW demanded power output.

4.2.1 Effects of Varying Power Loads on the Engine Performance

The effect of utilizing biogas and producer gas on the operation of the compressor over the power load settings from 50 to 100 kW is shown in Fig. 9. In Fig. 9, the relative pressure ratio is plotted versus the relative mass flow rate for different relative speed values. The relative parameters are described by the following equations:

$$\pi_{\mathrm{rel}} = \frac{\frac{P_{out}}{P_{in}}}{\frac{P_{out,des}}{P_{in,des}}} \tag{1}$$

$$\mathrm{N_{rel}} = \frac{\frac{N}{\sqrt{T_{in}}}}{\frac{N_{des}}{\sqrt{T_{in,des}}}} \tag{2}$$

$$\dot{\mathrm{m}}_{\mathrm{in,rel}} = \frac{\frac{\dot{m}_{in}\sqrt{T_{in}}}{P_{in}}}{\frac{\dot{m}_{in,des}\sqrt{T_{in,des}}}{P_{in,des}}} \tag{3}$$

where N is the rotational speed and π denotes pressure ratio. T, P, and ṁ are temperature, pressure, and mass flow rate, respectively. Subscript “des” and “rel” indicate respectively design point and relative values, with “in” being those at the inlet of compressor and "out" referring to those at the outlet. These non-dimensional parameters are used to reduce the number of variables required to define each operating point of the compressor.

At a given power by changing the fuel from natural gas to biogas and producer gas, the operating point of the compressor moves in the direction of lower speed and reaches a point with lower pressure ratio and mass flow. This can be explained by the fact that the engine tries to keep the power output constant at the demand value. Since the heating value of the biogas and producer gas is lower than that of natural gas, the fuel flow increases. This leads to an increase in turbine inlet flow and therefore an increase in the pressure ratio over the turbine. Thereby, power output could increase. However, to deliver the demanded power output, the intake mass flow to the compressor decreases via a reduction in the rotational speed, which results in the reduction of the pressure ratio over the compressor. Reduction in mass flow and pressure ration in producer gas case is much greater comparing to biogas fired case. This is since the heating value of the producer gas is lower than that of the biogas and consequently larger fuel flow is provided to generate the required heat input.

Figure 10 shows how the surge margin varies depending on the fuel type at various power output demands. The surge margin reduces at each power loads when the fuel composition deviates from standard fuel i.e. natural gas. As the heating value of the fuel decreases, the operating point moves toward the surge line as shown and discussed in Fig. 9. The surge margin deterioration becomes much worse when the engine is fueled by producer gas, specifically at low power loads, where the risk of surge and unstable operation turns out to be much higher.

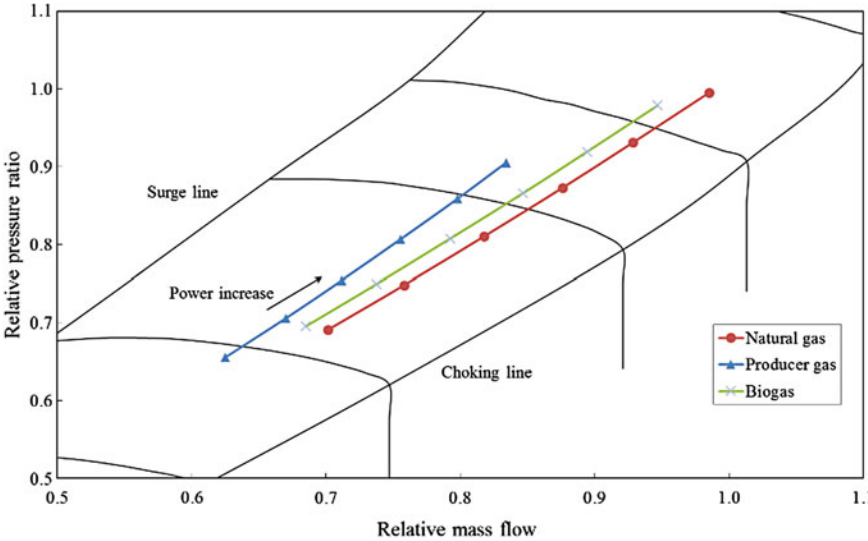

Fig. 9 Effects of biogas and producer gas utilization on the performance of the compressor at various power output demands

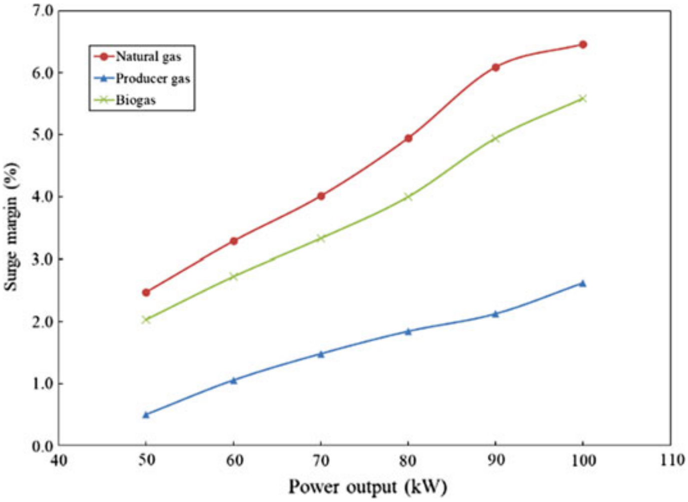

Fig. 10 Effects of biogas and producer gas utilization on the compressor surge margin at various power output demands

However, operating points do not still exceed the surge limit. At 50 kW power, the surge margin reduces by about 2.0 percentage point for producer gas case and reaches to 0.5%.

Figure 11 shows the effects of burning biomass-derived gases on the electrical efficiency of the MGT at various power output levels. For all fuels, the electrical efficiency increases with increasing power and reaches its maximum at 100 kW

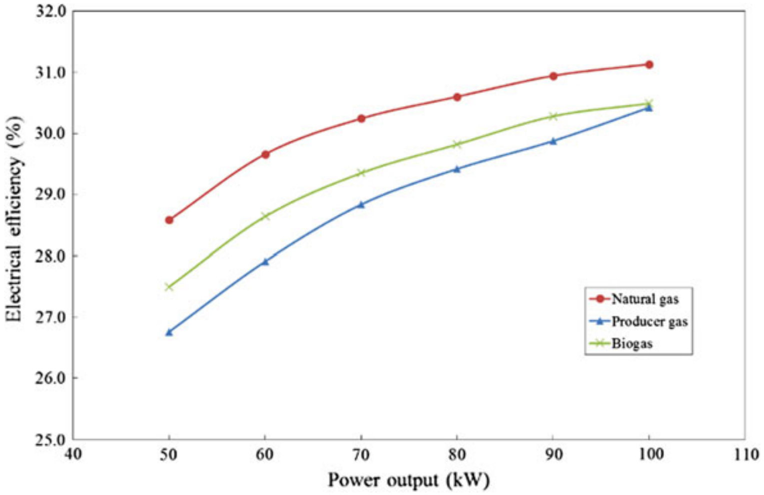

Fig. 11 Effects of biogas and producer gas utilization on the electrical efficiency at various power output demands

load operation. The low efficiency of the MGT at part load operational conditions is mainly due to the reduction in the mass flow rate (i.e. via the reduced rotational speed) and the decrease in the turbine inlet temperature. Nevertheless, compared to the natural gas fired case, the efficiency decreases with biogas and producer gas at a particular power load demand. As the heating value of the fuel decreases, the fuel flow increases instead to keep the power output, leading to the increased heat input and eventually, reduced electrical efficiency. The efficiency drop becomes larger from full load to part load operation and it further worsens when the producer gas is fed to the engine. Compared to natural gas, the efficiency drop at 100 kW is about 0.7 percentage point for both gaseous biofuels, which deteriorates at low power loads and becomes 1.1 and 1.8 percentage point at 50 kW for biogas and producer gas, respectively.

4.2.2 Effects of Varying Ambient Temperature on the Engine Performance

The effects of the biogas and producer gas utilization on the operating lines in the compressor map due to changes in the ambient temperature from −20 to 30 °C at 100 kW power demand are shown in Fig. 12. Both pressure ratio and air mass flow increase with increasing ambient temperature. The same pattern occurs for biogas and producer cases. As the ambient temperature increases, the air density is decreased, resulting in less air mass flow and consequently, a lower power output. However, to keep the power output at 100 kW, the compressor mass flow increases via a higher rotational speed, leading to an elevated pressure ratio over the compressor. This causes the turbine inlet mass flow and pressure ratio to rise. Figure 12

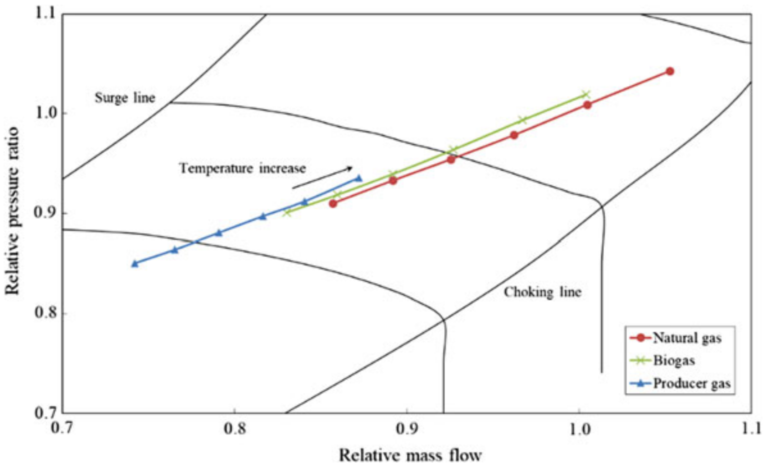

Fig. 12 Effects of biogas and producer gas utilization on the performance of the compressor at various ambient temperatures

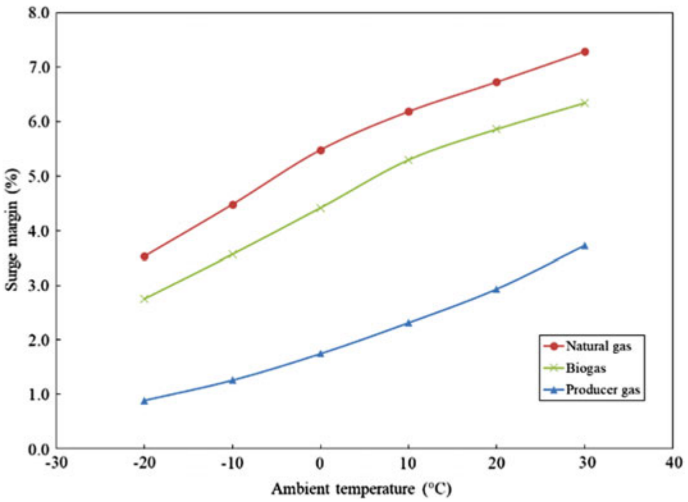

Fig. 13 Effects of biogas and producer gas utilization on the surge margin at various ambient temperatures

also shows that, at a given ambient temperature, the pressure ratio and air mass flow decrease as the heating value of the fuel reduces from natural gas to producer gas.

Variations in compressor operating line for biogas case with 45 mol% methane are not too far from the standard natural gas case but when it comes to producer gas, these variations are larger and the risk for surge becomes higher, especially for low temperatures. Figure 13 indicates that the surge margin decreases with decreasing the ambient temperature. This can be observed in Fig. 12, as the operating lines converge to the left toward the surge line with decreasing ambient temperature. Therefore, operation at very low ambient temperature needs great caution due to the considerable reduction of the surge margin.

The effects of changing ambient temperature and utilization of biogas and producer gas on the electrical efficiency are illustrated in Fig. 14. The efficiency constantly reduces as the ambient temperature increases, and this trend occurs for all fuel cases. As the ambient temperature rises, a decrease in the power output could have been experienced. To avoid this, the fuel mass flow is increased to generate the demanded power, leading to a larger heat input to the engine and thus lower efficiency.

Figure 14 also shows that, at low ambient temperatures, the efficiency reduces with decreasing the heating value of the fuel. This is mainly owing to the increased heat input by adjusting the fuel flow to keep the power output constant. However, the efficiency drop becomes less and less by increasing the ambient temperature and finally at a certain temperature i.e. 30 °C, the biogas and producer gas cases almost generate the same heat as the standard fuel case does, resulting in almost the same level of electrical efficiency for all fuel cases.

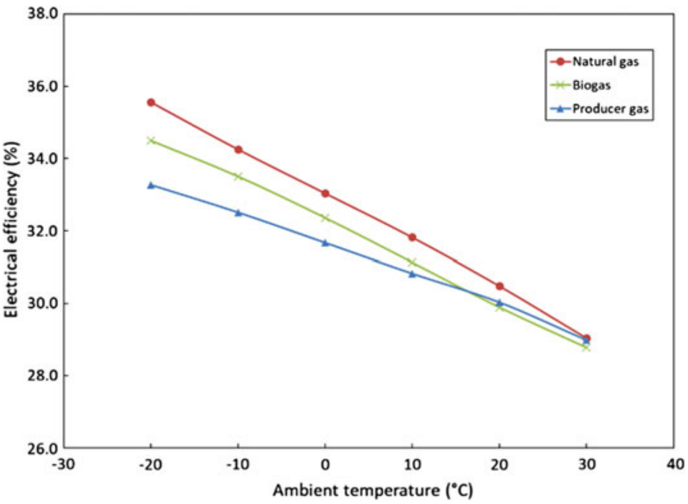

Fig. 14 Effects of biogas and producer gas utilization on the electrical efficiency at various ambient temperatures

5 Application of ANN in MGT Systems

In the context of small-scale distributed generation, a key issue is to achieve a high reliability by minimizing the required resources for repair and maintenance. Thermodynamic models are still very valuable tools for in-depth analysis of the system, but they might not be enough alone to satisfy the abovementioned requirement. To develop an accurate model, thermodynamic models require detailed and exact components' characteristics, which are not usually available outside original equipment manufacturers (OEMs). Depending on the complexity of the models, the solution of these models might be demanding regarding computational time. Therefore, there is an incentive to study other alternatives such as data-driven based methods like ANNs. The ANN presents the advantage of providing a reliable model based solely on the data, even when sufficient physical knowledge of the system is not available. The ANN model is very simple and does not require an iterative solution process so that when the inputs are supplied the outputs are predicted instantly. These features make them suitable for monitoring in real-time applications, optimization, certain operating point analysis, and for training purposes. ANN models are tailor-made for a certain setup and therefore should be retrained with the new system's data from a different setup.

ANN models specifically for the modeling of gas turbines have been used in different studies [37–42]. System simulation, condition monitoring, sensor validation, fault diagnostics and control are some of the applications of these models. The ANN has been shown to be a suitable method for the modeling of nonlinear and multi-dimensional energy systems. Together with a concise introduction to the basics of ANN, this section therefore presents the application of ANN in the development of accurate models to predict the performance of the MGTs as a small-scale CHP plants for monitoring purposes to improve their reliability and keep their operation and maintenance costs low. The ANN model was built up based on the extensive experimental data obtained from the MGT test rig described in the preceding section.

5.1 Artificial Neural Networks

The artificial neural network is an adaptive system, which mimics the biological neural network of the human brain. It learns the knowledge about a system represented by a data set through a training process. The ANN mainly consists of interconnected processing units called artificial neurons with linear and nonlinear transfer functions. These interconnections, known as synaptic weights, are the adaptive parameters of the ANN, which are tuned during the training process to store the underlying knowledge contained in the data [43].

Figure 15 shows a typical multi-layer feedforward network i.e. called multi-layer perceptron or in short MLP. It consists of a number of hidden and output processing units or neurons with linear or nonlinear transfer (activation) function. Each unit in the network is fully connected to every unit in the next layer. The connections represent the weights. The weighted input values are summed and transformed while passing through the hidden neurons. The outputs of each hidden layer are the inputs for the next layer. This process is continued in forward direction, layer by layer, until the network outputs corresponding to applied inputs are calculated in output neurons. These computations are carried out based on initial guesses of weights, which are adjusted during the training process. The training process is carried out, aiming at minimizing an error function i.e. usually defined as the difference between predicted outputs obtained from the network and the desired ones (measured outputs), by adjusting the weights. Errors are firstly evaluated in the output layer and then propagated in a backward path through the network. Accordingly, weights are updated using calculated errors and this process is repeated until the error is reduced to an acceptable level. This algorithm is known as back-propagation.

5.2 ANN Modeling of MGT

The data obtained from the Turbec T100 MGT was used for training and validation of the ANN. The test rig with additional instrumentation allowed use of parameters that are not measured in the standard version of the micro gas turbine. Therefore, the development of a comprehensive model at both component and system level was enabled. This model indeed supports detailed condition monitoring to detect impending failures in components.

In ANN, the relations between input and output parameters are established during the training process by adjusting the synaptic weights. Unlike mathematical models, these relations are not necessarily directly explained by physical principles. The dependency between inputs and outputs is therefore studied by performing a sensitivity analysis. In this study, a systematic sensitivity analysis was carried out in different steps to shed light on the impact of the initially selected parameters on the prediction accuracy of the model and to sort out the optimum input parameters for accurate prediction of engine performance [44]. Finally, three parameters, namely, power set, compressor inlet temperature and pressure, emerged as the optimum set of input data. This shows the capability of ANN to produce accurate predictions even if some measurements are not available for reasons such as lack of instrumentation or sensor faults. Moreover, this analysis illustrated the optimal instrumentation required to develop an accurate ANN model for the micro gas turbine. The list of inputs and outputs for the final ANN model concluded upon from these studies is listed in Table 5.

The average prediction error of the model was 0.2% and for most testing samples (more than 92%), the prediction error (i.e. MRE) was less than 1%. The testing samples were not used during the training process and they were only used to validate the ANN model after training. The accuracy of the ANN model to predict compressor outlet temperature, turbine inlet and outlet temperatures are shown in Figs. 16, 17 and 18, respectively. These figures present the result of the comparison between measured and predicted values. It can be seen that ANN not only can provide accurate predictions, but also has the capability to reduce the level of noise or uncertainty in measured parameters. In monitoring application, this feature of ANN comforts to avoid false alarms due to presence of noises. Moreover, since the

Fig. 15 Schematic of a multi-layer feed forward network [39]

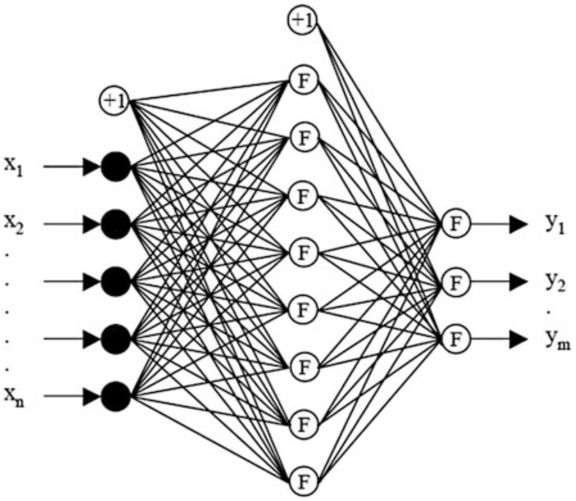

Table 5 Input and output parameters

Input parameters	Output parameters
Power set	Power output
Compressor inlet temperature	Turbine inlet temperature
Compressor inlet pressure	Turbine outlet temperature
	Compressor outlet temperature
	Compressor outlet pressure
	Combustion chamber inlet temperature
	Combustion chamber inlet pressure

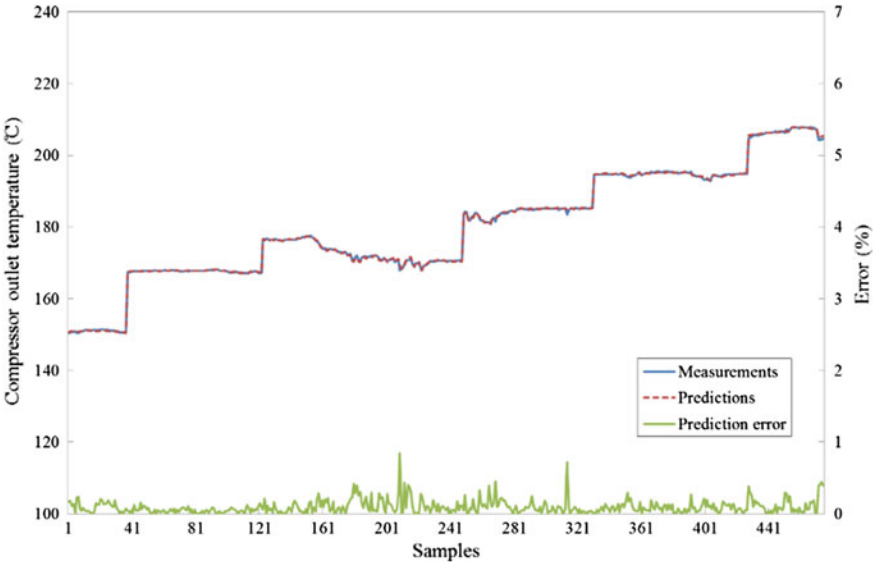

Fig. 16 Compressor outlet temperature predictions of the ANN model compared to measured values

turbine inlet temperature is not measured in the standard gas turbines, the obtained results support the idea that ANN is also helpful to provide an accurate estimation if the measurement for a parameter is not available.

As shown in Table 5, the input parameters of the final model are independent of variations in the MGT operational conditions; hence, the model can be used effectively for condition monitoring applications by comparing predictions with actual measurements. Having accurate predictions of the performance parameters of the turbine and compressor provides the possibility to detect degradation and impending failure at the component level before a major and costly malfunctioning occurs. Consequently, the resources and time required to repair the engine can be optimized, and its availability can be improved.

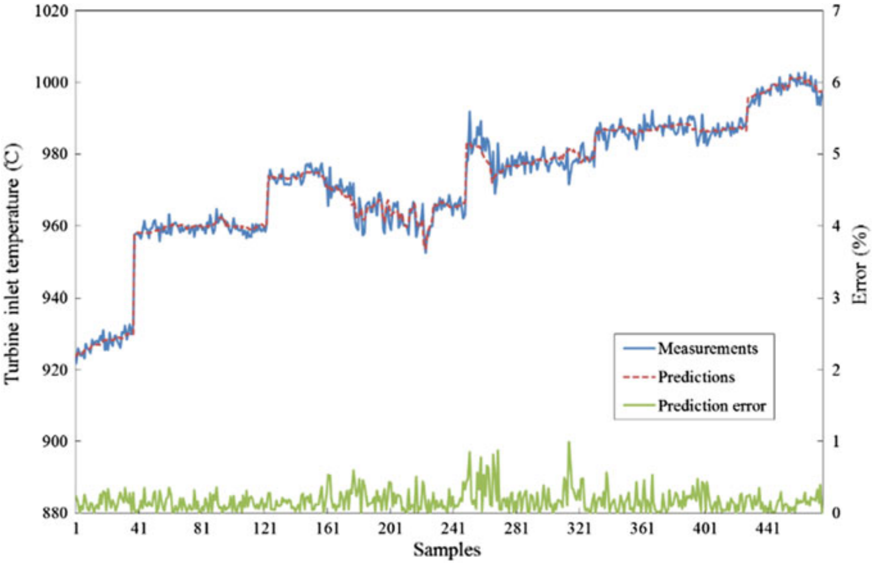

Fig. 17 Turbine inlet temperature predictions of the ANN model compared to measured values

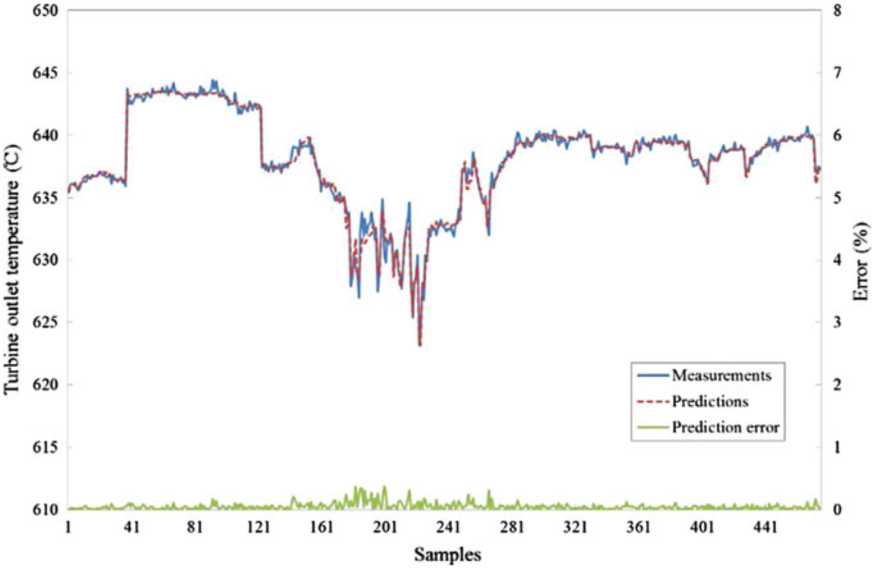

Fig. 18 Turbine outlet temperature predictions of the ANN model compared to measured values

6 Conclusion

The detailed assessment of the performance of an MGT fed with biogas and producer gas illuminates the possibility of the MGT for use in bioenergy application to generate heat and power. Compared to the standard case i.e. natural gas, the surge margin reduces when the engine is operated with low heating value fuels. A great cautious should be given to the producer gas fired case, specifically at low power loads and/or low ambient temperatures, where the surge margin drops below 1.0%. The electrical efficiency decreases when the fuel deviates from natural gas and further declines from full load to part load operations at ISO condition. Compared to natural gas, about 1.1 and 1.8 percentage point decrease was observed in efficiency at 50 kW for biogas and producer gas, respectively. However, the efficiency gap between gaseous biofuels and standard cases becomes less and less as the ambient temperature increases.

In distributed generation application, tools for condition monitoring which are easy to apply would be needed to enhance the technology operation, minimizing the maintenance and increasing the reliability and availability. In this respect, the ANN modeling approach was successfully demonstrated for the MGT plant due to the availability of the extensive measured data obtained from an MGT test rig in Norway. The results show that the ANN model can predict the performance parameters of the MGT with high accuracy. The ANN model was thus found to be a reliable baseline model for online monitoring applications at both system and component level. The monitoring tools based on ANN comes up as a user-friendly tool that can be used by operators without prior knowledge of the MGT or ANNs. This could further promote the use of MGT integrated to small-scale bioenergy plants to produce on-site heat and power.

Biomass derived gases namely, biogas and producer gas supply a renewable and carbon neutral energy that not only can contribute to reducing greenhouse gas emissions, but since it is produced by the treatment of waste, it can also help prevent environmental pollution. With some technical modifications, these bio-based low calorific fuels can be utilized in different energy conversion technologies. The MGT in bioenergy application has emerged as a lucrative opportunity, which can effectively deal with two main energy related issues, security of supply and global warming, which can efficiently contribute to a sustainable energy future. This can be considered as an efficient alternative to the costly generation and transmission of electricity, especially in remote areas and in CHP applications, to reduce energy poverty.

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Life Cycle Cost and Benefit Analysis of Low Carbon Vehicle Technologies

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Abstract The transportation sector is currently responsible for about a quarter of global energy demand and emissions. To limit temperature increase to two degrees Celsius, the International Energy Agency projects that about 21% of emissions reduction should come from transport. In recent years, various alternative technology vehicles have emerged, in response to climate targets. Unfortunately, the sustainable energy wave has made it easy for marketing campaigns to influence and shortcut decision making for deployment of new technologies in some countries. This chapter discusses a life cycle-based cost-benefit analysis framework to serve as decision-support for policy makers in lieu of emerging alternative vehicle technologies. The proposed tool evaluates based on two main impacts: net ownership costs and net external benefits. Within each are more specific cost- and emission-related impacts which are assessed using the AFLEET and GREET tools of the Argonne National Laboratory, and using inputs from published studies. The tool is used to evaluate the effects of shifting to alternative energy vehicle technologies for new and in-use vehicles. The approach is demonstrated via a case study in the Philippines. Results favor LPG as a replacement for in-use, gasoline-powered passenger cars, diesel for new passenger cars, and diesel hybrid electric for public utility jeepneys. The data also reflects the good health and social benefits of electric vehicles, but high fueling infrastructure investment costs deter its deployment.

Keywords Alternative energy vehicles · Life cycle · Cost-benefit
Emissions · Electric vehicles · Biofuels

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1 Introduction

1.1 Transportation, Climate Change and Health

In 2013, the transportation sector was responsible for 26% of global energy demand (103 EJ) and 21% of global energy-related CO_2 emissions (7.3 $GtCO_2$). In lieu of meeting climate targets, member countries of the Organization for Economic Co-operation and Development (OECD) are expected to peak transport energy demand before 2050. On the other hand, non-OECD countries are at least expected to stabilize demand by 2030, with the exception of Africa from which continued growth is foreseen beyond 2050 [15].

Across regions, the emission intensity of transport activities vary greatly. For example, even though motorized transport activity was 50% higher in China than in the United States, equivalent emissions were 51% less in the former. This is because of the greater prevalence of bus and rail transport in China, and the preference of the United States for large cars and high demand for domestic air travel.

From a transport emissions reduction perspective, electric vehicles are now on center stage. Rapid electrification of multiple urban travel modes is expected to offset at least a quarter of total transport energy demand in order to limit temperature rise to a two-degree Celsius scenario (2DS) until 2050. Unfortunately among emerging alternative technologies, only electric vehicles (EV's) are assessed to be on track by the International Energy Agency [15], based on deployment, market penetration and technology development information. The total EV stock crossed the 1 millionth mark in 2015 with an annual sales growth rate of 70% in 2015. The EV market will have to sustain an average annual growth rate of at least 39% to meet the 2DS.

However, electrification as a solution is not applicable to all vehicle types. Outside electric vehicles, biofuels are expected to offset plenty of emissions especially from non-urban freight transport, of which use-cycle requires high energy density fuels. On a lesser degree, the same is expected from natural gas technology for the 2DS.

As important, are the effects of transportation to human health. Recent data reports that outdoor air pollution is responsible for more than 3.2 million deaths per year, worldwide [40]. Fine particulate matter (PM2.5) and ozone are associated with increased mortality and respiratory diseases, while exposure to nitrous oxide, ozone and PM is linked to allergic responses [5, 17]. Some studies have also presented evidences linking air pollution to cardiovascular diseases [4]; lung cancer [30]; and premature birth [36]. Though evidences in literature have yet to reach a consensus, there is definitely an agreement that significant exposure to vehicular air pollution poses adverse effects to human health.

In addition to climate-related and health effects, noise from transport has also been found to affect learning and comprehension [8]; sleep [7]; and high blood pressure [19].

1.2 The Emergence of Alternative Technology Vehicles

In response to the multiple adverse effects of conventional transport, various alternative technologies have emerged, and have been the subject of continuous research and development in recent years. These include biofuel blends such as E20, E85, M15, and B20; electric vehicles (EV); plug-in hybrid electric vehicles (PHEV); diesel hybrid electric vehicles (DHEV); liquefied petroleum gas (LPG); compressed natural gas (CNG); and fuel cell vehicles (FCV).

In Metro Manila, Philippines, alternatives have long been present in the public transport sector market. For example, LPG-powered taxis have been operational for more than a decade already. It was backed by strong government support to provide the necessary fueling infrastructure, though not without concerns on health issues [9, 37]. Also, the first 100% natural gas-powered vehicles were introduced in the Philippines in 2002 [12]. With regards to the signature minibuses of the Philippines called jeepneys, the electric versions were launched in 2008 though full-scale adoption had been facing serious barriers until now. Finally, the gasoline-electric hybrid Toyota Prius C was launched in the country in 2012 [6]. Incremental penetration and deployment of such technologies is to be expected in the coming years to shoulder the national sustainability targets.

1.3 The Role of Policymaking

To stimulate penetration and deployment of such alternatives, strong policies are implemented. For example, strong R&D support can allow the cost of new technologies to catch up with conventional ones. Also, the implementation of vehicle taxes and high fuel taxes can create an even playing field for alternative technologies against fossil-based technologies. Similarly, policies may be used to analyze the market for strategic deployment of new technologies.

Of specific interest, the Philippine senate approved the Electric, Hybrid and Other Alternative Fuel Vehicle Incentives Act in January of 2013. The bill opt to improve market conditions for alternative vehicle technologies by providing tax, importation, and other non-financial incentives to manufacturers and developers of the said technologies.

However, the bill currently does not differentiate priority technologies among specific vehicle types. This creates an opportunity to guide further decision making by developing a decision-support tool for the deployment of alternative vehicle technologies. Considering the weight of investments put into transport infrastructure, serious consideration from planning is demanded, to ensure that the long-lasting effects are for the best interests of the country.

As raised in the first sub-section, solutions for each vehicle type and for each region are not necessarily the same. First and foremost, the performance of various technologies would depend on unique geographical, economic, climatic and technological contexts. Further, suitability of alternatives to specific vehicle types need to consider energy density of fuels, supply pathways, and the usage cycles of specific modes [15]. Different vehicle types would also have different baseline technologies to compare from.

In this regard, a comprehensive cost-benefit analysis framework should be able to help justify, and peg taxes and incentives to required values. Fortunately, all of these tasks can be addressed by a life cycle-based cost-benefit analysis framework, which will be specifically discussed in this chapter.

1.4 Life Cycle Analysis as a Preferred Tool

Methodology-wise, life cycle analysis (LCA) has been the preferred tool in similar studies, such as in the comparison of alternative fuels for transit buses [1, 24]; emissions performance of electric, compressed natural gas and internal combustion engine vehicles [14]; and after-treatment technologies implemented in urban buses (Sánchez et al. [31]). The novelty of the approach to be presented in this chapter shall be towards the selection of system boundaries and in the presentation of results. The method shall be designed in such a way that it can assess costs and benefits simultaneously for potential adopters and society, in lieu of prioritizing technologies for deployment and/or estimating necessary subsidies and incentives to make the fuel shift possible. To do this, the framework shall evaluate and plot ownership benefits versus external benefits to fuel shifting of different vehicle types. The methodology shall be discussed in detail in Sect. 3.

The proceeding sections shall discuss the development of the framework, and demonstrate its use via an illustrative case study performed for various vehicle types in the Philippines. The chapter proceeds with a literature review of LCA applied on transport technologies, followed by the discussion of methods, results, and of the conclusions.

2 Literature Review: LCA as a Tool to Evaluate Emerging Vehicle Technologies

Available literature on life cycle-based comparison of alternative energy vehicle technologies vary greatly in scope, approaches and contexts. Findings of past studies evaluate alternatives for different vehicle types, note sensitivity of results to system boundaries (e.g. well-to-tank, tank-to-wheel, use-phase, etc.), uncover pros and cons of biofuels, and highlight the promises of electric vehicles (EV’s) and fuel cell vehicles (FCV’s).

2.1 On Different Vehicle Types

Ahouissoussi and Wetzstein [1] compared four alternative fuels for transit buses (i.e. biodiesel, CNG, methanol and diesel) based on fuel, maintenance, infrastructure and operating costs. Biodiesel was proven to be cost competitive among considered alternatives. McKenzie and Durango-Cohen [24] also favor alternatives (i.e. Hybrid, CNG, FCV) in terms of operating costs for transit buses, but however note the sensitivity of such results to changes in passenger demand and fuel prices. Also on buses (urban buses), Sánchez et al. [31] favor biodiesel (i.e. B20 and B100) in terms of environmental impacts.

On trucks, López et al. [20] recommend the use of B30 biodiesel considering well-to-tank analysis and CNG from a tank-to-wheel analysis. For light trucks, Lave et al. [18] highlight the issue of limited capacity, range, and high costs for alternative fuel-powered vehicles. The authors found CNG to have low GHG emissions, but noted that the vehicle would need redesigning to increase capacity. The same limitation is true with battery-powered vehicles. Still on the same study, FCV, CNG and bioethanol provide better fuel economy, and also low emissions but are limited by high costs. With considerations for data uncertainty using Monte Carlo Simulation, Sen et al. [32] investigated alternative fuel technologies use on heavy-duty trucks. Results showed that battery-electric had the best performance based on life-cycle emissions and externalities, despite high costs. It is noted that GHG emissions from such vehicles are highly dependent on the emission intensity of electricity generation.

2.2 On Sensitivity of Results to System Boundaries

Studies also demonstrate the sensitivity of results to the scope, approach and boundary used. As mentioned above, in a comparative study of diesel, biodiesel and CNG in refuse trucks, López et al. [20] had different results when energy consumption and GHG emissions were evaluated from well-to-tank and tank-to-wheel approaches. Results recommended the use of the B30 biodiesel pathway from a well-to-tank perspective, while CNG's were more beneficial from a tank-to-wheel perspective.

With regards to use-phase and manufacturing-phase emissions, studies have shown that use-phase emissions greatly outweigh manufacturing-phase emissions, such as in Dai and Lastoskie [10].

2.3 On Biofuels

Specifically looking into biofuels, a good number of researches [1, 20, 28, 31] and forecasts [15] recommend its use for large vehicles such as buses and trucks. However, a limiting factor would be its impact on land-use and potential competition with food supply. Sánchez et al. [31] notes that the environmental benefits of using B20 or B100 biodiesel greatly outweigh life cycle costs when used in urban buses in Madrid, but benefits decrease as the soon as direct land-use is affected. On the other hand, MacLean et al. [22] favors CNG over biofuels in an economic input-output LCA analysis, noting that biofuels can be attractive if they do not compete with food supply.

2.4 On the Promise of Electric and Hydrogen Fuel Cell Vehicles

Finally, recent researches are optimistic on EV's and FCV's. For example, Tong et al. [38] report that battery EV's can reduce life cycle emissions by up to 40%, while FCV's can offer comparable life cycle emissions with conventional gasoline-powered vehicles. Dai and Lastoskie [10] also support battery EV's and FCV's over conventional gas-powered vehicles from an emissions perspective. With a combined criterion of life cycle economic and environmental costs, Sharma and Strezov [33] favor hydrogen FCV's over various conventional and alternative technologies. A couple other researchers commend its potential over other alternatives, but also shed light on deterring issues. Messagie et al. [26] show low environmental impact and operating costs for EV's, but note that the high purchase cost of large battery packs is an issue. High initial/production costs of EV's are also reported by the findings of Goedecke et al. [13] in a life cycle cost analysis of 13 alternative fuel vehicle technologies in Thailand. Lave et al. [18] also note the high costs of FCV's in comparison to current petroleum prices. Ogden et al. [29] believes mass production will significantly reduce FCV life cycle costs.

Another limiting factor for EV's is its dependence on the emission intensity of electricity generation. In a comparison of fuel-cycle emissions from EV's, CNG's and ICEV's, Huo et al. [14] noted that EV's were not able to decrease emissions of other pollutants except for GHG's. Shen et al. [34] also note the potential of hybrid electric vehicles, provided that the electricity source is clean.

On an extreme note, researchers have pondered on the integration of carbon capture and storage to EV deployment, noting its dependence on electricity generation mix. Specifically, this integration is mentioned by Jaramillo et al. [16] in a study of hybrid-electric vehicles, and Dai and Lastoskie [10] in a study of battery EV's and FCV's.

3 Methods and Data

3.1 Life Cycle Framework

This sub-section goes into the details of the life-cycle framework for estimating ownership costs and externalities. Figure 1 shows the life cycle framework.

The analysis can first be separated into two main parts: life cycle ownership costs (LCOC) and life cycle externalities (LCE). For LCOC estimates, the considered system boundary is the vehicle owner (for private cars) or operator (for public transit). From the context of designing policies to increase deployment and encouraging adoption for potential users, this perspective makes more sense than evaluating costs from a national perspective. Ownership costs primarily estimate the immediate benefits to the user. On the other hand, for LCE estimates, the considered system boundary is the society. LCE considerations include fueling infrastructure, health impact, and GHG social impact costs. In this particular study, the emissions are limited to use-phase or fuel-cycle emissions. As cited in Dai and Lastoskie [10], use-phase emissions greatly outweigh manufacturing-phase emissions. Fuel-cycle emissions are estimated from well-to-wheel, which means fuel extraction, conversion and preparation (for conventional); feedstock extraction (for biofuels); and power generation (for electric vehicles) are all covered.

For impact assessment, the functional unit is 1 vehicle lifetime. The reported impacts are for 1 vehicle lifetime. For the resulting case study, the assumed lifetime is 15 years per vehicle.

As mentioned above, the impacts assessed include fueling infrastructure cost, maintenance cost, investment cost, fueling cost, health impact cost and GHG social cost. All impacts are normalized in terms of monetary values for uniformity, using

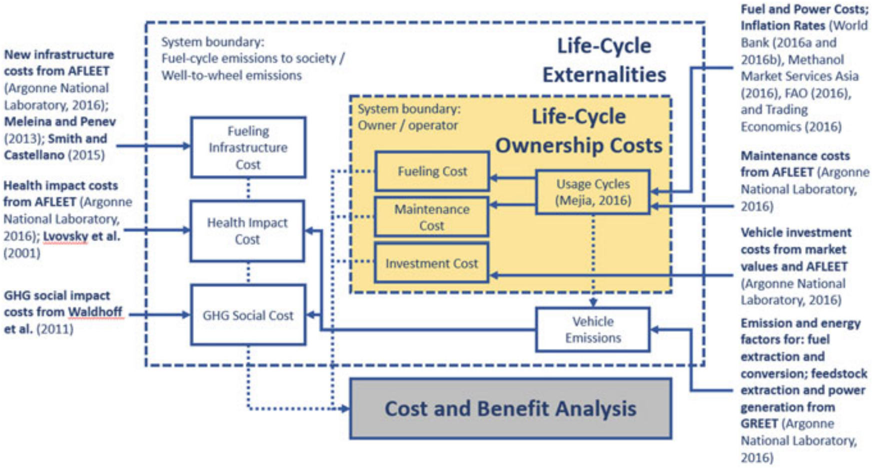

Fig. 1 Life cycle analysis framework

conversion factors from previous studies (e.g. for health and GHG social cost). The results presentated are aggregated in terms of the two main clusters: life cycle ownership costs and life cycle externalities.

While other issues such as ride quality, insurance costs and safety are equally important when it comes to customer satisfaction, the authors focus on major components of net ownership costs and net externalities (as mentioned above) since the ultimate purpose of the study is to aid policy makers in pegging incentives and/ or subsidies to help make the deployment of alternatives economically feasible.

3.2 *Cost-Benefit Analysis Framework*

As shown on Fig. 2 below, cost and benefits will be evaluated in terms of life cycle ownership costs and externalities. Inputs to the model are obtained from the AFLEET [2] and GREET [3] tools, and other published studies. Life-cycle ownership costs are obtained by taking the net present values of investment cost, fueling cost, and maintenance cost. Investment cost data are estimated from actual market values except for flex fuel and fuel cell vehicles, which are derived by adjusting values from the AFLEET Tool. Maintenance costs were also estimated from adjusted values of the AFLEET Tool.

With regards to life-cycle externalities, net present values of fuel dispensing infrastructure cost, health impact cost, and GHG social cost are obtained. Fuel dispensing infrastructure costs are estimated from the AFLEET Tool, with inputs

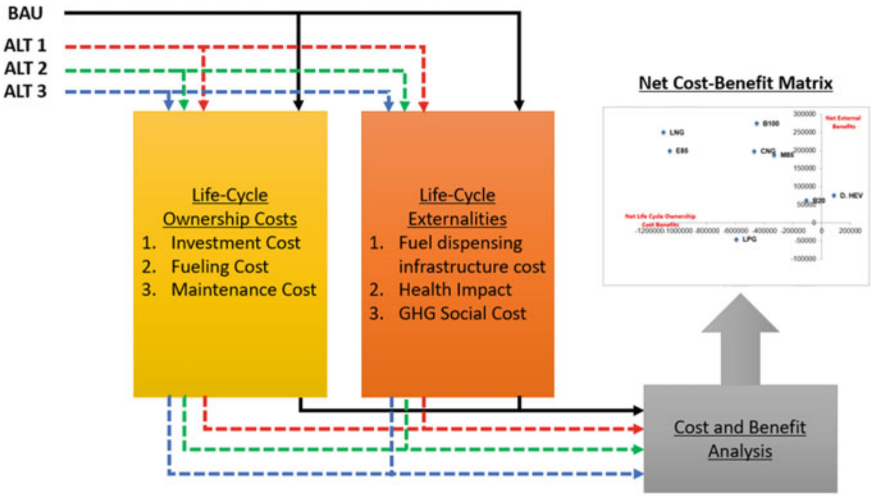

Fig. 2 Cost-benefit analysis framework. Legend: business-as-usual scenario (BAU), alternative technology vehicle 1 (ALT1), alternative technology vehicle 2 (ALT2), alternative technology vehicle 3 (ALT3)

from Meleina and Penev [23] and Smith and Castellano [35]. Similarly, health impact costs are derived from the AFLEET Tool, with inputs from Lvovsky et al. [21]. Adjustments for health impact costs took account of local power purchase parity, population density and inflation rate. Lastly, GHG social costs are derived from Waldhoff et al. [41]. Energy and emission factors are obtained from the GREET tool. Fuel and power costs, and future inflation rates were derived from World Bank [42, 43], Methanol Market Services Asia [27], FAO [11], and Trading Economics [39].

To commence with the analysis, life-cycle ownership costs and externalities are estimated for each alternative technology being considered, based on the usage cycles of business-as-usual (BAU) options. The usage cycles are obtained from Mejia [25]. For new vehicles, alternative fuel vehicle technologies are compared against the corresponding Euro 4 conventional fueled units that they have to compete with, should the technologies be adopted in the market from 2017 onwards. It should be noted that the Philippines adopts the Euro 4 vehicle standards in the said year. Passenger cars were compared with Euro 4 gasoline units while Euro 4 diesel units served as the reference vehicle for all other vehicle types.

The net life cycle ownership cost savings and net external benefits are then estimated for all BAU options against each alternative. Finally, a net cost-benefit matrix is generated for each BAU option, which plots the net life cycle ownership cost savings of each alternative against its net external benefits. The scores for ownership and external costs are the sum of the individual costs contributing to them (e.g. fueling, investment, and operating costs for ownership). No weighting has been used in this study.

Plotting the costs and benefits in a matrix provides an insightful way to present the life cycle results. Highly preferred alternatives should populate the top-right quadrant, suggesting that the switch to the alternative would have both positive ownership cost savings for the user, and external benefits to society. On the other hand, being situated in the bottom-left quadrant would mean that nothing positive can be derived from the technology shift of that vehicle type/use.

4 Illustrative Case Study: Fuel Shift in the Philippines

This section demonstrates the use of the decision-support tool via a case study on in-use vehicles, and new private cars and jeepneys in Metro Manila, Philippines. To start, the cost-benefit analysis matrix for the fuel shift of all in-use vehicles is shown in Fig. 3. The individual cost-benefit analyses for new vehicles are discussed in the succeeding sub-sections as well.

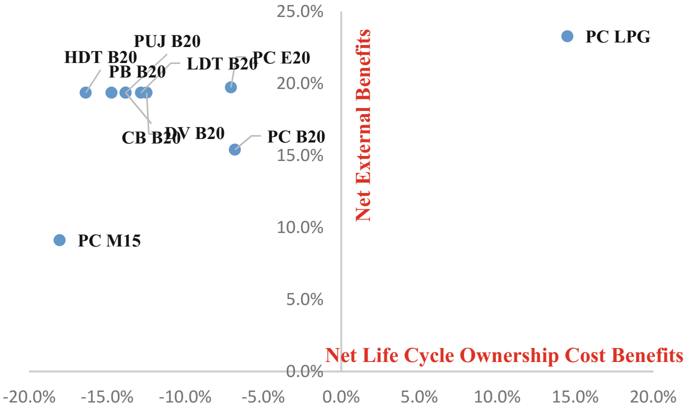

Fig. 3 Net cost-benefit matrix for fuel shift of in-use vehicles. Legend—Vehicles: passenger car (PC), public utility jeepney (PUJ), provincial bus (PB), city bus (CB), delivery vans (DV), light duty trucks (LDT), heavy duty trucks (HDT). Fuels: liquefied petroleum gas (LPG), ethanol blend (E20), biodiesel blend (B20), methanol blend (M15)

4.1 Fuel Shift of In-Use Vehicles

The first scenario tested is if only in-use vehicles are shifted. For this particular case study, existing in-use vehicles (i.e. gasoline for private, diesel for public utility) are used as the baseline. The alternatives are noticeably limited (e.g. no electric alternative). The considered alternatives include B20 (20% biodiesel, 80% diesel), E20 (20% ethanol, 80% gasoline), M15 (15% methanol, 85% gasoline) and LPG. The impacts for each shift are normalized in monetary units (USD), and are presented in terms of percentage improvements in comparison to the baseline. It is noticeable that the only shift that will make immediate sense is the shift of in-use passenger cars from conventional gasoline to LPG. This is attributed to the baseline fuel not being desirable, in the first place. Conventional gasoline is too expensive while LPG is cheap, making the fueling cost difference significant. The emissions of LPG are also notably far cleaner than conventional gasoline. Other alternatives present comparable positive external benefits to society, but would however need subsidies to become financially viable and attractive to potential adopters.

4.2 Fuel Shift of New Vehicles

For the new vehicles scenario, the baseline is conventional Euro 4 fuel. With a better quality, cleaner baseline fuel in comparison to the in-use vehicle scenario, external benefits would notably decrease. The assessed impacts have also been normalized in monetary terms (USD), and are reported for the whole lifetime (i.e. 15 years) of

1 vehicle unit. Looking at the results, one vehicle lifetime's worth of net ownership costs greatly outweigh the net external benefits for most alternatives.

However, from a societal perspective, these net externalities would become significant when summed up altogether. For passenger cars (Fig. 4), diesel-powered vehicles seem attractive even in comparison to Euro 4 gasoline. Low fueling cost mostly contribute to its positive ownership cost benefits. With regards to LPG, it is notable that it now incurs higher ownership costs when put against Euro 4 fuel. For EV's, it is important to highlight that they have commendable health and social benefits. However, the high cost of commissioning new fueling infrastructure contributes to most of its negative externalities. For most other passenger car alternatives which have positive external benefits, the major deterring factor on ownership is the high investment cost for the vehicle. Significant subsidies and/or incentives need to be put in place to make them financially attractive to potential adopters.

For public utility jeepneys (Fig. 5), shifting to diesel hybrid electric vehicles (DHEV) is most attractive. This is mainly because of its very low fueling cost, amid its high initial investment cost. On the other hand, electric vehicles remain unattractive due to high infrastructure cost requirements for refueling, amid very good health and social benefits. For biofuels, the high fuel cost in comparison to the baseline diesel fuel make them unattractive for potential adopters. Either way, the external benefits from biofuels are marginal in comparison to DHEV's. It is notable that for both private cars and public utility jeepneys, CNG vehicles pose negative net external and net ownership benefits, primarily due to high fueling and infrastructure costs. Emissions related benefits from CNG's are also not impressive.

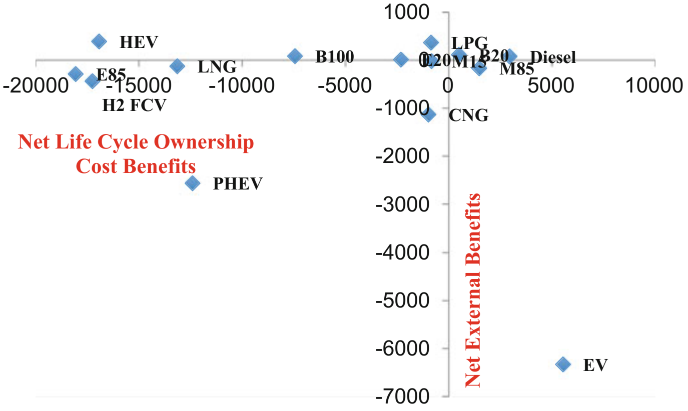

Fig. 4 Net cost-benefit matrix for new passenger car fuel shift. Legend—Fuel: methanol blend (M85, M15), biodiesel blend (B20, B100), liquefied petroleum gas (LPG), ethanol blend (E20, E85), liquefied natural gas (LNG), compressed natural gas (CNG), hybrid electric vehicles (HEV), hydrogen fuel cell vehicle (H2 FCV), plug-in hybrid electric vehicle (PHEV), electric vehicle (EV)

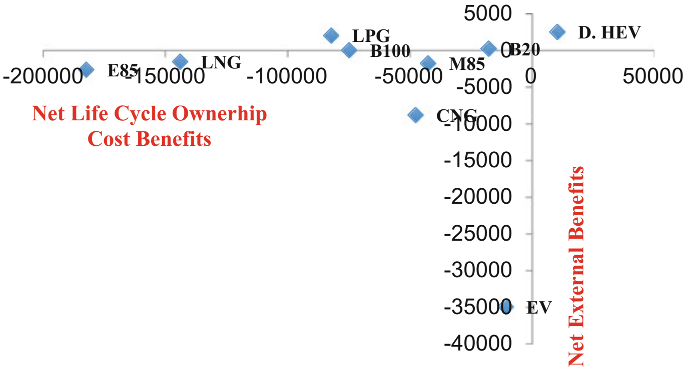

Fig. 5 Net cost-benefit matrix for new public utility jeepney fuel shift. Legend—Fuel: methanol blend (M85, M15), biodiesel blend (B20, B100), liquefied petroleum gas (LPG), ethanol blend (E20, E85), liquefied natural gas (LNG), compressed natural gas (CNG), diesel hybrid electric vehicles (DHEV), electric vehicle (EV)

From a long term perspective, public utility vehicles such as jeepneys and buses have the advantage of benefitting early from the development of EV and hybrid vehicles due to a few aspects which electric drive trains do better than internal combustion engines (ICE's). Since public utility vehicles are heavy, they will benefit from the high torque of electric motors. Moreover, since these vehicles require stopping a lot, they will benefit from getting this at low speeds. Additionally, batteries can recover energy from frequent braking. From an economic perspective, public utility vehicles would also enjoy less maintenance due to less moving parts in EV's, and less per passenger-mile cost compared to private passenger vehicles.

5 Conclusions

The study presented a practical and visual way to look into costs and benefits of shifts to alternative vehicle technologies, using a life cycle-based cost-benefit analysis framework. The framework assesses impacts from a functional unit of 1 vehicle lifetime (15 years), and considers as system boundary the individual owner/operator for ownership costs, and the society for external benefits. The results are presented in a net cost-benefit matrix to serve as a decision-support tool for policy making.

The illustrative case study discussed only the key insights from the data—plenty other insights can be obtained from the results. Based on the results for passenger cars and public utility jeepneys, the following recommendations can be made:

1. Promote LPG to in-use, gasoline-powered passenger cars.
2. Promote diesel hybrid electric to public utility jeepneys.
3. Improve productivity of coconut industry and explore other feedstocks to lessen fuel cost for biodiesel in the Philippines.
4. Perform an in-depth study on tax incentives and infrastructure commitments for electric vehicles.

In comparison to the 2DS scenario created by IEA [15], the chapter results support that EV's can potentially be impactful because of their very good health and social benefits. However, government intervention in the form of potentially large infrastructure investments are needed to make it work. With regards to biofuels, marginal external benefits can also be achieved if subsidies are offered to adopters.

From a longer-term perspective, if it is agreed that ICE's would eventually be replaced by EV's, policy makers should aim for reducing the emissions during the transition period. It may not make much economic sense to develop new fueling infrastructure which will be irrelevant in a foreseeable future. In this regard, biofuels would appear to be a more reasonable alternative during this transition period, coupled with EV's and hybrid EV's. For biofuels, an advantage is being able to use the existing fuel distribution and vending infrastructure, and having minimal modification to the existing ICE-based vehicles – translating to less investment from the part of the owner.

Acknowledging that an EV-future is well-favored in literature, the alternative did not appear too attractive in this particular study. This is due to the fact that the perspective used is immediate, and transition-based. Considering that there are almost zero EV's and zero charging infrastructure in the Philippines at present, deploying this technology would require heavy investment from the government, translating to large external costs. It would be impractical for the government to suddenly promote its use to the public. To make successful EV deployment, the government would have to make creative programs such as public-private partnerships to finance the needed infrastructure. Otherwise, EV's are already in an attractive position.

To conclude, with the excitement brought about by the sustainable energy wave, it is very easy for marketing campaigns to influence policies and shortcut policy-making. However, objective and evidence-based policy making should never be put aside. Decisions pertaining to transport infrastructure have long-term impacts and, in a way, cause technology lock-in so decisions have to be made right the first time. Experiential learning through literature review, and the creation of practical tools such as the one presented in this study, aid in this process. The preferred approach in this study has the following advantages:

1. The plotting of external benefits versus ownership benefits help policy makers identify which alternatives are ready for deployment (e.g. DHEV's for jeepneys), which ones can produce external benefits through subsidies (e.g. biodiesel and LPG), and which ones require heavy infrastructure investments in order to work (e.g. EV's).

2. The visual presentation is a good tool for evaluating potential policy impacts. A comparison of costs and benefits between two policies may be performed.
3. Separate analysis for in-use and new vehicles show the effect of varying baseline scenarios.
4. The use of tested tools and databases (i.e. AFLEET and GREET) add credibility to the results and make implementation easier.

With the transport sector supplying about a quarter of emissions globally, similar tools will continue to be developed and evolve to fit changing needs in the field. Abundance of research in the field can only help researchers from different regions learn from each other's experiences and methods.

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Systematic Analysis for Operability and Retrofit of Energy Systems

Viknesh Andiappan and Denny K. S. Ng

Abstract This chapter presents a systematic analysis framework for design operability and retrofit of energy systems. This analysis framework consists of Disruption Scenario Analysis (DSA), Feasible Operating Range Analysis (FORA) and debottlenecking analysis for an energy system design. In the proposed DSA, equipment failure scenarios are examined to determine the operability of an energy system design. Meanwhile, FORA determines the feasible operating range of an energy system, taking into account the interdependency between utilities produced and represents a range of net utility output that can be delivered within design and performance limitations. Such range allows designers to determine whether an operating energy system requires debottlenecking and retrofitting. In the event where debottlenecking of an existing energy system is required, the proposed framework incorporates step-by-step debottlenecking procedures. To illustrate the proposed framework, biomass energy system (BES) design is used as a illustrative case study. In the case study, the BES is analyzed to determine if it would require retrofitting in order to increase its heat production to 1.5 MW. Based on the results from the analysis, it is found that additonal 50% and 100% increase in anaerobic digester and fired-tube boiler capacity respectively are required. This addiotional capacities yield a favorable benefit-cost ratio (BCR) value of 1.95 which indicates that the benefits from increased heat production is greater than the costs of increasing equipment capacities, hence, making this a viable retrofit action.

Keywords Design operability and retrofit analysis · Feasible operating range analysis · Disruption scenario analysis

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Nomenclature

Indices

w	Index for source/raw material stream
j	Index for process units

Parameters

a_{wj}	Output of stream w from process unit j at the baseline state (dimensionless)
b_j	Binary variable indicating operation ($b_j = 1$) or non-operation, ($b_j = 0$) of process unit j (dimensionless)
x_j^{L}	Lower limit of operability of process unit j (fraction)
x_j^{U}	Upper limit of operability of process unit j (fraction)
C_j^{Cap}	Annualized capital cost of technology/process unit j at the baseline state per unit main product (US$/kg.yr)

Variables

x_j	Operating capacity of process unit j (fraction)
y_w	Net flow of stream w from plant (kg/h)
BCR	Benefit cost ratio (fraction)
C_w^{Stream}	Unit cost of stream w (US$/kg)
CAP^{Add}	Total capital cost of additional technologies (US$/yr)

1 Introduction

Energy systems are vital for the production of energy for various process plants. An energy system typically produces heat, power and cooling simultaneously, usually from various fuel sources [1]. As various fuel sources used to produce several forms of energy, the overall fuel utilization efficiency in energy systems is much higher as compared to purchasing energy from centralized facilities [2]. This feature allows industrial plants to reduce their importation of external power from the grid, subsequently reducing operating costs. Besides, on-site energy systems can improve power quality and system reliability by utilizing locally available fuel resources and focuses on meeting local energy demands. However, the benefits of an energy system can only be realized if several aspects are given appropriate attention during its design phase. These aspects include technology selection, equipment sizing, process network configuration, demand profiles, etc. The field of Process Systems Engineering (PSE) offers many approaches to address these aspects.

PSE is a field/discipline concerning the development of systematic approaches and tools to perform process synthesis [3] and design [4]. Process synthesis and design is defined as the "*act of determining the optimal interconnection of* *processing units as well as the optimal type and design of the units within a process system*" [5]. Process synthesis and design requires process designers to find an optimum chemical process design that fulfils aspects such as efficiency, sustainability, economics, etc. [6]. Various systematic approaches have been developed to provide process designers a methodological framework for designing chemical processes [4]. Specifically, these approaches provide guidance in identifying the feasibility of a process before the actual detailed design of its process units. In addition, multiple alternatives are generated and evaluated, thus leading to design decisions and constraints. After ranking by performance criteria, the most convenient alternatives are refined and optimized. By applying these systematic approaches, near-optimal targets for process units can be set well ahead of their detailed sizing [6].

Traditionally, process synthesis and design is performed in a hierarchical manner. Process synthesis and design starts with determining the process plant topology and the process parameters. Subsequently, operating conditions are calculated considering steady state conditions based on economic objectives and process constraints. Finally, control systems are designed to attain the desired dynamic behavior [7]. A similar sequence can be observed in the synthesis of energy systems. According to Frangopoulos et al. [8], the hierarchical approach for energy systems is divided into the following three levels:

1. Synthesis optimization
2. Design optimization
3. Operational optimization

At the synthesis level, optimization is performed to establish the configuration of the energy system. This would consist of the selection of the technological components and the optimal layout of their connections. At the design level, technical specifications (e.g. capacity, operating limits, etc.) are defined for the process units selected during synthesis. Lastly, the optimal operation mode is to be defined in the operational level given that the system synthesis and design is provided.

Despite having an ordered design procedure, the hierarchical approach may pose a disadvantage [9], especially when operational issues occur (e.g., supply and demand profiles, fluctuating prices, etc.). This is evident as such issues are typically considered only at the later stages of synthesis, namely the operational optimization level. At this level, the selected system configuration (which was defined in the earlier synthesis and design levels) might not be sufficiently flexible to cope with anticipated operational problems. Consequently, the energy system may be under- or overdesigned, thus leading to a need to reconsider some of the early stage decisions. However, such key decisions are not to be changed at this stage. This is because design teams suffer from limited engineering budgets; hence, changing an early design decision would cause massive rework and extra cost for completion of the design. If the objective is to establish a completely efficient energy system, the three (e.g. synthesis, design and operation) optimization levels cannot be considered in complete isolation from one another [10]. This is because system operations issues have a direct influence on the solution of design and synthesis level. To address this issue, analysis on system operability, flexibility and retrofit should be given high importance. Operability and flexibility considerations allow designers to recognize the true operating potential of the system and use it to analyze its performance for an intended seasonal energy demand [11]. Once operability and flexibility of the energy system are analyzed, designers can proceed to consider foreseeable operational changes in the future. Future operational changes often refer to varying energy demands and regulatory limits on emissions imposed by policymakers. Based on these changes, designers can thereafter make provisions in the current system design so that it is flexible enough to accommodate for these changes, after it has been put into operation. These provisions include retrofitting and debottlenecking the system design.

Several works have presented approaches to identify bottlenecks and debottleneck processes from various fields. For instance, Harsh et al. [12] presented a work that uses a flowsheet optimization strategy to identify process bottlenecks in an ammonia process. Following this, a mixed integer non-linear programming (MINLP) model was applied in Harsh et al. [12] to determine where retrofitting is required in the ammonia process. Subsequently, Diaz et al. [13] introduced minor plant structural modifications for an ethane extraction plant using an MINLP model. The model was used to determine the optimal configuration and operating conditions for the ethane extraction plant. Later, Litzen and Bravo [14] proposed a heuristic approach based on a methodological flowchart to visualize the benefit-to-cost ratio of each step taken towards the debottlenecking goal. In their work, the approach emphasized the interdependencies among process units, rather than the individual units. On the other hand, Ahmad and Polley [15] adapted pinch analysis to debottleneck a heat exchanger network (HEN). In Ahmad and Polley [15], pinch analysis is used to predict the minimum energy required and capital cost of HEN retrofit for increased throughput. Similarly, Panjeshi and Tahouni [16] attempted to debottleneck a HEN by considering pressure drop optimization procedure. With the optimization procedure, the additional area and the operating cost involved in the HEN was optimized and verified against a crude oil pre-heat train. Alshekhli et al. [17] modelled and analyzed bottlenecks for an industrial cocoa manufacturing process via process simulation tools. This work was focused on increasing the cocoa production rate and determining an economically viable production scheme. Likewise, Koulouris et al. [18] presented a systematic methodology that uses simulation tools to identify and eliminate bottlenecks in a synthetic pharmaceutical batch process. Tan et al. [19] also presented a process simulation strategy to debottleneck batch process in pharmaceutical industry. Recently, Tan et al. [20] developed a algebraic methodology to identify bottlenecks in a continuous process plant by expressing it as a system of linear equations. Later, Kasivisvanathan et al. [21] proposed an MILP model to determine the optimal operational adjustments when multi-functional energy systems experience disruptions. Kasivisvanathan et al. [22] then extended the previous work to develop heuristic frameworks for designers to identify bottlenecks in a palm oil-based biorefinery, especially when variations in supply and production demand are considered.

Despite the usefulness of the aforementioned conitbutions, it is evident that system operability and flexibility is given attention during debottlenecking. As such, this chapter describes a systematic analysis for design operability and retrofit of energy systems (Fig. 1). In this systematic analysis, operability of process units is expressed using inoperability input-output modeling (IIM), a tool developed based on the well-known work of Leontief [23]. In this chapter, operability is defined as the complement of inoperability, which is based on the definition used by Haimes and Jiang [24], who defined inoperability as the fractional loss of functionality (either due to internal factors or due to interdependence on other inoperable sub-systems). This definition differs from the use of the same term by Grossmann and Morari [25] because it explicitly focuses on the concept of a system that may contain several process units functioning at different levels of operability. In this context, inoperability of a process unit can result from internal factors, such as reductions in equipment efficiency (e.g., fouling on heat transfer surfaces) and/or complete failure (i.e., breakdown); however, it may also result from an otherwise functional process unit being linked to a partially inoperable unit elsewhere in the plant (e.g., a gas engine forced to run below capacity due to problems with biogas supply from an inoperable anaerobic digester). These unit specific instances could cause negative impacts on system flexibility unless necessary design interventions (e.g., retrofitting) are taken. In this respect, the application of IIM in energy systems is fortunately an employable tool.

Via IIM, a simple mixed integer linear programming (MILP) model can be developed to analyze the flexibility of an energy system design when process units experience disruptions. This can be employed with assumptions such as partial or complete inoperability of some individual process units within the energy system. This approach also assumes that the process network of an energy system involved can be described by a system of linear equations, with each process unit being characterized by a fixed set of material and energy balance coefficients. Following this, the MILP model is used to analyze the impact of inoperability of individual process units towards energy system flexibility. If a design is deemed to possess insufficient flexibility to meet demands due to specific unit inoperability, this chapter subsequently entails a step-by-step guide to debottleneck and retrofit a given design based on benefit-cost ratio (BCR).

2 Systematic Analysis Framework

As shown in Fig. 1, the presented systematic analysis framework can be applied using various methods such as mixed integer non-linear programming (MINLP) models, input-output models, Monter Carlo simulations and etc. In this chapter, linear inoperability input-output modelling (IIM) was used to demonstrate the procedure [23]. Although most complex systems are non-linear, locally linear

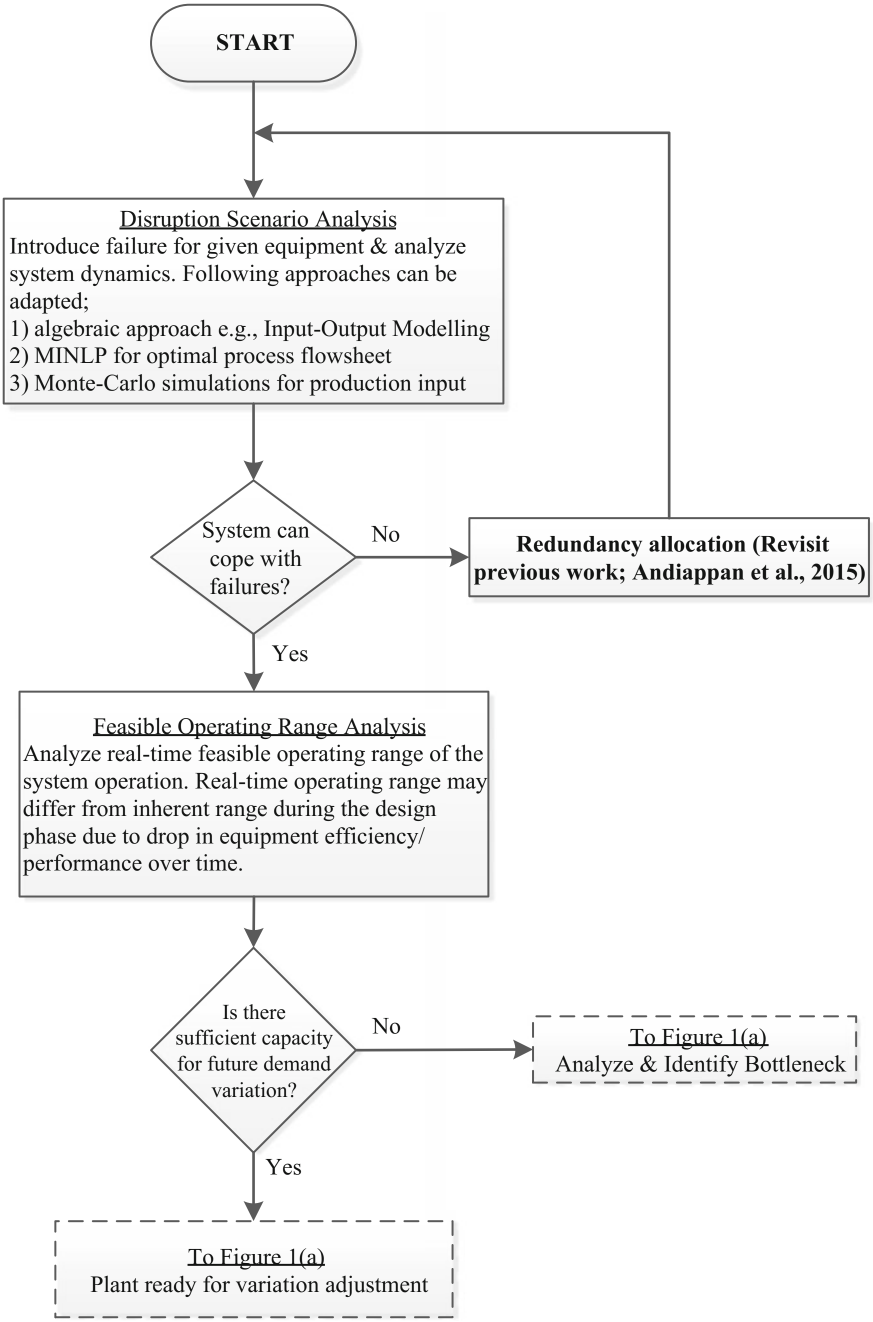


Fig. 1 Systematic analysis framework for design operability and retrofit of energy systems

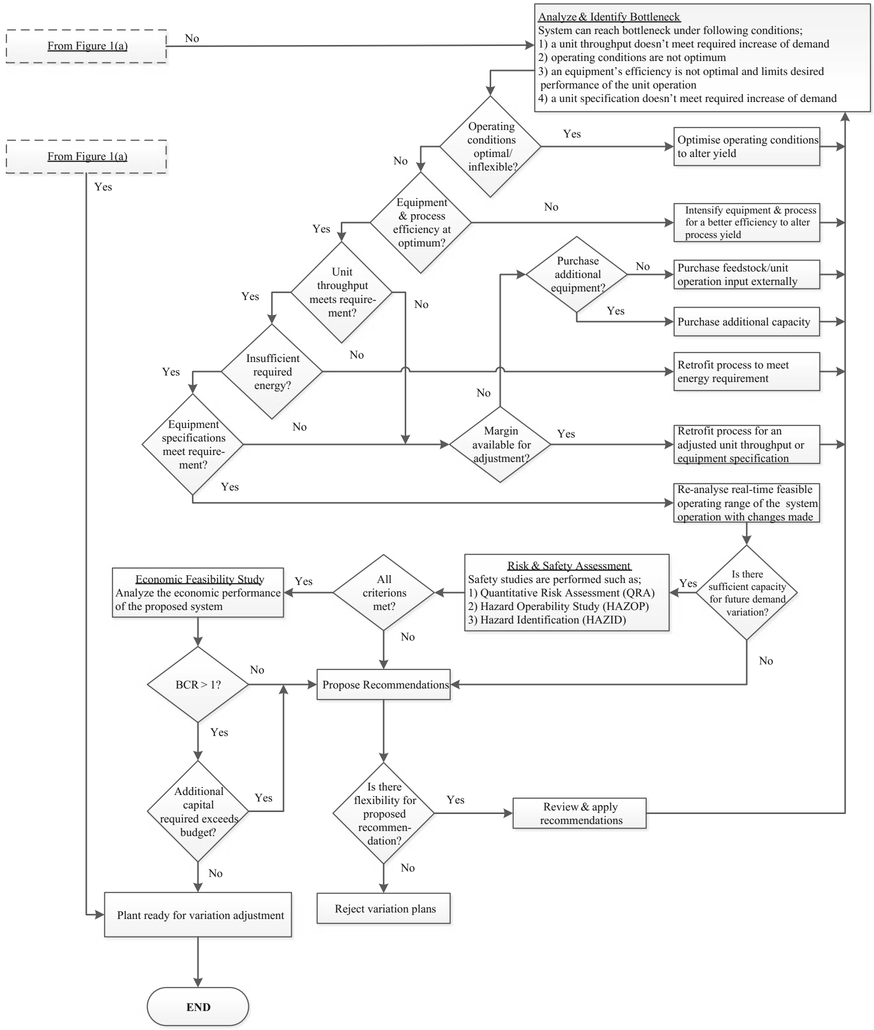


Fig. 1 (continued)

approximations usually provide a good approximation. This is because non-linear, higher order or polynomials terms vanish at the limit of small perturbations [26]. IIM is used to express the performance (e.g., operability, material and energy balances) of units in an energy system in terms of linear correlations as shown by the following equation:

$$\sum_{j=1}^{J} a_{wj}x_j = y_w = \forall w \tag{1}$$

where a_{wj} represents the process matrix of input and output fractions to and from a certain process unit j. Meanwhile, x_j is the fraction of operating capacity for a process unit (where 1 represents a unit at 100% operation, i.e., baseline capacity and 0 for a unit which is shut down). y_w is the net flowrate of a given stream w (i.e., input or output). Note that positive values for y_w represent purely product streams, while negative values for purely input streams. Zero values for y_w denote streams with intermediates. To better illustrate the concept of IIM in Eq. 1, consider a process unit with an operating capacity of x_1. Figure 2 shows a sample gas engine unit which converts 105.31 kg/h of biomethane (y_1) to 416.30 kW of power (y_2) and 526.57 kg/h flue gas (y_3). All process streams (i.e., biomethane, power and flue gas) are expressed in terms of Eq. 1 to give the following;

(i) Biomethane: $105.31x_1 = -y_1$
(ii) Power: $416.30x_2 = y_2$
(iii) Flue gas: $526.57x_3 = y_3$

where matrix a_{wj} for y_1, y_2 and y_3 flow rates are 105.31, 416.30 and 526.57 respectively. If the gas engine operates at 100% under normal operation (baseline capacity), x_1 becomes 1. This results in −105.31 kg/h of biomethane, 416.30 kW of power and 526.57 kg/h of flue gas. It is worth emphasizing that the negative values for biomethane denote that it is a process unit input.

During operation of the energy system, x_j may operate within constraints:

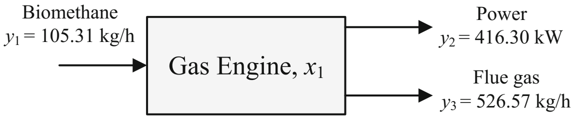
$$x_j^{\mathrm{L}} b_j \leq x_j \leq x_j^{\mathrm{U}} b_j \quad \forall j \tag{2}$$

where x_j^{L} and x_j^{U} are the minimum and maximum operating capacity limits for process unit j, respectively. The maximum limit represents the true maximum capacity of process unit j, which includes safety margins.

2.1 Disruption Scenario Analysis (DSA)

Based on Eqs. 1 and 2, the systematic analysis begins with Disruption Scenario Analysis (DSA) (Fig. 1a). In DSA, equipment failure scenarios are simulated to determine if a designed energy system is able to remain operable, despite facing simulated disruptions. Disruptions within an energy system can result from dips in efficiency and/or failure (e.g., breakdown) in a given process unit. To illustrate this, it is assumed that the gas engine unit in Fig. 2 experiences drop in efficiency as a result of compressor fouling. Due to such drop in efficiency, the gas engine unit

Fig. 2 Illustrative example of gas engine unit operating at baseline capacity



now operates below baseline capacity with operating capacity of 80%. In this respect, x_1 becomes 0.8. As such, input and output values for the gas engine would be −82.25 kg/h of biomethane, 333.04 kW of power and 421.26 kg/h of flue gas as shown in Fig. 3.

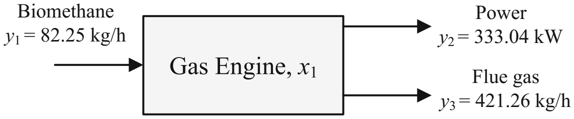
Alternatively, if the gas engine experiences sudden breakdown, x_1 would be set to 0. It is noted that the drop in efficiency inhibited the system from meeting its normal operation of 416.30 kW power, in which it was designed for. In such case, process designers are required to revert back to the previous design approaches related to allocating redundant process units [27]. In this step, optimization parameters considered (e.g., minimum reliability level) can be revised to design an improved energy system. If the revised design is sufficiently equipped to handle such failures, the design is then analyzed via Feasible Operating Range Analysis (FORA).

2.2 *Feasible Operating Range Analysis (FORA)*

Feasbile Operating Range Analysis (FORA) can be described using the previous shown illustrative example in Fig. 3. Since the gas engine unit operating at 80% capacity is unable to meet its normal operation of 416.30 kW power in Fig. 5, an additional gas engine unit must be allocated. Once an additional gas engine unit is allocated and both units are able to produce 416.30 kW of power, they are analyzed further via FORA. In FORA, Eqs. 1 and 2 and used to examine the real-time feasible operating range of an energy system. Feasible operating range is a function of the process network topology as well as the stable operating range of individual process units themselves. The feasible operating range is a representation of system flexibility as it accounts for the interdependency between utilities produced and represents a range of net utility output an energy system can deliver within its design limitations. To determine the feasible operating range, the minimum and maximum net output flowrates for each utility supplied by the energy system is determined. The algebraic procedure for FORA, as applied to a system with three output streams, is as follows:

1. Let A, B, C be the net output flowrates of utilities supplied by a designed energy system.
2. Flowrate of output A is varied while keeping the B and C constant to determine its minimum and maximum flowrates. The minimum value for A is the lowest value of A before the system reaches an infeasible operation. Meanwhile, maximum value for A is the highest value of A before the system reaches an infeasible operation. This is represented in Fig. 4a.

Fig. 3 Illustrative example of gas engine unit operating below baseline capacity



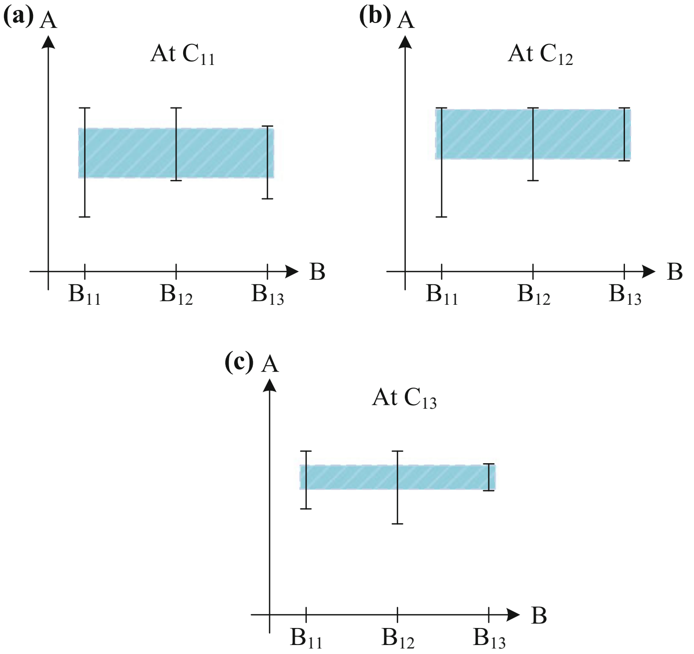


Fig. 4 Feasible operating range analysis (FORA)

3. Step 2 is then repeated for a different output values of B (shown in subsequent data points in Fig. 4a). The corresponding minimum and maximum flowrates for A are noted respectively. Based on the values plotted in Fig. 4a, the common region for the values of A is then identified as shown by the blue shaded region.
4. Steps 2 and 3 are then repeated for several output values of C as shown in Fig. 4b–c.
5. The common regions of A obtained from in Fig. 4a–c are then plotted on a separate Fig. 5. By plotting the common blue regions of A on Fig. 5, the feasible operating region of the energy system is then identified. The feasible operating region is represented by the overlapping region of A values (shown in red on Fig. 5). This overlapping region is considered the region of outputs in which an energy system can operate at without experiencing system capacity limitations.
6. It is important to note that if the number of utilities considered for analysis exceed 3, it may not be possible to express in the form of a (4 or 5 dimensional) diagram. However, the feasible operating range can be still determined by the overlapping regions of each point. This is done by taking the highest common value of the minimum points and the lowest common value of maximum points without the aid of a diagram.

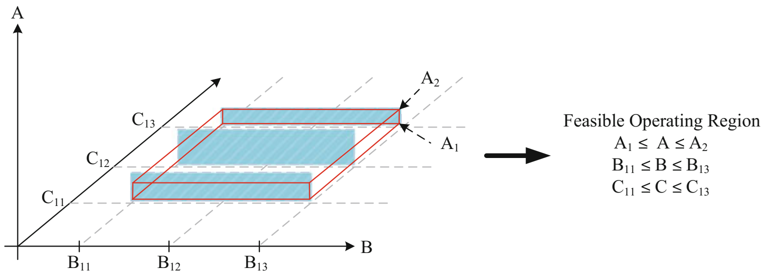


Fig. 5 Identification of feasible operating range

As mentioned previously, the feasible operating range allows process designers to understand the range of net output (i.e., maximum and minimum of each output) in which the synthesized system can deliver without succumbing to system infeasibility and capacity constraints. Such information not only enables designers to validate the energy system performance with the intended seasonal demand requirements, but also provide an idea of the potential design modifications that can be made in production if demand variations are considered future. Even when no provisions can be made to accommodate for future changes, the designer is at least forced to document these considerations. This information can be very useful in the future during operation. It is important to note that the current framework does not account for process dynamics, but considers only multiple operational steady states.

If there is adequate capacity, the existing system can be approved for operational adjustments. In the case where no adequate capacity is available, the existing system design would need to be debottlenecked and retrofitted.

2.3 Debottlenecking and Retrofitting

The subsequent task is comprised of several sequential steps for a process-oriented debottlenecking. The sequential steps proposed in this framework is extended from the debottlenecking framework developed by Kasivisvanathan et al. [22]. In general, when the demand of a single utility changes, all stream flowrates of the system will experience an incremental change. On the other hand, if there are multiple utility demand changes, the percentage of change in stream flowrates would depend on the system configuration. The incremental change is used to analyze the system for limitations in the current process specifications and configuration. Such limitation in an energy system leads to a process bottleneck. A process unit is considered a bottleneck when there are limitations in feedstock and equipment capacity, insufficient energy supply, or sub-optimal operating conditions and equipment efficiencies that prevent satisfactory operation from being achieved.

Once the process bottleneck is located, several strategies can be used for debottlenecking depends on the nature of bottleneck. These strategies include;

- Adjusting operating conditions (e.g., pressure, temperature, efficiency)
- Altering equipment throughputs and specifications
- Ensuring adequate supply of energy
- Purchasing input or raw materials can be purchased externally.
- Purchasing additional equipment to increase the overall system capacity
- Process intensification [28, 29], which has been proposed as a synergistic strategy with Process Integration [30] and PSE [31].

It is important to note that each step in Fig. 1 is performed based only on one bottleneck process unit at a time. For instance, if a bottleneck is addressed by purchasing additional equipment, it is important to ensure that the entire network does not experience a similar bottleneck before moving to the next step. Once the network design is clear of a similar bottleneck, the design is assessed for the next criteria which is ensuring adequate energy supply, as shown in Fig. 1. If there are no further bottlenecks identified, the system design is re-assessed with the FORA to determine the new feasible operating range of the energy system design. The new feasible operating range would ensure whether the system design has sufficient capacity for the demand variations considered.

After re-analyzing the feasible operating range, the subsequent steps would be analogous to the steps stipulated in Kasivisvanathan et al. [21]. Subsequent steps include basic risk assessments such as quantitative risk assessment (QRA), hazard operability study (HAZOP), hazard identification analysis (HAZID) [32] and economic feasibility assessment. In the economic feasibility assessment, benefit-cost ratio (*BCR*) is used. *BCR* is the ratio of overall savings gained from proposed modifications in a system to the additional investment for modifications as shown in Eq. 3;

$$BCR = \frac{\sum_{w=1}^{W} C_w^{\text{Stream}} y_w}{CAP^{\text{Add}}} \tag{3}$$

where C_w^{Stream} is the unit cost of stream i and CAP^{Add} is the capital cost of additional equipment. CAP^{Add} is given by Eq. 4 below:

$$CAP^{\text{Add}} = \sum_{j=1}^{J} C_j^{\text{Cap}} x_j^{\text{U}} \tag{4}$$

where $\mathrm{C}_j^{\text{Cap}}$ is the annualized capital cost of process unit j with maximum operating capacity x_j^{U}. If the *BCR* is greater than 1, it would mean that the benefits of the modifications outweigh the investment costs associated with the modifications. On the other hand, if the *BCR* is not greater than 1, new modifications must be proposed. In this respect, it is possible to consider an entirely new design all together.

The following section illustrates the systematic analysis frameworks in Figs. 1, 4 and 5 via a case study. This case study focuses demonstrating the systematic analysis framework to analyze the impact of individual process unit inoperability on the feasible operating range of a palm biomass energy system (BES) design and debottleneck it to meet future energy demand increase.

3 Illustrative Case Study

In this case study, the framework in Fig. 1 is demonstrated using a biomass energy system (BES) design. As shown in Fig. 1, palm oil mill effluent (POME) is used as biomass feedstock for the BES. POME is digested in two anareabic digesters to produce bio-methane. The produced bio-methane is utilized in a fired-tube boiler to produce and/or in a gas engine to produce heat and power. The BES operates at a heat output of 1.0 MW. A portion of this heat generated is supplied to neighboring facilities. In the near future, heat demands of neighboring facilities are expected to rise to 1.5 MW. However, after a duration of operation, certain process units may experience inoperability due to drop in efficiency. As such, the systematic analysis framework described in Sect. 2 is used to analyze impact of such individual unit inoperability on the feasible operating range of the BES design and to determine if the BES design would require retrofitting.

Figure 6 shows the process flow diagram of the BES design. Table 1 shows the type of equipment in the BES as well as their respective minimum and maximum feasible capacities. Table 2 summarizes the overall material and energy balances for the BES. Note that the positive and negative values in the table represent the outputs and inputs to the BES, respectively. The information in Tables 1 and 2 is then used to formulate the model for the BES based on Eqs. 1 and 2. The model for this case study is developed using LINGO v14 [33] with Dell Vostro 3400 with Intel Core i5 (2.40 GHz) and 4 GB DDR3 RAM.

Based on the framework, the developed model is used to review the capability of the BES design to handle inoperability arising from dips in efficiency/performance over time. Such changes in equipment performances would certainly affect the real-time feasible operating range of the BES. If such changes in efficiencies are ignored, it may prove costly as decision making procedures would be made based on inaccurate representation of the BES performance. To address this issue, DSA is

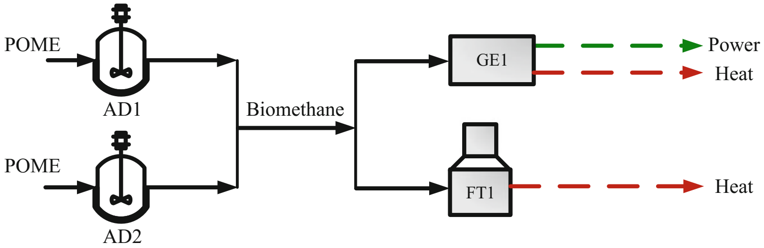


Fig. 6 System configuration of BES

Table 1 Minimum and maximum feasible capacities for equipment in BES

Equipment	Input-output variable, x_w	Minimum feasible fractional capacity, x^L	Maximum available capacity, x^U
Anaerobic digester, AD1	x_1	0.60	0.70
Anaerobic digester, AD2	x_2	0.60	1.00
Gas engine, GE1	x_3	0.12	1.00
Fired-tube boiler, FT1	x_4	0.12	1.00

Table 2 Mass and energy balance data for technologies in BES

	AD1	AD2	GE1	FT1	Net flow
POME (kg/h), $-y_1$	−27750.00	−27750.00			−55500
Biomethane (kg/h), y_2	159.57	159.57	−159.57	−159.57	0.00
Power (kW), y_3			523.98		523.98
Heat (kW), y_4			100.00	1310.49	1410.49

carried out. For this case study, y_3 and y_4 are specifically discussed to present the interaction of the matrices within the system in Fig. 6. Analysis is focused on the net flow rates of heat and power between the equipment shown in Fig. 6. The equation below shows the formulation which represents the net flowrate of heat and power (y_3 and y_4, based on sequence in Table 2) for this case study:

$$623.98x_3 = y_3 \tag{5}$$

$$100x_3 + 1310.49x_4 = y_4 \tag{6}$$

where x_1, x_2, x_3 and x_4 (based on sequence of streams in Table 2) are the operating capacities of anaerobic digesters, gas engines and fired tube boiler respectively. In this case study, DSA assumes the efficiency of a anaerobic digester unit, AD1 has reduced after several years of operation as a result of fouling (shown in Fig. 7). Due

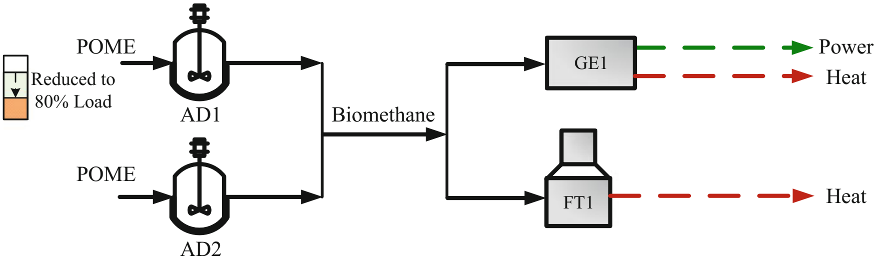


Fig. 7 DSA for case study—Response to anaerobic digester efficiency drop

to fouling, AD1 operates below its normal operation, with operating capacity of 70%. This operability is programmed into the model as;

$$x_1 = 0.70 \tag{7}$$

Based on the analysis, Fig. 7 suggests that the BES is still adept to produce its intended heat output of 1.0 MW despite experiencing reduced efficiency. Following this, FORA is performed to determine the feasible operating range of the existing BES. Figure 8 shows the resulting feasible operating range for the existing BES. Figure 8 suggests that there is a slight reduction in the range of power output from the BES, due to the drop in efficiency experienced by the membrane separator. The real-time feasible operating range indicates that the BES is unable to deliver 1.5 MW of heat with its current configuration and performance. As such, the BES must be analyzed for bottlenecks before making changes in design to cater for 1.5 MW heat.

Based on the procedure presented in Fig. 1, process bottlenecks are identified and summarized in Table 3. The bottlenecks were identified by first tabulating the anticipated capacity increase in each process unit for the BES to deliver 1.5 MW heat (see fifth column in Table 3). Following this, the anticipated capacities are then compared to existing maximum operating capacities shown in the fourth column of Table 3. The comparisons suggest that the bottlenecks present in the BES are the anaerobic digester (AD1) and fired-tube boiler (FT1).

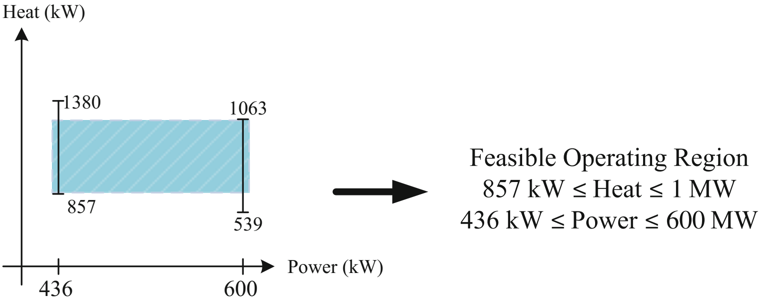


Fig. 8 Identified feasible operating range for case study

Table 3 Identifying bottlenecks in case study

Equipment	Input-output variable, x_i	Minimum feasible capacity, x^L	Maximum available capacity, x^U	Anticipated capacity increase for 1.5 MW, x_i	Bottleneck?
AD1	x_1	0.60	0.70	0.70	Yes
AD2	x_2	0.60	1.00	0.60	No
GE1	x_3	0.12	1.00	0.70	No
FT1	x_4	0.12	1.00	1.00	Yes

To debottleneck the BES design, the model in this case study considers each process unit as a "black box" whereby constant yield and efficiency are assumed for each process units. In this respect, thermodynamic changes in the processes involved were not considered. This means that steps (see first two diamond boxes) from the top of the framework in Fig. 1 is ignored in this case study. Thus, the next step to consider is to increase the amount of raw materials. To achieve this, input of raw materials into the BES must be increased. However, in this example, there is not additional POME required since the bottleneck originates from the fired tube boiler's inability to produce more heat due to capacity restrictions. The next step in the framework is to ensure there is sufficient energy supply for the BES operations. Since the developed model for this case study determines the total energy consumption within the network, it would allocate energy accordingly to fulfil its own energy requirement. As such, proceeding down to the fifth diamond box of the framework leads to increasing the unit maximum operating capacities for anaerobic digester as the next debottlenecking step. It is recommended to increase design capacity of the anaerobic digester and fired tube boiler units with an additional of 50% and 100% respectively to accommodate for the new operation. This capacity is chosen specifically based on discrete size made available in the market by vendors. At this point, it is important to re-analyze the BES to ensure that it is free from other possible process bottlenecks. It is noted that additional iterations through the framework would not yield any further bottlenecks, allowing the new feasible operating range of the BES design to be re-analyzed (via FORA). The analysis yields a new feasible operating range as a result of additional changes in the BES design (Fig. 9). Figure 9 affirms that the modified BES design is now equipped to deliver 1.5 MW power and can be evaluated for associated potential risks. In this case study, it is also assumed that safety assessments do not yield any critical concerns. Following the safety assessment, the proposed design changes are then analyzed for its economic feasibility.

The economic feasibility of the proposed design is analyzed over a year's period via *BCR*. As mentioned previously, *BCR* is a ratio of savings gained from changes in design to the additional capital cost for retrofit. Savings gained from design changes are computed as the difference between income gained by the BES from

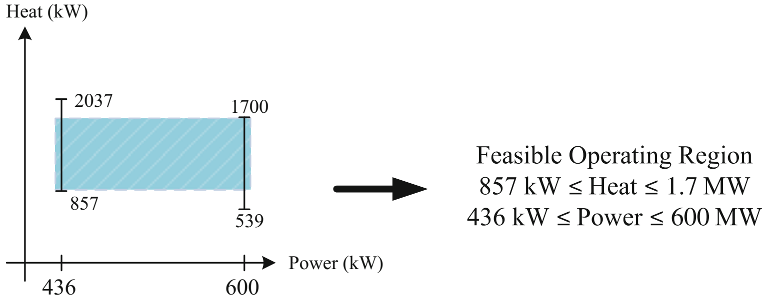


Fig. 9 Identified feasible operating range after proposed retrofit in case study

supply additional heat to the total cost of consuming of additional POME. All costs of the POME along with the price of exported heat are summarized in Table 4. Using the Eqs. 3 and 4, the proposed design yields an economic performance as shown in Table 5. As shown in Table 5, the BCR obtained is greater than unity (1), which indicates that the proposed changes is cost beneficial. In this case, the obtained BCR suggests that this modification should be considered for the BES retrofit.

Table 4 Price and cost of power and palm-based biomass

Stream, y_i	Cost, $\boldsymbol{C}_w^{\text{Stream}}$ (US$)
Exported heat (kW)	0.05/kWh
Palm oil mill effluent (kg/h)	–

Table 5 Economic performance of alternative modification in case study

Economic Performance		
Cost of additional feedstock consumption (US$/yr)		–
Additional income gained (US$/yr)		200,000.00
Additional capital cost (US$)		
Fired-tube boiler	100% Capacity	457,500.00
Anaerobic digester	50% Capacity	330,225
Annualizing factor (/yr)		0.13
CAP^{Add} (US$/yr)		102,404.00
BCR		1.95

4 Conclusions

A systematic analysis framework for operability and retrofit of energy systems is presented. This systematic analysis is a framework that explicitly analyzes process units functioning at different operability levels and corresponding impacts on system flexibility. In particular, the inoperability of process units was expressed using inoperability input-output modeling (IIM). Via IIM, a simple mixed integer linear programming (MILP) model is developed to analyze the flexibility of an energy system design when a process unit experiences inoperability. In the case where a design is deemed to possess insufficient flexibility to meet demands, the described framework subsequently entails a step-by-step guide to debottleneck and retrofit a given design based on benefit-cost ratio (*BCR*). This framework was then demonstrated using an illustrative example to determine if the biomass energy system (BES) would require retrofitting in order to increase its heat production to 1.5 MW. To achieve 1.5 MW heat production, the framework suggests a 50% and 100% increase in anaerobic digester and fired-tube boiler capacity respectively as this yields a favorable *BCR* value of 1.95. Such *BCR* value indicates that the benefits from improved heat production outweighs the costs of increasing its fired tube boiler capacity, hence, making this a viable retrofit action. The presented framework can be applied to various other problems such as re-powering plants, future capacity retirement studies. In addition, the framework can be applied at the design phase of an energy system, or even when it is in operation where modifcations are required.

Appendix

Definitions

Operability: Grossmann and Morari [25] defined operability as the ability of a process to perform satisfactorily under conditions different from the nominal design conditions. In addition, Grossmann and Morari [25], discussed several objectives that are paramount to achieve operability of process. One of these objectives discussed is process flexibility.

Flexbility: Process flexibility is defined as the ability of a process to achieve feasible steady state operation over a range of uncertainties [34]. Based on the aforementioned definitions, it is noted that operability and flexibility are similar as both considerations give importance to ensuring feasible operation by avoiding design constraint violations. However, the key difference between the two is that operability assumes that disturbance scenarios are known in advance while flexibility identifies the worst-case scenario within the range of uncertain parameters and disturbances [34].

Retrofit: Retrofit is a process in which existing capacity is upgraded by implementing energy-efficient technologies or measures such as increasing capacity [31]. The decision to retrofit a process can arise when equipment bottlenecks are present in a process. A piece of equipment is considered a bottleneck when its capacity limits the capability of the entire plant to operate at new conditions.

Debottlenecking: Debottlenecking is a classical approach of modifying existing equipment to remove throughput restrictions and achieve a desired performance that was initially thought to be impossible for a system with its existing configuration [35].

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A Parametric Performance Analysis of a Novel Geothermal Based Cogeneration System

Kiyan Parham and Mohsen Assadi

Abstract This work is an attempt to propose and analyze a geothermal based multi-generation system. The proposed cogeneration system consists of different sections, namely: organic Rankine cycle, geothermal wells, absorption heat transformer, domestic water heater and proton exchange membrane electrolyzer. To assess the cycle's performance, thermodynamic models were developed and a parametric study was carried out. For this purpose, energetic analysis are undertaken upon proposed system. Also, the effects of some important variables such geothermal water temperature, turbine inlet temperature and pressure on the several parameters such as energy efficiencies of the proposed system, water production, net electrical output power, hydrogen production, are investigated. It is shown that, by boosting geothermal water temperate, COP of the AHT increases and flow ratio decreases. Additionally, increasing absorber temperature leads to the reduction of energy utilization factor.

Keywords Geothermal · Organic rankine cycle · Absorption heat transformer Desalination · Hydrogen

1 Introduction

The energy demand increases with industry development and population growth which leads to enhancing air pollution and significant CO_2 emission [1]. Due to latter mentioned problems, a considerable attention has been paid to substituting energy sources by renewable energy resources [2]. Geothermal stands as an outstanding heat source among different categories of renewable energies by the capability of utilization in several industrial applications. Bearing in mind different products of tri-generation cycles, it has the potential to be employed in several

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branches of industrial plants besides technical, economical and environmental benefits [3].

Recently, by the aim of hydrogen production, a novel combined system utilizing geothermal heat source was proposed by Bicer and Dincer [4]. They studied in detail mostly the energy and exergy efficiencies of the proposed cycle. They demonstrated that at the optimum situation first and second law efficiencies were 10.8 and 46.3%, respectively. The exergy and exergoeconamic investigation of a system comprising geothermal heat source and organic Rankine cycle (ORC) was carried out by El-Emam et al. [5]. They results revealed that 5 MW net power output was obtainable. Energy and monetary performance analyses of a geothermal based heating and cooling system, through a dynamic simulation was carried out by Calise et al. [6]. They evidenced that the main two parameters affecting the system performance were nominal geothermal flow rate and natural gas cost. In another work [7], the same group studied exergy and exergoeconomics analysis of a geothermal based poly-generation cycle through a dynamic simulation and assessed the performance of the system. A solar-geothermal based multi-generation system comprising two ORCs, an absorption refrigeration system and a dryer was proposed and investigated by Suleman et al. [8]. A sensitivity analyses besides energy and exergy efficiencies were investigated in detail. A novel geothermal fed system generating cooling, heating, power, hot water and hydrogen was studied by Ratlamwala et al. [9] from both energy and exergy view of points. They revealed that the ambient temperature rise had improving impact on exergetic efficiency and the geothermal source temperature, pressure and mass flow rate had negative impacts on cooling effects. Tempesti et al. [10] designed and analyzed two different solar-geothermal based CHP-ORC systems thermodynamically and investigated the performance of different working fluids. Their thermo-economic assessment studies [11] demonstrated that R245fa had the best performance. Malik et al. [12] proposed and examined a biomass-geothermal multi generation system from the view point of both first and second laws of thermodynamics. The largest exergy destructions occurred in combustion chamber and boiler.

There are lots of works published about coupling ORC into geothermal heat sources. A huge amount of heat is wasted next to ORC in mid/low level temperature range. On the other hand, second category of absorption cycles known as absorption heat transformers convey the capability of boosting temperature to more useful levels. Furthermore, employing a PEM (Proton exchange membrane) seems to be a worthy candidate as the succeeding element of ORC for hydrogen production utilizing the turbine power. The role of hydrogen as the future vehicles fuel besides its environmentally friendly characteristics is upcoming more and more stressed incessantly [13].

At the current work an organic Rankine cycle is coupled into a geothermal heat source followed by a single stage absorption heat transformer employed for desalination purpose. Additionally, an electrolyzer for hydrogen production is integrated to the turbine of ORC for hydrogen production.

The present work aims to investigate the performance of the above mentioned tri-generation cycle in detail. An exhaustive and widespread thermodynamics examination and efficiency assessment of the proposed configuration will be done. In order to identify the effects of some parameters such as; geothermal water temperature, turbine inlet temperature and pressure, absorber, flow ratio, concentration of weak and strong solutions on the cycle performance and the quantity of distilled water, a parametric study is carried.

2 System Description

The schematic diagram of the proposed setup is presented in Fig. 1. As it is evident, there are five subsystems within this multi generation cycle. It starts by geothermal well, then followed by ORC and PEM and absorption heat transformer coupled into desalination system. The scenario of the cycle is as follows:

The evaporator of the ORC is fed by the hot water coming from geothermal well and a portion of its thermal energy is transferred to ORC which produces power. Next to that the flow is divided into two sections and flows towards the AHT

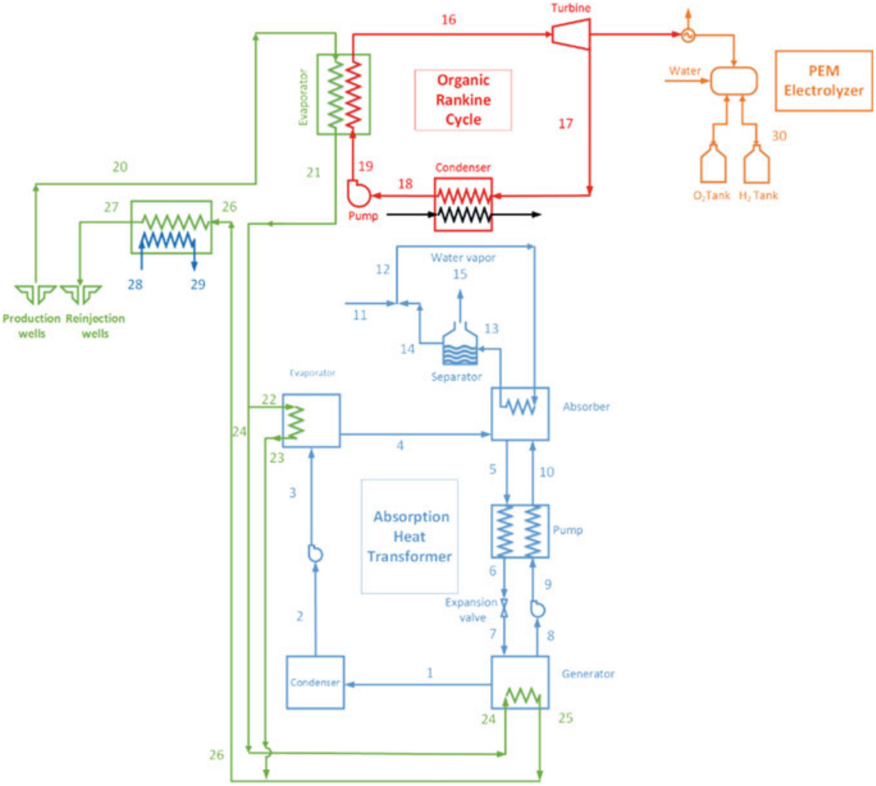

Fig. 1 Schematic diagram of proposed multi-generation system producing power, hydrogen, desalinated water and domestic hot water

evaporator and generator at the same time which provides the demanded heat of AHT. The working pair of AHT is of great importance [14–16] and at the current work the solution of LiBr–H_2O and water are employed as the solution and refrigerant. After unifying the both streams, the mid-level geothermal brine affords the required heat for domestic water heater and then it is reinjected back to the ground via the reinjection well. A portion of the produced power of ORC (50%) is consumed for hydrogen production through a PEM while the upgraded heat of AHT absorber provides the necessitated heat for desalination system. Considering the fact that, isobutene owns lots of outstanding features in terms of negligible Ozone Depletion Potential (ODP) and Global Warming Potential (GWP) besides high latent heat, it is considered as the working fluid in ORC [2, 17]. The considered assumptions within current study are as follows:

1. All the ongoing processes are considered to be in steady state.
2. Negligible changes in kinetic and potential energies [18].
3. Some proper values have been considered for pumps and the turbines isentropic efficiencies [2, 19].
4. Pressure losses through all the pipelines are neglected [20, 21].
5. A liquid-dominated reservoir is considered for the geothermal field [22].
6. Fed temperature to the evaporator and generator are at the same level [23].
7. In the AHT, the refrigerant (water) exiting the condenser and evaporator is assumed to be saturated [2, 24].

3 Thermodynamic Model

For the aim of thermodynamic simulation of the proposed system, a code is developed in Engineering Equation Solver (EES) [25], any element of the system has been assumed as a control volume and first and second laws of thermodynamic besides mass conservation principle have been applied on them.

3.1 Performance Evaluation

Three main products are the outcome of the current multi-generation system in terms of power, desalinated and hot water and hydrogen. It is well known that on assessing the performance of such systems from the view point of first law of thermodynamics, the thermal efficiency is denoted by Energy Utilization Factor (EUF) [26]. For the investigated system in the present work, the is defined as [27]:

$$EUF = \frac{\dot{m}_{30}HHV + \dot{W}_{net} - \dot{W}_{PEM} + Q_u + Q_{heat}}{Q_{in}} \tag{1}$$

where:

Q_u is the useful part of the utilized geothermal heat for desalination purposes by means of the absorber of the AHT:

$$Q_u = \dot{m}_{12}(h_{13} - h_{12}) \tag{2}$$

$$Q_{heat} = \dot{m}_{26}(h_{26} - h_{27}) \tag{3}$$

$$Q_{in} = \dot{m}_{20}h_{20} \tag{4}$$

Considering the fact that AHT is the second type of absorption chillers, coefficient of performance (COP) can be defined for it as the indicator of the cycle's capability to promoting the thermal energy given to the generator and the evaporator of the system:

$$COP = \frac{Q_{abs}}{Q_{gen} + Q_{eva}} \tag{5}$$

Another important parameter in absorption cycles is the flow ratio (f) which is of great importance in cycle performance optimization and is defined as the ratio of the mass flow rates of the strong solution and refrigerant:

$$f = \frac{\dot{m}_s}{\dot{m}_r} = \frac{\dot{m}_8}{\dot{m}_4} = \frac{X_7}{X_8 - X_7} \tag{6}$$

The ability of AHT in boosting the fed temperature level is indicated by gross temperature level which is defined as the temperature difference between absorber and evaporator/generator:

$$\Delta T = T_{abs} - T_{gen} \tag{7}$$

Half of the power by ORC is consumed for hydrogen production through PEM. The quantity of hydrogen produced by the electrolyzer is:

$$\dot{m}_{h2} = \frac{\eta_{elec} * \dot{m}_{PEM}}{HHV} \tag{8}$$

where:

$$\eta_{elec} = 0.56 \tag{9}$$

and

$$\mathrm{HHV_{h2}} = 141{,}800 \ \ (\mathrm{kJ/kg}) \tag{10}$$

Table 1 demonstrates the operational properties at any point.

Table 1 Thermodynamic properties of the system at each state point

Point	m (kg/s)	T (°C)	h (kJ/kg)	P (kPa)
1	0.6618	80	2650	3.169
2	0.6618	25	104.8	3.169
3	0.6618	25	104.8	47.37
4	0.6618	80	2643	47.37
5	6.804	130	291.5	47.37
6	6.804	98.02	226.9	47.37
7	6.804	68.89	226.9	3.169
8	6.142	80	227.6	3.169
9	6.142	80	227.6	47.37
10	6.142	120	299.2	47.37
11	0.09	15	62.92	101
12	10	66.67	279.1	26.95
13	10	100	439.4	101.3
14	9.91	100	419.1	101.3
15	0.09	100	2676	101.3
16	0.09	150	646.2	1509
17	429.9	109.9	586.2	408.2
18	429.9	35	96.55	408.2
19	429.9	35.18	98.79	1509
20	100	128	2722	208.5
21	100	88	368.6	208.5
22	50	88	368.5	208.5
23	50	80	334.9	208.5
24	50	88	368.5	208.5
25	50	80	334.9	208.5
26	100	80	334.9	208.5
27	100	60	251.2	208.5
28	50.07	20	83.84	101.3
29	50.07	60	251.2	101.3
30	0.04903	–	–	–

3.2 Model Validation

The results of Rivera et al. [28] for SAHTs have been employed for validating our simulation outcomes. As demonstrated on Fig. 2, by increasing absorber temperature, flow ration increases slightly and there is an acceptable agreement between our results and those of Rivera et al. It is worth mentioning that the considered assumptions for the both works are the same:

Negligible pressure losses in pipe lines, isenthalpic expansion valve, economizer effectiveness of 0.7, $T_{gen} = T_{eva} = 74.1$ °C and $T_{con} = 20$ °C. The maximum

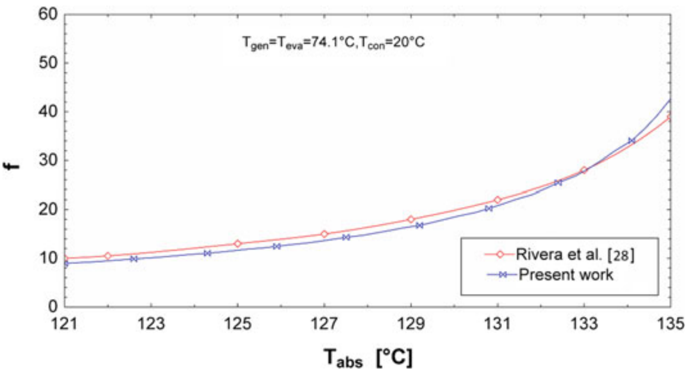

Fig. 2 Validation of the simulation model developed for the AHT system

relative error of 1.21% with respect to the absorber temperature is witnessed which proves the high accuracy of our simulation.

4 Results and Discussion

Figure 3 demonstrates the variation of COP by geothermal water and AHT absorber temperature. As shown by boosting water temperate, COP of the AHT increases. This is because by enhancing geothermal temperature, the temperature and pressure of the AHT evaporator increase which lead to reducing the weak solution concentration out coming from absorber (Fig. 4) and flow ratio (f) (Fig. 5) [29]. The lower flow ratio results in a higher absorption heat capacity and a higher COP. It is evident that, increasing geothermal water temperature which is equal to boosting evaporator and generator temperature has the same trend of decreasing absorber temperature. This is as a result of decreasing flow ratio which leads to higher COP [23].

Figure 4 shows the variation of weak solution concentration by geothermal water temperature. It is clear that geothermal water temperature plays the role of heat source for AHT. The higher the generation or evaporation temperature is, the higher absorption and corresponding gross temperature [23, 29]. But since herein, the absorber temperature is kept constant, so gross temperature lift (ΔT) which is the difference between evaporator and generator temperature, decreases. Decreasing ΔT, will lead to smaller flow ratio which results is smaller weak solution concentration [30]. Apparently, by increasing absorber temperature, Xw will increase which is confirmed on Fig. 4.

As demonstrated in Fig. 5, the flow ratio decreases by increasing geothermal water temperature. The reason is the fact that by enhancing T_{eva}, the maximum pressure of the system will upsurge and the weak solution concentration will decrease (Fig. 4) by decreasing the flow ratio. According to Fig. 3, the lower flow

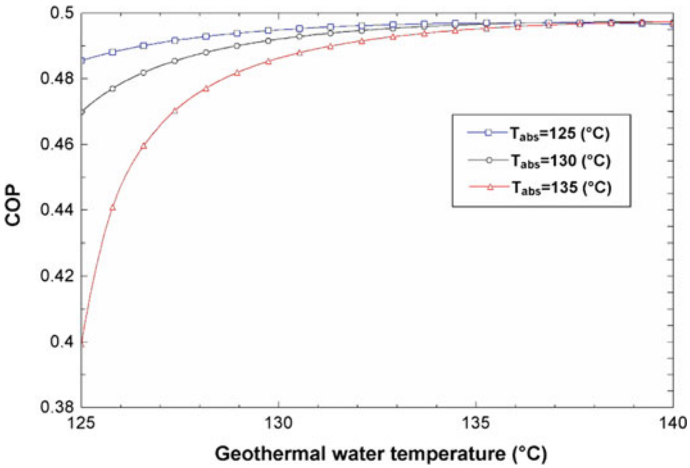

Fig. 3 Effects of geothermal water temperature on absorption heat transformer COP for different absorber temperatures

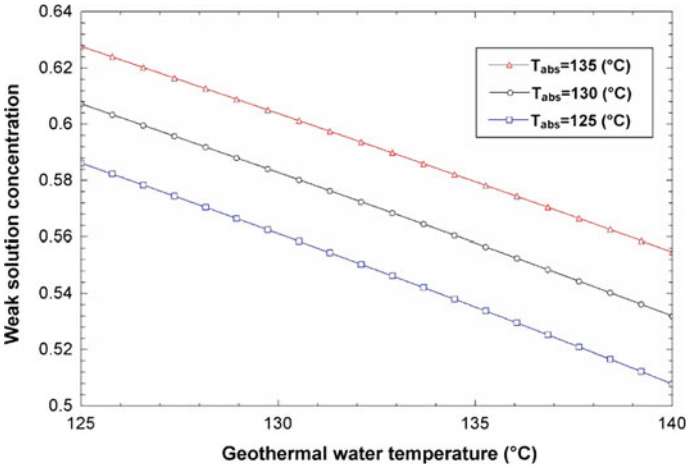

Fig. 4 Effect of geothermal water temperature on weak solution concentration

ratio results in higher absorption heat capacity and a higher COP. As expected, larger flow ratio results in higher Tabs and more mechanical power losses [19].

The variation of strong solution concentration against geothermal water temperature is plotted in Fig. 6. By increasing geothermal water temperature, the temperature of evaporator and at the same time generator increase and as expected Xs will increase. The higher Xs results in the higher flow ratio and can also cause a crystallization of LiBr problem [16, 30]. As it is evident, changing absorber

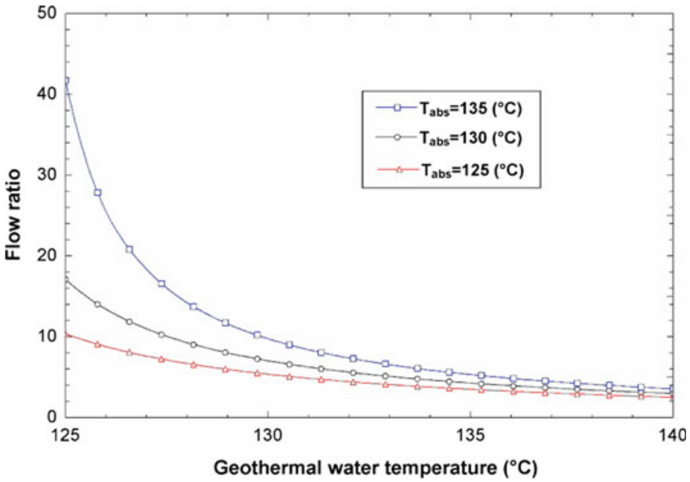

Fig. 5 Effect of geothermal water temperature on flow ratio

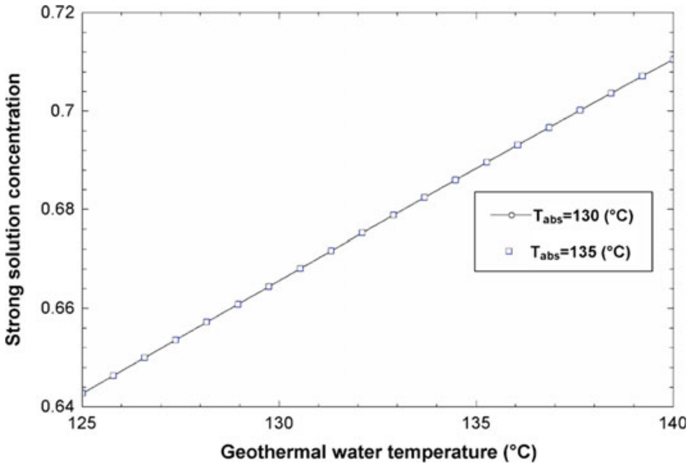

Fig. 6 The effect of geothermal water temperature on strong solution concentration

temperature will not influence strong solution concentration since Xs is not dependent to absorber temperature.

Figure 7 investigates the overall effects of geothermal water temperature on strong and weak concentration differences versus. It is evident that by increasing absorber temperature, the concentration difference will decrease. According to the definition of $\Delta X = Xs - Xw$ and bearing in mind that strong solution concentration increases (Fig. 6) while Xw decrease (Fig. 4), it is predictable that the concentrations difference will increase. Obviously, by enhancing geothermal water

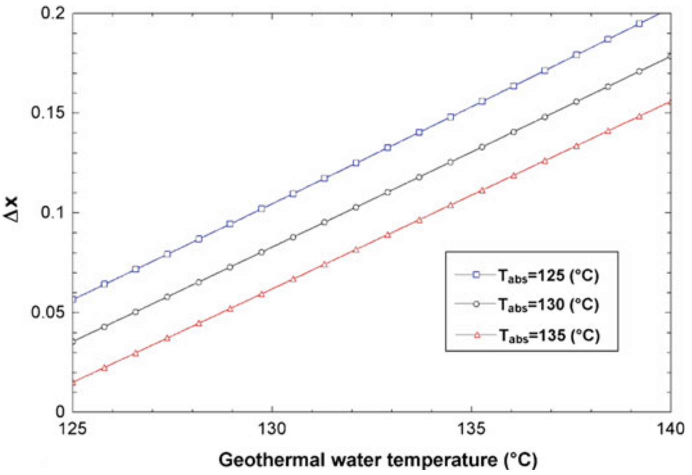

Fig. 7 The effect of geothermal water temperature on weak and strong solution concentration difference

temperature, ΔX will increase. It is worth mentioning that while absorber and condenser temperatures are constant, ΔX will only vary with flow ratio which is important and easily controllable operation parameter. Larger flow ratio also results in slighter heat source temperature (geothermal water temperature) and smaller mechanical loss (Fig. 5). According to the results reported in the literature, the larger the concentration difference is, the larger driving force for mass transfer in generator or absorber [31].

Figure 8 reveals the variation of EUF by geothermal water temperature. Energy utilization factor of the multi-generation system decreases sharply by the change of the geothermal water temperature. For clarifying the decline tendency of the system EUF, investigating the affecting parameters on it in terms of power production, utilized heat for desalination and water heating capacity by changing the geothermal water temperature, seems to be necessary.

The variations of net produced power and organic mass flow rate flowing in ORC have been examined in Fig. 9. It is clear that by increasing geothermal water temperature, organic fluid mass flow rate decreases which leads to the reduction of net power produced. On the other hand, by boosting geothermal water temperature the quantities of both utilized heat for desalination and domestic water heating increases (Fig. 10). According to the definition of EUF and considering the fact that the increment of Qu and Qwh is not so high to overcome the reduction of net power produced, EUF decreases by boosting geothermal water temperature as shown in Fig. 8.

Additionally, Fig. 8 shows that, by increasing absorber temperature, EUF decreases. This is for the reason that, as Tabs increases, the concentration of the weak solution and consequently the flow ratio (f) increase resulting in a decrease in

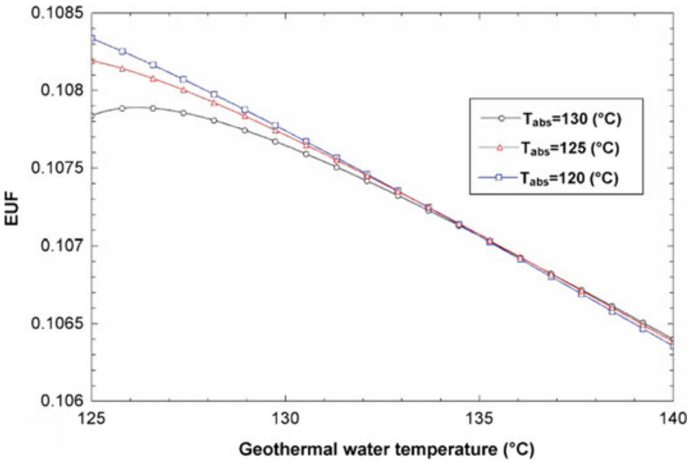

Fig. 8 The influence of geothermal water temperature on energy utilization factor by changing absorber temperature

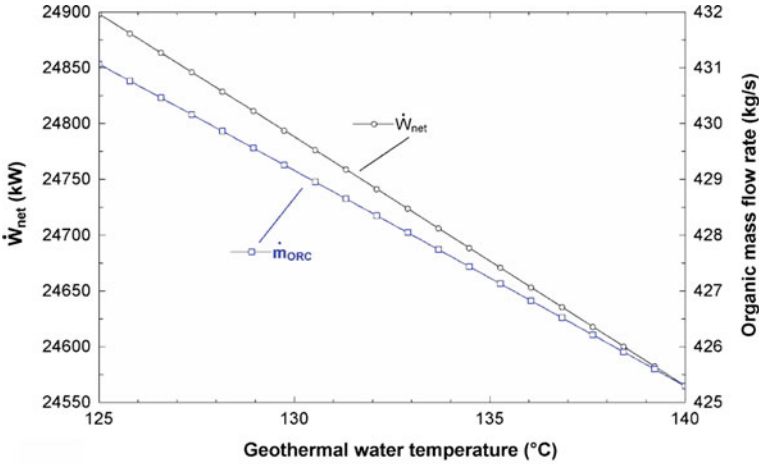

Fig. 9 Variations of net produced power and organic mass flow rate flowing in ORC by geothermal water temperature

the absorber heat capacity. This result is in agreement with those of reported in the literature [32, 33].

Figure 11 examines the effect of turbine inlet temperature on net produced power and EUF. According to the explanations of Fig. 8, it is anticipated that by increasing turbine inlet temperature, the organic fluid mass flow rate will decrease which will lead to the reduction of net power produced and consequently EUF.

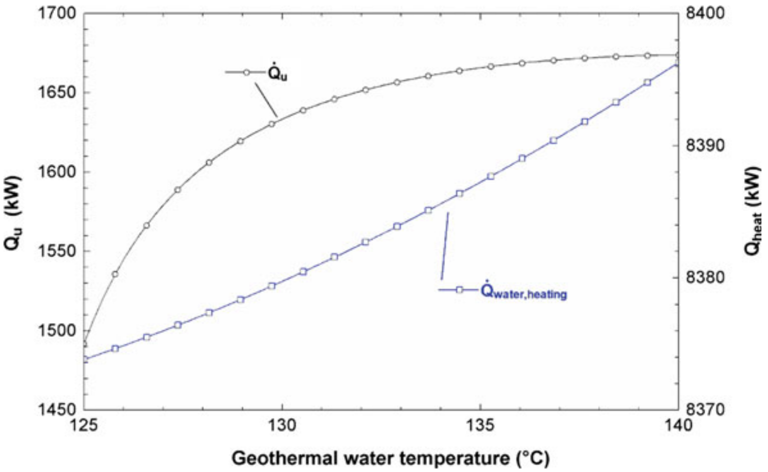

Fig. 10 Variations of utilized heat for desalination and domestic water heating by geothermal water temperature

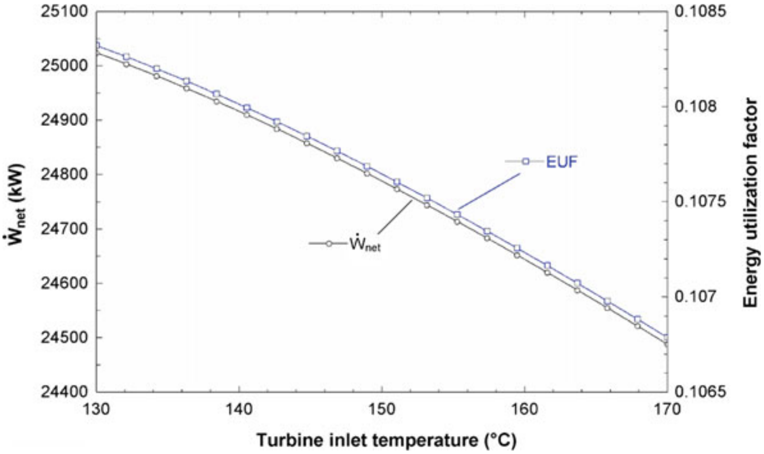

Fig. 11 The influence of turbine inlet temperature on net power produced and EUF

Net power consumed for hydrogen production and hydrogen quantity have a similar trend to the previous figure. At the current study half of the net power is assumed to be employed in PEM. Thus, both the produced hydrogen quantity and power devoted for PEM will reduce by enhancing the turbine inlet temperature as revealed in Fig. 12.

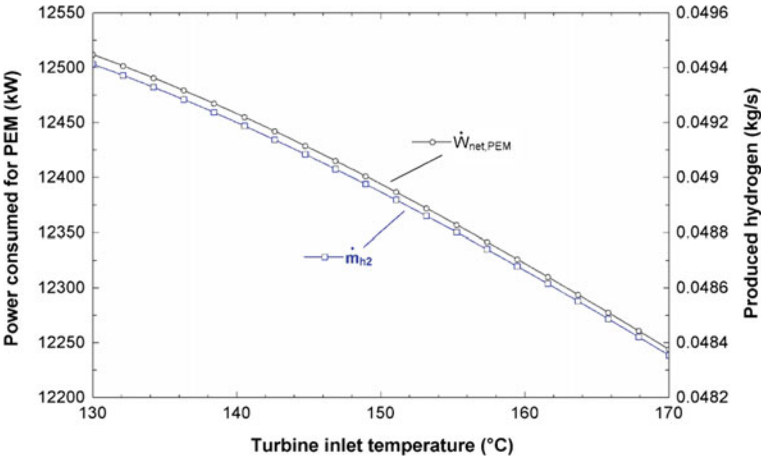

Fig. 12 Variations of power consumed by PEM and produced hydrogen by turbine inlet temperature

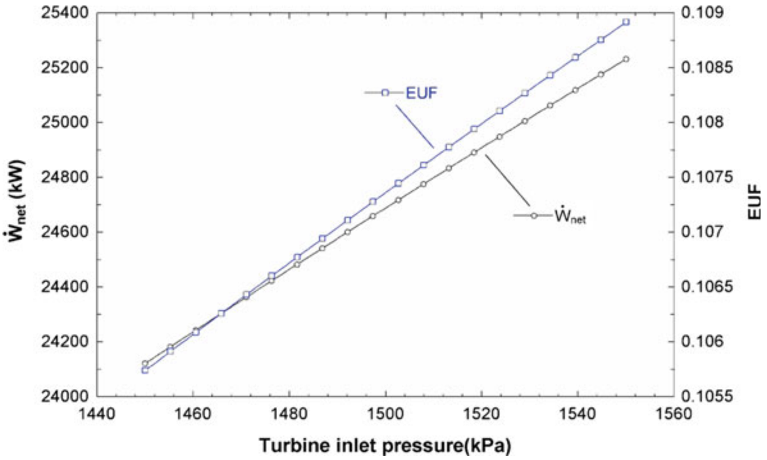

Fig. 13 The influence of turbine inlet pressure on net power produced and EUF

The effect of variation in pressure in turbine entrance is shown in Figs. 13 and 14 for net produced power, EUF, power consumed by PEM and produced hydrogen quantity. As shown, the influence of this parameter's change is like the fluid temperature entering to the turbine. This means that all the above mentioned parameters increase by enhancing turbine inlet pressure.

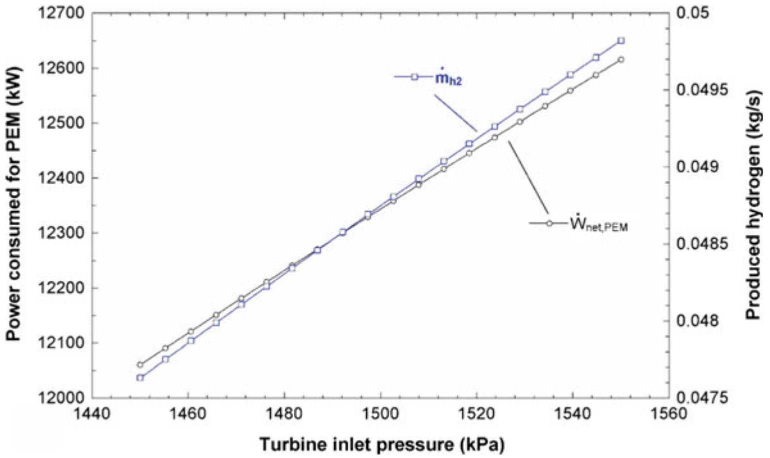

Fig. 14 Variations of power consumed by PEM and produced hydrogen by turbine inlet pressure

5 Conclusions

A multi-generation system producing power, hydrogen, desalinated water and domestic water heating was proposed and investigated at the current study. A thermodynamic model was developed by EES through applying energy analyses for each system component. Based on the analysis and optimization results, following conclusions are drawn:

- By boosting geothermal water temperate, COP of the AHT increases and flow ratio decreases.
- Energy utilization factor of the multi- generation system decreases sharply by the change of the geothermal water temperature.
- By increasing geothermal water temperature, strong solution concentration enhances which boosts the possibility of crystallization problem of LiBr within the absorber of the AHT.
- By increasing absorber temperature, energy utilization factor decreases.
- Both the produced hydrogen quantity and power devoted for PEM will reduce by enhancing the turbine inlet temperature.

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Augmented Heat Integration in Multipurpose Batch Plants Using Multiple Heat Storage Vessels

Thokozani Majozi

Abstract Energy minimisation in batch plants has garnered popularity over the past few decades, leading to direct and indirect heat integration techniques being formulated for multipurpose batch plants through the utilisation of mathematical formulations and insight-based methods. Some mathematical formulations utilise predetermined scheduling frameworks which may result in suboptimal results, whilst other formulations only use one heat storage vessel which may cause limitations in the plant. The work presented in this chapter is aimed at minimising energy consumption in multipurpose batch plants by exploring both direct and indirect heat integration through multiple heat storage vessels. It investigates the optimal number of heat storage vessels as well as design parameters, i.e. size and initial temperature of vessels. The cost of the heat storage vessels is considered within the model. The model is applied to two case studies resulting in significant increase in profits.

Keywords Batch plants · Heat integration · Energy · Minimisation
Heat storage · Optimisation

Nomenclature: The following sets, variables and parameters are used in the formulation.

Sets

J	$\{j \mid j$ processing unit$\}$
J_c	$\{j_c \mid j_c$ cold processing unit$\}$
J_h	$\{j_h \mid j_h$ hot processing unit$\}$
P	$\{p \mid p$ time point$\}$
S_{jh}^{in}	$\{s_{jh}^{in} \mid s_{jh}^{in}$ task which needs cooling$\}$
S_{jc}^{in}	$\{s_{jc}^{in} \mid s_{jc}^{in}$ task which needs heating$\}$
S_{j}^{in}	$\{s_{j}^{in} \mid s_{j}^{in}$ any task$\}$

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S_p	$\{s_p \mid s_p$ any product$\}$
V	$\{v \mid v$ is a heat storage vessel$\}$

Variables

$Ec(s_{jc}^{in}, p)$	Duty of task which needs heating
$E_h(s_{jh}^{in}, p)$	Duty of task which needs cooling
$c_u(s_{jh}^{in}, p)$	Cooling water required by a hot task
$h_u(s_{jc}^{in}, p)$	Steam required by a cold task
$mu(s_{jc}^{in}, p)$	Amount of material processed by cold task
$mu(s_{jh}^{in}, p)$	Amount of material processed by hot task
$T^i(v, p)$	Initial temperature of a storage vessel
$T^f(v, p)$	Final temperature of a storage vessel
$T^{out}(s_{jc}^{in}, p)$	Outlet temperature of a cold task
$T^{out}(s_{jh}^{in}, p)$	Outlet temperature of a hot task
$T^{in}(s_{jc}^{in}, p)$	Inlet temperature of a cold task
$T^{in}(s_{jh}^{in}, p)$	Inlet temperature of a hot task
$t_u(s_{jc}^{in}, p)$	Time at which a cold task starts being active
$t_u(s_{jh}^{in}, p)$	Time at which a hot task starts being active
$t_p\left(s_{jc}^{in}, p\right)$	Time at which a cold task stops being active
$t_p\left(s_{jh}^{in}, p\right)$	Time at which a hot task stops being active
$t_o(s_{jc}^{in}, v, p)$	Time at which a heat storage starts being active when integrated with a cold task
$t_o(s_{jh}^{in}, v, p)$	Time at which a heat storage starts being active when integrated with a hot task
$t_f(s_{jc}^{in}, v, p)$	Time at which a heat storage stops being active when integrated with a cold task
$t_f(s_{jh}^{in}, v, p)$	Time at which a heat storage stops being active when integrated with a hot task
$qs(s_p, p)$	Amount of product at the end of the time horizon
$Qc(s_{jc}^{in}, v, p)$	Heat transferred from storage to cold task
$Q_h(s_{jh}^{in}, v, p)$	Heat transferred from hot task to storage
$Q_e(s_{jh}^{in}, s_{jc}^{in}, p)$	Amount of heat directly transferred between a hot and cold task
$W(v)$	Capacity of heat storage
$e_{sto}(v)$	Binary variable indicating the existence of a heat storage vessel
$x(s_{jc}^{in}, s_{jh}^{in}, p)$	Binary variable indicating direct integration between a hot and cold task

$y(s_{jc}^{in}, p)$	Binary variable indicating an active cold task
$y(s_{jh}^{in}, p)$	Binary variable indicating an active hot task
$z(s_{jc}^{in}, v, p))$	Binary variable indicating an active heat storage vessel integrated with a cold task
$z(s_{jh}^{in}, v, p))$	Binary variable indicating an active heat storage vessel integrated with a hot task

Parameters

α_{sto}	Fixed cost of heat storage vessel
β_{sto}	Variable cost of heat storage vessel
$\alpha(s_j^{in})$	Coefficient of constant term for processing time of a task
$\beta(s_j^{in})$	Coefficient of variable term for processing time of a task
A^F	Annualizing factor
a	Annual fractional discount factor
θ	Cost function exponent
$c_p(s_{jc}^{in})$	Specific heat capacity of a cold task
$c_p(s_{jh}^{in})$	Specific heat capacity of a hot task
C_p^w	Specific heat capacity of heat transfer medium
cu_c	Cost of cold utility
hu_c	Cost of hot utility
hr/yr	Amount of hours the plant operates per year
H	Time horizon of interest
M	Any large number
n	Lifespan of heat storage vessels in years
$SP(s_p)$	Selling price of products
$T^s(s_{jh}^{in})$	Inlet temperature of a hot task
$T^s(s_{jc}^{in})$	Inlet temperature of a cold task
$T^t(s_{jh}^{in})$	Outlet temperature of hot task
$T^t(s_{jc}^{in})$	Outlet temperature of a cold task
T^L	Lower bound for initial temperature of a heat storage vessel
T^U	Upper bound for initial temperature of a heat storage vessel
ΔT^L	Minimum allowable temperature difference
W^L	Lower bound for size of a heat storage vessel
W^U	Upper bound for size of a heat storage vessel
Q_e^L	Lower bound for amount of heat transferred between two tasks
Q_e^U	Upper bound for amount of heat transferred between two tasks

1 Introduction

The use of batch chemical processes has gained popularity globally, due to their use in the production of low volume and high value products in the pharmaceutical, food, explosives, and speciality chemical industries [26]. Due to the escalating growth in the utilisation of batch chemical processes, research and development within the field has been intensified in order to develop optimisation techniques that can be used to operate the processes at optimal conditions. In the past the focus has been on design methods that are aimed at minimising the capital investment based on the selection of capital equipment. The focus has since shifted to optimisation methods that lead to a reduction in operating costs, such as utility costs by reducing the energy requirement in the process [5]. Direct and indirect heat integration can be used to minimise energy in batch processes. Direct heat integration is applied when a hot stream and a cold stream exchange heat with each other and indirect heat integration refers to heat/energy savings via a dedicated heat storage facility for later use. There are two main ways in which energy minimisation in batch plants has been studied, namely; the graphical optimisation methods, where the schedule is predetermined, and mathematical modelling optimisation methods. Some heuristics methods, where the schedule is also predetermined, have also been developed in minimising energy.

1.1 Graphical and Algebraic Techniques

Energy minimisation in batch plants was first conducted through the use of graphical techniques. There are two main methods which are used in the graphical techniques, i.e. the time average model as well as the time slice model. The time average model was first introduced by Clayton [11] where the energy of each stream was averaged over the batch cycle time. The minimum external utility requirement was then determined by taking into account the heat exchanged internally between streams. This method does not consider the discontinuous existence of streams which results in an overestimation of energy exchanged between streams.

The second method is the time slice model. This method uses the schedule of the batch process and divides the starting and ending times of tasks into slices or intervals. Each interval is then observed as a continuous process. The pinch point of every interval is then obtained in a similar manner like that in continuous processes. This method was first introduced by Obeng and Ashton [23]. The vast majority of energy minimisation techniques in the last three decades constituted of mainly graphical techniques [16, 17, 29] and were continuously explored in the 21th century [13].

Recent work in energy minimisation through graphical techniques includes the work of Yang et al. [30] which uses the Pseudo-T-H diagram (PTHDA) and the time slice model. The model applies both direct and indirect heat integration with the objective of minimising the total annual cost (TAC). Anastasovski [2] presented work that aims to design a common heat exchanger network for batch operations with the use of the time slice model. Chaturvedi and Bandyopadhyay [7] proposed a methodology aimed at overcoming the limitations that occur when using Time–Dependent Heat Cascade Analysis (TDHCA). The novelty of the methodology proposed by Chaturvedi et al. [8] is the shifting or delaying of product streams, in order for the product streams to be integrated with available cold/hot stream later in the time horizon.

Although graphical techniques offer conceptual insight, these techniques have proved to be insufficient due to their use of time as a parameter, which implies that the start and ending times are specified a priori. In order to obtain a more realistic representation of batch processes, time should be allowed to vary, and this can be achieved through mathematical modelling techniques.

1.2 Mathematical Modelling Techniques

Time can be captured in its exact form through the use of mathematical modelling as demonstrated by Papageourgiou et al. [24] through the study that involved direct and indirect heat integration in batch plants. In the formulation, indirect heat integration made use of a heat transfer medium (HTM) which acted as a mechanism for transferring heat from one operation to another as well as for storing energy over time. Bozan et al. [6] presented a study in which scheduling as well as utility usage was considered. An integrated approach was developed which included a simple synthesis algorithm and a nonlinear model. Barbosa-Povoa et al. [4] presented a methodology based on the work of Barbosa-Povoa and Macchietto [3] which was aimed at designing a batch process plant that considered the operation of the plant as well as the energy requirements.

A methodology which only considered indirect heat integration was presented by Chen and Ciou [10]. Due to the fact that a predetermined schedule of the process was used which only considered the production of one overall batch in which each task only occurred once in the time horizon, the possibility of direct heat integration was not explored. Chen and Chang [9] proposed a different technique from that of Chen and Ciou [10]. The technique was aimed at incorporating direct heat integration through the basis of resource task network scheduling which was executed simultaneously [9]. The formulation was a more general formulation in terms of the heat integration part of the model originally proposed by Majozi [20].

Moreover, Stamp and Majozi [27] presented a formulation that optimised the schedule together with the direct and indirect heat integration, as well as optimised the capacity and initial temperature of the heat storage vessel. Although heat losses of the storage vessel were taken into account in the mathematical formulation, which had previously not been done by Majozi [21], the capital cost of the heat storage vessel was not considered. The work reported by Seid and Majozi [25] introduced the ability for a task to be integrated with more than one task at a specific time interval. The heat integration framework was based on a robust scheduling formulation [26].

1.3 Heuristics and Hybrid Methods

Research in energy minimisation has also been conducted through the use of heuristics as well as a combination of the above mentioned techniques.

The seminal work done on heat integration in batch plants was by Vaselenak et al. [28] which made use of heuristics. The approach used temperature profiles and the heuristic approach as well as a mixed integer linear programming model to determine the optimal heat integration of batch plants. De Boer et al. [12] presented a case study which was performed on a process from the Dutch chemical company Dr. W. Kolb BV for the evaluation of high temperature storage units. Holczinger et al. [15] presented a study based on the S-graph approach proposed by Adonyi et al. [1] where it was assumed that heat exchangers are present for all hot-cold stream pairs and that each hot or cold stream is allowed to be matched with only one hot or cold stream. The aim of this work is an extension of the work proposed by Adonyi et al. [1] by allowing the streams to have heat exchanges with multiple other streams and takes into account the limitation on the number of available heat exchangers and their scheduling.

In this chapter, mathematical optimisation is used to optimise the schedule of batch processes together with energy requirement of the plant. Most of the work done on heat integration either focuses on direct heat integration or indirect heat integration. The schedules used in these models are, in most cases, predetermined which can lead to suboptimal results. In the proposed formulation, simultaneous optimisation of the schedule and heat integration is carried out by using the schedule as a foundation of the model and adding the heat integration techniques. The objective function of the schedule is then combined with the heat integration objective function and the two models are solved as one, as shown in Fig. 1. The chapter proposes a novel mathematical formulation based on the design of multiple heat storage vessels, where the operation of heat transfer between units and the heat storage vessels are adequately taken into account by allowing the time of heat transfer to coincide with the task duration. The proposed formulation uses a unit-specific model based on a continuous-time representation and State Sequence Network recipe representation (SSN).

2 Motivation for the Study

The objective of most mathematical models used in energy optimization of batch plants is to maximise profits by maximising throughput while minimising utility costs. The nature of batch processes makes it possible that there could

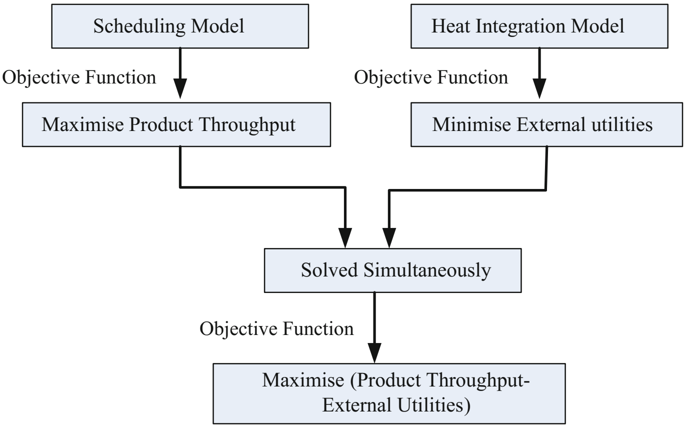

Fig. 1 Flowchart for proposed formulation

simultaneously be a task in the process that needs heating, s_{jc}^{in}, and another task that needs cooling, s_{jh}^{in}, as shown in Fig. 2a. Traditionally, this occurrence would provide an opportunity for process-process heat integration, if the thermal driving forces allow. However, if the thermal driving forces do not allow, heat storage provides another viable option towards energy minimisation. There are two scenarios that could occur, should there only be one heat storage vessel available in the plant. One of the tasks could be integrated with the heat storage vessel while the other is supplied by external utilities in order for its temperature requirement to be satisfied. This describes the first scenario depicted in Fig. 2b. The second scenario is when one task is integrated with the storage vessel while the other task is delayed for later use into the time horizon so that it could be integrated with the same heat storage vessel once the latter is available for integration, as illustrated in Fig. 2c. Clearly, this would ultimately reduce the number of batches which could be processed within the given time horizon. This drawback could be avoided by using multiple heat storage vessels that could allow for multiple heat integration between processing tasks and heat storage units in a situation where heating and cooling are required simultaneously as aforementioned. This is shown in Fig. 2d. Almost invariably, this option would allow more batches to be produced within the time horizon of interest, whilst taking advantage of available heat in the process. Consequently, this contribution is aimed at determining the optimum number, size and thermal profiles of heat storage vessels to achieve minimum energy use in multipurpose batch plants.

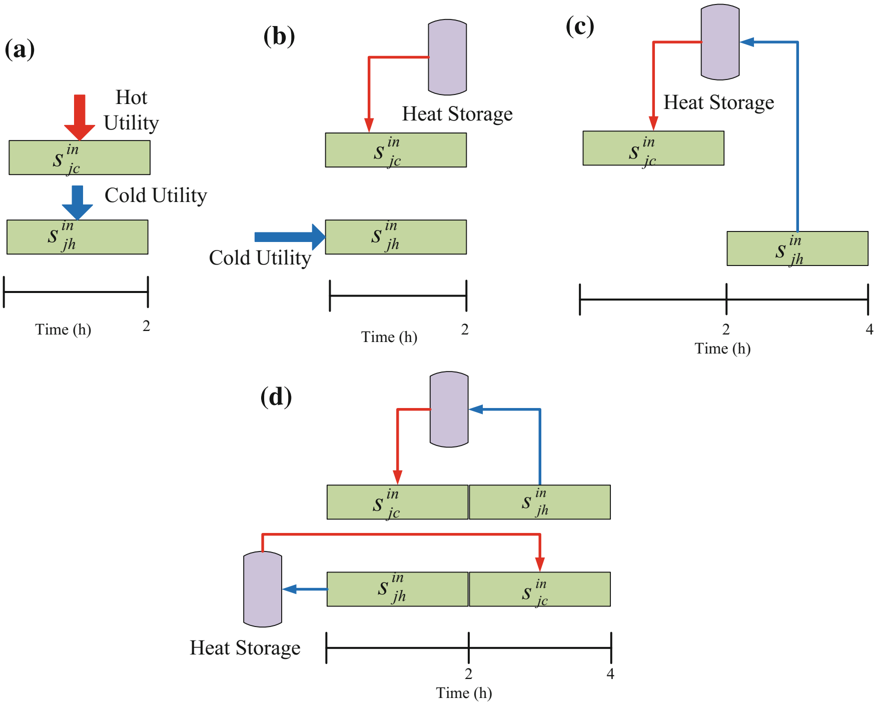

Fig. 2 **a** Tasks requiring heating/cooling, **b** one heat storage vessel, **c** one heat storage vessel and **d** multiple heat storage vessels

3 Problem Statement and Objectives

The problem addressed in this work can be stated as follows:

Given:

(i) Production scheduling data including duration of tasks, capacities of processing units, storage capacities, product recipe and time horizon,
(ii) Supply and target temperatures of hot and cold tasks,
(iii) Specific heat capacities of hot and cold states,
(iv) Cost of hot and cold utilities,
(v) Minimum allowable temperature difference,
(vi) Size limits for the heat storage vessels and temperature limits for the initial temperature of the heat storage vessels,
(vii) Cost parameters of the heat storage vessels, and
(viii) Life of equipment and discount factor.

Determine:

The optimal production schedule where the objective is to maximise profit and determine the optimal number of heat storage vessels with their respective optimal sizes and initial temperatures.

4 Mathematical Formulation

The formulation is based on the superstructure depicted in Fig. 3. This shows all the possible heat integration connections in the form of direct integration, indirect integration and the use of external utilities for a hot unit J_h and a cold unit J_c.

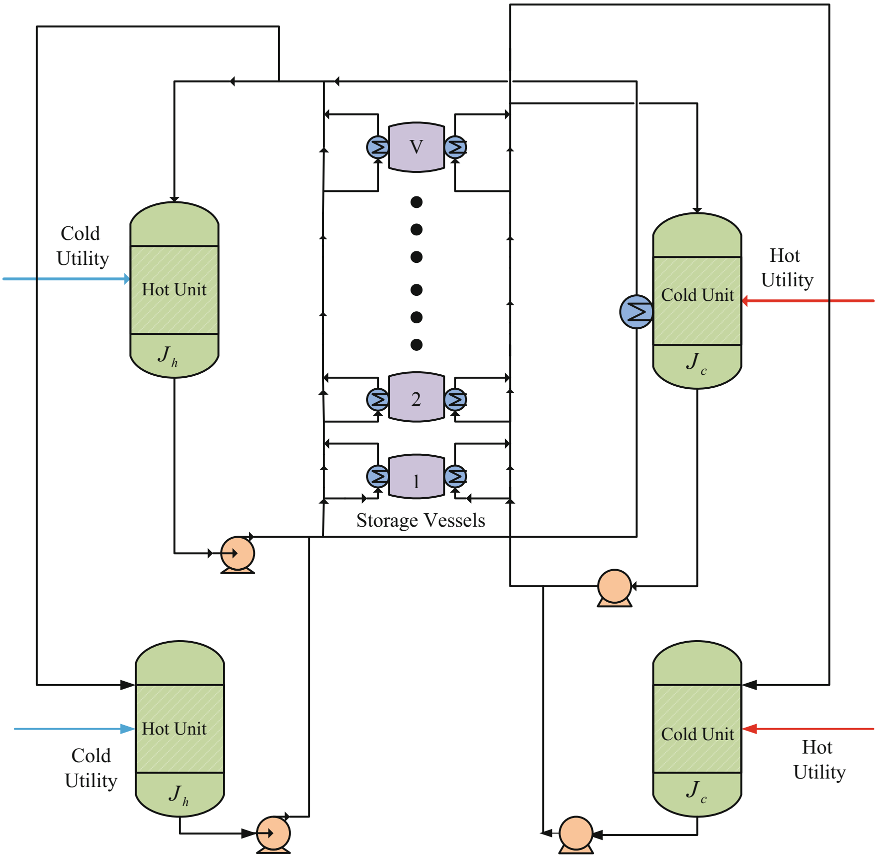

Fig. 3 General superstructure for model development

4.1 Scheduling Constraints

Scheduling constraints are critical in the mathematical formulation of batch processes. These constraints include capacity constraints of process units, duration constraints for the processing time, material balances for storage, sequence constraints, as well as allocation constraints of units. The scheduling formulation used is that of Seid and Majozi [26], which employs a unit-specific model based on a continuous-time representation.

The scheduling formulation proposed by Seid and Majozi [26] is based on finite intermediate storage which means that intermediates are stored in storage vessels of a specific size. The formulation does not take into account the transfer times of materials from one unit to another and it also does not take into account the washing or cleaning operations between tasks. Seid and Majozi [26] focused the proposed model in accurately addressing the storage constraints as well as proposing a formulation that could be solved in shorter CPU times. The proposed model allows for non-simultaneous transfer of states. Non-simultaneous transfer means that when a task requires more than one state, a state can be transferred to the unit in which it will be processed in and wait for the other state to be transferred, then only can the task begin. The model is a base scheduling model which can then be used as foundation for heat integration or water minimisation.

4.2 Allocation Constraints

Constraints (1) and (2) state that direct heat integration can take place between two units when the units are active. However, units can be active without direct heat integration taking place depending on the tasks that are conducted. These constraints work simultaneously to ensure that one unit which needs cooling will be integrated with one cold unit which needs heating at time point p in order for heat transfer to take place between the two units. It is important to note that heat transfer can take place between units that can perform multiple tasks. Although direct heat integration will take place between the units, integration will only take place when specific tasks within those units that can directly transfer heat to one another are active.

$$\sum_{s_{jc}^{in}} x\left(s_{jc}^{in}, s_{jh}^{in}, p\right) \leq y\left(s_{jh}^{in}, p\right) \quad \forall s_{jh}^{in} \in S_{jh}^{in}, s_{jc}^{in} \in S_{jc}^{in}, p \in P \tag{1}$$

$$\sum_{s_{jh}^{in}} x\left(s_{jc}^{in}, s_{jh}^{in}, p\right) \leq y\left(s_{jc}^{in}, p\right) \quad \forall s_{jh}^{in} \in S_{jh}^{in}, s_{jc}^{in} \in S_{jc}^{in}, p \in P \tag{2}$$

Constraints (3) and (4) state that indirect heat integration can only take place between a task that requires heating or cooling and a heat storage vessel when that task is active. This ensures efficient heat transfer in that the heat transfer medium from a heat storage vessel will not heat or cool a unit when that unit is not active.

$$z\left(s_{jc}^{in}, v, p\right) \leq y(s_{jc}^{in}, p) \quad \forall, s_{jc}^{in} \in S_{jc}^{in}, p \in P \tag{3}$$

$$z\left(s_{jh}^{in}, v, p\right) \leq y(s_{jh}^{in}, p) \quad \forall s_{jh}^{in} \in S_{jh}^{in}, p \in P \tag{4}$$

Constraint (5) states that only one unit can be integrated with a heat storage vessel at time point p, and this condition applies to all heat storage vessels. One heat storage integration to one unit at a point in time will aid in simplifying process dynamics and promote efficient use of process resources.

$$\begin{gathered}\sum_{s_j^{in} \in S_{jc}^{in}} z\left(s_j^{in}, v, p\right) + \sum_{s_j^{in} \in S_{jh}^{in}} z\left(s_j^{in}, v, p\right) \leq 1 \\ \forall s_{jh}^{in} \in S_{jh}^{in}, s_{jc}^{in} \in S_{jc}^{in}, p \in P, v \in V\end{gathered} \tag{5}$$

Constraints (6) and (7) state that a unit can undergo either direct, $x\left(s_{jc}^{in}, s_{jh}^{in}, p\right) = 1$, or indirect integration, $z\left(s_j^{in}, v, p\right) = 1$ at a point in time, and not both. This is so that the operation of the heat transfer between units is simplified and systematic.

$$\begin{gathered}\sum_{s_{jc}^{in}} x\left(s_{jc}^{in}, s_{jh}^{in}, p\right) + z\left(s_{jh}^{in}, v, p\right) \leq 1 \\ \forall s_{jh}^{in} \in S_{jh}^{in}, s_{jc}^{in} \in S_{jc}^{in}, p \in P, v \in V\end{gathered} \tag{6}$$

$$\begin{gathered}\sum_{s_{jh}^{in}} x\left(s_{jc}^{in}, s_{jh}^{in}, p\right) + z\left(s_{jc}^{in}, v, p\right) \leq 1 \\ \forall s_{jh}^{in} \in S_{jh}^{in}, s_{jc}^{in} \in S_{jc}^{in}, p \in P, v \in V\end{gathered} \tag{7}$$

4.3 Duties of Tasks and Heat Storage Vessels

Constraints (8) and (9) describe the amount of heat exchanged between a unit and a heat storage vessel for both cooling and heating by multiplying the mass of the heat transfer medium i.e. size of heat storage vessel with its heat capacity and the difference in temperature before and after integration has taken place Heat is transferred to or received from the heat storage vessel when the binary variable $z\left(s_{inj}, v, p\right)$ is equal to 1. The heat capacities of the heat transfer medium, c_p^w, can be found in Appendix A.

$$Q_c\left(s_{jc}^{in}, v, p\right) = W(v)c_p^w\left(T^i(v,p) - T^f(v,p)\right)z\left(s_{jc}^{in}, v, p\right) \quad \forall s_{jc}^{in} \in S_{jc}^{in}, p \in P \tag{8}$$

$$Q_h(s_{jh}^{in}, v, p) = W(v)c_p^w\left(T^f(v,p) - T^i(v,p)\right)z\left(s_{jh}^{in}, v, p\right) \quad \forall s_{jh}^{in} \in S_{jh}^{in}, p \in P \tag{9}$$

The duties of the heating and cooling tasks are obtained by using the difference between the supply temperatures and the target temperatures of the tasks. The duties are obtained in this way because the formulation is based on variable batch size that must be taken into account in determining the duties as the duties are a function of the batch size. The cooling duty is given by constraint (10) and the heating duty is given by constraint (11). The heat capacities, $c_p\left(s_j^{in}\right)$, of the states can be found in Appendix A

$$E_c\left(s_{jc}^{in}, p\right) = mu\left(s_{jc}^{in}, p\right)c_p\left(s_{jc}^{in}\right)\left(T^t\left(s_{jc}^{in}\right) - T^s\left(s_{jc}^{in}\right)\right) \quad \forall s_{jh}^{in} \in S_{jh}^{in}, p \in P \tag{10}$$

$$E_h\left(s_{jh}^{in}, p\right) = mu\left(s_{jh}^{in}, p\right)c_p\left(s_{jh}^{in}\right)\left(T^s\left(s_{jh}^{in}\right) - T^t\left(s_{jh}^{in}\right)\right) \quad \forall s_{jc}^{in} \in S_{jc}^{in}, p \in P \tag{11}$$

4.4 Design Constraints

The upper and lower bounds of the initial temperatures of the heat storage vessels are defined by constraint (12). This constraint ensures that the heat storage vessels are always kept within the range of the operating temperatures of the heat storage vessels based on design characteristics such as material of construction.

$$T^L \le T^i(v,p) \le T^U \quad \forall p \in P, v \in V \tag{12}$$

Constraint (13) describes the size limits of the heat storage vessels. These limits ensure that the sizes of the heat storage vessels are practical. The decision variable e_{sto} in the constraint is used to denote the existence or non-existence of a heat storage vessel.

$$e_{sto}(v)W^L \le W(v) \le e_{sto}(v)W^U \quad \forall v \in V \tag{13}$$

4.5 Temperature Constraints

The outlet temperature of any task at time point p should be equal to the specified target temperature of the task. This is described by constraints (14) and (15). The target temperature $T^t\left(s_j^{in}\right)$ is given as a parameter and the outlet temperature $T^{out}\left(s_j^{in}, p\right)$ is a variable. This aids the model in choosing the optimum points in time where a specific task should take place.

$$T^{out}\left(s_{jc}^{in}, p\right) = T^t\left(s_{jc}^{in}\right) \quad \forall s_{jc}^{in} \in S_{jc}^{in}, p \in P \tag{14}$$

$$T^{out}\left(s_{jh}^{in}, p\right) = T^t\left(s_{jh}^{in}\right) \quad \forall s_{jh}^{in} \in S_{jh}^{in}, p \in P \tag{15}$$

The inlet temperature of any task at time point p should be equal to the specified supply temperature of the task. This is described by constraints (16) and (17).

$$T^{in}\left(s_{jc}^{in}, p\right) = T^s\left(s_{jc}^{in}\right) \quad \forall s_{jc}^{in} \in S_{jc}^{in}, p \in P \tag{16}$$

$$T^{in}\left(s_{jh}^{in}, p\right) = T^s\left(s_{jh}^{in}\right) \quad \forall s_{jh}^{in} \in S_{jh}^{in}, p \in P \tag{17}$$

The initial temperature of a heat storage vessel at time point p must be equal to the final temperature of the heat storage vessel at time point $p - 1$. This constraint assumes that the storage vessels are well insulated and no heat is lost to the environment.

$$T^i(v, p) = T^f(v, p - 1) \quad \forall p \in P, v \in V \tag{18}$$

Constraints (19) and (20) are related to constraint (18) and state that the temperature of the heat storage should not change when indirect heat integration does not take place. In a scenario where indirect heat integration takes place, then constraints (19) and (20) become redundant.

$$T^f(v, p) \le T^i(v, p) + M\left(\sum_{s_{jc}^{in}} z\left(s_{jc}^{in}, v, p\right) + \sum_{s_{jh}^{in}} z\left(s_{jh}^{in}, v, p\right)\right) \tag{19}$$
$$\forall s_{jh}^{in} \in S_{jh}^{in}, s_{jc}^{in} \in S_{jc}^{in}, p \in P, v \in V$$

$$T^f(v, p) \ge T^i(v, p) - M\left(\sum_{s_{jc}^{in}} z\left(s_{jc}^{in}, v, p\right) + \sum_{s_{jh}^{in}} z\left(s_{jh}^{in}, v, p\right)\right) \tag{20}$$
$$\forall s_{jh}^{in} \in S_{jh}^{in}, s_{jc}^{in} \in S_{jc}^{in}, p \in P, v \in V$$

Constraints (21) and (22) ensure that for direct heat integration to take place, the minimum allowed temperature difference between the cold and hot units should be satisfied. The minimum allowable temperature difference ΔT^L is a parameter which is given depending on the process and it enables heat to be transferred between units efficiently because of the temperature difference that exists between units.

$$T^{in}\left(s_{jh}^{in},p\right) - T^{out}\left(s_{jc}^{in},p\right) \geq \Delta T^L - M\left(1 - x\left(s_{jc}^{in},s_{jh}^{in},p\right)\right)$$
$$\forall s_{jh}^{in} \in S_{jh}^{in}, \forall s_{jc}^{in} \in S_{jc}^{in}, p \in P \tag{21}$$

$$T^{out}\left(s_{jh}^{in},p\right) - T^{in}\left(s_{jc}^{in},p\right) \geq \Delta T^L - M\left(1 - x\left(s_{jc}^{in},s_{jh}^{in},p\right)\right)$$
$$\forall s_{jh}^{in} \in S_{jh}^{in}, \forall s_{jc}^{in} \in S_{jc}^{in}, p \in P \tag{22}$$

Constraints (23), (24), (25) and (26) ensure that for indirect heat integration to take place, the minimum allowable temperature difference between a unit and a heat storage vessel should be satisfied for both cooling and heating.

$$T^{in}\left(s_{jh}^{in},p\right) - T^{f}(v,p) \geq \Delta T^L - M\left(1 - z\left(s_{jh}^{in},v,p\right)\right)$$
$$\forall s_{jh}^{in} \in S_{jh}^{in}, s_{jc}^{in} \in S_{jc}^{in}, p \in P, v \in V \tag{23}$$

$$T^{out}\left(s_{jh}^{in},p\right) - T^{i}(v,p) \geq \Delta T^L - M\left(1 - z\left(s_{jh}^{in},v,p\right)\right)$$
$$\forall s_{jh}^{in} \in S_{jh}^{in}, s_{jc}^{in} \in S_{jc}^{in}, p \in P, v \in V \tag{24}$$

$$T^{i}(v,p) - T^{out}\left(s_{jc}^{in},p\right) \geq \Delta T^L - M\left(1 - z\left(s_{jc}^{in},v,p\right)\right)$$
$$\forall s_{jh}^{in} \in S_{jh}^{in}, s_{jc}^{in} \in S_{jc}^{in}, p \in P, v \in V \tag{25}$$

$$T^{f}(v,p) - T^{in}\left(s_{jc}^{in},p\right) \geq \Delta T^L - M\left(1 - z\left(s_{jc}^{in},v,p\right)\right)$$
$$\forall s_{jh}^{in} \in S_{jh}^{in}, s_{jc}^{in} \in S_{jc}^{in}, p \in P, v \in V \tag{26}$$

4.6 Utility Usage by Tasks

The energy requirement of any task can be satisfied through three different mechanisms. These are indirect heat integration between a heat storage vessel and a task, direct heat integration between two tasks or external utilities depending on the energy requirement of the task. In a situation where energy requirements cannot be satisfied through direct and indirect heat integration, the use of external utilities is allowed to supplement the deficit. The aim of the formulation is to minimise the use of the external utilities. This is described by constraints (27) and (28).

$$E_h\left(s_{jh}^{in},p\right)y\left(s_{jh}^{in},p\right)=\sum_{v}Q_h\left(s_{jh}^{in},v,p\right)+c_u\left(s_{jh}^{in},p\right)+\sum_{s_{jc}^{in}}Q_e\left(s_{jh}^{in},s_{jc}^{in},p\right)$$
$$\forall s_{jh}^{in}\in S_{jh}^{in},\forall s_{jc}^{in}\in S_{jc}^{in},p\in P,v\in V \tag{27}$$

$$E_c\left(s_{jc}^{in},p\right)y\left(s_{jc}^{in},p\right)=\sum_{v}Q_c\left(s_{jc}^{in},v,p\right)+h_u\left(s_{jc}^{in},p\right)+\sum_{s_{jh}^{in}}Q_e\left(s_{jh}^{in},s_{jc}^{in},p\right)$$
$$\forall s_{jh}^{in}\in S_{jh}^{in},\forall s_{jc}^{in}\in S_{jc}^{in},p\in P,v\in V \tag{28}$$

4.7 Limits of Heat Exchanged During Direct Heat Integration

Constraint (29) sets the bounds for the heat exchange between hot and cold tasks through direct heat integration. This ensures that amount of heat transferred between units is practical and is not insignificant or too large which can have a negative effect on the operating tasks.

$$Q_e^L x\left(s_{jc}^{in},s_{jh}^{in},p\right)\le Q_e\left(s_{jh}^{in},s_{jc}^{in},p\right)\le Q_e^U x\left(s_{jc}^{in},s_{jh}^{in},p\right)$$
$$\forall s_{jh}^{in}\in S_{jh}^{in},s_{jh}^{in}\in S_{jh}^{in},p\in P \tag{29}$$

4.8 Time Constraints

When two units are directly integrated, the tasks of the units must start at the same time. Constraints (30) and (31) work together to ensure that integrated tasks start at the same time so that start of heat transfer between the two tasks can be the same. The constraints become redundant when there is no integration i.e. $x\left(s_{jc}^{in},s_{jh}^{in},p\right)=0$.

$$t_u\left(s_{jh}^{in},p\right)\ge t_u\left(s_{jc}^{in},p\right)-M\left(1-x\left(s_{jc}^{in},s_{jh}^{in},p\right)\right)$$
$$\forall s_{jh}^{in}\in S_{jh}^{in},s_{jc}^{in}\in S_{jc}^{in},p\in P \tag{30}$$

$$t_u\left(s_{jh}^{in},p\right)\le t_u\left(s_{jc}^{in},p\right)+M\left(1-x\left(s_{jc}^{in},s_{jh}^{in},p\right)\right)$$
$$\forall s_{jh}^{in}\in S_{jh}^{in},s_{jc}^{in}\in S_{jc}^{in},p\in P \tag{31}$$

Constraints (32), (33), (34) and (35) ensure that when integration takes place between a unit and a heat storage vessel, the starting times of the unit and the heat storage vessel must be equal. This ensures that heat transfer starts taking place as the tasks start. This applies for a unit requiring heating or cooling.

$$\begin{gathered} t_u\left(s_{jh}^{in}, p\right) \geq t_o\left(s_{jh}^{in}, v, p\right) - M\left(y\left(s_{jh}^{in}, p\right) - z\left(s_{jh}^{in}, v, p\right)\right) \\ \forall s_{jh}^{in} \in S_{jh}^{in}, s_{jc}^{in} \in S_{jc}^{in}, p \in P, v \in V \end{gathered} \tag{32}$$

$$\begin{gathered} t_u\left(s_{jh}^{in}, p\right) \leq t_o\left(s_{jh}^{in}, v, p\right) + M\left(y\left(s_{jh}^{in}, p\right) - z\left(s_{jh}^{in}, v, p\right)\right) \\ \forall s_{jh}^{in} \in S_{jh}^{in}, s_{jc}^{in} \in S_{jc}^{in}, p \in P, v \in V \end{gathered} \tag{33}$$

$$\begin{gathered} t_u\left(s_{jc}^{in}, p\right) \geq t_o\left(s_{jc}^{in}, v, p\right) - M\left(y\left(s_{jc}^{in}, p\right) - z\left(s_{jc}^{in}, v, p\right)\right) \\ \forall s_{jh}^{in} \in S_{jh}^{in}, s_{jc}^{in} \in S_{jc}^{in}, p \in P, v \in V \end{gathered} \tag{34}$$

$$\begin{gathered} t_u\left(s_{jc}^{in}, p\right) \leq t_o\left(s_{jc}^{in}, v, p\right) + M\left(y\left(s_{jc}^{in}, p\right) - z\left(s_{jc}^{in}, v, p\right)\right) \\ \forall s_{jh}^{in} \in S_{jh}^{in}, s_{jc}^{in} \in S_{jc}^{in}, p \in P, v \in V \end{gathered} \tag{35}$$

Constraints (36), (37), (38) and (39) are similar to constraints (32)–(35) but apply to the finishing time of a task and the corresponding heat storage unit. They ensure that the finishing time of a task and the finishing time of the heat storage vessel are equal when indirect integration takes place between a task and a heat storage vessel.

$$\begin{gathered} t_p\left(s_{jh}^{in}, p\right) \geq t_f\left(s_{jh}^{in}, v, p\right) - M\left(y\left(s_{jh}^{in}, p\right) - z\left(s_{jh}^{in}, v, p\right)\right) \\ \forall s_{jh}^{in} \in S_{jh}^{in}, s_{jc}^{in} \in S_{jc}^{in}, p \in P, v \in V \end{gathered} \tag{36}$$

$$\begin{gathered} t_p\left(s_{jh}^{in}, p\right) \leq t_f\left(s_{jh}^{in}, v, p\right) + M\left(y\left(s_{jh}^{in}, p\right) - z\left(s_{jc}^{in}, v, p\right)\right) \\ \forall s_{jh}^{in} \in S_{jh}^{in}, s_{jc}^{in} \in S_{jc}^{in}, p \in P, v \in V \end{gathered} \tag{37}$$

$$\begin{gathered} t_p\left(s_{jc}^{in}, p\right) \geq t_f\left(s_{jc}^{in}, v, p\right) - M\left(y\left(s_{jc}^{in}, p\right) - z\left(s_{jc}^{in}, v, p\right)\right) \\ \forall s_{jh}^{in} \in S_{jh}^{in}, s_{jc}^{in} \in S_{jc}^{in}, p \in P, v \in V \end{gathered} \tag{38}$$

$$\begin{gathered} t_p\left(s_{jc}^{in}, p\right) \leq t_f\left(s_{jc}^{in}, v, p\right) + M\left(y\left(s_{jc}^{in}, p\right) - z\left(s_{jc}^{in}, v, p\right)\right) \\ \forall s_{jh}^{in} \in S_{jh}^{in}, s_{jc}^{in} \in S_{jc}^{in}, p \in P, v \in V \end{gathered} \tag{39}$$

These constraints ensure that a heat storage vessel is active for the duration of a task that it is integrated with at time point $p-1$, before it can be integrated with another task at time point p. Constraint (40) applies to tasks that need heating and constraint (41) describes tasks that need cooling.

$$\begin{aligned} t_o(s_{jc}^{in}, v, p) \geq\, & t_o(s_{jc'}^{in}, v, p-1) + \alpha(s_{jc'}^{in}) y(s_{jc'}^{in}, p-1) \\ & + \beta(s_{jc'}^{in}) mu(s_{jc'}^{in}, p-1) \quad \forall s_{jh}^{in} \in S_{jh}^{in}, s_{jc}^{in} \in S_{jc}^{in}, p \in P, v \in V \end{aligned} \tag{40}$$

$$\begin{aligned} t_o(s_{jh}^{in}, v, p) \geq\, & t_o(s_{jh'}^{in}, v, p-1) + \alpha(s_{jh'}^{in}) y(s_{jh'}^{in}, p-1) \\ & + \beta(s_{jh'}^{in}) mu(s_{jh'}^{in}, p-1) \quad \forall s_{jh}^{in} \in S_{jh}^{in}, s_{jc}^{in} \in S_{jc}^{in}, p \in P, v \in V \end{aligned} \tag{41}$$

Constraints (42) and (43) are the same as constraints (40) and (41) but apply in a situation where a heat storage vessel is integrated with different units.

$$\begin{aligned} t_o(s_{jh}^{in}, v, p) \geq\, & t_o(s_{jc}^{in}, v, p-1) + \alpha(s_{jc}^{in}) y(s_{jc}^{in}, p-1) \\ & + \beta(s_{jc}^{in}) mu(s_{jc}^{in}, p-1) \quad \forall s_{jh}^{in} \in S_{jh}^{in}, s_{jc}^{in} \in S_{jc}^{in}, p \in P, v \in V \end{aligned} \tag{42}$$

$$\begin{aligned} t_o(s_{jc}^{in}, v, p) \geq\, & t_o(s_{jh}^{in}, v, p-1) + \alpha(s_{jh}^{in}) y(s_{jh}^{in}, p-1) \\ & + \beta(s_{jh}^{in}) mu(s_{jh}^{in}, p-1) \quad \forall s_{jh}^{in} \in S_{jh}^{in}, s_{jc}^{in} \in S_{jc}^{in}, p \in P, v \in V \end{aligned} \tag{43}$$

4.9 *Objective Function*

The objective of the model is to maximize profit in the batch process which consists of the revenue from the products, cost of external cold utility and hot utility defined as cu_c and hu_c, respectively, and the capital cost of the heat storage vessels which was omitted from the indirect heat integration formulation of Stamp and Majozi [27]. The cost function of the heat storage vessels is nonlinear and was obtained from the work of Li and Chang [19]. The plant is assumed to be operational for 7920 h per year while the exponent of the cost function is assumed to be 0.6. The fixed cost of a single heat storage vessel is c.u[1] 48,000 and the variable cost of a single heat storage vessel dependent on the size of the heat storage vessel is given as c.u 280,000. The objective function is given by constraint (44) and the annualizing factor is given by constraint (45) obtained from Foo [14] where the annual fractional discount factor is assumed to be 15% and lifespan of the heat storage vessels is 3 years. The cost of raw materials used in the process is not taken into account in the objective function.

---

[1] c.u = cost units

$$\max\left(\begin{array}{l}\left(\sum_{s_p} qs(s_p,p)SP(s_p) - \sum_{p}\sum_{s_{jh}^{in}} c_u(s_{jh}^{in},p)cu_c \right.\\ \left. - \sum_{p}\sum_{s_{jc}^{in}} h_u(s_{jc}^{in},p)hu_c\right)\frac{hr/yr}{H}\\ - \sum_{v}((\alpha_{sto}+\beta_{sto}W(v)^{\theta})e_{sto}(v))A^F\end{array}\right) \quad \begin{array}{l}\forall s_p \in S_P, s_{jh}^{in} \in \\ S_{jh}^{in}, s_{jc}^{in} \in S_{jc}^{in},\\ p \in P, v \in V\end{array} \tag{44}$$

$$A^F = \frac{a(1+a)^n}{(1+a)^n - 1} \tag{45}$$

5 Literature Examples

The mathematical formulation was applied to two illustrative examples adapted from Majozi [22] and Kondili et al. [18]. The examples involve multipurpose batch plants which have tasks that require either heating or cooling. The models were solved in GAMS 24.3.2 using the general purpose global optimisation solver BARON in Intel® Core™ i7-3770 CPU @ 3.40 GHz, RAM 8.00 GB.

5.1 First Illustrative Example (Adapted from Majozi [22])

A batch plant which consists of two reactors, two filters and a distillation column was considered for the first example. The recipe, that is the procedure that must be followed in order to convert the raw materials to the final products, is represented as a state sequence network (SSN) in Fig. 4. SSN is a representation of the recipe as a diagram. The materials/states used in the process such as raw materials, intermediates, waste products and products that are used in the sequence and the processes/tasks which take place i.e. reaction and filtration are denoted as nodes. The mass fraction of the states used to perform a certain task is also denoted on the SSN in

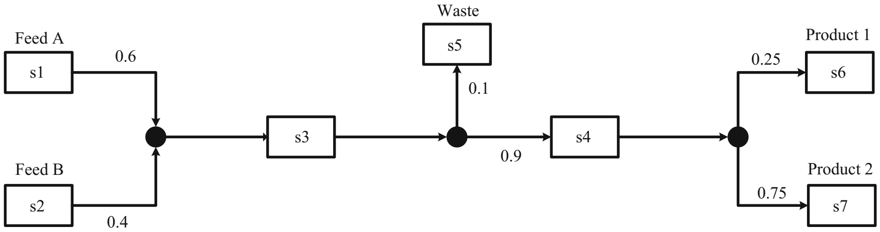

Fig. 4 SSN for first illustrative example

order to quantify the amount of state used for each task. The first illustrative example consists of three main tasks which is reaction, filtration and distillation/separation. The reaction task can take place in either reactor 1 or 2, using state 1 and 2 as raw materials to produce state 3 and needs to be cooled from 100 to 70 °C. The filtration task can be carried out in filters 1 and 2 where state 3 is filtered to obtain state 4 and state 5 which is a waste product. The separation task distils state 4 into state 6 and 7 is carried out in the distillation column and should be heated from 65 to 80 °C. Figure 5a shows the process flow diagram of the illustrative example.

The reaction task is 2 h long and a maximum batch size of 60 kg can be produced in each reactor. The filtration is 1 h long and can handle a maximum batch size of 80 kg as its feed. The distillation task is 2 h long and takes a maximum batch size of 140 kg as the feed to the distillation column. The batch plant has a tank farm where each state used or produced from the process can be stored. The maximum storage capability of the intermediate states is shown in Fig. 5b. The initial inventory of the raw materials, state 1 and 2 is given as 1000 kg each at the start of production.

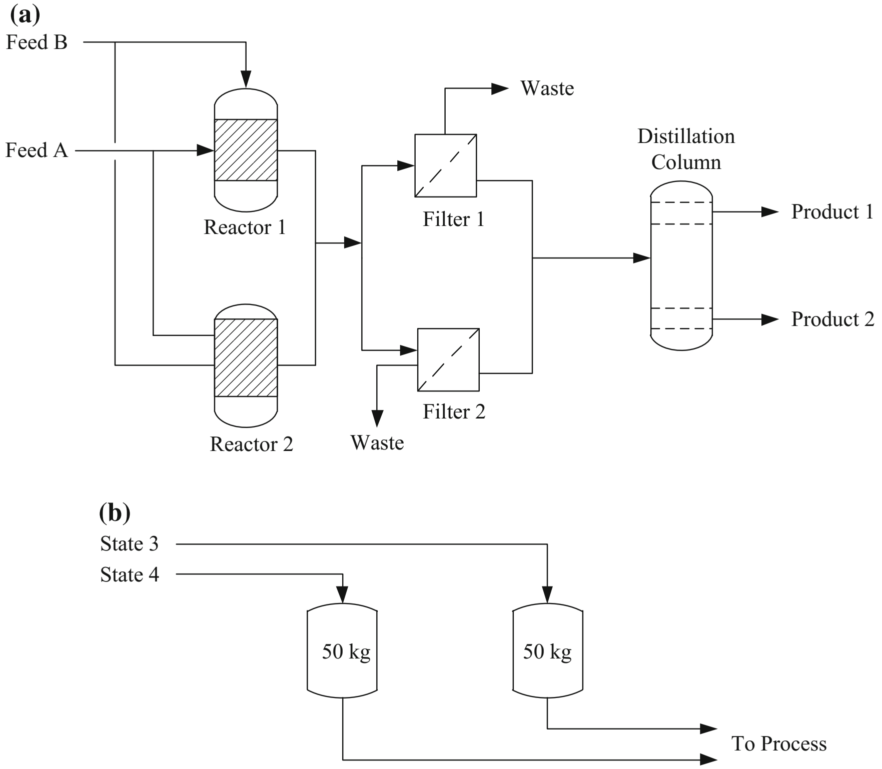

Fig. 5 **a** Process flow diagram, **b** tank farm for first illustrative example

The detailed scheduling data and the detailed heating/cooling requirement data is given in Tables 3, 4 and 5, and the detailed heat storage vessel cost function parameters are given in Table 6 in Appendix A. The superstructure of the example is given in Fig. 6. The superstructure had a maximum of four heat storage vessels which could be used for indirect heat integration together with opportunities for direct heat integration and the use of external utilities.

Three different scenarios of the illustrative example were considered. The first scenario (scenario 1) is a base case where there is no heat integration. The second scenario (scenario 2) is a single heat storage vessel model together with direct heat integration opportunities and the third scenario (scenario 3) involves multiple heat storage vessels. The selling price for products 1 and 2 is c.u 120 and the cost of the cold and hot utilities is c.u 0.02 and c.u 1, respectively. The model was applied to the example and the results were analysed and compared.

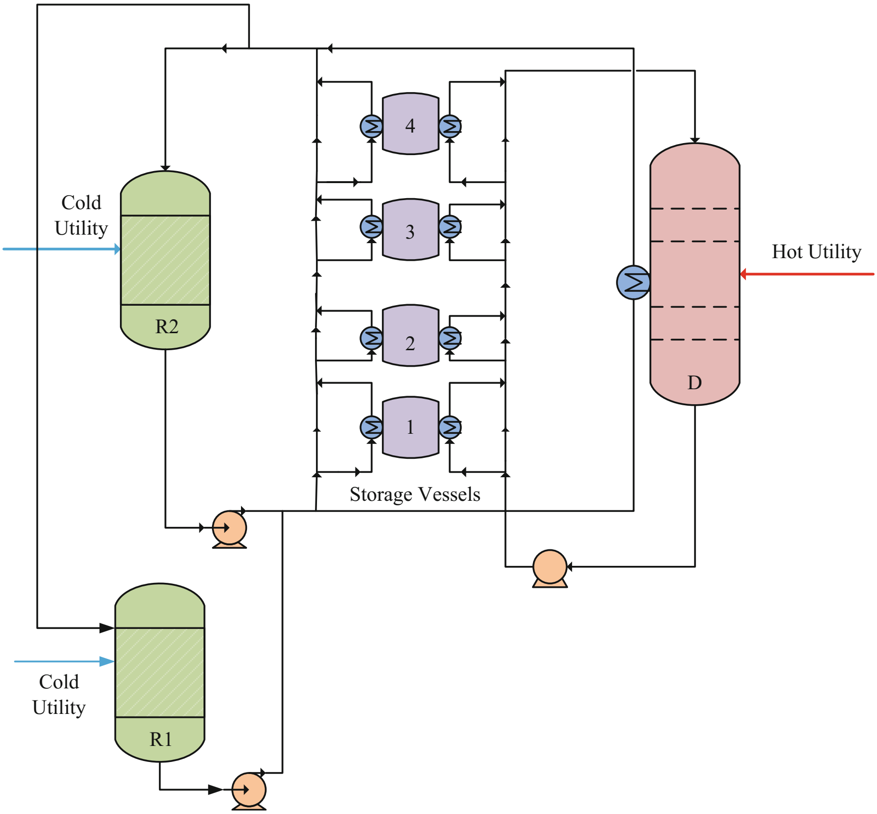

Fig. 6 Superstructure for first illustrative example

5.1.1 Results and Discussion

The results obtained from the application of the model are given in Table 1. The objective value obtained for scenario 1 was c.u 31.4×10^6. This is mainly due to the fact that only three main tasks take place in the process. Two of those tasks require heating/cooling and as such a huge amount of external utilities is used for the first scenario. Scenario 2 resulted in an objective value of c.u 33.5×10^6. The hot utility was eliminated and the cold utility requirement was 50.40 MJ. Scenario 3 resulted in an objective value of c.u 34.1×10^6 and no external utilities requirements.

The proposed mathematical formulation resulted in an optimal number of three heat storage vessels which are depicted in the resultant flowsheet in Fig. 7. The flowsheet shows that the model achieves its optimal objective value only when indirect heat integration occurs. It should be noted that 100% decrease of external utilities does not take into account the cold and hot utilities that are used in the heat storage vessels to achieve the initial temperatures although the cost of the heat transfer medium is taken into account with the cost of storage. The objective value of the scheduling model, where no utilities are considered, was found to be c.u 34.2×10^6 and scenario 3 (multiple heat storage vessels model) resulted in an objective of c.u 34.1×10^6. It can be seen that the multiple heat storage vessels model achieved an objective value closest to the scheduling model objective value, as compared to scenario 1 and 2. This shows that the proposed mathematical formulation not only minimises the use of external utilities, but also allows for flexibility with regards to time. This means that more batches can be produced within the time horizon as though utilities were not considered like in the scheduling model. The objective value of the proposed model is however not equal to the scheduling objective value because the capital costs of the heat storage vessels were accounted for in the objective function of multiple heat storage vessels model, whereas the scheduling model takes into account the amount of product with its selling price only.

Table 1 Results for first illustrative example

	No integration	One heat storage vessel	Multiple heat storage vessels
Objective (c.u $\times 10^6$)	31.4	33.5	34.1
Cold utility (MJ)	50.4	50.40	0
Hot utility (MJ)	41.47	0	0
Discrete variables	70	101	253
Continuous variables	265	429	1117
Time points	6	6	6
CPU time (s)	1	6000	6000

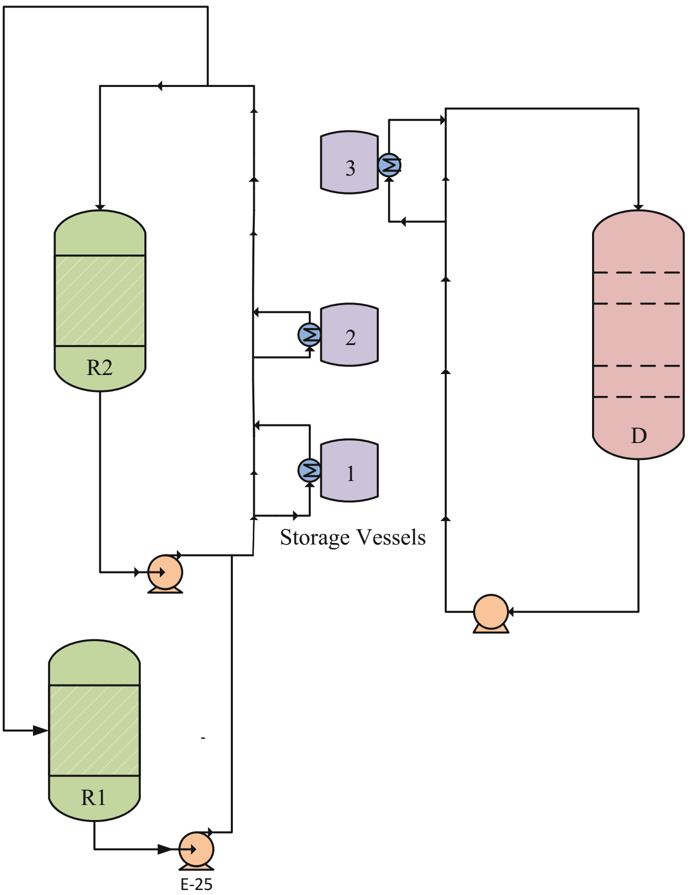

Fig. 7 Resultant flowsheet for first illustrative example

It is evident that the heat integration configuration of the heat storage vessels resulted in one heat storage being used to heat the distillation task, while the other two heat storage vessels were used to cool down the reaction task in both reactors as illustrated in the Gantt chart in Fig. 8. For this specific example, the configuration of using all heat storage vessels as both sinks and sources was not the best solution. This can be attributed to the fact that there were only two tasks which required external utilities, therefore segregating the usage of heat storage vessels to suit the needs of the tasks resulted in a simpler heat exchange configuration. The initial temperatures of the heat storage vessels also affect the type of configuration output.

The heat storage vessels had initial temperatures of 20, 20 and 160 °C and sizes of 112.5, 150 and 116.2 kg, respectively. The temperature profiles of the heat storage vessels are depicted in Fig. 9 which show the changes in temperature of each of the heat storage vessels throughout the time horizon. The heat loss of the

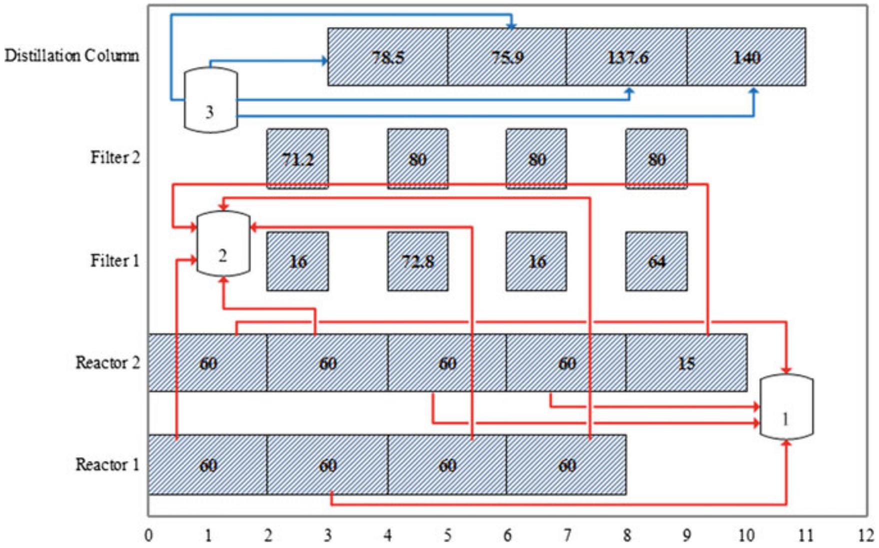

Fig. 8 Gantt chart using proposed model for first illustrative example

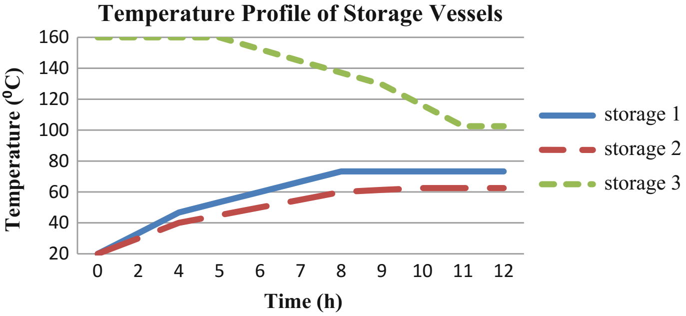

Fig. 9 Temperature profile for heat storage vessels for first illustrative example

heat storage vessels was not considered due to the short length of the time horizon. Due to the nonlinear nature of the model and the computational intensity required in solving it, the CPU time was set at a limit of 6000 s for the single heat storage vessel and the multiple heat storage vessel scenarios. Given that the problem being solved is a design problem a longer CPU time can be tolerated.

Piping costs were not taken into account in the mathematical formulation. Figure 10 shows the configuration of a unit with the heat exchanger used to facilitate heat transfer. The unit will have standard piping whether the heat transfer medium is from external utilities, direct or indirect heat integration. The additional piping costs will come from each heat storage vessel added to the heat transfer

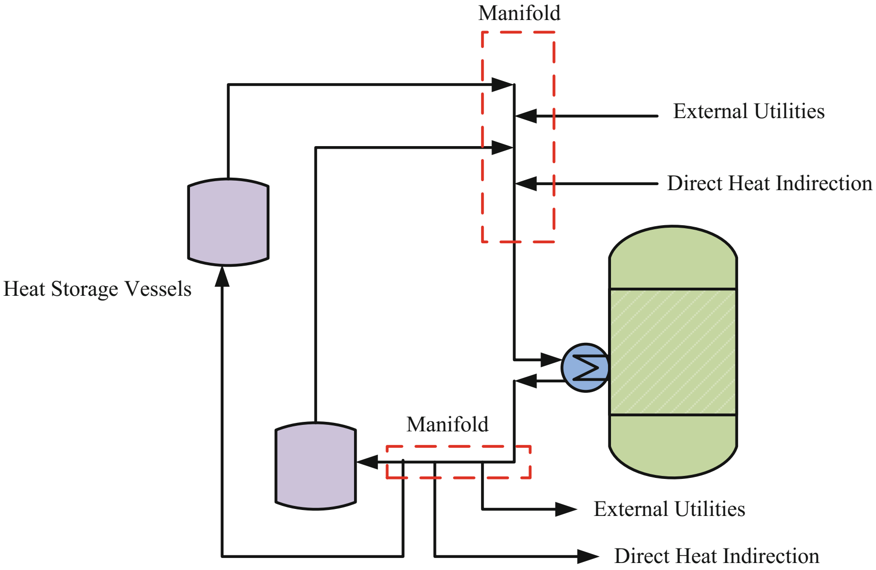

Fig. 10 Piping design of a heat storage vessel

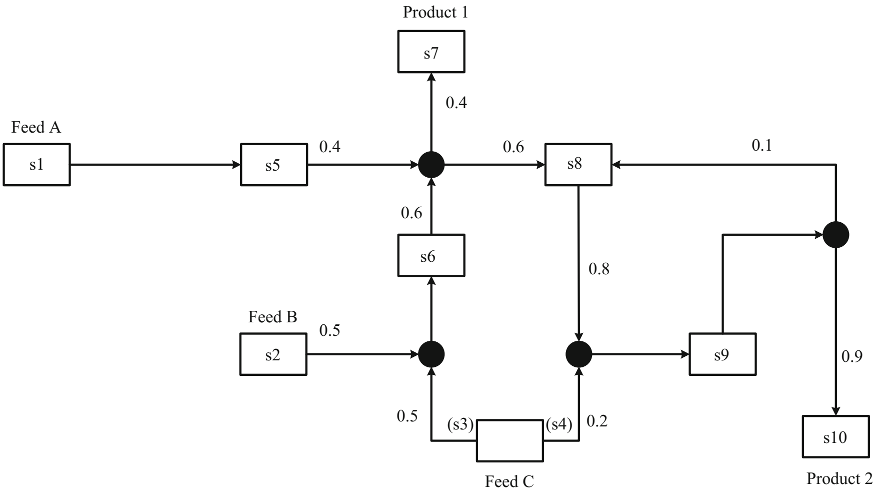

Fig. 11 SSN for second illustrative example

configuration through indirect heat integration as shown in Fig. 10. The total cost of piping can then be minimised by optimally arranging the configuration of the heat storage vessels and the units.

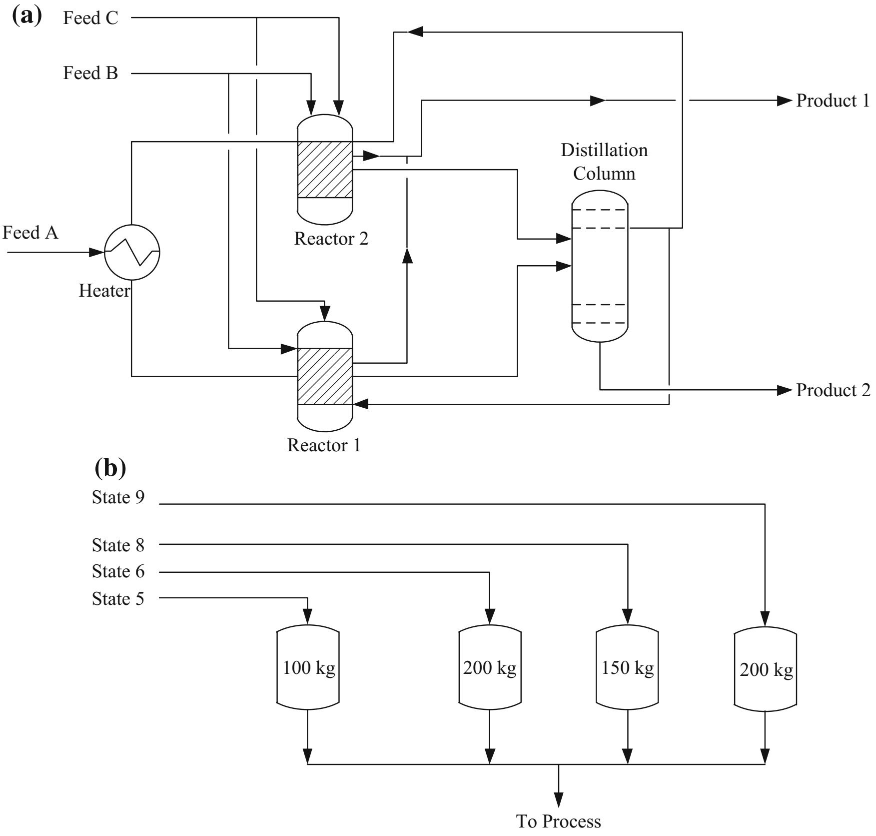

Fig. 12 **a** Process flow diagram, **b** tank farm for second illustrative example

5.2 Second Illustrative Example (Adapted from Kondili et al. [18])

A multipurpose batch plant which consists of a heater, two reactors, in which three reactions can occur and a separation unit was also considered. The recipe is represented as a State Sequence Network (SSN) in Fig. 11 which shows the procedural steps of the process. The SSN is represented in the same way as in the first illustrative example. The second illustrative example consists of heating, three reaction steps and separation. The heat task heats state 1 to produce state 5. Reaction 1 task reacts state 2 and 3 to produce state 6 and must be cooled from 100 to 70 °C. Reaction 2 reacts state 5 and 6 to produce state 7, which is product 1 and state 8 and must be heated from 70 to 100 °C. Reaction 3 reacts state 4 and 8 to produce state 9 and must be cooled from 130 to 100 °C. The separation task separates state 9 into state 10, which is product 2, and state 8 which is recycled back

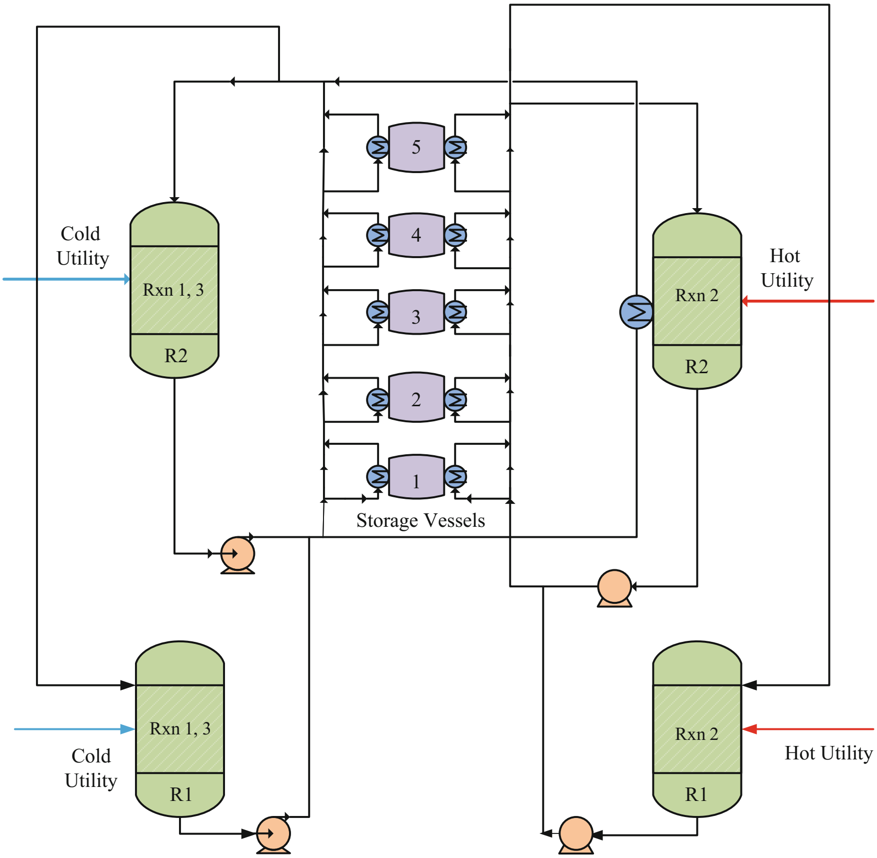

Fig. 13 Superstructure for second illustrative example

to be used for reaction 3. Figure 12a shows the process flow diagram of the illustrative example.

The duration of all tasks varies depending on the quantity of the batch being processed or produced. The constants used to determine the duration of the batches can be found in Appendix A. The maximum batch size that can be heated for the heating task is 100 kg. The maximum batch size to be produced in reactors 1 and 2 is 50 and 80 kg, respectively. The separation can handle a maximum of 200 kg of feed to be separated. The tank farm which shows the maximum storage capability of the intermediate states is shown in Fig. 12b. The initial inventory of the raw materials, states 1, 2, 3 and 4 is given as 1000 kg each at the start of production.

The detailed scheduling data and the detailed heating/cooling requirement data is given in Tables 7, 8 and 9, and the detailed heat storage vessel cost function parameters are given in Table 10 in Appendix A. The three scenarios considered for the first example were once again considered for the second example namely; base case scenario (scenario 1), one heat storage vessel (scenario 2) as well as multiple heat storage vessels (scenario 3). The superstructure for the example is given in Fig. 13. The superstructure had a maximum of five heat storage vessels which could be used for indirect heat integration together with opportunities for direct heat integration and the use of external utilities. The selling price for products 1 and 2 is c.u 20 and the cost of the cold and hot utilities is c.u 0.02 and c.u 1, respectively.

5.2.1 Results and Discussion

The resultant flowsheet and the Gantt chart with the heat integration configuration are presented in Figs. 14 and 15, respectively. Scenario 1 resulted in an objective value of c.u 465.2 × 10^3, hot utility requirement of 16.6 MJ and cold utility requirement of 21 MJ for a 10 h time horizon. Scenario 2 resulted in an increased objective value of c.u 2.5 × 10^6 and a cold utility of 15.6 MJ. A further increase in

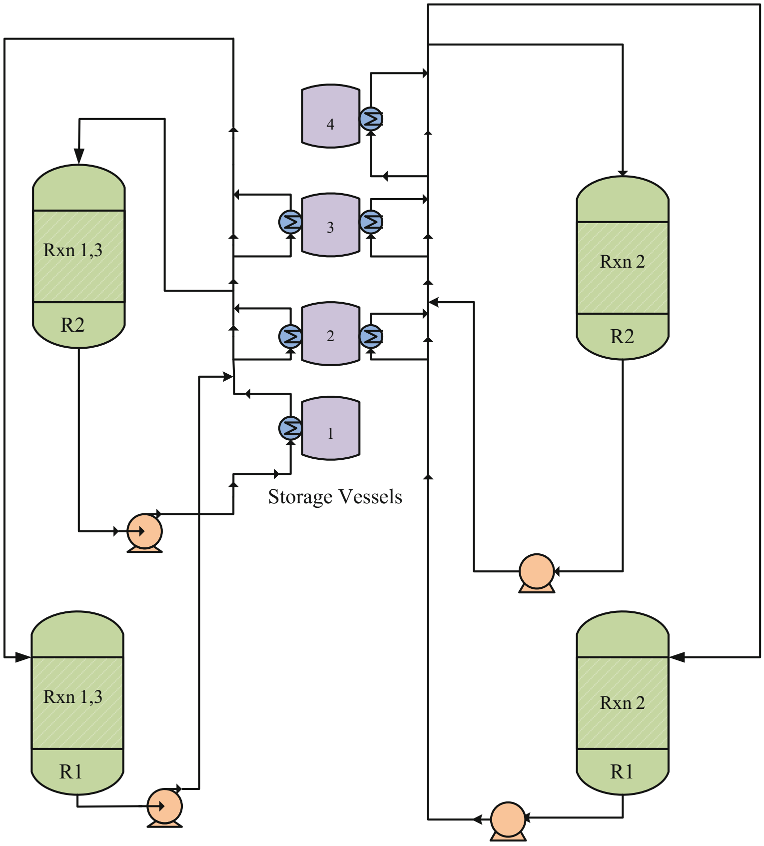

Fig. 14 Resultant flowsheet for second illustrative example

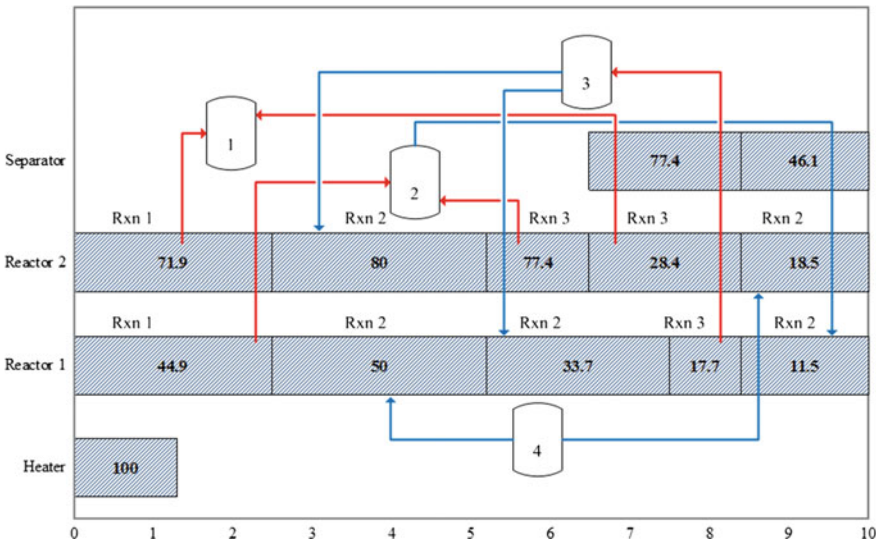

Fig. 15 Gantt chart using proposed model for second illustrative example

the objective value (c.u 2.9 × 10^6) was achieved for scenario 3. No external utilities were used when the proposed model was applied to the illustrative example. This demonstrates that the application of multiple heat storage results not only in the decrease of operational costs, in this instance external utilities, but can result in flexibility of time in the plant which will ultimately affect the revenue of the plant. There is trade-off between cost of the heat storage vessels and minimisation of energy using indirect heat integration. The results of the proposed model show that high savings in external utilities can still be achieved even with the consideration of the capital cost of the storage vessels. The results for the proposed formulation are given in Table 2.

Table 2 Results for second illustrative example

	No integration	One heat storage vessel	Multiple heat storage vessels
Objective (c.u)	465.2 × 10^3	2.5 × 10^6	2.9 × 10^6
Cold utility (MJ)	21.0	15.6	0
Hot utility (MJ)	16.6	0	0
Discrete variables	72	143	236
Continuous variables	337	639	1035
Time points	5	5	5
CPU time (s)	3	6000	6000

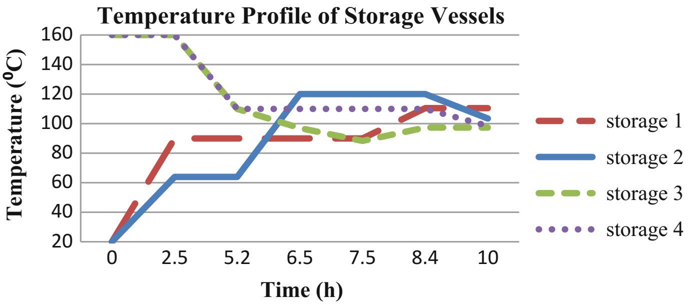

Fig. 16 Temperature profile of heat storage vessels for second illustrative example

The proposed model achieved an optimal number of four heat storage vessels together with the optimal sizes of 25.7, 25.6, 36.6 and 22.9 kg respectively. The optimal initial temperatures of the vessels were 20, 20, 160 and 160 °C respectively. The temperature profiles of the heat storage vessels for the 10 h time horizon are depicted in Fig. 16.

It is worth mentioning that although direct integration was considered in the mathematical formulation, the model did not yield any direct integration connections but integration took place through indirect integration only. This is due to the fact that direct integration places stringent time constraints on the tasks. With the use of multiple heat storage vessels, greater flexibility in terms of time is achieved in the plant, which surpasses that of one heat storage vessel and this is evident from the results obtained after the application of the mathematical model to the illustrative example. The CPU time was once again set at a limit of 6000 s for both scenario 2 and 3.

6 Conclusion

A mathematical formulation for direct and indirect heat integration with multiple heat storage vessels has been developed and applied to two case studies. The emphasis of the formulation is the use of multiple heat storage vessels by looking at the design of the heat storage vessels as well as the synthesis of the heat exchanger network of the batch process. The formulation is aimed at maximising profit in the plant while taking into account the utility and capital costs of the heat storage vessels as well as determining the size and initial temperatures of the heat storage vessels. The application of the formulation results in an increase in profit and the elimination of external utilities use in the plant. The first illustrative example resulted in a 100% decrease of external utilities and an 8.88% increase in profit was obtained when multiple heat storage vessels were considered as compared to when no heat integration is applied to the illustrative example. The second illustrative example resulted in a 100% decrease in external utilities as well as a 17.74%

increase in profit when multiple heat storage vessels were considered as compared to a scenario where only one heat storage vessel is available in the plant. The total reduction in external utilities used in both examples does not include the hot and cold utilities used in the heat storage vessels as heat transfer mediums which are already available at the beginning of the time horizon. The use of multiple heat storage vessels showed a resultant flexibility in time which maximised the throughput of the plant while minimising the operational costs of the plant.

Acknowledgements The authors would like to acknowledge the financial support from the National Research Foundation (NRF) of South Africa under project UID47440.

Appendix A

The scheduling data for the first illustrative example is given in Table 3. The table shows each task with the corresponding maximum batch size and the residence time.

Additional scheduling data is given in Table 4. This table shows each state with the corresponding initial inventory values, maximum storage and the revenue or cost of each state. As previously mentioned, the cost of raw materials is assumed to be zero.

Table 3 Scheduling data for first illustrative example

Task	Unit	Max batch size (kg)	Residence time, τ (hr)
Reaction	R1	60	2
	R2	60	2
Filtration	F1	80	1
	F2	80	1
Distillation	D	140	2

Table 4 Scheduling data for first illustrative example

State	Material state	Initial inventory (kg)	Max storage (kg)	Revenue or cost (c.u)
S1	Feed A	1000	1000	0
S2	Feed B	1000	1000	0
S3	Int AB	0	50	0
S4	Int BC	0	50	0
S5	Waste	0	1000	0
S6	Prod 1	0	1000	120
S7	Prod 2	0	1000	120
	Cold utility			0.02
	Hot utility			1

The heat integration data is given in Table 5. This table gives the supply and target temperatures for each task as well as the specific heat capacities.

The heat storage vessels cost function parameters are given in Table 6. These parameters are the fixed cost, variable cost, operational time, cost function exponent and the number of years a heat storage vessel can be used.

The scheduling data for the first illustrative example is given in Table 7. The table shows each task with the corresponding maximum batch size and the residence time.

Additional scheduling data is given in Table 8. This table shows each state with the corresponding initial inventory values, maximum storage and the revenue or cost of each state. As previously mentioned, the cost of raw materials is assumed to be zero.

Table 5 Heat integration data for first illustrative example

Task	Supply temp, $T^s(s_{inj})$ (°C)	Target temp, $T^t(s_{inj})$ (°C)	Unit	Specific heat, $cp(s_{inj})$ (kJ/kg°C)
Reaction	100	70	R1, R2	3.5
Distillation	65	80	D	2.6

Table 6 Heat storage vessel cost function parameters

Parameter	Symbol	Value
Fixed cost	α_{sto} (c.u)	48,000
Variable cost	β_{sto} (c.u/kg)	280,000
Operational time	hr/yr	7920
Cost function exponent	θ	0.6
Discount factor	a (%)	15
Number of years	n (yr)	3

Table 7 Scheduling data for second illustrative example

Task	Unit	Max batch size (kg)	Minimum time $\alpha\left(s_j^{in}\right)$ (hr)	Variable time $\beta\left(s_j^{in}\right)$ ($\times 10^{-3}$) (hr/kg)
Heating	1	100	0.667	6.67
Reaction 1	2	50	1.334	26.64
	3	80	1.334	16.65
Reaction 2	2	50	1.334	26.64
	3	80	1.334	16.65
Reaction 3	2	50	0.667	13.32
	3	80	0.667	8.33
Separation	4	200	1.3342	6.66

Table 8 Scheduling data for second illustrative example

State	Material state	Initial inventory (kg)	Max storage (kg)	Revenue or cost (c.u)
S1	Feed A	1000	1000	0
S2	Feed B	1000	1000	0
S3, S4	Feed C	1000	1000	0
S5	Hot A	0	100	0
S6	Int AB	0	200	0
S8	Int BC	0	150	0
S9	Impure E	0	200	0
S7	Prod 1	0	1000	20
S10	Prod 2	0	1000	20
	Cold utility			0.02
	Hot utility			1

Table 9 Heat integration data for second illustrative example

Task	Supply temp, $T^s(s_{inj})$ (°C)	Target temp, $T^t(s_{inj})$ (°C)	Unit	Specific heat, $cp(s_{inj})$ (kJ/kg°C)
Reaction 1	100	70	2, 3	3.5
Reaction 2	70	100	2, 3	3.2
Reaction 3	130	100	2, 3	2.6

Table 10 Heat storage vessels cost function parameters

Parameter	Symbol	Value
Fixed cost	α_{sto} (c.u)	48,000
Variable cost	β_{sto} (c.u/kg)	280,000
Operational time	hr/yr	7920
Cost function exponent	θ	0.6
Discount factor	a (%)	15
Number of years	n (yr)	3

The heat integration data is given in Table 9. This table gives the supply and target temperatures for each task as well as the specific heat capacities.

The heat storage vessels cost function parameters are given in Table 10. These parameters are the fixed cost, variable cost, operational time, cost function exponent and the number of years a heat storage vessel can be used.

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Corporates' Role in Addressing Energy Security: A Mahindra Perspective

Anirban Ghosh

Abstract Energy security plays a crucial role in any economy. For a developing country like India with rapidly increasing demand for energy it takes a multi-dimensional role with its economic, social and environmental facets to the issue. In this article we examine the status of energy security in India and the government and corporate response to this crisis and ends with an appeal to corporates to play a larger role in changing the narrative on energy.

Keywords Indian energy security · Corporate role in energy security
Mahindra response to energy security

1 Energy Security: A Growing Concern

India's annual energy import was at $120 billion in 2014.[1] As the economy grows this will become bigger. As long as dependence on fossil fuels is high, this spend will remain a millstone around India's neck.

India's primary energy demand is growing at 4.2% per annum compared to the global growth rate of 2%.[2] India's power consumption was 5% of global consumption in 2012 and India had overtaken Japan to become the fourth largest energy consumer.[3] Despite the size and growth, India is still far below the global per capita consumption average with only 875 kWh per head (at a population of 1.2 billion) compared to 11,900 kWh for the average US citizen, 6,600 kWh of the average German citizen or even the global average of around 3,000 kWh.[4] With greater energy access to rural India, increasing urbanization and growth in vehicle

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[1] GoldmanSachs Report 2014.
[2] BP ENERGY OUTLOOK REPORT 2017.
[3] US Energy Information Administration (EIA) report on energy outlook for India 2012.
[4] World energy council data.

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population, the overall consumption of energy can only become higher. Little wonder that India, with 66% energy sufficiency, ranks 81st in overall energy security.[5]

If by 2035 India were to provide its citizens (projected population of 1.5 billion) with the same amount of power that China generates today (2017), it would need to increase its energy generation to 5,250 TWh per year[6] up from 1,050 TWh in 2012. India's generation capacity will have to increase up to six times the present figure to meet our growth needs. This is the reality that shapes India's energy policy and dominates the external trade discussion.

Goldman Sachs anticipates that India's annual energy import bill could jump to $230 billion by fiscal 2023.[7] Greater import dependence for energy has driven up India's import bill and exposure to volatile energy prices. The import bill has declined in recent years with a dip in global oil prices, but increasing imports and fluctuating prices continue to pose risks. In 2014, India's net energy imports were at 6.3% of its gross domestic product while England which is heavily dependened on energy imports spend 2.8% of its GDP in the same period on importing energy.[8] Given the demand projections for the future, steps to enhance energy security are of paramount importance.

2 Energy Externalities

Besides the economic cost of fossil fuels there are also other risks associated with being over dependent on them. Turning fossil fuels into energy produces a variety of emissions that pollute our planet's air and water. Burning of coal, oil and gas has been linked to the rising levels of greenhouse gases in Earth's atmosphere and is a leading contributor of climate change. These damages or the true environment costs accrue at every point of the fossil fuel supply chain. The mining process involved in the collection of fossil fuels itself can cause damage to the environment. The Extraction processes of coal can generate air and water pollution, and potentially harm the climate of the local communities which could be detrimental to their health. Transporting fuels from the mine or well can cause air pollution and we have witnessed serious accidents and spills leading to irreversible damage. When these fuels are burned during their usage they emit toxins in the form of greenhouse gases. Even after years of their usage these gas are hazardous to public health and the environment.

Fossil Fuels are finite meaning they are non-renewable natural resource and will not be replenished. The limited nature of fossil fuels means we cannot rely on it

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[5] US Energy Information Administration (EIA) report on energy outlook for India 2014.

[6] Bridge to India report.

[7] GoldmanSachs report 2014.

[8] Energy in brief, www.gov.uk.

indefinitely. Also with the eminent climate crisis we as a globe are facing it is being said that globally 82% of today's energy reserves must be left underground to ensure that we meet the 2^0 Goal. What this means is that in major coal producing nations like the US, Australia and Russia, more than 90% of coal reserves will remain unused and in China and India, both heavy and growing coal users, 66% of reserves are unburnt.[9]

And realizing this India is responding to this crisis.

3 Government Response

By investing heavily in solar and wind, Indian government has helped drive down the cost of those technologies to a point where, in many places, renewable sources can generate electricity more cheaply than sources of energy like coal. The shift from fossil fuels has thus been much faster and more pronounced than most experts expected. Indian officials have estimated that country might no longer need to build new coal plants beyond those that are already under construction.

India has the world's fourth largest wind power market[10] and also plans to add about 100 GW of solar power capacity by 2020[11] as announced in the national solar mission. In fact, this year India will likely overtake Japan as the world's third-largest solar-power producer, after China and the US. This is ensuring that our dependency on coal plants is decreasing. India also foresees an increase in the contribution of nuclear power to overall electricity generation capacity which is one of the highest energy guzzlers from 4.2 to 9% within 25 years[12] according to the government plans. The country has five nuclear reactors under construction and plans to construct 18 additional nuclear reactors by 2025.[13] These commitments showcase the importance given by the government in response to the energy requirement.

On the electricity front, the country has developed an Energy Efficiency Code for Buildings and has launched one of the biggest effort worldwide for LED's to replace bulbs at affordable prices for consumers. According to the manufacturer's association till a couple of years ago less than 5 million LED lights were being used in the country, they estimate that now more than 100 million have been put to use. Even this is small because the manufacturers see the investments multiplying 24 times from the current level in less than 5 years to cater to the demand.[14] Though the vast majority of India's electricity needs still comes from heavily-polluting coal

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[9] World energy outlook 2012.

[10] Economic survey 2017.

[11] National solar mission—India.

[12] http://www.world-nuclear.org/information-library/country-profiles/countries-g-n/india.aspx.

[13] http://www.world-nuclear.org/information-library/country-profiles/countries-g-n/india.aspx.

[14] https://eeslindia.org/writereaddata/Ujala%20Case%20study.pdf.

power plants, just under two thirds of its total capacity, but India is aiming for a target of 40% renewable energy.[15]

In a recent auction in India, developers of solar farms offered to sell electricity to the grid for INR 2.44 rupees per kilowatt-hour.[16] That is about 50% less than what solar farms bid a year earlier and about 24% less than the average price for energy generated by coal-fired power plants.[17] Solar electricity price is going to become the benchmark price for deciding the other fuel prices (Petroleum products, LNG, CNG, LPG, coal, lignite, biomass, etc.) based on their ultimate use and advantages.

In all major energy intensive sectors—steel, aluminium, fertiliser, paper, cement—levels of energy efficiency in India are at global levels. The need for energy efficient products is also triggering innovation. The product portfolios of organizations are helping consumers become energy efficient with new energy efficient products accounting for a large and growing part of their revenue portfolio. Once upon a time there was a song that went "Video killed the Radio Star"; there can be a hundred songs like that now because energy efficiency is triggering innovation.

The good news is that India is on path and set to achieve this eight years ahead of schedule according to reports.[18] By doing right, India is finding that thinking green need not carry a big economic cost and can actually be beneficial.

4 Corporate Response

Companies are also partners in this response. Corporates today have an increasingly broad understanding of the risks and opportunities that climate change poses to their strategies and operations. There are discussions on the larger issues of sustainability triggered by climate change that are becoming an integral component of dialogues with the major stakeholders.

The most attractive environment-related initiatives that have evolved through these conversations involve the use of renewable energy, ranging from solar street lamps and lanterns to biomass cook stoves and using cleaner energy like the electric cars. One of the reasons why companies may prefer such projects would be that access to clean energy has several cascading effects on the social and economic development—ranging from opportunities for better education, health, and income to increased safety for women and lower deaths due to reduced indoor pollution.

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[15] http://www.business-standard.com/article/economy-policy/india-s-energy-mix-to-have-40-renewable-sources-by-2030-115092200057_1.html.

[16] http://www.thehindubusinessline.com/economy/solar-tariffs-fall-further-to-rs-244/article9694617.ece.

[17] http://www.independent.co.uk/environment/india-solar-power-electricity-cancels-coal-fired-power-stations-record-low-a7751916.html.

[18] http://indianexpress.com/article/india/india-aspiring-for-global-leadership-in-climate-action-4770895/.

There are already sustainable technologies, such as solar and wind power that can achieve energy independence and stabilize human-induced climate change.

Initiatives taken by corporates include initiatives like The Climate Group (a non-governmental organization) energy campaign—EP100—that aims to work with the world's most influential businesses in setting commitments to double their energy productivity and maximize the economic output from each unit of energy used. By signing up to EP100, companies commit to doubling their energy productivity by 2030, a core requirement for any business signing on to the campaign. The concept of energy productivity aligns energy efficiency more directly with business growth and development objectives. If more companies were to adopt energy productivity within their business models, the global fossil fuel bill could be reduced by an estimated €2 trillion (INR 1 crore 52 lakhs crores) and create more than six million jobs globally by 2020 as envisioned by the campaign.[19]

There is also RE 100 which as their website states is a collaborative, global initiative uniting more than 100 influential businesses committed to 100% renewable electricity, working to massively increase demand for—and delivery of—renewable energy. RE100 shares the compelling business case for renewables, such as greater control over energy costs, increased competitiveness, and delivery on emissions goals. It also showcases business action on renewables and encourages supplier engagement, while working to address barriers that will enable many more companies to reap the benefits of going 100% renewable. Companies joining RE 100 are strongly encouraged to set a public goal to source 100% of their global electricity consumption from renewable sources by a specified year. They disclose their electricity data annually, and RE 100 reports on their progress.[20]

There is also the Vision 2050 Project taken up by the World Business Council for Sustainable Development (WBCSD) which saw 29 WBCSD member companies develop a vision of a world well on the way to sustainability by 2050. The members were supported by the WBCSD secretariat, the wider business community and regional network partners around the world, in mapping out not what they think will be, nor what they fear will be, but what could be. Given the megatrends of climate change, global population growth and urbanization, and given the best efforts of business, governments and society, Vision 2050 is a picture of the best possible outcome for the human population and the planet it lives on over the next four decades. In a nutshell, that outcome would be a planet of around 9 billion people, all living well—with enough food, clean water, sanitation, shelter, mobility, education and health to make for wellness—within the limits of what this small, fragile planet can supply and renew, every day. And in this new world every corporation would be do its bit while being sustainable.

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[19] https://www.theclimategroup.org/project/ep100.

[20] https://www.theclimategroup.org/RE100.

The critical pathway as mentioned in this document includes[21]:

- Halving carbon emissions worldwide (based on 2005 levels) by 2050, with greenhouse gas emissions peaking around 2020 through a shift to low-carbon energy systems and highly improved demand-side energy efficiency.
- Providing universal access to low carbon mobility.

The government has been an active participant in generating this dialogue within the industry.

India's Green Power Market Development Group (GPMDG), led by World Resources Institute (WRI) and the Confederation of Indian Industries (CII), is one such group that brings together government, utilities, regulators, companies and energy developers to scale up renewable energy purchasing in the private sector. So far, the group has worked with over 30 leading businesses in India to facilitate 200 megawatts (MW) of renewable energy transactions across several states, including Karnataka, Tamil Nadu and Maharashtra. The vision of GPMDG as stated on their website is that it aims to bring 1,000 MW of additional clean energy online by 2020, enough power to energize 200,000 typical two-bedroom apartments. Over the past four years, GPMDG has pursued several strategies to make clean energy procurement more streamlined and accessible to large buyers in India.[22]

Another major push has been through the National Action Plan for Climate Change which has 8 high impact programs which is also leading to improvements on the floor shop. There have been focussed programs like the energy rating program that has made air-conditioners about 70% more energy efficient.[23] The cement industry has moved from using 1000 kcal/kg of clinker to 680 kcal/kg, very close to the world best of 650 kcal/kg.[24]

Companies are eager to help the government on their energy goals, given the cost savings and environmental benefits of renewable energy, but many face barriers to sourcing wind and solar power. What is needed is a long-term certainty in policy implementation and access to innovative business models and financial products. Commercial and industrial customers account for close to 52% of India's electricity consumption and hence can have a significant impact on the energy story.[25]

A sustainable corporation needs to thus proactively work on the energy issue. Case in point is the Mahindra Group. A list a few initiatives taken by the group which demonstrate the possibilities for corporates to contribute towards addressing the issue of Energy security in the larger context of a Sustainable organization.

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[21] http://www.wbcsd.org/Overview/About-us/Vision2050.

[22] http://www.wri.org/our-work/project/charge/buying-green-power.

[23] https://www.nrdc.org/experts/anjali-jaiswal/india-pushes-more-super-efficient-climate-friendly-acs.

[24] http://knowledgeplatform.in/portfolio/cement/.

[25] http://www.wri.org/blog/2017/03/how-companies-are-buying-clean-energy-4-lessons-india.

5 Baking Sustainability into Business

It wouldn’t be wrong to say that the last few years have been witnessed a lot of action on the Sustainability front including response to the energy crisis. From adoption of the Paris Agreement and the UN Sustainable Development Goals (SDGs), we have witnessed historical achievements and generated hope that the international community is finally uniting in pursuit of ambitious, long-term solutions to mankind’s most significant challenge. There is growing consensus among world leaders across business, government and civil society about the future direction of climate action and the need for concerted, coordinated, systemic responses to resource conservation and deployment. The focus is now on the deliverables.

And Mahindra is aligned to this purpose.

Delivering on the purpose requires an actionable definition of Sustainability. The most frequently cited definition comes from the 1987 report of the World Commission on Environment and Development, titled “Our Common Future” (also known as the Brundtland Commission Report). It reads, “Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.”[26] Although this definition reflects the ethos of Sustainability, it does not specify a course of action.

So the group took upon itself to craft a working definition of Sustainability when viewed from the perspective of a Corporation (Fig. 1).

Fig. 1 Mahindra sustainability framework. http://www.mahindra.com/resources/pdf/sustainability/mahindra-integrated-report-FY17.pdf

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[26] http://biodiversitya-z.org/content/sustainable-development.

The definition as laid out above reads, "Sustainability is to enable enduring business by rejuvenating the environment and enabling stakeholders to Rise." This definition is action-oriented, makes the areas of action clear and lays out the objectives for business and beyond, or shall we say, people, planet and profit.[27]

The definition translates into includes making its work places great places to work, fostering inclusive development and making sustainability personal for colleagues and their families on the People front. Through the planet pillar the company address carbon neutrality, water positive and making waste a resource and not just mere refuse while protecting biodiversity. In the profit pillar the company aims to develop products and services which generate an evergreen stream of green revenue, mitigate risks for its business including climate risk evangelizing sustainability through the supply chain for greater impact, recognize that the role of technology and innovation in shaping progress on sustainable development will remain paramount and ensure that they enhance brand equity through sustainable work. The base for all this would be the work that the company does on sustainability through sharing and learning of best practices and in the process the aim is to give back to the earth more than they take. There are multiple ways in which the definition is operationalized within the Mahindra Group.

The work that the group is doing has led to it attaining a leadership position on the Sustainability front with recognition coming in from across the globe. This has led to accolades, one of which was Mr. Anand Mahindra, Chairman, Mahindra Group representing the world's business community at the signing ceremony of the Paris Accord at the UN Headquarters in New York in 2016 and committing to invest in a greener future.[28]

6 Green Revenue Portfolio

One of the ways in which the definition has been operationalized is through Mahindra's green revenue portfolio. Mahindra Group is disrupting the narrative of sustainability from conservation to rejuvenation. Which is why they are committed to pursue the path of Carbon Neutrality which is aligned to the Sustainable energy story of the country. The company has been working on sustainability are the Multiple revenue opportunities being leveraged in its business. These areas are closely connected to climate change such as setting up solar power generation capacity (Mahindra Susten), micro-irrigation (Mahindra EPC), electric cars (Mahindra Reva), electric scooters (Mahindra GenZe), cars that run on CNG (alternative fuel), building green buildings (Mahindra Lifespaces), building a carbon neutral city (Mahindra World City) and leveraging cloud based services in IT

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[27] www.mahindra.com.

[28] www.mahindra.com.

applications and the IT business (Tech Mahindra). Revenue from these businesses amounts to over 400 million dollars.[29]

It's widely acknowledged that increasing transportation efficiency is the best place to start efforts to reduce emissions of carbon dioxide (CO_2), which is a primary culprit in global warming. Climate action often focuses on energy and industrial activity, but the transport sector must be included to keep global warming below the dangerous two-degree scenario. Transport is responsible for 22% of energy-related greenhouse gas (GHG) emissions worldwide, according to a 2014 report by International Agency Energy's World Energy Outlook, and its emissions are increasing at a faster rate than any other sectors.[30] Implementing low-carbon transport options can create multiple economic and social development benefits, in addition to reducing emissions. These local benefits include improved air quality, safer streets, and poverty alleviation. Outdoor air pollution was associated with 3.7 million premature deaths in 2012, and fuel combustion in motor vehicles is responsible for up to 75% of urban air pollution.[31] Improving fuel technologies and shifting passengers to more sustainable modes like public transport, walking, and bicycling can both improve air quality and lower carbon emissions.

Electric cars produce fewer greenhouse gases. Although the cars can cause environmental damage when getting power from coal-producing plants, electric cars would dramatically reduce the amount of greenhouse gasses when powered by plants that don't produce greenhouse gases. Even when generated from coal-burning plants, electric cars would reduce carbon dioxide emissions by as much as 22% when compared to other fuel.[32]

To respond to this Mahindra Electric focuses on the future of transportation. In deploying their detailed "5C strategy" (clean, convenient, connected, clever, cost-effective) Mahindra Electric has managed to deliver sustainable transportation solutions to customers across the world. For a company who first made its name and profits largely through the manufacturing of rugged diesel-powered SUVs in India to so willingly explore the EV sector evidences the financial and ethical viability of alternative transportation.

Mahindra Electric has one of the world's largest deployed fleets of electric cars—customers in 24 countries have driven more than 200 million kilometers, absolutely emission free.[33] The company manufactures cars, licenses out its electric vehicle technologies, electrifies existing platforms, and helps to deliver. The business has developed e_2oPlus—A hatch back, built ground up by Mahindra Electric. Also the eVerito—The all-electric version of the sedan, Vertio eSupro—The electrified variant of the passenger vehicle, Supro.

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[29] http://www.mahindra.com/resources/pdf/sustainability/mahindra-integrated-report-FY17.pdf.

[30] International agency energy's world energy outlook 2014.

[31] World health organization survey 2017.

[32] http://www.newsmax.com/FastFeatures/cars-global-warming-electric-cars/2015/03/23/id/631734/.

[33] http://www.mahindraelectric.com/mahindraelectric/.

As researchers look for more alternative ways to replace oil-producing vehicles that can damage the environment, electric cars provide cleaner energy when power comes from a cleaner electric grid. The environment will benefit from the growing use of electric cars as improvements are made for renewable power generation and the Mahindra group is invested in this.[34]

Another example of the way in which the green product portfolio is being addressed by the Mahindra Group is Mahindra Susten. Driven by and committed to providing state-of-the-art climate sustainability solutions, Susten offers diversified services within the renewable energy sector, including utility scale and rooftop solar panels, solar DG hybrid solutions, solar car charging stations, telecom tower solarization, and solar PV O&M and analytics. Perhaps the leading player in Indian solar power, Mahindra Susten has over 556 MWp commissioned to date with 450 under current execution.[35]

India is endowed with vast solar energy potential. About 5,000 trillion kWh per year energy is incident over India's land area with most parts receiving 4–7 kWh per Sq. m per day.[36] Hence, both technology routes for conversion of solar radiation into heat and electricity, namely, solar thermal and solar photovoltaics, can effectively be harnessed providing huge scalability for solar in India.

On the energy front the company also strives for optimized use of resources. Hundreds of projects in the areas of heat recovery, energy efficient cooling, energy efficient lighting, retro fitment of equipment to enhance energy efficiency, etc. within the company and with suppliers has led to energy consumption per vehicle being reduced by one-third in less than a decade.[37]

Mahindra also worked extensively on its energy mix promoting use of renewable energy. Examples of the work that the company has done through its different businesses:

- Implementation of Renewable energy projects (Solar/Solar Thermal/Solar PV) at all manufacturing sites.
- Procurement of RECs from power exchange thus promoting renewable energy deployment.
- Installation of solar PV panels to harness solar energy.

Mahindra is also an active advocate in the corporate space. The company has already made important commitments on the energy front.

Mahindra & Mahindra (M&M), the largest company in the Mahindra group, became the first Indian company to sign up for the EP 100 program. Dr. Pawan Goenka, Managing Director, M&M, said on the occasion of the signing of EP 100, "Sustainability is an integral part of Mahindra's approach to business. At Mahindra, it has always been our endeavour to drive positive change by making every aspect

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[34] http://www.mahindraelectric.com/mahindraelectric/.

[35] http://www.mahindrasusten.com/.

[36] http://www.mahindrasusten.com/.

[37] http://www.mahindra.com/resources/pdf/sustainability/mahindra-integrated-report-FY17.pdf.

of our business sustainable. This is our philosophy behind "Rise for Good". By signing up for EP100, the company is making a significant commitment to doubling our energy productivity by 2030 on a baseline of 2005, and hope to make a strong contribution towards achieving the climate goals agreed upon at COP21. We hope many other corporations will become a part of this campaign."[38] Mahindra Holidays & Resorts India Ltd. (MHRIL), another group company, has since then signed on EP 100 and in the process has become the first Indian hospitality company to join program.[39]

Post the commitment, the automotive and farm equipment businesses of M&M has found that they can replace all their lights with LED and magnetic induction lighting with a payback period of less than 15 months and returns that are higher than that generated by the core business. The company has learnt that every business will have multiple opportunities to get high returns from investments in energy productivity and the initial investment obviously thus is not a deterrent. If availability of funds is a problem, then businesses also have the option of getting the service provider make the initial investment.

The company knows that the energy productivity at suppliers is critical to reduce emissions and cost. Mahindra engages extensively with its suppliers to make this happen. The program includes capacity building, best practice sharing, goal setting, audits, technology exposure and recognition of work done by the channel partner. This helps Mahindra be a responsible manufacturer and take sustainability beyond its own boundary.

Mahindra & Mahindra was also the first company in India to launch an internal carbon fee. The internal carbon fee announced of $10 per metric ton will help reduce M&M's carbon footprint and achieve its goal of reducing GHG emissions 25% by 2019.[40] The carbon price helps the company to accelerate its transition to clean energy sources (for example, investment in LED lighting) as well as reduce the company's energy and operating costs.

The company has plans to spend the $4 million investment of funds raised from the carbon fee to convert all 17 manufacturing plants to LED lighting which will yield a return on investment in less than one year.[41] Since the adoption of the carbon fee in October 2016, M&M has continued to increase its investment in energy efficiency and renewable energy projects, including a 4.2 MW wind energy project, compared with its 2015 "business as usual" levels. The company has plans to add additional renewable energy projects in its new fiscal year.[42]

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[38] www.mahindra.com.

[39] www.mahindra.com.

[40] www.mahindra.com.

[41] http://www.mahindra.com/resources/pdf/sustainability/mahindra-integrated-report-FY17.pdf.

[42] http://www.mahindra.com/resources/pdf/sustainability/mahindra-integrated-report-FY17.pdf.

7 Opportunities

Access to energy is the mainstay for economic growth in our country. India is on a fast trajectory of development with government boosting business through initiatives like ‘Make in India’, but to keep the momentum of growth high, availability of uninterrupted power supply is a must. India needs electricity to fuel the growth of every industry, be it large-scale or small scale, manufacturing or service driven across all sectors. This makes it important that corporates work alongside government and social sector to deliver a solution that works for all.

It is also important that one recognizes important to recognize that the role of technology and innovation in shaping progress on sustainable development which will remain paramount. The key is to increasingly look at cost-effective renewable technologies, new energy efficiency measures and exciting innovations in robotics and big data which could potentially change the way we address the energy requirements of the country. This can be achieved through challenging conventional thinking which is driven on high fuel and innovatively using all our resources in this specific case energy to deliver greener products.

Renewable energy has a lot of advantages and the time to make a move is now. India is aggressively pursuing the low-carbon power generation plan with the government pursing a lot of programs designed around the same. Energy statistics 2013 (twentieth Issue) pegged the potential of the Renewable energy generation in the country at 89,774 MW.[43] The country though a late entrant has the advantage of catering to a huge population not having access to fossil-fuel-generated power and is better placed to perform once the renewable energy rates beat the traditional ones.

The country’s renewable energy programme would need investment to expand its generation capacity and eventually, to make the sector efficient and commercially viable. For the same what is required is supporting mechanisms within the corporate and the government sector to strengthen the call for clean and renewable energy policies. This can be done through advocacy and awareness building and creating a supportive renewable energy implementation environment across all sectors. The government can help by initiating activities aimed at helping compliance by evolving renewable energy deployment targets; and building supportive policy evidence through research around grid as well as off-grid business models.

Progress of the energy sector towards green power has tremendous potential with the opportunities for employment, accessibility to electricity and responding on the climate change combat plan. Besides this, these investments will also help us as communities to address the enormous challenge of energy security towards a better future for our planet.

The appeal is for corporates to play a larger role in this conversation.

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[43] Energy statistics 2013 (twentieth Issue).

National Mission on Bio-Diesel in India (2003): An Assessment Based on Strategic Niche Management

Duke Ghosh and Joyashree Roy

Abstract Rapid economic growth, rising connectivity and increased mobility means increased demand for transportation fuel. Like the rest of the world, India's hydrocarbon demand in the mobility domain continues to rise and is a major cause for concern given the implications concerning greenhouse gas emissions. Assuming the country's energy demand maintains its present trajectory, it is predicted, that by 2030 India will have to import about 94% of its crude oil consumption. The Indian government introduced the National Mission on Biodiesel in 2003 and subsequently promulgated the National Policy on Biofuels in 2009. The policy proposes an indicative target of 20% blending of biofuels—both bio-diesel and bio-ethanol, by 2017. The availability of feedstock crops, the presence of a large sugar industry and favourable climatic conditions for plants like *Jatropha carcus* is conducive for producing bio-fuels in the country. Despite these policy initiatives, in 2017 it was clear that the bio-diesel is yet to become a popular alternative fuel in the mobility sector in India. The present paper deploys the strategic niche management framework to understand the policy attempts and observed lag in this experiment of bio-diesel mission. Within the framework of transitions literature, the study aims at presenting the findings from the process tracing study of the Indian experimentation on bio-diesel since inception. It investigates as to what extent the experiment has been embedded in the incumbent mobility regime. This study can offer an insight into the uniqueness of challenges in up-scaling any experiment that aims at transforming the hydrocarbon dominated mobility sector in India.

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1 Introduction

More than a decade has elapsed since India launched its National Mission on Biodiesel (NBM) in 2003[1] with an aim to transform the road transport sector which is characterized by high consumption of fossil fuels. Key considerations that had influenced the launch of NBM are: energy security, geo-political considerations, trade deficits and the global thrust towards exploring sustainable sources of energy. The NBM aimed at diffusion of a set of inter connected innovations through diffusion of novel techniques (cultivation of feedstock, biofuel extraction, blending, etc.) to foster a sustainability transition in the socio-technical norms guiding the mobility regime. The literature on sustainability transition posits that transition is heralded when there is 'systemic' and 'radical' change in the ways the human needs are satisfied [33]. Path-breaking innovations, also called experiments, aim at transforming the socio-technical configuration. The experiments are often interconnected and emerge outside the regime, i.e. in niches which act as protective spaces where the experiments can thrive relatively free from the pressures of market selection [17]. When the niches develop, supported by the exogenous factors—called 'landscape', they can put pressure on the prevailing regime and destabilize it [16].

The NBM in 2003, thus, constituted an emerging niche. It planned to mainstream biofuel in the mobility regime in two phases—an initial research, development and demonstration phase followed by a self-sustaining expansion phase. The National Policy on Biofuels in 2009 (NPB) was subsequently announced by the Government of India (GoI) as a reinforcing landscape factor to design a roadmap for taking forward and maturing the biofuels niche in the short to medium run. The NPB proclaimed the diffusion and promotion of biofuel in the mobility regime as a way to address, apart from the goals proclaimed in the NBM, the issues concerning income generation and poverty alleviation, rural development, economic development of the marginalized social groups and fostering equity among different layers of socio-economic groups and regions, which now feature in sustainable development goals (SDGs).[2] Therefore, the NBM in India did aim at transformation by increasing sustainability gains—accruing benefits to the economy and society along with environmental gains. This is of supreme importance to a developing/emerging economy like India whose development challenges are far-reaching and transcends environmental paradigm. Hence, we regard the NBM experiment as experiments for sustainability transition.

Despite announcing a blending target in the year 2009, in a phased manner, for both bioethanol and biodiesel, the experiments are still at a niche stage [8, 40]. A deep-rooted 'societal embedding' [13] is awaited. Given the "top–down" nature (initiated by the government, as a part of national policy) of the experiments, this

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[1] The process started with the publication of the report of the expert committee on development of biofuels under the aegis of the Planning Commission, Government of India.

[2] Particularly, the following goals—1, 2, 5, 7, 8, 10, 13.

article hypothesises that the architecture for carrying out the experiment and the promises of strategic gains that the experiment uphold for the Indian economy had missing links. So far the experiment has been evaluated by the scientific community from various perspectives—agronomy, value chain analysis, economics, political economy, sociology, etc., and each study has indicated a set of barriers that prevented the process of maturing.

In this article, we concentrate on the experiments concerning biodiesel in India under NBM 2003 using strategic niche management (SNM) framework [42, 47]. Diesel constitutes about 70% of the fuel demand in the transport sector. Switching over to biodiesel, at least partially, is expected to have an enormous positive impact on the Indian economy. Further, switching costs associated with the blending of biodiesel is lower compared to bioethanol [40]. From their very inception the policies have stressed on the promotion of *Jatropha carcus* (jatropha) and *Pongamia pinnata* (pongamia) as the two most potential sources of biodiesel in the country and many farmers have started cultivating these two varieties of tree-borne oilseeds (TBO). In our current discourse we focus mostly on jatropha. Studying the biodiesel niche in India under the lens of strategic niche management (SNM), we try to answer the following research questions:

(a) What has been the mechanism for forming a biodiesel niche in India?
(b) What set of barriers does the niche face that thwarts the possibility of its maturity and up-scaling?
(c) To what extent do the factors specific to the emerging (and/or developing) countries influence the barriers?

The article is arranged as follows: Sect. 2 discusses the core concepts of the theoretical framework of niche development and strategic niche management which are used to assess the NBM. Section 3 describes the incumbent regime of road based mobility in India and it's evolution with special focus on pre and post NBM and NBP. Section 4 describes the context in which NBM and NBP experiments were planned. Section 5 uses the theoretical framework described in Sect. 2 to make an assessment of performance of the NBM. Then we briefly discuss the incumbent regime of hydrocarbon dependent road-based mobility system in India and, subsequently, we delve into a discussion on the initiation and progress of the experiment on biodiesel in India. Later we deploy the SNM approach to critically analyze the experiment and trace out the missing links. Concluding remarks are in Sect. 6.

2 Analytical Framework: Niche Development and Strategic Niche Management

The term "innovation" refers to a technological breakthrough that gradually emerges and strives to find a permanent place in the current socio-technical regime. What drives systems innovations for sustainability gains? How do some of these innovations find a somewhat permanent place in the incumbent socio-technical configuration? Why do a set of innovations not mature? This set of critical research questions have attracted the attention of the scholars since the mid 1990s [42]. Researchers in sustainability transitions [48, 16, 46] proposed a multi-level perspective (MLP) incorporating the complex interactions and dynamics within and between landscape, regime and niches as explanatory factors for system innovations. In this framework, a regime is a configuration of a set of established rules and routines that makes the society "blind to radical variations" in technologies. Raven et al. [43] describes the socio-technical regime as "retention mechanisms in the minds of engineers like genes are in biological variation." On the other hand, the socio-technical landscape encompasses the more slowly changing factors [48, 42]

The early researchers [48, 29] termed innovations (at their early stages) as "societal experiments"—accounting for the uncertainty and the learning associated with such activities. They also advocated the need to protect such experiments. A number of experiments, having a common goal and purpose, collectively form a niche. The challenge is to upscale the niches and aim at social embedding of the innovation(s).

Literature identifies two distinct niches. The "technological niches" are intentionally created protected spaces with supportive measures (economic and otherwise). These niches are regarded as crucial steps for maturing innovations and fostering sustainability transitions [42]. In Strategic Nice Management (SNM) approach (Fig. 1), the governance of the sustainability transition is seen as a process of articulating expectations, initiating and withdrawing the protection(s), building of social networks, experimentation, learning and, finally, branching into new market niches and eventually mainstreaming markets [42]. The second type of niche—the "market niches", is the relatively small market segments where there exists demand for novel technologies [29]. These niches are characterized by a revealed willingness to pay for better technologies, even with lower than expected performance. Based on such demand—a small number of firms undertake production on a "stable basis". This also leads us to the fact that niches can be situated at the firm-level. Firms also build protected spaces for enabling continued research and development on technological innovations. The protected spaces, most often, do not lead to immediate financial gains—the motivation is derived from the firms' "expectations" about future demand in the market [58]. A more recent development in literature is the concept of niches at the grassroots where niches exist at the level of communities—NGOs, civil societies, etc. [25]. SNM describes a theoretical framework that deliberates on strategies for managing the niches, and harnessing maximum gains—both in the short and long term, as promised by the niches. Hoogma et al. [26] and Raven [42], etc. mention certain important components of the SNM—articulation of vision and expectations, shaping social networks and alliances, second order learning and protection of the niche (Fig. 1). We deploy this framework in this article.

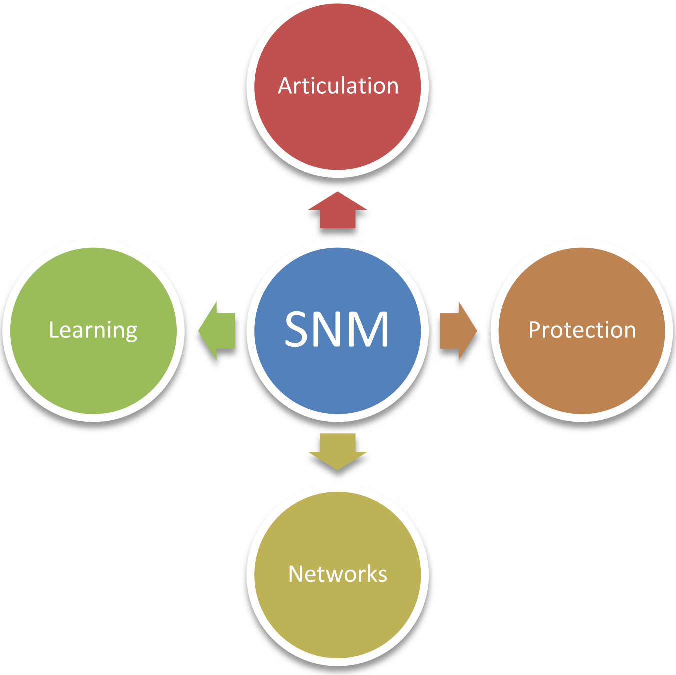

Fig. 1 The SNM approach (based on Raven [42])

3 Road Based Mobility in India: Landscape and Regime

The emerging economies in Asia are at crossroads—while the pace of economic growth in these countries is high, there are serious doubts concerning the changes to socio-cultural and environmental aspects [5]. India is experiencing an economic growth that is changing the patterns of economic incentives and structure, social norms and cultural orientations. A burgeoning 'middleclass' with changing aspirations is fostering a change at the societal level [36]. How a growing economy manages the environmental sustainability is posing challenges and opportunities for India.

3.1 Road Based Mobility Regime in India: Evolution Over Time

Since the adoption of the Industrial Policy Resolution 1956, the GoI started emphasizing on policy interventions for evolving road based mobility (for both passengers and goods) as a facilitator of economic growth and development. However, given its modal mix, the road based mobility regime in India is characterized by high fossil fuel consumption and emission intensity.[3] Motorization has been growing and there is an increasing preference among the people for private space and flexibility in mobility [10]. Consumption of fossil fuels is increasing and traffic congestion on roads is further driving up the fuel use. With large volume of traffic on roads and high emissions the environmental sustainability of the system is in question.

Immediately after independence in 1947, the economic priorities led to a reshaping of the transport sector in the country. Providing adequate transport infrastructure and giving access to multiple services to the remotest nook and corner of the nation were the priorities of the first few national five-year plans. Since the early 1990s, India has been witnessing high economic growth (relative to the past years) together with a spectrum of changes in the cultural and societal domains. What started as a set of economic reforms [27] has gradually influenced the culture and aspirations of the common man in the country [33]. Technology changes have taken place at many different domains—particularly in the field of communications, and the erstwhile 'information gap' between the non-urban and urban India has reduced to some extent. India is 'catching up' with the growth pattern of the developed countries [28, 51].

Multiple trends have influenced the mobility sector—particularly, the urban road based mobility system. While demand for mobility has risen partially due to 'economic' reasons, cultural shifts and availability of technologies (and options)—motorized two and three-wheelers, CNG and LPG fuelled vehicles, etc. have also played an important role in changing the pattern of demand for various types of transport services (Table 1). The opening up of the economy has facilitated a good volume of foreign direct investment in the automobile sector and this has increased the supply of options and affordability for the Indian consumer. The growth of the tertiary sector has influenced the pattern of income distribution and the emergence of a professional middle class is a defining characteristic of the economy. These changes have also caused a substantial shift in the demand for comfortable mobility.

During the 1990s, although the Indian economy grew by 6–7% p.a., the transport demand grew by about 10% p.a. [50]. The overall structure of the Indian transport sector has been gradually (and continuously) changing and this change is expected to continue in the future [55]. This is a defining characteristic of the incumbent urban road transport regime in the country.

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[3] Transport accounts for 7% of the national GHG emission [23].

Table 1 Passenger mobility regime in India: past, present and future

Mode of transport	2000–01			2010–11			2020–21			2030–31			
	BPKm	Energy demand (PJ)	Energy use per person (MJ)	BPKm	Energy demand (PJ)	Energy use per person (MJ)	BPKm	Energy demand (PJ)	Energy use per person (MJ)	BPKm	Energy demand (PJ)	Energy use per person (MJ)	CAGR (energy demand) (%)
Car	283	266	261	720	677	573	1511	1420	1069	2635	2477	1712	7.72
Two-wheeler	364	193	190	920	488	413	1921	1018	766	3362	1782	1232	7.69
Auto-rickshaw	102	59	58	254	147	125	532	308	232	941	546	377	7.70
Bus	2330	443	434	4006	761	645	5363	1019	767	5608	1066	736	2.97
Total	3079	954	937	5900	2065	1749	9327	3731	2807	12,546	5897	4075	6.26

Note BPKM billion passenger kilometer, *PJ* peta joules (10^{15} Joules), *MJ* mega joule (10^{6} Joules)
Source Singh [49]

3.2 Fuel Consumption in Road Transport Regime: Dependence on Imports

In 2015, India ranked third in the world in terms of consumption of petroleum, consuming 4142 thousand barrels per day [56]. The share of transport sector in the overall national consumption of diesel is 70% and 99.6% in the case of petrol [35]. In India, road is the most dominant mode of transport for passenger and goods mobility. It is estimated that road transport accounts for 85–90% of the passenger traffic and about 65% of the freight [14]. Diesel and petrol accounts for 95% of the road transport fuel and the consumption is expected to grow by about 6–8% p.a. in the future [14].

The Indian economy is increasingly depending on the import of crude oil. From a level of 13 million metric ton (MMT) in 1972–73, the import of crude oil has touched 174 MMT in 2011–12. During the same period, the domestic production has remained fairly stable (Fig. 2). As of 2014–15, almost 83.5% of the crude oil requirement of the economy is met through imports [21].

For the purpose of this article we concentrate more on the years preceding and following the announcement of NBM and NBP. This will provide us with a better understanding of the context. During the period 1996–97 to 2011–12, the average annual growth rate of import of crude oil in India had been 13%. The annual growth rate of domestic production during the same period was about 1%. The transport sector is one of the largest consumers of oil—constituting approximately 30% of the national demand [11]. Out of this demand by the transport sector, 70% is on account of diesel [53]. The oil consumption by the road transport sector in India is expected to witness a steady increase—growing at a rate of 4.8% p.a., and for the

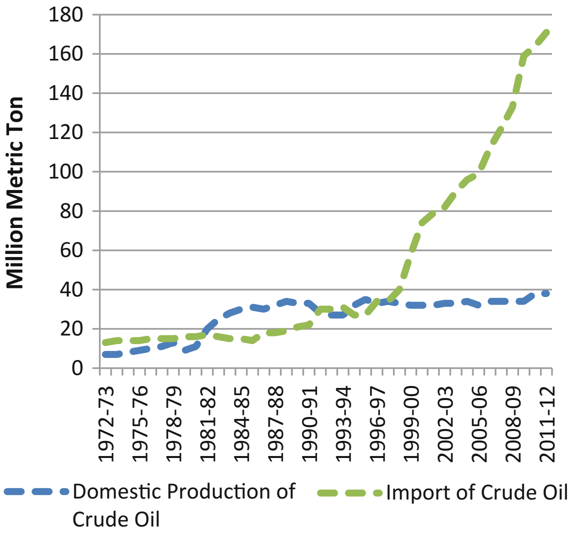

Fig. 2 Trend in domestic production and import of crude oil in India (1972–2012). *Source* RBI [44]

Table 2 CAGR of domestic production and import of crude oil in India

Period	Domestic production of crude oil (% p.a.)	Import of crude oil (% p.a.)
1972–73 to 1995–96	7.25	3.23
1996–97 to 2011–12	0.94	11.37

CAGR refers to compound annual growth rate.
Source RBI [44]

overall economy it is expected to double by 2030 [31]. Growth in the volume of private vehicles and a planned shift from railways to road for freight transportation are the major contributors to this increasing trend [11] (Table 2).

Overdependence on the import of crude oil to meet domestic demand is affecting the Indian economy in a number of ways. Apart from the issue of energy security of the country [30], the import of crude oil creates pressure on the national balance of payments [40]. The economy is also exposed to the foreign exchange risk and in a regime characterized by a depreciating rupee the increasing price of crude oil may contribute to national inflation. Equally important is the issue of emission and pollution that are associated with the increasing consumption of hydrocarbon based fuels in the mobility sector, particularly, road transport in India [18].

4 Biodiesel in India: Strategic and Top–Down Experiments Towards Sustainability Transitions

Existing literature identifies a set of distinct motivations for the GoI to promote bio-fuels, particularly, as an alternate fuel in the incumbent mobility regime. Various elements of the landscape have influenced the decision by the GoI to invest heavily (during early years of 2000) in the development of biofuels as an alternative and cleaner source of fuel in the country [6, 40]. Important, among these, are:

- Increase in crude oil prices by the oil importing countries, together with a volatile Indian Rupee (INR), which further adds to the increasing trend[4] and thus generates a concern for getting to a favourable position in national accounts in oil imports.
- Decision by the GoI to phase out subsidies in petroleum products gradually—aiding to a further rise in domestic price of petroleum products.
- Disturbance in political relations with oil exporting countries, particularly those in the middle east.

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[4] The average annual growth rate of Import price of crude oil in India (in USD/bbl) during 2002–03 to 2010–11 is 17.17%. The peak value of the annual growth rate is 42.11% in 2005–06

- Increasing interest among multilateral development agencies like the World Bank and Asian Development Bank in promoting agriculture as a means for attaining sustainable development in India. As a result the cultivation of biofuel crops has received a relatively high level of importance by these agencies.
- Growing awareness and concern among the global community on environmental sustainability and need for transition to a renewable and eco-friendly source of energy.

In addition to sustainability gains,[5] the GoI also aims at delivering rural development, generation of employment and promotion of economic and social equity. Evidence of transnational influence is also present in India's emphasis on bio-fuels [8] as India wanted to catch up with the global trend in promoting bio-fuels. While formulating its plans on biofuels, the country also considered the traditional debate between "food versus fuel"[6] and mandated that the issue of food security cannot be compromised for the cause of bio-fuels. Therefore, while planning for the biofuel experiment all paradigms of sustainability gains have been considered.

The first major step in the process was the declaration of the National Biofuel Mission in 2003. The two major components of this mission were ethanol blended petrol programme (EBPP) and biodiesel blending programme (BDBP). In both the programmes, "specified, time-bound targets have been laid for blending of 5% (2012), 10% (2017) and 20% (beyond 2017) biofuels with petrol and diesel in a phased manner so as to catalyze the transition from a completely fossil fuel based transport system a partially biofuel driven system" [40]. India had aspired to achieve the desired transition by 2017 when 20% compulsory blending[7] (of bioethanol and biodiesel) was expected to become a norm in the oil industry [2, 19]. NBP also proclaims bio-fuels as a "potential means" to augment rural development and generate employment at the grassroots and "aspires to reap environmental, economic (and social) benefits arising out of their large scale use" [40]. The national policy also categorically mentions that the biofuels programme will be "carried out solely on the non-food feedstock that is raised on the degraded wastelands not suitable for agriculture, thus avoiding a possible conflict between food security and energy security" [40]. The other ancillary benefits expected to be derived from the biodiesel niche are greening of waste lands and conservation of soil [19].

The process of producing biodiesel is well documented in literature [1, 3, 4]. National Oilseeds and Vegetable Oils Development Board (NOVOD) identifies the existence of about 10 species of plant in India with a potential for economic

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[5] While the literature on sustainability transitions define sustainability gains in terms of environmental gains (see [6]), in the developing country contexts the other pillars of sustainable development (economy and society) are no less important. For the purpose of this article, we adopt the concept of sustainability gains comprising of all three pillars of sustainable development.

[6] For a literature review please see Timilsina and Shreshtha [54]

[7] As of 2015, the blending rate is 2.3%. This is way below the target rate.

production of biodiesel. Out of these species jatropha and pongamia have received the most attention from the scientific community associated with development of technology for biodiesel in India [8]. The NBP emphasizes on the use of a wide range of TBO like jatropha and pongamia for the production of biodiesel. Given the properties of biodiesel, there is a possibility of smooth transition to an alternative fuel based mobility system [31], as the switching costs at the users' end are substantially low. The advantages are described in Table 3. Cultivation of Jatropha has been encouraged on waste/degraded/marginal lands as this TBO has a host of advantages, viz. (a) it is draught resistant and perennial; (b) grows well in the marginal and poor soil; (c) produces seeds for 50 years; and, (d) seeds have an oil content of 37%, which is regarded as considerably high. Further, the collection period of Jatropha seeds do not coincide with the rainy season—hence there is no switching of labour from reaping of traditional crops to these oilseeds. For jatropha seeds, the collection time being June–July, the agriculture workforce finds alternate avenues of employment during the slack season in the traditional agriculture [8]. The policy explicitly advocates that the plantations on the fertile irrigated lands would not be supported.

During the last fifteen years, efforts have been made to form institutions and actor networks involving research and development institutions, manufacturers and oil marketing companies to scale up the niche.

5 Performance Assessment of the Biodiesel 'Niche' in India—Using the Lens of 'SNM'

Raju et al. [40] opines that the development of a commercial biodiesel industry based on jatropha and other non-edible oilseeds is at a nascent stage in India. The biodiesel industry still remains at the incubation stage and has not matured. Despite the policies, India is yet to achieve the targeted production of Biodiesel even

Table 3 Advantages of biodiesel

Parameter	Advantages
Mixing	Can be mixed easily with the mineral diesel
Change in the engine of the automobile	Use of biodiesel does not require any change in the design of the engine of the automobile as the properties of biodiesel are similar to those of diesel
Reduction in local pollutants	Use of pure biodiesel in the road transport sector can reduce emission of soot by 60%, carbon monoxide and hydrocarbons by 50%. The emission of NOx may vary by ±10% depending on the combustion characteristics of the engine. Emission of SO_2 is completely prevented
Reduction in CO_2	Use of pure biodiesel can reduce CO_2 emission by about 80%

Source Adapted from Biswas et al. [8] and Leduc et al. [31]

Table 4 Desired biodiesel demand and actual production

Year	Diesel consumption (MMT)	Estimated biodiesel demand (MMT)			Production of biodiesel (MMT)	Percentage of biodiesel target met (@5% blending rate)
		5% blending rate	10% blending rate	20% blending rate		
2009–10	56.20	2.81	5.62	11.24	0.026	0.93
2010–11	60.10	3.01	6.01	12.02	0.095	3.14
2011–12	64.80	3.24	6.48	12.96	0.103	3.19
2012–13	69.10	3.46	6.91	13.82	0.105	3.04
2013–14	68.40	3.42	6.84	13.68	0.112	3.27
2014–15	69.40	3.47	6.94	13.88	0.069	1.99
2015–16	74.60	3.73	7.46	14.92	0.088	2.37
2016–17	76.00	3.80	7.60	15.20	0.086	2.26

Source GAIN [15] and GoI [21]

considering a 5% blending (Table 4). The 20% blending target by 2017 is seen by a number of researchers as a dream [8, 12]. As mentioned above it was planned to mainstream biofuel in the mobility regime in two phases—an initial research, development and demonstration phase followed by a self-sustaining expansion phase. It is important to understand what went wrong so that the biodiesel targets could not be met.

5.1 Production of Biodiesel in India

As on 2016–17, there are only 5–6 large biodiesel production units in India, with capacities ranging from 0.01 to 0.25 MMT per year. The rest are smaller units. Most of the units have resorted to producing biodiesel from multiple feed stocks, thus reducing their dependence on Jatropha. The average level of capacity utilization in the biodiesel manufacturing is approximately 30% [15]. Most of the biodiesel produced in the country is sold to the unorganized sector (irrigation pumps, mobile telephone towers, diesel generators, etc.) [14, 15, 40]. Some amount of biodiesel is sold to experimental projects being carried out by the automobile manufacturers and transport companies. Although some of the bulk consumers like Indian Railways and some State Transport Corporations (e.g. Karnataka State Road Transport Corporation) are buying biodiesel for pilot projects, institutional arrangements stipulating mandatory and guaranteed purchase by the bulk consumers is yet to be in place [15].

Although the thrust on bio-fuels and, particularly, biodiesel was initiated in India in 2003, the performance of the niche has been less than satisfactory by target year 2017. Why has the niche underperformed? What are the bottlenecks in the strategic management of the niche? In the next few subsections, we investigate this important research question in the light of SNM.

5.2 Articulating the Goals and Purpose

In the literature on SNM, articulating expectations from the experiment among the actors assume a great importance. Scholars posit that effectively articulating expectations such as tangible benefits for specific actors reduces uncertainties in the innovation process and allows mobilization of resources through promising future benefits [42, 59]. Research in investments for sustainable development and climate change asserts that such investments may not result in an immediate return—returns may be delayed [60] and is characterized by an anticipated volatility due to a set of risks that shroud the landscape [10, 57]. The scholars of SNM, based on their studies in the context of developed countries, stresses on the promise of "future" benefits. Even if the benefits are delayed, actors must be ready to wait, watch and expect the gains in a distant future. However, India being a developing country, in the context of NBM, assessment shows that expectation of short term and not long term benefits influence the choice and action of the network of actors. Simultaneously, the continuation of protective command and control measures by regulators vis-à-vis market mechanism in the developing economies also impact the expectations of the actors.

With regard to the biodiesel niche in India, although the government had launched the programme in a mission mode, the relevant policies were less grounded on social science research and evidences. Too simplistic assumptions regarding the market's role in blending biodiesel with conventional diesel was articulated, thereby leaving out many nuanced challenges. Though more than a decade has passed, no extant law (regulation) has yet been introduced stipulating the targeted blending as a mandatory action. There is no provision for adequate supply-side stimulants to create a market and effect the transition. When experiments are policy-led, there are scopes for the government to correct market failures. Unfortunately, the biodiesel mission could not provide enough policy support to the niche for stimulating market forces that encourages all actors on the supply and demand side to enter into an efficient market mechanism.

Policies articulated that plantations of jatropha can happen in waste land and arid areas. Small and marginal farmers, many of whom have limited ability to access adequate irrigation, were therefore encouraged to undertake such cultivation. However, studies by Ariza-Montobbio and Lele [2] found a strong correlation

Table 5 Survival rate of jatropha plants in Tamil Nadu during the first year

Type of irrigation	Survival rate (median) (%)
Purely rain-fed	80
Irrigated	99
Combined	90

Source Ariza-Montobbio and Lele [2]

between water availability and survival and yield of jatropha seeds.[8] Similar results have also emerged from earlier studies in India (Table 6). It was also found that the frequency of fruiting is also a positive function of the frequency of irrigation. Therefore, high water requirement turns jatropha into a "large farmer's crop" who can afford timely irrigation. Also the claim that dry and barren lands are suitable for jatropha plantation can be contested. Therefore, the reality turned out to be contrary to the articulated expectation. This not only points at the possibility of jatropha cultivation being unviable to the targeted farmers but also to the emergence of informal water markets[9] together with depletion of ground water resources.

Many such examples show how wrong articulation of expectation increased uncertainty in creating enough market incentives which were envisaged as one of the factors in driving NBM. Primary studies in Tamil Nadu (Table 5) show that with current levels of yield of jatropha seeds, the net annual return is negative in the short run. Positive returns accrue to farmers after almost 5 years (Table 6). To ensure positive returns, it is imperative to increase the yield of jatropha seeds so that revenue increases appreciably. However, survival rate and increase in yield is only possible through proper irrigation and use of fertilizers, which escalate costs. Among the farmers, therefore, there exists a high degree of uncertainty with respect to returns from jatropha cultivation [2]. In studies conducted in the states of Rajasthan, Chhasttisgarh and Uttarakhand, the internal rate of return (IRR), at the farm level[10] has been found to vary in the range of 25–85% p.a. [40]. However, the IRR and payback period is highly dependent on the agro-climatic condition—for example, in Rajasthan, which is a dry region, the payback period for the initial investment occurs as late as in the 6th or 7th year.

Given the uncertainty in returns in the short run, there is a distinct tendency among farmers to dropout and/or leave the plantation without maintenance [2]. This contributes to uncertainty in supply of the feedstock for biodiesel, a necessary condition for success of NBM.

In India the goals and purpose of the biodiesel niche has multiple dimensions: individual income opportunities for farmers and biodiesel extraction units, national energy security, global emission reduction, etc. The cultivation of jatropha is encouraged in the wastelands, majority of which falls under the category of

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[8] The correlation is observed in their study in the state of Tamil Nadu. The differences in median survival rates are found to be statistically significant at 1% level.

[9] This would also benefit the large and affluent farmers.

[10] The calculations are made under an assumption that the life of the plant is 20 years.

Table 6 Indian experience on yield and maturity of jatropha plants

Parameter	Global opinion	Indian experience
Yield (kg/ha/year)	400–12,000 [37]	• 7500 in case of irrigated plots [38, 39] • 2500 in case of plots without irrigation [38, 39] • $\leq$ 1000 in case of dry lands in Maharashtra even after 3 years [41] • $\leq$ 2500 without irrigation and use of fertilizer [34] • 231–750 (at the end of three years depending on the irrigation) [2]
Age of maturity[a] (Years)	2.5–5.0 [1]	• 3–5 years under experimental conditions [38, 39]

[a]Maturity implies when economically sufficient seeds are available from the plant

common property resources. Studies have revealed that in many communities there is a marked unwillingness to cultivate jatropha unless property rights of land are transferred to the cultivators [8]. A possible explanation of this phenomenon is that since the cultivators are uncertain about returns from jatropha cultivation, they want to seize the opportunity to own an asset in anticipation of future capital gains.

The above analysis points to a set of important points relevant for SNM in a developing country context. First, the prospects of individual gains play an important part and can overshadow the national and global goals. Second, the promises of long term future gains are not as important as short term gains for small and medium scale farmers in the context of a developing economy. It is the short term gains of the actors that decide the relative success and failure of a programme. So, success of NBM became contingent on decision of small and medium farmers to stay in the market while absorbing short term losses.

5.3 *Network of Actors: A Source of Conflict?*

The SNM literature argues that the social networks in a value chain play an important role in niche management and maturing innovations. The networks are the vehicles of expectations and promises, articulators of renewed requirements and demand, sources of resources and enablers of learning and dissemination of knowledge across (and between) actors and locations [42]. It is argued that the prevalent regime networks are insufficient as they imbibe the incumbent rules and routines and are more prone to tread the existing trajectory and desist from exploring new ones [42, 45].

While the biodiesel niche in India is policy-led, it needs to be assessed if enough actions have been taken to put in place an ‘inclusive’ actor network to strengthen the value chain and information flow. A major mandate in the NBP is research and development. Several research institutes—both at the national and sub-national levels have been involved in the development of biodiesel niche in India. The federal structure of the government in the country has necessitated that actors from various levels of governance are included in the network and state and region specific policies are formed under the central guidelines issued by the GoI. But is this large network a source of potential conflict? Tables 7 and 8 show how governance structure and new institutional mechanism was set up. Table 9 presents various state level actions. We make an assessment as to where in this long chain, gaps, missing links and multiplicity of institutions created confusion, conflicts of interest and uncertainty in strategic niche management.

In administering the policies related to the promotion of biodiesel, the GoI has demarcated and assigned roles and responsibilities to various ministries at the central level. In addition, the NBP recommends setting up of an inter-ministerial national biofuel coordination committee, with the Prime Minister as the chairperson and a biofuel steering committee under the chairmanship of a cabinet secretary of the GoI. Simultaneously, in line with the federal structure of governance, the GoI has advised the states to formulate and adopt state specific policies on biofuels in congruence with the goals of the NBP. Some states, in their own policies have included state level institutions like village panchayats, forest departments, universities and research institutions. A brief presentation is made in Table 9. Thus the actor network in the biodiesel niche in India is large and includes actors with diverse origin and capabilities.

Although GoI has refrained from levying central taxes on biodiesel and/or the feedstock crops, the tax policies of different states are not uniform. Tax structures and tax rates differ among states and are regarded as an obstacle for the nationwide procurement, processing and blending of biodiesel [40]. Rates and nature of subsidies also differ across states. Absence of alignment of the fiscal instruments causes a spatial variation in the cost structure and affects the economic incentives in biodiesel niche across regions.

Table 7 Biofuels in India: roles and responsibilities of ministries

Actors	Roles and responsibilities
Ministry of the New and Renewable Energy	• Overall policy making • Supporting the research and development
Ministry of Petroleum and Natural Gas	• Developing the pricing and procurement policy • Evolving the channel for blending—the oil marketing companies are under the purview of this ministry
Ministry of Agriculture	• Research and development of feedstock crops
Ministry of Rural Development	• Indentifying wastelands • Promoting plantation of feedstock crops
Ministry of Science and Technology	• Biotechnological research on feedstock crops
Ministry of Environment and Forests	• Tree-borne oilseeds in forest wastelands • Research on health and environmental impacts of biofuels

Source GoI [19]

Table 8 Research organizations engaged in the development of biodiesel in India

Organizations Driving Innovation and Development	Thrust areas of Research
National Oilseeds and Vegetable Development Board (NOVOD) Indian council of Agricultural Research (ICAR) State Agricultural Universities Council of Scientific and Industrial Research (CSIR) Indian Council of Forestry Research and Education Indian Institute of Technology, Delhi The Energy Research Institute	• Establishment of National Network on Jatropha and Karanja (2004) • Identification of elite planting material • Development of high yielding variety seeds • Developing sound intercropping practices and farm level practices • Developing detoxification practices
Central Soil Salinity Research Institute (CSSRI)	• Developing site-specific genomes for combating adverse climatic conditions
Central Research Institute for Dry-land Agriculture (CRIDA)	• Research in genetic diversity and a range of biotechnical traits of jatropha
Department of Biotechnology (DBT) TERI	• "Micro Mission on Production and Demonstration of Quality Planting Material of Jatropha" • Selection of good germplasm and developing quality planting material • Developing a clonal culture that can yield oil bearing seeds in one year
International Crop Research Institute for Semi-Arid Tropics (ICRISAT)	• Introducing Jatropha and Pongamia plantations in the watershed

Source Raju et al. [40] and Ariza-Montobbio and Lele [2]

Table 9 Bio-diesel: state-specific actors, roles and responsibilities

State	Key actors	Roles and responsibilities
Rajasthan	Biofuel Authority of Rajasthan	• Encouraging plantation of biodiesel crops as a part of the wasteland development programme and agro-forestry measure • Targeted plantation: 2.10 Mha of waste lands with Jatropha • Leasing of land for a period of 20 years
	Self Help Groups (SHGs), Community Development Organizations, Panchayats, Private Sector	• Production and marketing of Jatropha seedlings at subsidized prices • Distributing other input • Carrying out planting operations under the Mahatma Gandhi Rural Employment Guarantee Scheme (MGNREGS)

(continued)

Table 9 (continued)

State	Key actors	Roles and responsibilities
Chhattisgarh	Chhattisgarh Biofuel Development Authority (established in 2005) under the Chhattisgarh Renewable Energy Development Authority, Department of Rural Development, Department of Forests, Joint Forest Management Committees	• Administering subsidy and exemption programmes (interest subsidy, capital investment subsidy, tax exemption, electricity duty exemption, stamp duty exemption on land registration) • Lease of fallow lands to public sector entities and private sector entities entering into a joint sector with the CBDA • Distribution of Jatropha seedlings at subsidized price • Contract farming with local farmers • Setting up a trans-esterification plant • Establishing biodiesel based power generators for rural electrification • Research and development • Linking Jatropha cultivation with the MGNREGS
Uttarakhand	Uttarakhand Biofuel Board, Forest Development Corporation, Van Panchayats, Joint Forest Management Committees, Private Entrepreneurs	• Targeted Jatropha Plantation: 0.20 Mha (by 2012) • Bio-fuel based rural electrification • Allotment of land
Odisha	Odisha Renewable Development Agency (OREDA), Odisha Forest Development Corporation, District Rural Development Agencies, The Odisha University of Agriculture Technology, Pani Panchayats, SHGs	• Targeted plantation of Jatropha and Pongamia: 30% of the wastelands (0.60 Mha) • Setting up a revolving fund for providing fiscal and financial support to the entities comprising value chain of bio-fuels • Establish Linkages with the programmes like Swarnajayanti Gram Swarozgar Yojna, MGNREGS, Integrated Tribal Development Agency, Compensatory Afforestation, etc. • Establishing private seed collection centres with facilities for storage, grading, certification and quality control of oils
Karnataka	State Taskforce on Biofuels (established in 2009), Karnataka State Biofuel Development Board, Land Revenue Department, Forest Department	• Promoting State Bio-fuel Policy (2009) • Identification and allotment of wastelands • Administering fiscal and financial benefits • Evolving models for contract farming • Establishing a Biofuel Park

(continued)

Table 9 (continued)

State	Key actors	Roles and responsibilities
Andhra Pradesh	Rain Shadow Area Development Department, Department of Panchayati Raj and Rural Development, Acharya N. G. Ranga Agricultural University	• State Biodiesel Policy (2005) • Promote tripartite partnership between the Government, cultivators and manufacturers • Monitoring pricing and buy-back arrangements • Research and Development
Tamil Nadu	State Agricultural Department, Forest Department, Rural Development Department, Tamil Nadu Agricultural University, Agricultural Cooperative Banks	• Biofuel Policy of Tamil Nadu (2007–08) • Target Plantation of Jatropha: 0.10 Mha over a period of 5 years • Developing linkage with other programmes like National Watershed Development Programme for Rainfed Areas, MGNREGS, Comprehensive Wasteland Development Programme • Administering fiscal and financial incentives • Evolving models of contract farming

Source Compiled by the authors based on various documents

Since the sub-national governments can exercise their autonomy in fixing the minimum support price (MSP) for the feedstock for biodiesel, conflicts emerged. There is a significant difference in price set by different states (Table 10). In many states, the MSP is so low that it fails to cover the cost of production, rendering the cultivation of Jatropha non-remunerative [24]. Many researchers feel that there is an urgent need for harmonization of MSP across states to restore parity in incentives for farmers within and across regions. A possible policy option is to bring the issue of setting MSP for feedstock under the purview of the Commission for Agricultural Costs and Prices [40].

The actor network involves non-government organizations and self-help groups to a large extent. The purpose is to include such facilitators working at the community level in the transition dynamics and disseminate knowledge and resources

Table 10 Price of jatropha oilseeds in some selected states in India

State	Market price (Rs/kg)
Rajasthan	6.00 (Government) 7.00–10.00 (private buyers)
Chhattisgarh	6.50
Uttarakhand	3.50

Source Compiled by authors

among the actors at the grassroots. However, studies indicate that there may be pressure groups at the grassroots whose stance is anti-biodiesel and their role is contradictory to the community-level workers working to mature the biodiesel niche. These alternate pressure groups argue that biodiesel is neither pro-poor, nor appropriate for the development of the marginalized classes and communities. Rather, biodiesel aggravates rural poverty and indebtedness [2]. Further, jatropha creates a lock-in—a tendency towards mono-cropping among farmers and reduces the options for diversification of livelihood. The definition of wasteland is also contested by such anti-biodiesel pressure groups. The wastelands are widely used by the rural poor for grazing of animals and fuel wood. Converting the wastelands to jatropha cultivation creates an alternative crisis—the crisis of fodder[11] and fuel among the marginalized economic groups. There is also an argument that jatropha cultivation may increase the rural-urban migration, particularly during the initial years when the plant is yet to mature to produce seeds [2]. The conflict between the two sets of community-level working groups, with contradictory views on biodiesel, aggravates confusion among the farmers and leads to high degree of indecision. The conflict also slows down the process of dissemination of knowledge and technology among willing farmers.

With respect to the marketing of biodiesel, the policy of Government of India stipulates that it is the oil marketing companies (OMC) which can purchase biodiesel from the producers. No other channel of sale is encouraged and/or developed. With this policy in place, the biodiesel niche possibly faces a resistance from a cartel of actors in the incumbent hydrocarbon based regime. There is a high probability that collusive oligopolies consisting of the incumbent petroleum processing companies are formed to lobby, bargain and discourage the OMCs from blending biodiesel. The investigation initiated by the Competition Commission of India is indicative of this issue [60].

With the aforementioned conflicts within the network, the network ceases to become a cohesive and well aligned one to gain the required momentum for growth and maturity of the NBM niche. The actors suffer from a great deal of uncertainties.

5.4 Learning Through Market Experience

The evolving SNM literature highlights the role of learning in the maturing of a niche and effecting transition. While learning in technical or economic dimensions is important, learning about user preferences, cultural and symbolic meaning,

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[11] Some researchers have termed this as the “other food crisis”.

industry and production networks, regulations and government policy and the societal and environmental effects of the new technology(ies) is important [26, 42]. The literature also emphasizes on the second order learning—a transition from “are we doing things right” to “are we doing the right things” [42]. Hoogma et al. [26] emphasizes the need for creation of a broad network of users and outsiders to support maturity of niche innovation. Otherwise, learning is restricted only to upgradation of the technical knowledge and may fail to include the learning in the normative and cognitive dimensions that are extremely essential in mainstreaming a niche innovation in the market.

However, the above views are based on the experiences in the developed economies where the very first step in the niche formation is the creation and development of the technology. This layer of learning forms the basis of invention. On the other hand, in the context of developing economies, very often, the technology is imported from the developed world and is deployed—with some degree of re-engineering, taking into account the national, local and regional needs. Thus, in the context of the developing economies, learning begins at the stage of deployment of technologies. Developing policies, institutions, incentives, orienting user preferences, etc. are some of the elements in this stage. Therefore, in the context of the developing countries, the scope of first order learning may be limited.

Since the biodiesel niche in India is at its incubation stage, and is yet to be mainstreamed into the market, the scope of learning from market experience is rather limited. Earlier analysis of the biodiesel niche suggests that the policy actors are yet to address the uncertainty that resides within the actor network. While correcting anomalies in the supply side is important, we have argued, that demand side should not be overlooked. Low capacity utilization of biodiesel processing units is making the units incur losses and, in the short to medium run, investments may be withdrawn and diverted to more remunerative channels [14, 60]. Creation of a market—through addressing both supply and demand side factors, and ensuring economic incentives provides further insights as to how the market can be matured, market failures corrected and market efficiency ensured.

The latent conflict within the value chain and the actor network is another area that merits attention. Putting in place effective mechanisms for institution building and conflict resolution are important requirements. The niche still remains policy-led in nature with the government institutions deciding on pricing and distribution strategies of biodiesel. Effectiveness of such approach is questionable. Oil sector in India is highly regulated—in terms of institutions, pricing, etc. How biodiesel—a product with a host of actors from the private sector, will perform in this government dominated and controlled market segment remains a serious question. For up-scaling of the niche some landscape level changes—in terms of regulation and policies concerning the oil sector may be required. Further research is needed in this area.

5.5 Is There Too Little Protection of the Biodiesel Niche?

Hoogma et al. [26] argues that the innovations that have promises for sustainability transitions may not be economically viable in the short run. Positive expectations about future profits and/or social benefits may induce the investors to invest in these niche products and processes. This brings us to the idea of "protection". Protection can be in the form of financial instruments or regulatory instruments. However, the researchers opine that protection should never completely hide an innovation from the pressure of market selection nor should it continue indefinitely [29, 42]. Thus designing protection and deciding on the continuity of the protection is a critical element in the SNM approach. In this section we investigate the protection accorded to the biodiesel niche in India.

Since the formulation of NBM in 2003, the GoI has taken various measures to protect this emerging niche. The steps include declaration of MSP (to boost production of the feedstock crop), MPP i.e. maximum procurement price (to ensure economic returns to the producers of biodiesel), exemption of taxes, etc. Biodiesel[12] is deemed as a "declared goods" so that the product can be transported freely across states without attracting any cross-border taxes. NPB has also stipulated that no taxes and duties are to be levied on biodiesel. To include international players in the actor network, 100% foreign equity through automatic approval route has also been declared. This policy is expected to boost foreign direct investment flows into the biodiesel niche.[13] While the rationale for protection may attract little debate, the mechanism and quantum of such protection have attracted a strong criticism [8, 40].

The economic analysis of jatropha cultivation points to an important aspect—the support to farmers, at least in the initial years of cultivation, must be high. Studies reveal that there exists a significant difference between the prices (of oilseeds) offered by the government and private entities. In most instances, the price offered by the government range from 50 to 70% of the price offered by the private sector. Since most of the farmers are small and marginal farmers and have limited access to the private buyers, they are forced to sell the seeds to the government. Also, since the government agencies are the key actors, they exercise significant influence on the farmers and the market. Thus returns for farmers are abnormally low.

The policies advocate a MSP with a provision for periodic revision. The MSP is intended to be "fair" [40]. Many researchers feel that, given the existing yield level, the MSP does not cover the cost of cultivation for the farmers [24]. However, it is also important to note that a "one size fits all" approach may prove to be counterproductive. The vastness of the country and the diversity in the agro-climatic conditions and farm-level practices imply diversity in cost structure between and within the regions of the country. This crucial issue needs to be inbuilt in the decision on MSP. The periodicity of revision is also an important challenge. Raju

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[12] Bio-ethanol is also accorded the same status.

[13] The provision is subject to the fact that the biofuel produced is entirely consumed within the country.

et al. [40] argues that there is some degree of arbitrariness in deciding on the frequency of revision.

The MPP of biodiesel is proposed to be linked to the prevailing retail price of diesel. The manufacturers of biodiesel argue that given the volatility of price of the feedstock and low capacity utilization of the plants, the linking of MPP to the retail price of diesel is not economic. The MPP needs to be linked to the price of the feedstock [7]. Gunatilake [24] also voices a similar concern and advocates the introduction of subsidies for biodiesel producers.

In the as-is scenario, the protection offered to the biodiesel niche is a matter of debate. Adequacy and exhaustiveness are important issues to be addressed. Further research needs to focus on these issues to weed out anomalies and gaps in protection and generate a favourable environment to encourage the creation and operation of a well formed market.

Protection might be needed from competing niches as well. For example, competing niche for biodiesel is electric vehicles. In 2015, India published its intended nationally determined contribution (INDC). In this document, the GoI declared a programme named FAME (faster adoption and manufacturing of hybrid and electric vehicles). This is expected to provide a stimulus to the electric car manufacturing industry. On the other hand, the INDC is silent on biofuels. Even, while rolling out the goods and services tax (GST), the Government has levied a GST of 18% on biodiesel compared to 12% on electric vehicles. Thus, the landscape factors seem to weaken the biodiesel niche.

6 Conclusion

The biodiesel mission was initiated as an import substitution strategy in the incumbent fossil fuel driven road based mobility regime. It had multiple goals together with delivering sustainability gains. The gains would not only be limited to environment protection but would also ensure socio-economic benefits for small and medium farmers.

The policy led biodiesel niche in India has, so far, underperformed. Goals and purposes have not been adequately articulated. Articulation of expected returns in the long term is at variance with the objectives of small and marginal farmers—the intended beneficiaries. For these beneficiaries short term gains are important. They are also constrained by the lack of access to irrigation that has been proven to be a crucial input in profitable cultivation of jatropha. This has been a primary hurdle for sustaining cultivation and this has added to the uncertainty in the supply of feedstock. Protection needed for maintaining the value chain was insufficient and was poorly managed in the face of a multi actor institutional mechanism. State wide variation in policy design added another layer of uncertainty in managing the value chain. Uncertainties in returns, conflicts within the network, absence of conflict resolution mechanisms and ambiguity in the protection mechanism have prevented the emergence of a well-functioning market for biodiesel. Cartels and divergence in lobbying power have also restricted the maturity of the biodiesel niche. There is need for further research to identify drivers and enablers for transition of this niche to maturity.

The analytical framework used in this study clearly brings out the missing links in strategic management of NBM in a developing country context. Unless short term gains are assured through policy mechanisms, consistent feedstock supply cannot be ensured for downstream activities and sustenance of the value chain. Instead of leaving a niche to struggle in the market for survival, strategic protection and handholding can add certainty to the value chain for growth and expansion. Policy mechanisms should also aim at making the feedstock price competitive relative to the fossil fuels. Only technology innovation cannot push a niche too far. Social acceptance may remain low due to inefficient and incomplete management of the niche. Unless protected against competing niches such as electric vehicles and the regime of fossil fuel, biodiesel may fail to be up-scaled despite having potential for addressing sustainable development goals.

In August 2016, the GoI has proclaimed that by 2022 biodiesel production will be about 6 MMT [52]. However, as our analysis suggests, this is a challenging task since regressive factors concerning the management of the niche are yet to be addressed. This calls for redefining the rules of managing the niche.

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Biomass Gasifier Integrated Hybrid Systems as a Sustainable Option for Rural Electrification

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Abstract 'Ensuring access to affordable, reliable, sustainable and modern energy for all' is a prime objective listed in the Sustainable Development Goals of the United Nations. Uninterrupted power supply is an essential requirement for urban as well as rural areas. In developing countries, steps are being taken to ensure 100% electrification. The total number of un-electrified villages in India is 3361 based on recent statistics. Many such villages are located in regions where grid extension could be uneconomical. Renewable energy based electrification systems offer a sustainable solution though they have the limitation of being dependent on a dilute and intermittent source. Integrated or Hybrid Energy Systems which combine multiple energy sources improve the situation. A hybrid system incorporating a diesel generator or any other dispatchable source of power along with a photovoltaic system would be preferable as compared to a purely photovoltaic based system. However, diesel based generators have the inherent limitations of being costly and unsustainable. Biomass gasifier integrated hybrid systems can be adopted in such cases where locally available biomass feedstock can be utilized for the system operation. Certain studies on system planning have been undertaken for biomass gasifier based hybrid energy systems in the past, specific to rural applications in developing economies. The salient features of biomass gasifier integrated hybrid systems for rural electrification from the design and operational point of view are discussed in this chapter. In India, biomass gasifier systems having a cumulative capacity of 18 MW are being used for meeting electricity needs in rural areas. Considering the potential of biomass energy source, its utilization in isolated power generation has been minimal in India. A study on the cost optimal design and performance assessment of biomass gasifier integrated hybrid systems is a vital step in this context. A case study involving the detailed design of biomass gasifier integrated hybrid energy system for a typical rural location in India following the *design space* approach is also presented in this chapter.

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Nomenclature

A	Photovoltaic array area, m^2
B	Battery bank capacity, Wh
B_{min}	Minimum battery energy value, Wh
B_r	Maximum battery energy value, Wh
C_0	Capital cost, USD
d	Discount rate
D	Demand, W
E_{dem}	Energy delivered, Wh
f	Net charging/discharging efficiency
I_T	Solar insolation on tilted surface, W/m^2
m	Fuel flow rate, kg/s
n	Life, in years
P	Power generated by the gasifier integrated generator, W
P^*	Net power generated by the gasifier integrated generator, W
P_{min}	Minimum generator power, W
P_P	Power generated by the photovoltaic array, W
P_r	Rated generator power, W
Q_B	Battery energy, Wh
x_f	Diesel fraction
z_g	Substitution ratio

Greek Symbols

η_0	Photovoltaic system efficiency
η_c	Charging efficiency
η_{conv}	Converter efficiency
η_d	Discharging efficiency

Abbreviations

ACC	Annualized capital cost, USD/year
AFC	Annual fuel cost, USD/year
AOM	Annual operation and maintenance cost, USD/year
COE	Cost of energy, USD/kWh
CRF	Capital recovery factor
DOD	Depth of discharge

1 Introduction

Energy is a vital component for the development of a nation. However, even in the current global scenario it is observed that about 20% of the world population still lacks access to electricity. A vast majority of people in the rural sector of developing countries rely on wood, coal, charcoal or animal waste for cooking and heating. Predominantly fossil fuel based modern energy systems extensively used in the developed world are the major contributors for the global green house gas emissions. Consequently, '*ensuring access to affordable, reliable, sustainable and modern energy for all*' has been a prime objective listed in the Sustainable Development Goals of the United Nations. In India, based on recent statistics, there are 3361 villages which are unelectrified [13]. Of this, there are many villages which can not be electrified by grid extension due to the geographical location and sensitive ecosystem prevailing in such places. Renewable energy based electrification is a preferrable alternative in such locations. The options include systems based on solar photovoltaics, wind generators, small hydro systems etc. Diesel generators have been conventionally used in such locations due to the proven technology and flexibility of operation. However, diesel being a non-renewable and expensive fuel, there are attempts to substitute diesel by sustainable alternatives. In India it has been estimated that an excess of about 120–160 million tonnes of agricultural residues are available every year [16]. Biomass available in various forms can be conveniently converted to producer gas in a gasifier. Gasifiers are the reactors in which the gasification reactions take place which convert carbonaceous materials to a gaseous fuel. The commonly used types of gasifiers are updraft type, downdraft type and fluidized bed type. Downdraft gasifiers are mostly used in internal combustion engine applications as it produces gas with relatively less tar content. Utilization of producer gas generated in a biomass gasifier, in engine systems is considered as an appropriate choice in locations where abundant supply of suitable biomass feedstock is available. Gasification involves several chemical processes of which partial combustion of the biomass under sub-stochiometric conditions and subsequent reduction results in the formation of producer gas, which is a mixture of hydrogen (H_2: 15–19%), carbon monoxide (CO: 18–22%), methane (CH_4: 1–5%), nitrogen (N_2: 45–55%) and small amounts of water vapour and hydrocarbons. With air gasification of biomass, the producer gas generated has a calorific value of 4–5 MJ/kg.

Gasifier based power plants have been considered as one of the promising options for renewable energy based rural electrification in India. Biomass gasifier systems having a cumulative capacity of 18 MW are being used currently for meeting electricity needs in rural areas [9]. A 500 kW gasifier based off grid power plant had been installed in the Gosaba island of Sundarbans, West Bengal in July 1997 for electrification of five villages inhabited by around 10,000 people. Due to the remoteness of the location, it was infeasible to extend the grid and the region had remained un-electrified till the commissioning of this plant. The Gosaba power plant included five 100 kW downdraft closed-top gasifiers. Each gasifier unit of

100 kW unit has a water-sprayed gas cooling system, a two-stage gas cleaning system, a blower, an engine (Ruston make) of 165 HP coupled with a 125 kVA alternator [5]. Mukhopadhyay [9] had evaluated the socio- economic and environmental impact of a biomass gasification based power plant in Chottomollakhali islands of Sunderbans, West Bengal. Four villages of Chottomollakhali Island were supplied with electricity from the power plant, which served 225 consumers comprising household, commercial and industrial sectors. Dasappa et al. [4] had illustrated the operational experience of a grid connected gasification power plant of 100 kW_e rating located at Tumkur district of Karnataka. The overall efficiency of conversion of biomass to electricity was reported to be about 18%. A review of biomass gasification as an option for decentralized power generation in Indian context had been given by Buragohain et al. [3]. Detailed economic analysis of biomass based power generation in the Indian perspective had been reported by Nouni et al. [10]. The levelized unit cost of electricity for dual fuel biomass gasifier based power project was observed to be in the range of 0.219–0.408 USD/kWh in this study. Hybrid energy systems combining multiple energy conversion devices (like biomass gasifier integrated generators and photovoltaic units coupled with battery storage) are also preferred options for remote electrification. In India, hybrid systems utilizing solar and biomass is a promising option. India has abundant solar resource and has a wide variety of biomass species suitable for gasification. There have been quite a few studies reported on biomass gasifier integrated hybrid energy systems in the Indian context also. The implementation of a new control strategy in a biomass gasifier integrated hybrid system had been reported to overcome the various operational issues of such systems such as optimal allocation of sources, varying load demand and intermittent behaviours of resources. The hybrid system operating in a university campus in southern India which integrated 8 kW photovoltaic units, gasifier units of 100 and 200 kW rating and battery bank of 192 kWh capacity had been analysed for implementing this new control strategy as reported by Balamurugan et al. [2]. The details of hybrid system integrating photovoltaic panels, a biomass gasifier and a battery bank designed and installed at the Distributed Energy Resources Laboratory for supplying electricity for a laboratory complex in the Democratic Republic of Congo was illustrated by Hurtado et al. [6]. In a recent study, a hybrid system integrating solar photovoltaics, fuel cell, biomass gasifier generator set and battery has been proposed for a university campus located in Madhya Pradesh, India. The optimized system comprises of 5 kW biomass gasifier generator set, 5 kW solar photovoltaic array and 5 kW fuel cell resulting in cost of energy of 0.251 USD/kWh based on the study by Singh and Baredar [12]. It has been shown that for a village of about 2000 inhabitants, situated in Patna, Bihar, a proper mix of solar and biomass energy with energy storage and an optimized management of the schedulable loads, resulted in reduction of cost of energy by 40% as compared to a system based only on diesel generators as reported by Mazzola et al. [8]. Design of a hybrid system based on photovoltaic-biomass gasifier-diesel generator and grid and optimization of the system configuration for different load profiles corresponding to rural location in Assam had been reported by Rajbongshi et al. [11].

The design of such hybrid power generation units involves the estimation of the capacities of the generating units and storage for satisfying a given demand pattern. Design space approach is a methodology which can be adopted for the system sizing and optimization of hybrid energy systems as described by Arun et al. [1]. This method has been extended for gasifier integrated hybrid systems in this work and has been illustrated using a case study for a representative location in southern India. The optimized costs of energy for various configurations have been reported for this case.

2 Biomass Gasifier Integrated Hybrid Energy Systems

The schematic diagram of the biomass gasifier integrated hybrid system is given in Fig. 1. The gasifier-integrated diesel generator is connected to the AC bus. The gasifier integrated diesel engine coupled to the electrical generator operates in co-fired mode utilizing a mixture of diesel and producer gas (produced in the gasifier). The utilization of producer gas in the diesel engine in dual fuel mode of operation results in conservation of diesel (pilot fuel) and diesel replacements up to 70–90% have been possible in the dual fuel mode of operation. The engine may take in up to 90% of its power output from producer gas (the remaining diesel being necessary for ignition of the combustible gas/air mixture). In co-firing, in case of shut down of the gasifier or lack of biomass fuel, a quick change to full diesel mode of operation is possible without much delay. The photovoltaic arrays in the system are connected to the DC bus. The operation of the system in parallel mode permits meeting of demand by the shared generation from both the sources together with energy storage. The system sizing involves determination of ratings of the generation units (photovoltaic arrays and the gasifier integrated diesel generator), and the capacity of the battery bank.

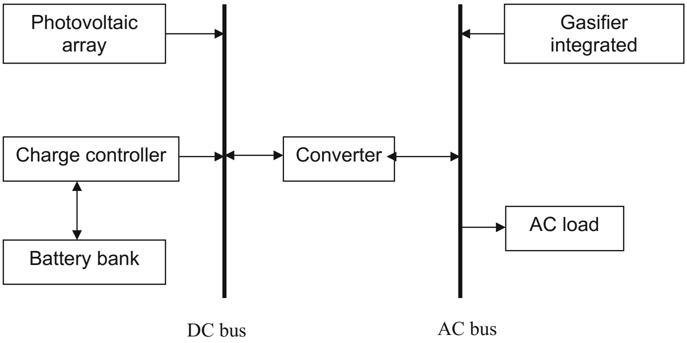

Fig. 1 Schematic of a hybrid gasifier integrated generator system

3 System Sizing and Optimization

A methodology to obtain the sizing of the integrated system is given in this section. It follows the basic approach reported by Arun et al. [1] adopted for a photovoltaic-diesel generator-battery system sizing. The methodology utilizes a time series simulation based on the energy balance of the overall system. The net power generated is represented as the difference between the total power produced (from the gasifier integrated generator (P) and the photovoltaic array (P_P)) and the power required by the load (D) as:

$$\frac{dQ_B}{dt}\begin{cases} = (P_P(t) + P^*(t)\eta_{conv})f(t) & \text{whenever} \quad P_P(t) + P^*(t) \geq 0 \text{ and } f(t) = \eta_c \\ = \left(P_P(t) + \frac{P^*(t)}{\eta_{conv}}\right)f(t) & \text{whenever} \quad P_P(t) + P^*(t) < 0 \text{ and } f(t) = \frac{1}{\eta_d} \end{cases} \tag{1}$$

where $P^*(t) = P(t) - D(t)$. In the above equations *f(t)* represents the efficiencies in charging and discharging processes of the battery bank and η_{conv} represents the converter efficiency. The power generated by the photovoltaic array at any given time t is given by:

$$P_P(t) = \eta_0 A I_T(t) \tag{2}$$

where η_0 is the photovoltaic system efficiency, A is the total array area (m^2) and I_T the total insolation incident on the array (W/m^2) at that time step. For a relatively small time period Δt, the stored energy Q_B may be expressed as follows for charging:

$$Q_B(t+\Delta t)\begin{cases} = Q_B(t) + (P_P(t) + P^*(t)\eta_{conv})f(t)\Delta t & \text{whenever} \quad P_P(t) + P^*(t) \geq 0 \\ = Q_B(t) + \left(P_P(t) + \frac{P^*(t)}{\eta_{conv}}\right)f(t)\Delta t & \text{whenever} \quad P_P(t) + P^*(t) < 0 \end{cases} \tag{3}$$

based on the model formulation given by Arun et al. [1]. During the system operation over the time period Δt, whenever the total energy supplied by the gasifier integrated generator and the photovoltaic array is greater than the demand, the energy surplus is used for charging the battery. If the generator dispatch is such that the total energy delivered by the generators is lower than the load, then the battery supplements the deficit. The load is met if the battery has not reached its depth of discharge and in that case, the stored chemical energy is converted into electrical energy. It is assumed that charging and discharging efficiencies of the battery bank and converter remains constant over time. Further the self-discharge loss for the battery is also assumed to be negligible. The gasifier integrated diesel generator system operates on a mixture of producer gas and diesel. In a given time step, for the required output of the generator, mass flow rates of diesel and producer gas needs to be estimated. The fuel flow rate in diesel-only mode is given by Skarstein and Uhlen [15]:

$$m_f(t) = aP_r + bP(t) \tag{4}$$

In the above equation, a and b are constants, P_r is the rated power of the generator and $P(t)$ denotes the actual power produced by the generator. The gas flow rate in the dual-fuel mode: $m_g(t)$ is given by Lambert et al. [7]:

$$m_g(t) = z_g(aP_r + bP(t))(1 - x_f) \tag{5}$$

In the above equation, z_g is the producer gas substitution ratio which is the ratio with which producer gas replaces diesel in the dual-fuel mode. Also, x_f is the diesel fraction which is the ratio of diesel used by the generator in dual-fuel mode to that required to produce the same output power in diesel-only mode. It may be noted that it is necessary to maintain a minimum fossil fraction to ensure proper operation of the gasifier integrated engine. The minimum generator ratings required and the corresponding storage capacity for meeting the specified load may be obtained by solving Eq. (3) over the entire duration. In the generalized methodology, to obtain the minimum generator ratings, a numerical search is performed that satisfies the energy balance and the following conditions:

$$Q_B(t) \geq 0 \quad \forall t \tag{6}$$

$$Q_B(t = 0) = Q_B(t = T) \tag{7}$$

Equation (6) ensures that the battery energy level is always non-negative, while Eq. (7) represents the repeatability of the battery state of energy over the time horizon. The required battery bank capacity (B_r) is obtained as:

$$B_r = \frac{\max\{Q_B(t)\}}{DOD} \tag{8}$$

where DOD is the allowable depth of discharge of the battery.

The procedure provides the value of the minimum gasifier integrated generator capacity ($P = P_{min}$) and the corresponding capacity of the battery bank (B) for a specified value of photovoltaic array rating. Alternately the minimum photovoltaic array rating or area ($A = A_{min}$) and the corresponding capacity of the battery bank (B) for a specified value of gasifier integrated generator rating may be determined by system simulation. The entire set of feasible configurations forms the design-space for a given problem of sizing. The complete set of feasible configurations of gasifier integrated generator, photovoltaic array and battery bank may be represented in a three-dimensional space. Hence the design space approach helps to identify the entire set of feasible design configurations. The identification of the design space helps the designer in choosing an optimum system configuration based on the desired objective. The cost of energy (COE), which accounts for the capital cost as well as the operating cost associated with the system, is chosen as an appropriate economic parameter to optimize the system configuration. It is calculated as:

$$COE = \frac{ACC + AOM + AFC}{E_{dem}} \tag{9}$$

The annualized capital cost (ACC) is calculated as

$$ACC = \sum_{i} C_{0_i} \times CRF_i \tag{10}$$

where

$$CRF_i = \frac{d(1+d)^{n_i}}{(1+d)^{n_i} - 1} \tag{11}$$

C_{0i} is the capital cost of the ith system component (corresponding to the gasifier integrated generator, photovoltaic array, battery bank, balance of system, converter and charge controller). CRF_i is the capital recovery factor for the ith component and it is a function of the discount rate (d) and life of the component (n_i). AOM is the annual operating and maintenance cost of the system. AFC is the annual fuel cost estimated based on optimum dispatch of the generator and E_{dem} is the total annual energy delivered. The generator dispatch is optimized so that the system operates under the most energy efficient conditions. The system operation has been modelled based on energy balance considering operating limits of the various components of the system. The optimum dispatch, $P(t)$ has been determined satisfying the load balance conditions (3) and charge constraints (6–7). The minimum loading on the gasifier integrated generator is taken as 30% of the rated power.

$$P_{\min} \le P(t) \le P_r \tag{12}$$

The battery energy has to be between the rated and minimum values depending on the allowable depth of discharge.

$$B_{\min} \le Q_B(t) \le B_r \tag{13}$$

For the system optimization, the cost of energy is evaluated over the various configurations in the design space to identify the minimum energy cost configurations.

4 Case Study

In this section, generation of design space for a gasifier integrated photovoltaic battery system has been illustrated through an example. The data corresponding to an existing system operating in the south Indian state of Tamilnadu, has been considered based on the data as given by Balamurugan et al. [2]. The design space approach is used to identify all the feasible combinations of generator ratings (i.e. gasifier integrated generator and photovoltaic array) and battery capacity. On identification of the design space, the system optimization is carried out on the basis of minimum cost of energy. The existing system is represented in the generated design space and is compared with the system optimized on the basis of cost of energy. The existing system in the site consists of biomass gasifier integrated generator of 300 kW (two units of 200 and 100 kW each), photovoltaic array of 8 kW_p and battery bank of capacity 192 kWh. The system has been installed in a university campus where the utility grid supply is available; however the system operation aims to avoid dependence on the grid. For generating the design space and determining the optimum system, the solar resource data, local biomass availability and electrical demand data at the location have been considered as given by Balamurugan et al. [2]. For a typical day, the load curve is shown in Fig. 2. The hourly variation in the solar insolation for an averaged day is presented in Fig. 3. Woody biomass (having a gross calorific value of 18.5 MJ/kg) is abundantly available in the location which is considered as the feedstock for the gasifier. The parameters considered for the system sizing are given in Table 1. The cost data considered for the economic analysis are given in Table 2. The set of sizing curves are generated for the hybrid system following the methodology presented in Sect. 3. For representing the feasible systems on a two dimensional space, the system configurations corresponding to a specified constant level of power generating system (gasifier integrated diesel generator rating or photovoltaic array rating) is presented. The sizing curves and associated design space are represented for a given value of gasifier integrated generator rating showing the corresponding photovoltaic array-battery combinations (Fig. 4). The set of sizing curves are plotted for no diesel generator system (corresponding to photovoltaic-battery systems) and for representative gasifier integrated generator ratings. At a generator rating of 167 kW and battery capacity of 900 kWh, the system can operate without any contribution from the photovoltaic array. The load can be met entirely by combination of gasifier integrated generator and battery bank. The corresponding generator-battery bank configuration is illustrated in Fig. 5. For the generator rating corresponding to the maximum demand of 230 kW, no storage is required and the load is entirely met by the gasifier integrated generator. The effect of integration of photovoltaic arrays starting from the set of gasifier integrated generator battery-bank configurations has been illustrated in Fig. 5. Existing system configuration is also identified on the design space. The costs of energy for the existing system as well as for some of the configurations represented in the design space are also given in Fig. 5. The optimum system is identified based on the minimum cost of energy. The minimum costs of energy configurations for different options are represented in Table 3. A ‘diesel generator only system’ with a capacity of 230 kW can be considered as a base case option for the location. For such a system the cost of energy is found to be 1.18 USD/kWh.

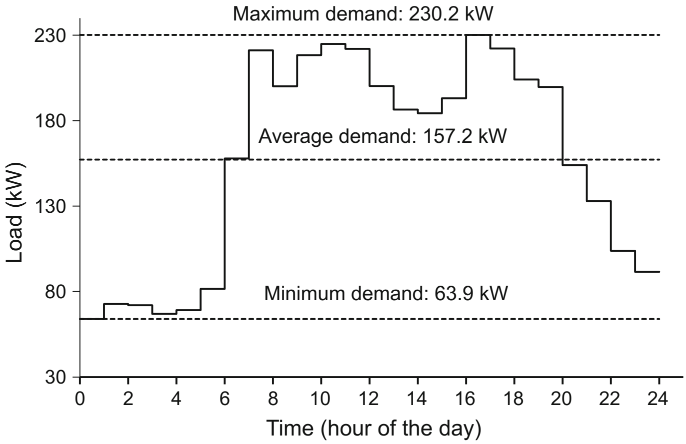

Fig. 2 Load curve for the location

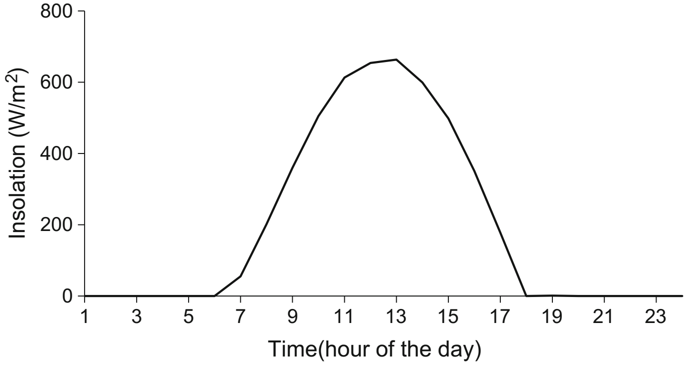

Fig. 3 Variation in the mean hourly solar insolation for an averaged day for the location

Table 1 Input parameters used in the system sizing and optimization

Photovoltaic system efficiency, %	10
Net charging efficiency, %	85
Net discharging efficiency, %	85
Inverter efficiency, %	90
Depth of discharge, %	70
Substitution ratio	8.5
Diesel fraction, %	20

Table 2 Input parameters used for system optimization

Discount rate, *d*%	10
Diesel generator life, years	10
Photovoltaic system life, years	20
Battery bank life, years	5
Converter life, years	10
Cost of diesel generator, USD/kW	500
Cost of photovoltaic system, USD/kW	1200
Cost of battery bank, USD/kWh	80
Cost of converter, USD/kW	720
Cost of diesel, USD/l	0.94

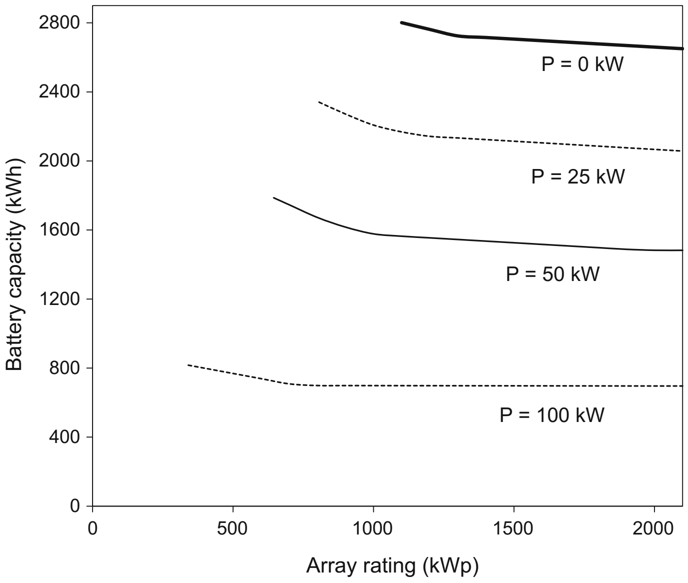

Fig. 4 Sizing curves for the hybrid system starting from the photovoltaic-battery configuration

It has been observed that the configuration with the minimum cost of energy is a hybrid configuration of gasifier integrated generator, photovoltaic array and battery bank. In the optimized hybrid configuration the diesel consumption is only 1.45% of the diesel generator only configuration and the cost of energy is about 25% of the diesel generator only configuration.

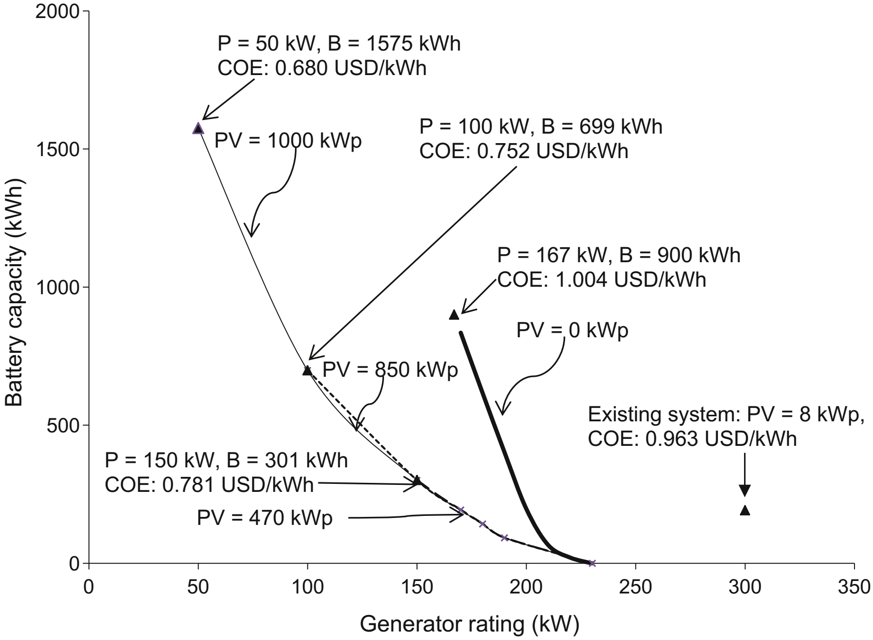

Fig. 5 Sizing curves for the hybrid system starting from the generator-battery configuration

Table 3 Minimum cost of energy configurations from the design space

Array rating (kW_p)	Gasifier integrated generator rating (kW)	Battery capacity (kWh)	Cost of energy (USD/kWh)	Diesel consumption (litres/year)
1300	130	15,960	0.292	7328
1350	210	–	0.804	213,302
–	220	3420	0.938	439,746
–	230	–	1.146	462,370

5 Conclusions

Biomass resource can be a significant contributor to meet the energy demands for power generation in remote and rural areas. Biomass gasifier integrated generators can be a preferred option for isolated power generation. The usage of a co-fired generator brings down the diesel fuel consumption significantly. System sizing and optimization of biomass gasifier integrated hybrid energy systems has been illustrated in this work. For given demand profile, solar resource profile and system characteristics, set of sizing curves may be plotted on the gasifier integrated generator rating versus storage capacity diagram for a given photovoltaic array rating. A set of sizing curves may also be plotted on the photovoltaic array rating vs. storage capacity diagram for a given gasifier integrated generator rating. The design process helps to identify system configurations which are economically feasible meeting the load requirements. The integration of biomass gasifier in the system makes the system more sustainable as indicated by the significant reduction in the diesel fuel consumption and emissions. The optimum system selection is based on the minimum cost of energy. For the illustrative case study, it has been observed that for a gasifier integrated hybrid energy system, the cost of energy decreases to 25% of that of ‘diesel generator only system’.

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Mahua and Neem Seeds as Sustainable Renewable Resources Towards Producing Clean Fuel and Chemicals

Ranjeet Kumar Mishra and Kaustubha Mohanty

Abstract The aim of the present study is to find out the feasibility of two non-edible oil seeds as a feedstock to produce fuel and value added products using thermochemical conversion technique. Mahua (*Madhuca longifolia*), and Neem (*Azadirachta indica*) seeds were characterized based on their characteristics. Kinetic analysis was carried out by using Horowitz and Metzger models. TGA confirmed that maximum degradation occurred in second stage (150–430 °C). Higher calorific value was observed 22.19 MJ kg^{-1} and 26.88 MJ kg^{-1} for Mahua and Neem respectively. Further both seed contain higher volatile matter and negligible sulfur content. All the above physicochemical characterization confirmed that these seeds have the potential to produce fuels and chemicals. Kinetic analysis confirmed that the extractive free seeds required higher activation energy to initiate reaction compared to raw seeds. Thermal pyrolysis of both seeds were carried out in a semi-batch reactor at optimized conditions (450 ± 10 °C temperature, 80 °C min^{-1} heating rate and 80 mL min^{-1} N_2 flow rate). The yield of pyrolytic liquid was found to be 34.50 and 56.65 wt% for Neem and Mahua seeds respectively. It was found that oil obtained have higher viscosity as well as calorific value which indicated their use as boiler fuel. GC-MS analysis confirmed the presence of valuable chemicals in pyrolytic liquid which may be further purified to obtain pure chemicals. The results of this work is encouraging and affirmed that both these seeds can be excellent renewable resources to produce fuels and chemicals using pyrolysis.

Keywords Biomass · Biooil · Characterization · Pyrolysis · Renewable fuel

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1 Introduction

Biomass is not only energy source in transition but it is a resource that becomes important as a modern energy carrier. The biomass and solid waste offered great potential for solving world energy and environmental issues. Biomass (wood and forestry biomass) was the major foundation of human civilization [1]. Recently, biomass became the main source of energy generation in many countries, particularly in its traditional forms, and almost providing 35% of energy consumption of three-quarters of the world's total energy consumption [1]. However, modern application of biomass increasing rapidly for both the sectors in both developed and developing countries. United States extracted about 4.0% energy from biomass, Finland and Sweden about 20.0% energy from biomass of their primary energy requirement [1]. India is also one of the emerging country for extraction of energy from the biomass. India has huge diversity of agriculture and forest area which include about 500 million metric ton of biomass availability per year [2]. At present in India, total biomass power generation capacity is 17,500 MW. In India, total installed capacity of electricity generation is 2666.64 GW as 31st March 2013 [2]. However, generation of total renewable energy contributed 10.5% out of 12.83% power is generated from the biomass [2]. Recently, biomass gained more attention due to having higher value chemicals either as unique specialties or as substitution of petroleum products [3]. Total annual bioenergy potential is about 2900 EJ which comes from various sectors such as: 1700 EJ energy comes from forest, 850 EJ comes from grassland, and 350 EJ comes from agriculture sectors [4]. The most interesting thing is that about 850 EJ energy comes from the agriculture sectors without affecting the world's food supply [5] which is the great advantage of biomass. In recent time, production of bio-oil or pyrolytic liquid from the biomass emerge as one of the best possible way to reduce the waste biomass and prevents formation of toxic and harmful gases. Continuous heating of biomass at moderate temperature in absence of oxygen results in decomposition of biomass into smaller molecular compounds and evolved as hot gases. Moreover, different types of biomass upon conversion resulted in different products which are listed under Table 1.

The bulky nature of biomass is one of the drawback in rapid shifting from fossil fuel to biomass based liquid fuel or energy. However, handling, storage and transportation of solid biomass is likely difficult than liquid and gaseous fuel thus, conversion of solid biomass into liquid or gases become essential. Conversion of biomass can be done by two major routes: biochemical conversion and thermochemical conversion. The detailed conversion scheme is shown in Fig. 1. Energy from the biomass can be extracted by four routes: combustion, pyrolysis, gasification and liquefaction. Combustion is operated at higher temperature with use of air or oxy-fuel for conversion of biomass into carbon dioxide and steams. Gasification is operated at higher temperature with oxygen-deficient environment. Pyrolysis occurred at relatively moderate temperature with absence or partial absence of oxygen. However combustion, pyrolysis, and gasification required

Table 1 Classification schemes of Bio-fuel

Production side, supply	Common group	Users side, demand examples
Direct wood fuel	Wood fuels	**Solid**: Fuel wood (wood in the rough, chips, sawdust, pellets) charcoal **Liquid**: black liquor, methanol pyrolytic liquid **Gases**: Product from gasification and pyrolysis gases
Indirect wood fuel		
Recovered wood fuel		
Wood-derived fuels		
Fuel crops	Agro fuels	**Solid**: Straw, stalk, husks, bagasse, charcoal **Liquid**: ethanol, raw vegetable oil, oil dieter, methanol, pyrolytic liquid Gases: biogas, producer gases, pyrolysis gases
Agricultural by-products		
Agro-industrial by-products		
Municipal by-products	Municipal by-products	Solid: Municipal solid waste (MSW) Liquid: Sewage sludge, pyrolytic liquid from MSW. Gases: Landfill gas, sludge gas.
Edible seeds	Edible and non-edible seeds	Solid: All edible and non-edible oil containing seeds Liquid: Pyrolytic liquid and various value added chemicals Gases: Products from pyrolysis and non-condensable gases
Non-edible seeds		

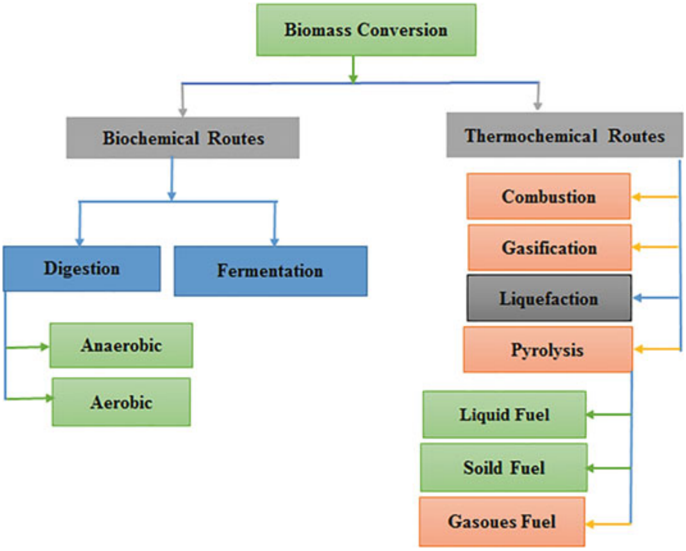

Fig. 1 General layout scheme of conversion of biomass

drying of biomass which is an energy penalty. Liquefaction is a thermochemical process in which large feedstock decomposed into liquids with smaller molecules by influenced of catalysts. Table 2 showed general comparison of thermochemical conversion process which is adopted from [6].

Out of all the above thermochemical processes, pyrolysis has gained attention in recent years due to it's simplicity in operation, can handle wastes including that of toxic wastes, reduction in water volume, can process wide variety of feedstock and low cost. During pyrolysis larger molecular weight compounds broke down into smaller molecular weight compounds due the continuous supply of heat. Pyrolysis is perhaps one of the best thermochemical route for conversion of waste biomass into fuel and other value added chemicals. Slow and fast pyrolysis depends on the heating rate. Slow pyrolysis leads to formation of more char and less liquid fuel while fast pyrolysis produce higher amount of liquid oil without changing the quality.

Non-edible oil seeds are one of such biomass which has the potential to be a feedstock for pyrolysis to produce fuels/chemicals. Singh and Shadangi [7] pyrolyzed caster seed and reported that at optimized condition (550 °C temperature and 20 mL min^{-1}) produced maximum liquid yield 64.40 wt%. Sinha et al. [8] worked on linseed seeds in a semi batch reactor at optimized condition (550 and 20 °C min^{-1} nitrogen flow rate) and reported that 68.0 wt% liquid fuel was obtained. Koul et al. [9] studied Kusum seed (*Schleichera oleosa*) in a semi batch reactor and reported that at optimized condition (550 °C temperature 25 °C min^{-1} heating rate) produced higher liquid yield (50.93 wt%). Shadangi et al. [10] reported that Karanja seed in a semi batch reactor without catalyst yielded 33.0 wt% liquid fuel and with catalyst, pyrolysis liquid yield and properties of liquid fuel is increased. Garg et al. [11] worked on babool seeds (*Acacia nilotica*) in a fixed bed reactor and reported that at optimized conditions (500 °C temperature, 100 cm^3 min^{-1} sweep gas flow rate (N_2) and particle size range up to 0.4 mm) produced maximum liquid and pyrolytic liquid yield (~49 and 38.3 wt%, respectively). From these studies, it can be inferred that non-edible oil seeds are good feedstocks for producing fuels and chemicals.

Mahua seed contains oil which is mostly considered as non-edible in India though in few other countries it is considered to be edible. It is found in dry tropical and sub-tropical climate condition and it is a large deciduous tree. Mahua seed and flower has greater value and there has religious and aesthetic value in the tribal

Table 2 Comparison of thermochemical conversion process

Process	Temperature (°C)	Pressure (MPa)	Catalyst	Drying
Liquefaction	250–330	5–20	Essential	No
Pyrolysis	380–530	0.1–0.5	No	Yes
Combustion	700–1400	>0.1	No	Yes but not essential
Gasification	500–1300	>0.1	No	Yes

Source Adopted from Doshi et al. [26]

culture. Its botanical name is *Madhuca Indica* and *Madhuca Longifolia* belonging to *Sapotaceae* family. The average height of tree reaches up to 20–25 m but some time it reaches up to 50 m and flowering in the month of February–April. The fruits ripen in the month of June–July in North India, however in southern India, it ripen in the month of August–September [12]. Mahua seed can produce 250 mL of oil from 1.0 kg of dried seed however, it depends on the extraction method.

Neem tree is one of the most common trees found in all parts of India. Neem tree is used for purification of air and environment. Moreover, Neem tree has religious and aesthetic value in number of states in India. The botanical name of Neem tree is *Azadirachta indica* which belongs to *mahogany* family *Meliaceae* [13]. Neem tree has higher amount of oil inside it's seeds. Neem tree can be grown a wide range of climatic as well as soil conditions. Neem tree have average life of 150–200 year and required less water and plenty of sunlight for growing. After plantation of about 10 years, an average sized neem tree produces about 30–50 kg of seeds every year [14].

In the present work, two non-edible oil containing seeds viz. Mahua and Neem were pyrolyzed to check their potential to produce fuel and chemicals. Detailed characterization of both the seeds were carried out along with the kinetic analysis of thermal data. The effect of various process parameters on pyrolysis of both the seeds were studied in detail.

2 Materials and Methods

2.1 Sample Collection and Preparations

Mahua as well as Neem seeds were collected from Basti district, Uttar Pradesh, India (26.80°N 82.74°E). Collected biomass was sundried for 24–48 h and placed in plastic bags or glass container. Biomass was pulverized into less than 1 mm particle size (0.5 μm). Smaller particle size offer greater heat transfer during thermochemical process while higher particle size biomass creates thermal lag during pyrolysis and moreover, larger particle size requires higher activation energy to start the process.

2.2 Extractive Content, Proximate and Ultimate Analysis

Extractive content of biomass has significant effect on pyrolytic liquid. It was reported that biomass containing higher extractives produced more pyrolytic liquid, however, some researchers reported that higher extractive content create several industrial problem during thermochemical process [15]. Extractives of biomass was extracted by soxhlet apparatus by using hexane and ethanol as solvent. About 5.0 g of dried biomass was taken in thimble (single thickness, cellulose thimble 25 × 100 mm size) and placed in the soxhlet tube. After 4 h of extraction using Hexane, extractive was separated and extractive free biomass was kept in hot air oven for 1.0 h at 60 °C. Thereafter the same biomass was again kept in soxhlet tube with ethanol solvent and the extraction was carried out for 4.0 h. During hexane extraction, soluble compounds got separated form biomass such as non-polar lipid compounds, hydrocarbons and terpenoids etc. and during ethanol extraction polar wax, chlorophylls, sterol, and other minor compounds removed [16]. Solvent recovery was done by Rota-evaporator at reduced pressure. Extractive yield was calculated by following equation.

$$Percentage\,Extractives(\%) = \left[\frac{Weight\,of\,extractives}{Weight\,of\,oven\,dried\,biomass}\right] \times 100 \qquad (1)$$

In the present study proximate and ultimate analysis was carried out by using ASTM Standards (ASTM D1102–84, ASTM D 1762-84. 84). 1.0 g of biomass sample was taken in ceramic crucible and placed in hot air oven for 1.0 h at 105 °C. The final and initial weight of biomass provides percentage of moisture content. For volatile matter, 1.0 g of dried biomass sample was placed in muffle furnace for 7.0 min at 925 ± 5 °C. The biomass sample removed and placed in a desiccator for isothermal cooling. The initial and final weight difference provides percentage of volatile matter. The inorganic residue left after the fuel is completely burned, known as ash. Ash comprises silica, iron, aluminum, calcium, and small amount of magnesium, titanium, sodium and potassium. Amount of ash was determined by taking 1.0 g of dried biomass in ceramic crucible and placed in muffle furnace at 575 ± 10 °C for 3.0 h. After 3.0 h, sample was removed and placed in desiccator for isothermal cooling. This was repeated until constant weight was observed. The final and initial weight difference of biomass sample gives percentage of ash.

CHNS elemental analyzer (Variael CUBE, Germany) was used for ultimate analysis. Analyzer was calibrated using 5 tiny capsules packed with a 5L-cystine test. 1.0 mg of biomass was taken in a tin capsule and heated at 980 ± 05 °C with continuous and constant flow of helium enriched oxygen gas. Obtained data was analyzed by using Callidus® software for calculation of composition of biomass. Elemental analysis was calculated on dry basis.

2.3 Bulk Density and Calorific Value

Bulk density play an important role for storage cost and transportation of fuel. In addition, bulk density of biomass helps in sizing of material, fuel storage requirements, handling of material and most importantly behavior of biomass during thermochemical or biological processes. Bulk density of biomass was measured and calculated based on the method described by Obernberger et al. [17]. Calorific value of fuels depends on elemental composition. Oxygen bomb calorimeter (Paar 1108P) was used for determination of calorific value of biomass. All the experiment was repeated thrice for predictability of accurate results.

2.4 XRD Analysis

XRD analysis was carried out to determine the nature of biomass. Lower crystallinity reduces thermal degradation temperature, activation energy and increase the rate of depolymerisation. Rigaku TT Rax Diffractometer in conjugation with Cu–Kα radiation source was used for determination of biomass nature. 9.0 KW and 250 mA voltage was applied for generation of X-ray with scanning angle (2θ) 5–50° at a speed of 0.03 min^{-1}. The crystallinity index of biomass samples was calculated by:

$$CrI\,(\%) = \left[\frac{I_{Crystalline} - I_{amorphous}}{I_{amorphous}}\right] \tag{2}$$

where, intensity of crystalline peak at about 2θ = 22.25 for the crystalline portion of biomass sample (i.e., Cellulose) and intensity of amorphous peak is 2θ = 16.12 for amorphous portion (i.e., Cellulose, hemicellulose, and lignin).

2.5 Thermal Analysis

TGA experiments were carried out in a NETZSCH TG 209 F1 Libra model. About 8.0 mg of biomass samples were taken and placed in the aluminum crucible (Al_2O_3) at 10 °C min^{-1} with temperature range from 30 to 900 °C under the inert (nitrogen) atmosphere at 40 mL min^{-1} flow rate. Chemical analysis of biomass also carried out by using TGA with the same conditions.

2.6 FTIR Analysis

Fourier transform infrared spectroscopy (FTS 3500 GX attached with DRS) was used for identification of useful functional group. Very small amount of dried biomass was mixed properly with oven dried potassium bromide (KBr) powder in 1:100 ratio and placed in sample holder with scanning rate of 40 with a step size of 4 cm^{-1} within the range of 400–4000 cm^{-1} wave number. FTIR analysis of liquid sample was done by Attenuated Total Reflectance (ATR) with the range of 400–4000 cm^{-1} wave number.

2.7 Kinetic Analysis

Kinetic study of biomass provides basic information which helps during designing, process parameter optimization, and development of new pyrolytic reactors. Kinetic study comprises calculation of activation energy (E_a), order of reaction (n) and frequency factor (A). In the present study, Horowitz and Metzger models were adopted [18] for determination of kinetic parameters of all biomass. According to Horowitz and Metzger, twofold logarithmic plot of reciprocal of reactant against temperature provides activation energy while assuming that order of reaction is first order. This model is easy to use as compared to other kinetic models. Proposed mathematical model by Horowitz and Metzger is given in following equation.

$$\ln\left[\ln\left\{\left(\frac{\alpha_0 - \alpha_f}{\alpha_t - \alpha_f}\right)\right\}\right] = \frac{E\varphi}{RT_{\max}^2} \tag{3}$$

where, α_0 = initial mass of biomass material, α_f = final weight of material, and α_t = weight of material at particular temperature, R = ideal gas constant, (J/mol K), ϕ = difference of particular and reference temperature. $T_{\max}$ = reference temperature effective when

$$\left(\frac{\alpha_t - \alpha_f}{\alpha_0 - \alpha_f}\right) = \frac{1}{2.718} \tag{4}$$

Kinetic plots obtained between $\ln\left[\ln\left(\frac{\alpha_0-\alpha_f}{\alpha_t-\alpha_f}\right)\right]$ verses ϕ gives a straight line (linear fit). Further, with help of slope, activation energy was calculated. There are several kinetic models available but we are only focused for determine of activation energy of biomass therefore chosen Horowitz and Metzger model because it gives minimum error (>1%).

2.8 Experimental Setup

The pyrolysis experiments were carried out in a semi batch reactor of stainless steel (SS-304). The required amount of biomass sample (50 g) kept in the reactor and placed vertically in the furnace. A control panel was installed at the bottom of the furnace for controlling temperature and heating rate with the help of PID controller. Nitrogen gas was used to maintain the inert atmosphere. A Rotameter was installed for controlling nitrogen gas flow rate before the reactor inlet. As temperature increases amount of volatiles generated in the form of vapor and condensed in the condenser. A chiller was installed to cool the condenser. The condensed vapor is collected and known as pyrolytic liquid. After cooling the reactor at room temperature char was removed and weighed. The details configuration of the experimental setup is given in Fig. 4. Calculation of liquid yield, char and non-condensable gases was done using following equations.

$$\%\,Liquid\,yield = \left[\frac{Liquid\,fuel\,weight}{Weight\,of\,Total\,feed}\right] \times 100 \tag{5}$$

$$\%\,Char\,yield = \left[\frac{Mass\,of\,remaning\,char}{Weight\,of\,Total\,feed}\right] \times 100 \tag{6}$$

$$\%\,Gas\,yield = 100 - (\%\,Liquid\,yield + \%\,char\,yield) \tag{7}$$

2.9 Characterization of Pyrolytic Liquid

Characterization of pyrolytic liquid was done on the basis of physical properties, functional groups and composition. Viscosity, density, calorific value, moisture content, and pH is known as physical properties. Functional groups were characterized by FTIR, NMR and composition of the liquid was done by GC-MS analysis. Viscosity of oil was determined by using rheometer (Cone and plate) (HAKEE Rheostress 1) at 40 °C at 50 rpm. A series of data obtained from the analysis and average data is reported in this study. Calorific value of pyrolytic liquid was carried out by using oxygen bomb calorimeter (Paar instruments). About 0.5 g of liquid was filled in the sample holder (Con type) and placed in the stainless steel cylinder. Burring of fuel was done in oxygen environment by use of sparking pluck and the increase in temperature with respect to time was noted down. pH and water content (moisture content) of pyrolytic liquid was carried out by Eutech water proof (pH Spear) pH meter and moisture content was carried out by Karl Fischer water analyzer (Metrohm 787 KF Titrino). Density of pyrolytic liquid was carried out by density meter (Anton Paar, DMA4500M). Pensky-Martens apparatus was used for determination of Flash and fire point. The pour point of pyrolytic liquid was determined by guideline given by Indian Institute of Petroleum [19]. ^{1}H NMR spectra was performed for pyrolytic liquid obtained from Neem and Mahua seed in a Bruker Advance 600 MHz NMR spectrometer (Bruker BioSpin, Canada) equipped with a 5 mm inverse triple resonance (TXI) probe for ^{1}H. Approximately 40 mg of the pyrolytic liquid was filtered using 0.2 µm sterilized filter disc (cellulose nitrate) and dissolved with 0.6 mL of Deuterated chloroform ($CDCl_3$). All the acquired NMR spectra were processed through Topspin version 2.1 software with a Gaussian function.

2.10 Gas Chromatography-Mass Spectrometry (GC-MS) Analysis

Gas chromatography and Mass spectroscopy (GC-MS) was used to identify the qualitative analysis of unknown samples. Separation of compounds is the major attraction while compound groups were separated by their mass percentages. In this study, GC-MS was used to identify the pyrolytic liquid composition. Perkin Elmer (*Clarus*600/680) GC-MS analyzer was set at 40 °C for 30 s, then increased at 10 °C min^{-1} to 300 °C. Total GC run time was set for 30 min. Elite 5 MS column (30 mm × 0.250 μm) was used. 1.0 μL oil sample was injected where carrier gas flow rate was set at 0.6 mL min^{-1}. The chromatograph was collected with their retention time and mass spectra of the compounds. NIST library was used to identify the compounds and their composition.

3 Results and Discussion

3.1 Characterization of Mahua and Neem Seeds

Extractive content of biomass was carried out in a soxhlet apparatus by using hexane and ethanol as a solvent. From the results, it was confirmed that Neem and Mahua seed contain 29.24 and 62.52% of extractives respectively. It is well known that biomass having higher extractive content produces more liquid at lower temperature (Table 3).

The detailed proximate and ultimate analysis was presented in the Table 4 on dry basis. From the proximate analysis it was confirmed that biomass NM and MH contained lower moisture of 7.32 and 6.88% respectively. According to Ahmad et al. [20], biomass which is associated with less than 10% moisture content is considered suitable feedstock for combustion. Volatile matter was found to be higher (78.20% for NM and 79.05% for MH respectively) along with low ash content (3.08–3.26%) which showed that ignition efficiency of fuels from these biomass will be higher. Amount of fixed carbon was also found to be in the significant range (10.58–11.12%). Fixed carbon and volatile combustible matter directly contribute to the heating value of any fuel. Ultimate analysis of biomass confirmed that NM and MH seed biomass contained higher carbon percentage (54.36 and 61.48% respectively) and lower amount of nitrogen (2.62–3.89%) and sulfur (0.34–0.70%) which indicated that theses biomass will produce less emission

Table 3 Extractive and chemical analysis of biomass

Biomass	Extractive analysis (%)		
	Hexane	Ethanol	Total extractives
NM	25.80	3.44	29.24
MH	54.49	8.03	62.52

Table 4 Proximate and ultimate analysis of biomass

Biomass	Proximate analysis (db %)				Ultimate analysis (db %)				
	MC	VM	FC	A_s	C	H	O	N	S
NM	7.32 ± 0.2	78.20 ± 0.1	11.12 ± 0.2	3.26 ± 0.02	54.36	7.36	33.68	3.89	0.70
MH	6.88 ± 0.5	79.05 ± 0.2	10.58 ± 0.3	3.08 ± 0.05	61.48	8.69	26.86	2.62	0.34

Note db represents on dry basis (wt%)

during pyrolysis. In addition, lower amount of sulfur indicates corrosion phenomena would be less during pyrolysis or combustion [21].

Bulk density and calorific value of biomass is summarized in Table 5. Bulk density and calorific value of seeds biomass was higher. Bulk density of biomass has good agreements with other reported biomass such as Palm Seed (560 kg cm^{-3}) [22], Wood pellets (590 kg cm^{-3}) [17], Hazelnut Husk (481 kg cm^{-3}) [23], Wood (500 kg cm^{-3}) [24], *Prosopis juliflora* (325 kg cm^{-3}) [25] (Table 5). The calorific value of Neem and Mahua seeds varied in range of 22.19–26.88 MJ kg^{-1} respectively. Calculated calorific value has good agreements with other reported biomass such as *Pinusbanksiana* (18.1 MJ kg^{-1}), wheat straw (20.3 MJ kg^{-1}) [16], *Jatropha curcas* (18.61 MJ kg^{-1}), *Pongamia pinnata* (18.72 MJ kg^{-1}) [26], Bonbogri (21.24 MJ kg^{-1}) [27]. Therefore, these biomass are considered as potential candidates for generation of alternative fuels. The biomass having crystalline nature produces more amount of liquid. From the XRD analysis, it was confirmed that biomass NM and MH, has 46.17, and 49.00% crystallinity index respectively. The calculated crystallinity index is in good agreement with other reported biomass such as Niger (46.74%), Linseed (44.19%), moj (Albizia lucida) (46.43%).

Thermogravimetric analysis was used to see the thermal degradation behavior of both the biomass. Recently, TGA was used to determine the chemical analysis (hemicellulose, cellulose and lignin) and proximate analysis of biomass [28, 29]. The chemical analysis of NM and MH seed was carried out in a TGA. The results confirmed that NM and MH seed contains 21.94 and 27.33% hemicellulose, 38.04 and 37.92% cellulose and 13.58 and 15.20% lignin respectively. The thermal decomposition profile of NM and MH seeds was presented in Fig. 2. From Fig. 2, it was confirmed that biomass splits into three major stages during thermal degradation process. The first stage is known as drying zone in which moisture and lower

Table 5 Compression of bulk density and calorific value of biomass with other reported biomass

Biomass	Bulk density (kg/cm^3)	References	Biomass	HHV (MJ kg^{-1})	References
NM	563.05	Present work	*NM*	22.19	Present work
MH	462.27	Present work	*MH*	26.88	Present work
Palm seed	560	[22]	*Pinus banksiana*	18.1	[16]
Wood pellets	590	[17]	*Jatropha curcas*	18.61	[26]
Hazelnut husk	481	[23]	*Pongamia pinnata*	18.72	[26]
Wood	500	[24]	Wheat straw	20.3	[16]
Palm leaf	298	[22]	Bonbogri	21.24	[27]
Prosopis juliflora	325	[25]	Moj	20.35	[27]

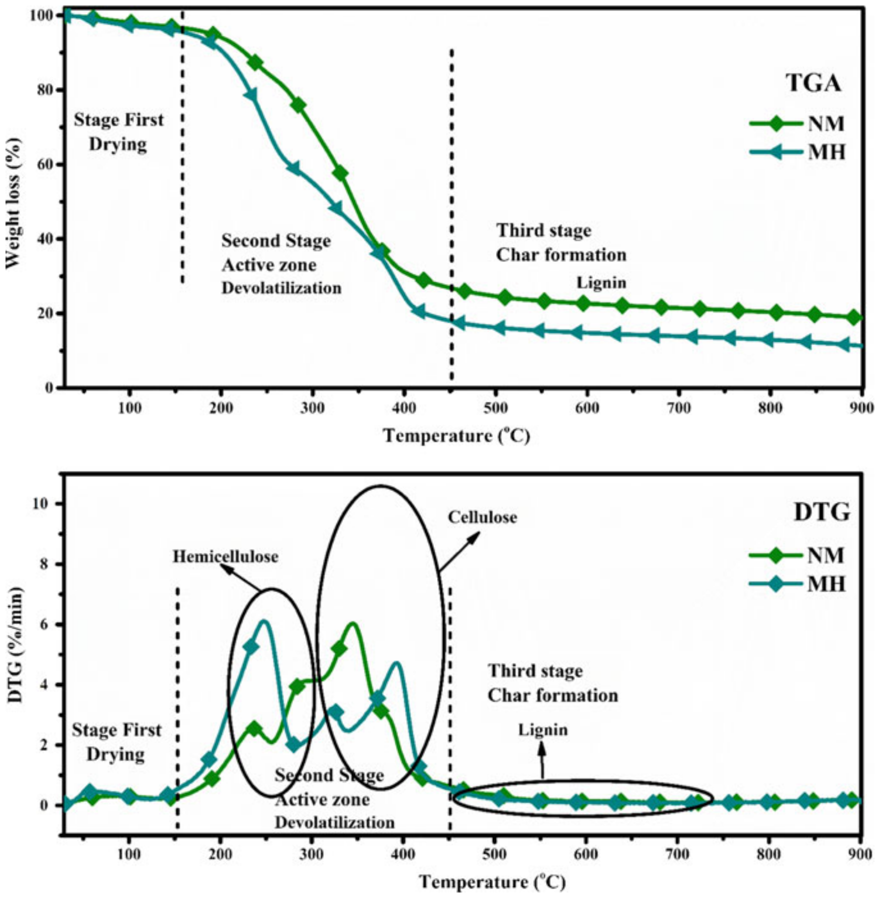

Fig. 2 TGA and DTG analysis of biomass Mahua and Neem seed

molecular weight compounds were removed up to 150 °C. In the second stage (temperature range 200–450 °C), maximum decomposition occurred therefore this zone is known as active pyrolysis zone. During second stage, higher molecular weight compounds fragmented into smaller molecular weight compounds due to continuous supply of heat or temperature. At final stage, lignin degrades at a very slow rate at higher temperature (>500 °C) because of presence of phenolic hydroxyl group in the raw biomass (from FTIR analysis), which provides higher thermal stability [16]. At the end of pyrolysis, char remains as residue which can be further utilized in different areas such as, solid fuel, bio-absorbent and various cosmetics products. From the DTG thermograph (Fig. 2), it was observed that all biomass decomposed below 10% in first stage, while about 70% was decomposed in second stage. Also, it was confirmed that very first peak appeared due to removal of moisture and light volatile compounds up to 150 °C temperature. Literature revealed that cellulose and lignin decompose at higher temperature than hemicellulose [30]. Decomposition peak of hemicellulose and cellulose appeared in temperature range of 200–450 °C. Lignin composed of crossed linked mono-nuclear polymer of higher carbon linked with an irregular structure of hydroxyl-and methoxy-substituted phenylpropane units. Formation of char during pyrolysis depend on composition of lignin content. Higher amount of lignin present in biomass promotes formation of higher char. In addition, higher energy is required to initiate reaction process. Moreover, during thermal depolymerisation, lignin provides more aromatic compounds with small chains of organic molecules and gaseous products such as CO and CH_4.

FTIR analysis confirmed the presence of useful functional group such as hemicellulose, cellulose and lignin. Figure 3 showed transmittance spectra against wave number. The IR peak 3624–3284 cm^{-1} indicates the presence of fibre in biomass, which is ascribed to axial deformation of OH group. Infrared radiation peak 2914 cm^{-1} attributed with $C–H_2$ asymmetric alkanes. Peak 2851 cm^{-1} focused axial deformation of C–H group. Band peak 2373 cm^{-1} indicates presence of C–H and =C–H stretching vibration (alkanes and alkenes). Further, presence of carbonyl group like ester (C=O) is observed at peak 1720 cm^{-1}, which indicate the presence of hemicellulose in sample. The peak 1445 cm^{-1} represents symmetric deformation of CH_2 group which indicates presence of cellulose and peak 1158 cm^{-1} refers C–O–C which indicates presence of cellulose and hemicellulose. Peak 1300 cm^{-1} signifies presence of C–H and aliphatic C–H stretching in methyl and phenol OH (Cellulose and hemicellulose). Infrared radiation peak 1636 cm^{-1} refers to C=C aromatic ring that indicates the presence of lignin and protein in biomass [16, 27]. Band peak 718 cm^{-1} represent C–H, aromatic C–H out of plane bend while 1945 cm^{-1} indicates presence of aromatic ring (aryl) group, aromatic combination bond (Fig. 4).

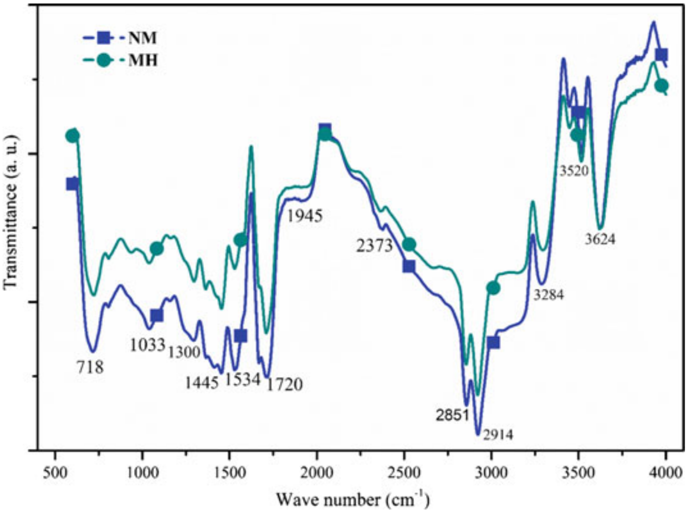

Fig. 3 FTIR analysis of biomass Mahua and Neem seed

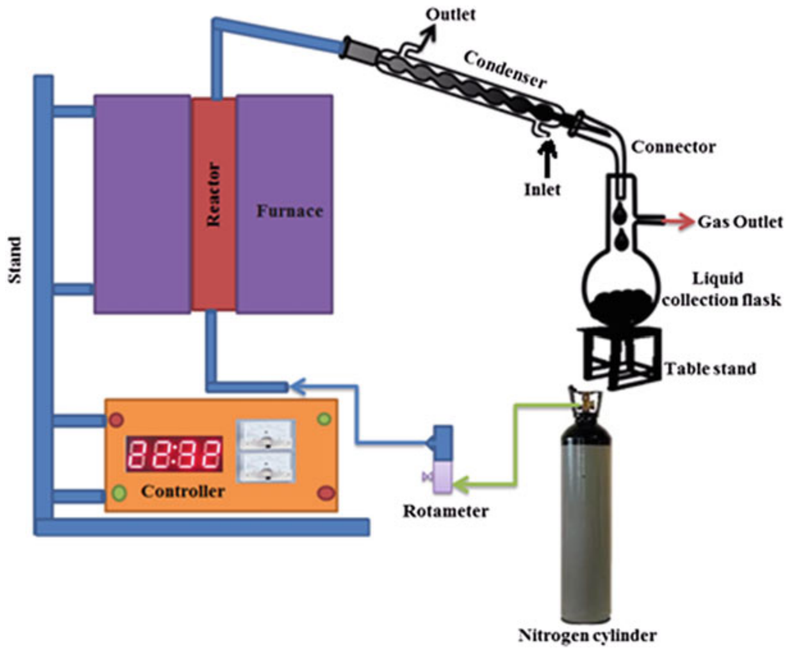

Fig. 4 Schematic layout of pyrolysis setup

3.2 *Kinetic Analysis*

Kinetic analysis of raw and extractive free seeds confirmed that extractive free seed required higher activation energy to start the reaction. From results, it was noticed that raw biomass requires lower activation energy (16.19 kJ mol^{-1} for NM and 10.63 kJ mol^{-1} for MH), while biomass without extractive contents require higher activation energy (23.33 kJ mol^{-1} for NM and 54.64 kJ mol^{-1} for MH) to start reaction or process. Thermal stability of biomass increases due to removal of extractive content from biomass. The correlation coefficient was varied for raw biomass (0.9978 for NM and 0.9739 for MH) and without extractive biomass correlation coefficient was varied from (0.9910 for NM and 0.9803 for MH).

3.3 *Pyrolysis of Mahua and Neem Seeds*

3.3.1 Process Parameter Optimization

Various process parameters such as particle size, heating rate, vapor residence time, type of feedstocks, composition of feedstocks, carries gases and their flow rates, and type of reactors extensively affects the pyrolysis products yield. To find out the optimum temperature for the pyrolysis, experiments were conducted at three temperature 400, 450, and 500 °C with heating rate of 50, 80 and 100 °C min^{-1}. It was reported that below 100 mL min^{-1} nitrogen gas flow rate did not affect liquid yield. Hence, in this study 80 mL min^{-1} nitrogen gas flow rate was used. Purging of the reactor was done before 15 min prior to start the pyrolysis experiments to evacuate the amount of air or unwanted gas from the reactor.

Effect of Temperature and Heating Rate on Product Yield

Pyrolysis experiment were carried out in a semi batch reactor at 400, 450 and 500 °C temperature. Product yield majorly depends on the temperature, heating rates, particle size and biomass composition. From the experiment it was confirmed that maximum pyrolytic liquid was achieved at 450 ± 10 °C at 80 °C min^{-1} heating rate with 80 mL min^{-1} nitrogen gas flow rate (34.50 and 56.65 wt% for Neem and Mahua seeds respectively) without aqueous fraction. From the results (Fig. 5) it was observed that products yield changed with increasing temperature. Temperature

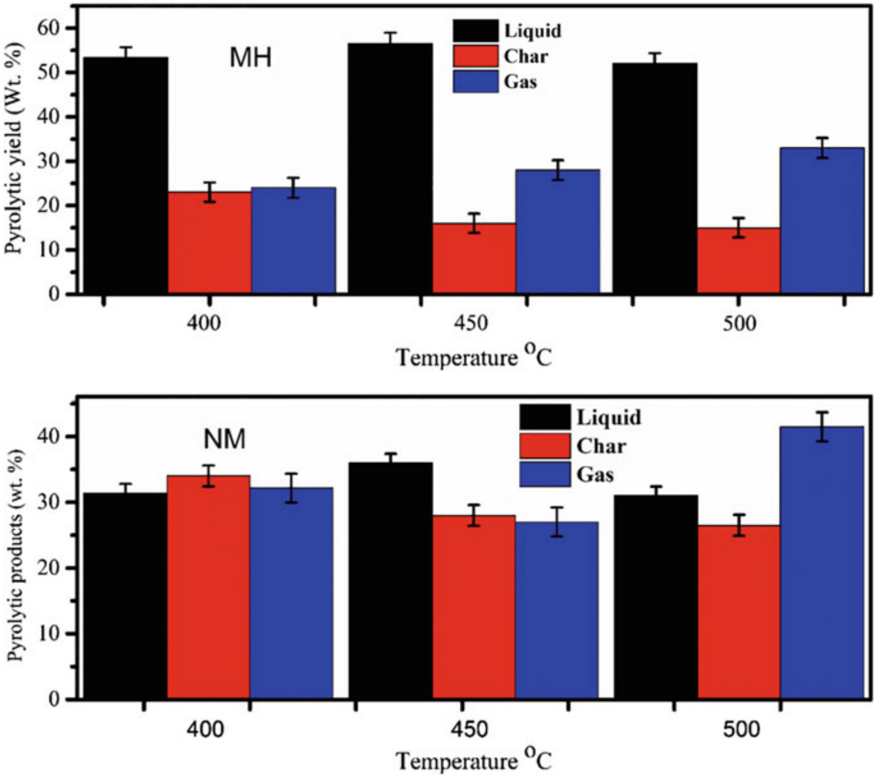

Fig. 5 Variation of product yields with respect to temperature

directly influenced the quality and quantity of products yield. At 400 °C liquid yield is lower, however, at 450 °C generation of liquid products maximum as compared to biochar and gaseous products. Further increasing temperature at 500 °C it was observed that formation of gaseous compound increases while liquid and char yield reduced. At higher heating rate volatile released very rapidly due to rapid endothermic decomposition of biomass. Based on the results, all the experiments was conducted at 450 ± 10 °C temperature in the present study. Nitrogen gas was used as inert gas, the advantage of inert atmosphere is that it is non-reactive with material vapors and provides suitable atmosphere to form and interacts all reactions to each other.

Heating rate is important process parameter which has positive impact on product yield. Heating rate of biomass was higher in fast pyrolysis than conventional system. Fast heating rate of biomass results in quick fragmentation of biomass, reduced vapor residence time and enhanced liquid yield. From the results (Fig. 6), it was observed that with increasing heating rate from 50 to 80 °C min^{-1} about 5.0% for MH and 2.0% for NM oil yield was increased. However, further increases in heating rate liquid yield was reduced 8.0 and 5.0% for MH and NM respectively. From the results (Fig. 6), it was observed that at heating rate 80 °C min^{-1} maximum liquid yield was obtained for all biomass (34.50 and 56.65 wt% for Neem and Mahua seeds respectively). Further, at higher heating rate (100 °C min^{-1}) oil yield was reduced and gaseous contents increased due to rapid endothermic decomposition of biomass. At lower heating rate (50 °C min^{-1}) liquid yield was reduced and char yield was enhanced because of heat and mass transfer limitation which results partial decomposition of biomass. 80 °C min^{-1} heating rate produced higher liquid yield therefore all the experiment was carried out at 80 °C min^{-1}.

3.4 Characterization of Pyrolytic Liquid (Bio-Oil or Liquid Fuel)

The liquid fuel produced from the pyrolysis have 30.0 and 35.0 cP viscosity for NM and MH seeds respectively and has close viscosities with other reported biomass such as Niger seed [31] and Karanja seed [32]. Higher viscosity of pyrolytic liquid is one of the major disadvantages which can be reduced by using appropriate catalysts or other process. NM and MH seeds' have higher calorific value 32.6 ± 0.9 and 41.0 ± 0.8 MJ kg^{-1} respectively which are close to that of diesel (45.5 MJ kg^{-1}). The calorific value of liquid fuel also can be enhanced by using appropriate catalysts. The liquid fuel contains small amount of moisture after separation of aqueous fraction. The results showed the NM and MH contain 1.3 and 1.8% moisture respectively. Higher moisture content reduced calorific value of fuels. pH has significant effect on pyrolytic liquid. Acidic nature of bio-oil has negative impact on fuel properties such as reduction in calorific value, corrosion in engine and boilers. NM and MH seed pyrolytic liquid has a pH of 5.1 and 3.8 respectively which can be increased by using base (alkaline) catalysts such as

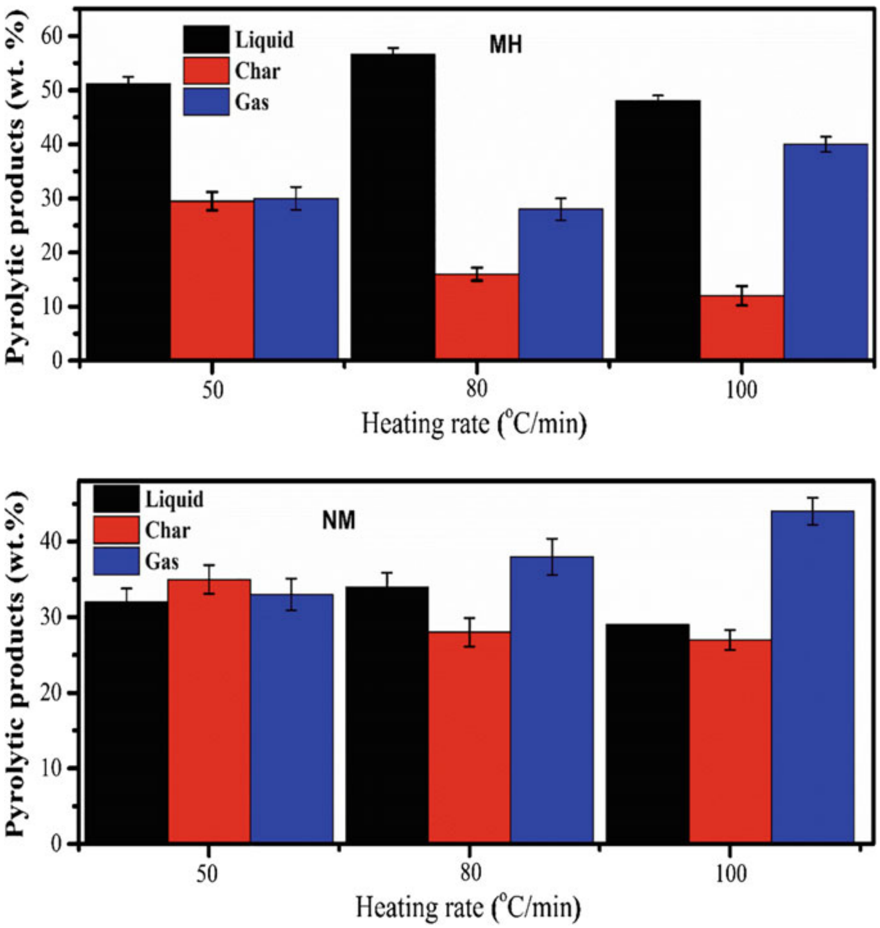

Fig. 6 Effect of heating rate on products yield at optimum condition

calcium oxide, magnum oxide sodium oxide, zeolites etc. Density of NM and MH liquid fuel are calculated to be 906.8 and 993 kg m^{-3} at 40 °C. Specific gravity of Mahua and Neem oil are 901 and 951 at 15 °C temperature. The flash point, fire point and pour point of Mahua and Neem seed oils are 221, 233, 12 °C and 42, 63, 10 °C respectively.

3.5 *FTIR Analysis of Pyrolytic Liquid*

Vibration spectra of molecules have unique physical property and are unique characteristic of the molecules. FTIR analysis was used to identify the presence of useful functional groups in liquid oil and is presented in Fig. 7. Peak

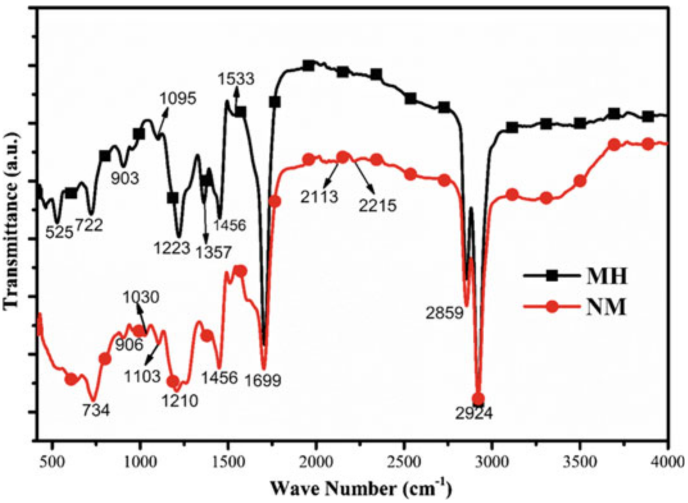

Fig. 7 FTIR analysis of Mahua and Neem bio-oil

2930–2860 cm^{-1} showed presence of C-H stretching vibration which indicates presence of alkane and saturated aliphatic groups. Peak 2113–2215 cm^{-1} showed presence of aliphatic cyanide and aliphatic nitrile while, peak 1700–1680 cm^{-1} showed presence of C=O stretching vibration which indicates presence of aldehyde, ketone and ester. Band peak 1575–1675 cm^{-1} confirmed presence of C=C stretching vibration (alkane group). Further, peak 1460–1377 cm^{-1} indicates presence of C–H bending vibration, CH_2, and CH_3 bending vibration which confirmed presence of alkanes group. Band peak 1223–1095 cm^{-1}, 820–690 cm^{-1}, and 722–770 cm^{-1} showed presence of aromatic compound in the liquid fuels. The details analysis of FTIR analysis of pyrolytic liquid is listed in Table 6.

3.6 NMR Analysis

The chemical shifts in ^{1}H NMR spectra were integrated to quantify various components based on their hydrogen and carbon bonding behavior. The proton NMR spectra of Mahua and Neem seed oil is presented in Fig. 8 and integral value of selected peak of the spectra are shown in Table 7. From Fig. 8, it was confirmed that spectra provided complete information of aromatic, olifineic, carbohydrates and aliphatic based on the proton type. Aromatic compound found in the region 2.78–2.30 ppm (chemical shift) and olefinic proton were observed in the region of 5.35–5.27 ppm. The detailed results and analysis was reported in the Table 7. Presence of phenolic groups and aromatics confirmed that both biomass can be used for chemical production while alkanes, methyl group confirmed production of

Table 6 FTIR analysis of Mahua and Neem pyrolytic liquid

Wave number	Functional group
2930–2860	Sp3 C–H stretching vibration, presence of alkane group, saturated aliphatic group
2113–2215	Aliphatic cyanide/nitrile (double bond compounds)
1700–1680	C=O (carbonyl), aldehyde, ketone and ester
1575–1675	C=C stretching vibration, presence of alkane group
1460–1377	C–H bending vibration, CH_2, CH_3, bending vibration, alkanes
1430–1470	Methylene C–H asymmetric./sym. starch
1357	primary and secondary OH in plane bending vibration
1210	C–N, amine
1223–1095	Aromatic C–H in plane bending vibration
820–690	Aromatic and phenolic
722–770	C–H, aromatic

hydrocarbons (fuel). The NMR analysis of Mahua and Neem oil are in good agreement with various other research works [33, 34].

3.7 GC-MS Analysis

GC-MS analysis is used to provide the quantitative and qualitative study of pyrolytic liquid. From the GC-MS analysis it was confirmed that pyrolytic liquid associated with number of compound such as octadecanenitrile, oleanitrile, 9-octadecenoic acid methyl ester, stearic acid methyl ester, heptadecane, 9-octadecenamide, 11-hexadecenal and pentadecane. Octadecanenitrile is used as a chemical intermediate for fatty amines while 9-octadecenoic acid methyl ester is used as primary raw material for emulsifiers or oiling agents for foods, spin finishes and textiles, lubricants for plastics, paint and ink additives, surfactants and base materials for perfumery. Moreover, Stearic acid has numerous value added applications like slip agent, anti-block agent for LDPE, HDPE, PP, mold release agent, internal lubricant for coatings and films, foam builder/stabilizer, viscosity stabilizer in synthetic detergent formulations, cosmetics, water repellent for textiles, oil-well corrosion inhibitor, improves dye solubility in printing inks, dyes, carbon paper coatings and fusible coatings for glassware and ceramics, pigment dispersant, thickener for paints, release agent for food packaging, intermediate for synthetic waxes, in food packaging adhesives, in surfing lubricants for manufacturing of food contact metallic articles, in closure sealing gaskets for food containers, packaging material for irradiated foods [35]. Hexadecanoic acid has many applications such as in making of soaps, various cosmetics products, and release agents. Pentadecane has application in jet fuel, oil heating, kerosene oil and finally diesel fuel. In

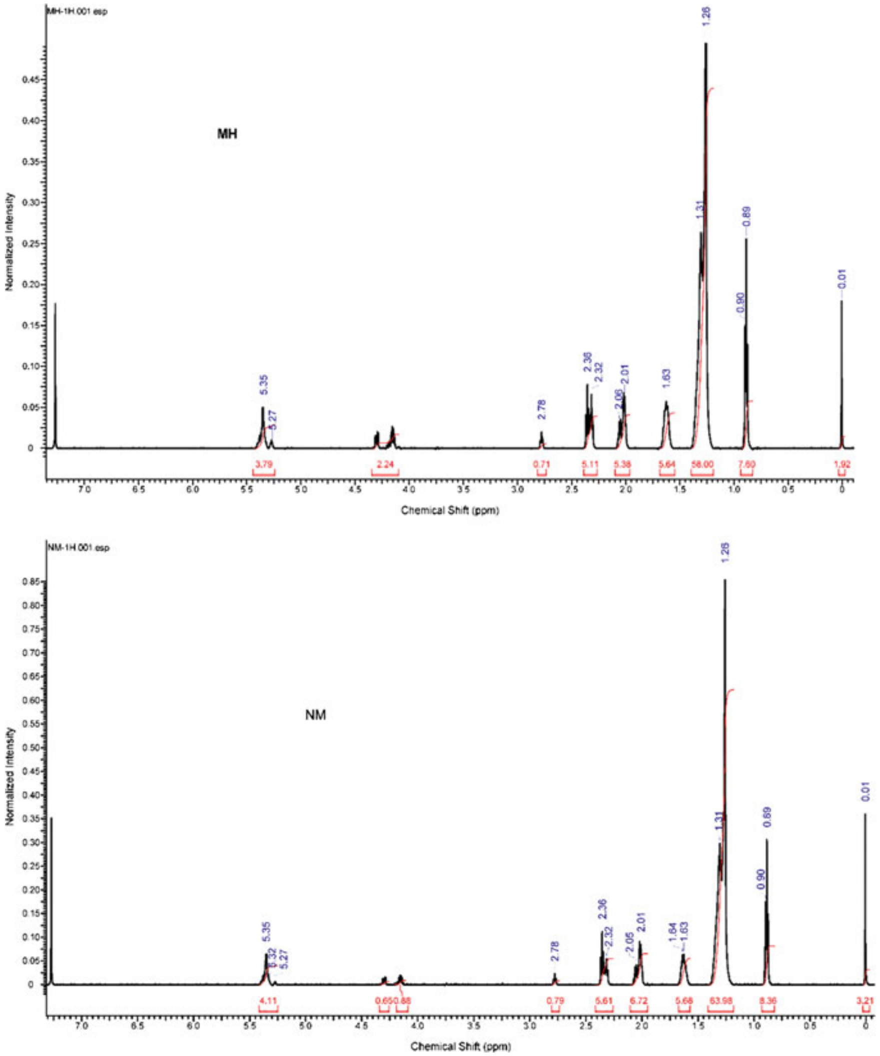

Fig. 8 NMR analysis of pyrolytic liquid of Mahua and Neem seed

addition, Neem pyrolytic liquid can be used for insecticidal application as it has Hexadecenal which is responsible for the insecticidal behavior [35]. Liquid oil contains long carbon chain range from C_6–C_{47} which is equivalent with mixture of gasoline and diesel. The detail analyses of GC-MS of both liquid oils are listed in Tables 8 and 9. Based on GC-MS results it can be conclude that both the oils can be used as alternative fuel and as a source for various chemicals.

Table 7 NMR result of Mahua and Neem bio-oil

Type of hydrogen	Chemical shift (ppm)
Mahua Bio-oil	
Phenolic (OH) or olefinic proton	5.35–5.27
CH_3 CH_2 and CH to an aromatic ring	2.78–2.30
CH_2 and CH_β to an aromatic ring (naphthenic)	2.02–2.00
β-CH_3, CH_2 and CH γ to an aromatic ring and some β-CH with C–C–H, Ar–C–H, C–CCH_3, H–C–COOR, H–C–COOH, H–C–C=O, CH_2, CH_γ, methyl and methylene groups, and for normal, branched alkanes	1.65–1.28
CH_3 γ or further from an aromatic ring and naphthenic-CH and CH_2	0.91–0.87
Neem Bio-oil	
Phenolic (OH) or olefinic proton	5.38–5.27
CH_3 CH_2 and CH to an aromatic ring	2.79–2.32
CH_2 and CH_β to an aromatic ring (naphthenic)	2.05–1.95
β-CH_3, CH_2 and CH γ to an aromatic ring and some β-CH with C–C–H, Ar–C–H, C–CCH_3, H–C–COOR, H–C–COOH, H–C–C=O, CH_2, CH_γ, methyl and methylene groups, and for normal, branched alkanes	1.66–1.27
CH_3 γ or further from an aromatic ring and naphthenic-CH and CH_2	0.91–0.87

Table 8 GC-MS analysis of thermal Mahua oil

RT.	Area (%)	Compound name	Molecular weight
8.71	1.659	Fumaric acid	116
8.81	0.97	Pyrimidine, 4,6-dichloro-5-nitro-	193
8.98	0.512	Acetamide, N-(4-bromophenyl)-2, 2-dichloro-	281
9.21	0.544	Benzamide, N-(2-iodo-4-methylphenyl)-3-fluoro	355
10.31	0.66	2-Methoxy phenol	120
10.43	5.354	Nitric acid, ethyl ester	91
10.70	1.099	Ptrin-6-carboxylic acid	207
10.90	1.63	Phenol, 2,4-dichloro-6-nitro-	207
12.41	0.96	3-Pyridinecarboxaldehyde	107
12.80	0.870	2,4-Dichloro-6-nitrophenol	207
12.90	0.822	1-Amino-2-ethylhexane	129
12.92	0.532	Phosphonic acid methyl-, bis(Trimethylsilyl) ester	240
13.00	0.627	Benzamide, N,N-didecyl-3-methoxy	431
14.68	0.685	Hentriacontane	436
14.88	0.834	Pyridine, 3-(trifluoromethyl)-	147
16.45	0.632	N-(4-trifluoromethylbenzoyl)-, dodecyl ester	429
16.59	0.536	Acetic acid butoxyethanol ester	320
18.22	0.657	Benzamide, N,N-diundecyl-2-fluoro-	447
18.67	0.675	4-chlorobutyric acid, octadecyl ester	374

(continued)

Table 8 (continued)

RT.	Area (%)	Compound name	Molecular weight
19.72	0.784	Fumaric acid, decyl 2,3,5-trichlorophenyl ester	434
21.00	1.026	Benzamide, N,N-diundecyl-3-methyl-	443
21.4	0.246	Oleic acid	282
21,10	1.001	Benzene, (2-bromo-1-methylethyl)-	198
22.30	0.938	1H,1H,2H-Perfluoro-1-decene	446
22.40	2.053	N-methyldodecanamide	213
23.58	1.283	Hentriacontane	436
23.26	0.265	Hexadecanamide	255
23.65	2.49	1,4-Benzenediamine, N-(1-methylethyl)-N 0-phenyl	226
24.66	5.815	1,2-Benzenedicarboxylic acid, 4-nitro-,dimethyl ester	283
24.83	2.358	Oxacyclohexadecan-2-one	240
25.01	0.921	Octadecanamide	283

Table 9 GC-MS analysis of thermal Neem oil

RT	Area	Name of compound	Molecular weight
6.21	1.26	o-Methoxyphenol	124
6.46	1.17	1,4-Dimethoxybenzene	138
8.65	1.44	Toluene, 3,4,5-trimethoxy-	182
8.67	1.8	Phenol,2,6 dimethoxy-4-(2-propenyl)	194
8.95	0.5	(E)-Isoeugenol	164
9.24	0.57	1-Octadecene	252
9.34	1.16	Heneicosane	296
9.74	0.28	1-Nonadecene	266
10.20	1.8	Nonadecane	268
10.26	2.34	Pyrogallol 1,3-dimethyl ether	154
11.30	0.40	1-Nonadecanol	284
11.54	0.56	1-Tetradecene	208
11.72	1.65	n-Tetradecane	198
12.65	6.89	Oleanitrile	263
13.02	4.3	e-11-Hexadecenal	238
15.19	0.8	1-Hexadecene	224
15.68	6.58	Stearic acid, methyl ester	298
16.10	2.1	3-Heptadecene	238
16.12	0.432	Hentriacontane	436
16.34	1.20	1-Heptadecene	238
17.25	0.78	4-Fluorophenyl	96

(continued)

Table 9 (continued)

RT	Area	Name of compound	Molecular weight
17.59	2.23	Nonadecane	268
18.02	0.60	2-propenyl decanoate	212
18.46	3.5	Pentadecane	212
19.20	2.08	Stearic amide	283
18.22	5.46	Heptadecane	240
19.71	0.83	Tridecane	184
20.31	0.8	13-Docosenamide, (Z)-	337
20.35	6.8	Hexadecanenitrile	237
20.38	1.1	1,2,4-Trimethoxybenzene	168
20.53	6.91	Hexadecanoic acid, methyl easter	270
20.49	0.95	N-methyloctadecanamide	297
20.71	4.70	9-Octadecenamide	281
20.76	1.023	Hexadecanoic acid, methyl ester	270
21.11	7.0	9-Octadecenoic acid, methyl ester	296
21.26	2.37	Hexadecanamide	255
21.69	0.70	Heptadecanenitrile	251
21.83	2.51	9-Eicosene	280
22.34	10.98	Octadecanenitrile	265
22.80	0.53	N-methyl hexadecanamide	269
23.96	0.90	1-Octadecene	252
25.07	0.623	Octadecanamide	283
25.68	0.75	Eicosane	282

4 Conclusion

Thermal pyrolysis of two non-edible oil containing seeds were carried out in a semi batch reactor at optimized conditions (450 °C temperature, 80 °C min^{-1} heating rate and 80 mL min^{-1} nitrogen gas flow rate). Both biomass was characterized based on their decomposition profile, structural constitutes, percentage of oil, and presence of extractives and minerals. Both biomass have lower moisture content and ash. TGA analysis confirmed that both biomass went through three degradation stage. Mahua and Neem seed have higher calorific value of 22.19 and 26.88 MJ kg^{-1} respectively. Thermal pyrolysis of both biomass gave higher liquid oil yield of 45 and 56.65 wt% for Neem and Mahua seeds respectively. FTIR analysis confirmed those functional groups present in the oils are very similar with other pyrolytic liquids. NMR analysis confirmed the presence of aromatic, olifineic, carbohydrates and aliphatic compounds in both the oils. The physical properties of pyrolytic liquid were found to be in the range of other pyrolytic liquids. In addition, pyrolytic liquids contain higher heating value. The physical and chemical property of pyrolytic liquids are comparable with other pyrolytic liquids from which it can be concluded that these pyrolytic liquids can be used as alternative fuel and as a source for several valuable chemicals.

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Biomass and Solar: Emerging Energy Resources for India

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Abstract The role of energy has been central in day to day life. Non-renewables sources such as fossil fuels have been exploited to an extent that unless we find new reserves, it will be difficult to sustain the energy demand for future. Conversely, renewable forms of energy, such as biomass and solar, have shown to provide alternatives. India houses around 17% of the world's population and is bound to play a deterministic role in driving the global energy demands in near future. Responsible usage of fossil fuels while compounding the role of renewable energy sources would pave the pathway to sustainable growth without burdening the environment. In this direction, the present chapter has deliberated the potential of two important renewable energy sources, i.e., biomass and solar. The authors have discussed the current state of technology development for converting the energy from these renewable sources to usable forms such as electricity, fuels, etc. Further, a detailed account of different policy initiatives taken up by the Government of India towards the promotion of their usage has been provided. In addition, the life cycle assessment (LCA) following a systems approach have been highlighted in the chapter as a mean to ensure the sustainable energy systems meeting the requirements of future. Lastly, the chapter has given insights on likely paths to optimize the usage of renewable energy sources.

Keywords Biomass · Solar · Life cycle assessment · Policies
Sustainable energy

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1 Introduction

Climate change has emerged as a global problem of the century having impacts on environment and health. Global temperature rise is around 0.17 °C per decade starting from 1950 and this trend is expected to continue due to our heavy reliance on fossils for fulfilling energy demand [18]. The researchers from Oxford in their recent publication estimated that the climate change will be responsible for 529,000 deaths by 2050 [51]. This consequences have lead researchers and policy makers to set up a financial institution to bring the issue under high priority area. Paris agreement and Green Climate Fund (proposed in 2009 at conference of the parties (COP) 15, in operation from 2014) are among the few initiatives which were taken at world level to reduce green house gases (GHG) emission. In order to keep the earths' temperature rise below 1.5 °C [39, 42], around 90% reserves of coal, 50% of gas, and two-thirds of oil reserves need to be kept intact by 2050 which appears practically infeasible without slowing down the world's economic growth. Therefore, the current trends of unsustainable consumption of fossil fuels and concomitant pollution levels have brought attention to the renewable energy sources in both developing and industrialized countries. Technological advancements in past few decades have brought the contribution of renewable energy sector to around 14% in meeting global energy demands [53]. Increasing renewable energy share would not only minimize the pressure on fossil fuels but also has environmental benefits. European union (EU) has set a target of increasing the share of renewable energy to 20% by 2020 [15]. Developing countries also have taken several policy initiatives in this direction.

As delineated in the report published by Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat recently it is expected that India's population would be the largest by 2024. In view of the rising population and growing economy, India is expected to play a deterministic role in driving the global energy demands in near future. There are plans of one trillion dollar investment to ensure access to the clean energy for every Indian [56]. Indian economy is the third largest economy after USA and China, and is expected to grow more than five times to its current size by 2040. In order to further strengthen economy, government has announced various schemes to improve industrialization, such as 'make in India'. Energy demand of India is expected to grow from 775 million tons of oil equivalent (Mtoe) to 1133 Mtoe by 2040, with an average growth rate of 3.4% per annum [21]. Industrialization along with urbanization will further affect the energy usage pattern. Figure 1 depict the contribution of various energy sources to primary energy demand along with energy consumption by various sectors such as transport, residential, industry, etc. In current scenario, there is an urgent pressure on energy systems to grow and meet the growing energy demand in India, pushing it towards becoming dominant user of fossils [19]. In view of the limited reserves and extravagant dependence on fossil fuels, India has resorted to importing the energy resources. According to the Ministry of Petroleum and Natural Gas, India is the third largest importer of crude oil after USA and China; which has

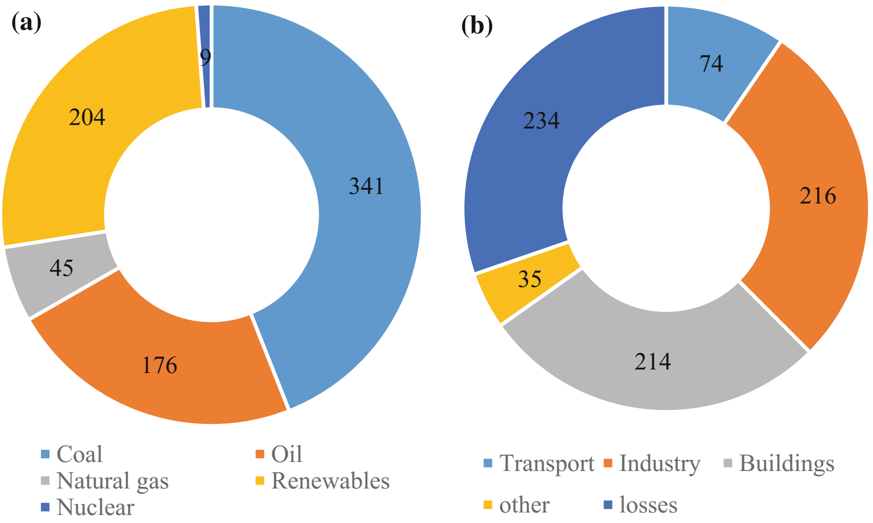

Fig. 1 Contribution of various energy sources **a** towards total energy demand and **b** consumption by different sectors of India for year 2013 in Million tons of oil equivalent (*Source* IEA [21])

imported 213 million ton worth of 70 billion USD during April 2016–2017 [57]. In addition to the economic burden, the exceeding use of fossil fuels is responsible for various environmental and health impacts which generally remained unaccounted. Achieving the optimum potential of renewable energy sources have been reckoned as an engine to bring about the transition to a future of sustainable energy [50]. India has a rich source of renewable energy available in various forms. Presently, the contribution of fossil fuels in the total primary energy demand is ~75% and rest comes from renewable sources (Fig. 1). Primarily, the growing energy demands and geopolitical pressures accompanied by limited reserves of fossils have driven the progressively increasing interest of India in renewable energy alternatives [19]. Renewable energy sources have potential for replacing the fossil fuels without further affecting the environment. Vast availability of renewable energy sources has reinforced the interest in promoting growth in the renewable energy sector in India. However, increased production of renewable energy to minimize the dependence on fossil fuels sets multiple challenges to be addressed in coherence. India's Intended Nationally Determined Contributions (INDCs) committed at COP 21 in 2015 has reinforces the attention to renewable energy industry. India targets to have 175 GW of installed capacity of renewable energy by 2030. Both biomass and solar would play major role in shaping the energy market in India. In order to accomplish its INDCs, multitude of efforts have been initiated at various levels, for an example draft report of third National Electricity Plan have specified that all renewable energy alternative together would account for 56% in the India's total installed power capacity by 2027. Here, an effort is made to highlight the importance of biomass and solar based renewable energy systems in India. Different schemes, action plans, challenges and emerging technologies in biomass and solar are discussed. It has also emphasized on taking a holistic approach for growing the renewable energy share in India incorporating the aspects of economic feasibility, environmental friendliness and societal welfare into account [45].

Although lot of research have been done already in biomass and solar energy, but some questions are still remained unanswered. These are primarily impact of biomass in carbon emission reduction, impact of solar energy in improving India's rural economy and large scale applicability of solar energy in transportation, etc. Considering these facts, the importance of biomass and solar energy in regards to India's future and described the policies related to these energy sources. A brief discussion has also been presented on the renewable energy sources. This chapter also includes the information about the lapses in the existing policies and thorough analysis of earlier conducted research and published reports which will lead to pave the way for the future policy design. It is worth to note that bioenergy has been emerging energy technology despite being some earlier evinced failures, and this has been explained in the life cycle assessment (LCA) analysis. LCA also confirmed about the complexities involved in the assessment process.

This book chapter is uniquely designed for the readers to provide information about the current state of the Government of India's policies in biomass and solar energy which is useful to understand the sequential progress made in these areas. Authors also discussed about various barriers in implementation of policies, impact of current socio-economic conditions on these energy sources and recent development made in these areas.

2 Biomass Based Energy Sources

Biomass is generally a plant material available abundantly in varied forms including dedicated energy crops and trees, agriculture food and feed crop residue, aquatic plants, microalgae, wood and wood residue, animal waste and other waste material [30]. While there are different renewable sources of energy such as wind, solar, hydropower, only agricultural biomass is the renewable carbon source [14]. Though biomass consumption has been continuing since ancient time, the advanced use of biomass for a variety of energy needs such as biofuel and power generation is relatively recent. Its use for biofuel and power generation does not add to the carbon dioxide emission. Theoretically the process is cyclic and sustainable use of biomass is expected to emit carbon almost equal to the amount sequestered during photosynthesis [49]. This new development has instigated further research and development in the biomass based energy systems. The substitution of fossil based carbon such as coal and crude oil with renewable biomass carbon has been recognized as a new platform of opportunities such as biofuels, electricity, heat, and biomaterials [14]. In view of the continuing energy demands and finite availability of fossil fuels, India has emerged as a strong promoter of renewable energy sources.

Several studies have estimated the biomass energy potential for India [19, 47, 49, 50] and some studies have provided descriptions for different biomass conversion routes [14, 27, 30, 33, 34, 49]. In an assessment of bioenergy potential from crop residues in India, it has been estimated that India produces 686 MT gross biomass annually of which 234 MT (34% of gross) has been estimated as surplus for bioenergy application which is equivalent to 17% of India's total primary energy consumption [19]. Among the states, Uttar Pradesh ranked at the top and sugarcane topped amongst all the crops. Singh and Gu [49] provided a critique on the scope, potential and implementation of biomass conversion to energy in Indian scenario. Though various studies have given estimates of biomass energy potential, accurate estimates for regional levels are still scarce [30]. Maity [30, 31] assimilated different estimates provided by government bodies (Ministry of Petroleum and Natural Gas, Ministry of New and Renewable Energy) for the potential generation of renewable energy sources. The surplus biomass can produce about 18 GW of power annually. The petroleum consumption for the year 2010–11 was 14.18×10^7 metric tons with major share accounted by transportation fuels, high speed diesel oil (42.2%), motor gasoline (10%) and aviation turbine fuel (3.6%). If all surplus biomass can be processed sustainably, it would substitute ~10% petroleum, ~90% petrol or ~22% diesel. The estimations for biomass in the form of non-edible oilseeds during 2010–11 amounted to ~20 MT with substitution equivalent of 2.5% for petroleum consumption. Similarly, the microalgae has been identified as rich triglycerides feedstocks which can be processed to produce petroleum diesel. The microalgae exhibit high productivity of ~20–22 g/m^2/d which if cultivated on a hectare land would produce biodiesel equivalent to 18.8–20.7 t (with 30% oil content by weight). Considering such high productivity, the estimations for microbial biomass have showed that diverting only 3% of arable land and 12–18% jatropha cultivation area to microalgae can produce biodiesel sufficient to meet transportation fuel demands. Though all the crop residues cannot be used for power generation, ~15–20% can be used without impacting the present usage for cooking and animal feeds. Additional improvement in biomass energy potential has been foreseen through technical improvements in cookstoves. Traditional cookstoves exhibit poor fuel use efficiency, ~10%, which if raised to, say 20%, can add 100 MT of the surplus biomass [9]. However, actual realization of bioenergy potential in India has been much lower than the estimated potential. This indicates huge scope of research advancements in the area in order to ensure complete utilization of the biomass potential.

There are three driving forces for attracting the progressively increasing interest in biomass based energy systems, namely reduced environmental emissions, more energy, and employment [10]. Several studies reported that developing countries have sizeable potential for large biomass production capacity in the longer term, thereby creating more income sources and employment [19]. Biomass based energy systems are generally located near their production site to be economical and the technological developments regarding the biomass conversion routes gives them a competitive advantage. The advanced technological options has showed cost-effective use of energy crops, e.g., gasification processes producing methanol and hydrogen which can be used as transportation fuels. Though the biomass energy market in India has not yet reached its optimum potential, developed nations including Europe and US have established biomass markets through the use of non-agricultural lands [49] and policy regulations.

Direct combustion of biomass has been the oldest way of producing energy. Other most commonly used conversion pathways to convert biomass into energy include: thermal (gasification and pyrolysis), biochemical (anaerobic digestion and fermentation) and chemical (transesterification). Thermochemical conversion involving thermal decay and chemical reformation of biomass in the presence of different oxygen levels has been proved to be advantageous over biochemical conversion since it can convert all the organic components [34]. The thermo-chemical conversion of biomass takes place through different processes such as pyrolysis, gasification and combustion for converting it into useful forms of energy. Anex et al. [3] have compared the biochemical and thermochemical pathways for converting biomass into fuel, and based on their economic analysis they concluded that the pyrolysis is the cheapest route for such conversion. Liu et al. 2014 found that, the stand-alone biomass-to-liquid fuel plants are anticipated to yield fuels in the range of $2.00–5.50 per gallon gasoline equivalent with pyrolysis the lowest and with biochemical the highest.

The biomass unlike any other renewable energy source is capable of producing multilayered outputs including all forms of energy, chemicals and polymers through integration of different conversion routes in a biorefinery. Though the research in this area is still underdeveloped, the concept of processing biomass to produce biofuels and large number of biochemicals has been considered analogous to a petroleum refinery and petrochemical industry termed as biorefinery [14, 30, 31].

2.1 *Biorefinery: Going Beyond Generation of Power and Fuel*

Crude oil is the feedstock in a petroleum refinery, which is refined into fuels and chemicals for petrochemical industry. For instance, naphtha is raw material for production of several building block chemicals (synthetic gas, olefins and aromatics) in petrochemical industry. Currently, more than 90% of the organic chemicals are derived from the fossils based building blocks [30]. Another important raw material other than naphtha is natural gas. It has been estimated that petrochemical industry consume around 10% of petroleum refinery output in form of naphtha and $\sim$30% of natural gas to produce these building block chemicals. Strong dependence of mankind on intensive consumption of limited fossil reserves causing environmental and health impacts has compelled the development of renewable energy alternatives. Among all renewable energy sources, biomass has shown to be most favoured fossil fuel alternative for producing transportation fuels and other chemicals, as it is the only carbon rich renewable energy source. Several studies reported that biomass can be processed to produce alternatives of these fossil fuel derived building block chemicals. However, the predominant use of biomass, so far, has remained limited to fuels and energy.

This quest for making biomass systems analogous to petroleum based systems has given attention to the concept of biorefinery. International Energy Agency (IEA) defines biorefinery as "Biorefining is the sustainable processing of biomass into a spectrum of marketable products and energy" [13]. Biomass refinery analogous to a petroleum refinery uses biomass as a feedstock to produce biofuels and a variety of biobased products through the integration of various conversion routes [14, 30, 31]. Criterion for classifying different existing and emerging biorefinery systems is heterogeneous in nature. Cherubini [14] attempted to provide a common classification approach based on four key aspects of a biorefinery, i.e., platforms, products, feedstocks and processes. Major classification type for biorefinery systems has been the type of conversion routes used in a biorefinery which classify them into three phases: I, II and III [23]. Phase I biorefineries generally has fixed processing capacities and use grain as feedstock. A dry mill ethanol plant is an example of phase I biorefinery. Phase II biorefineries allow processing flexibility. They also use grains as feedstock to produce an amalgam of products depending on the demands and market price. They employ a wet milling technology. Example of products include starch, ethanol, high fructose corn syrup and corn oil. The phase III biorefineries are considered most advanced as they use a mixture of biomass (whole crop, green biomass, lignocellulose feedstock) and combination of technologies to produce a multitude of products.

The biomass based fuels are characterized as first and second generation biofuels. The first generation biofuels are produced from seed or grain part of the plant (e.g., sugarcane, starch crops, rapeseed). It is the first generation biofuels which has actually showed competition with food industry and raised environmental concerns [14]. Their extended use is further influenced by the impacts on soil fertility along with the consumption of energy in production and conversion of the crop. The limitation identified in the use of first generation biofuels can be overcome in a biorefinery through production of second generation biofuels along with a variety of platform chemicals [27]. Further, the nature of biomass is heterogenous similar to conventional fossil fuels and producing only energy from biomass limits the complete utilization of their potential. Therefore, to become a true alternative to fossil fuels, biomass needs to also provide the alternatives of both fuels and platform chemicals. Cherubini [14] identified three main drivers, namely climate change, energy security and rural development for using biomass to produce bioenergy, biofuels and biomaterials and chemicals. In a biorefinery, the plant metabolites (primary and secondary) produced through photosynthesis can be processed to create industrially important platform chemicals as in petroleum refineries [34]. The primary metabolites are carbohydrates (sugars, cellulose, hemicellulose) and lignins termed as lignocellulosic biomass which can be converted into biofuels. These biofuels are called second generation biofuels avoiding the competition with food industry. The secondary metabolites, present in low amount, include biochemicals (gums, rubber, resins, waxes, terpenes, tannin, alkaloids, etc.) of high value. These secondary metabolites can be processed in a biorefinery to produce high value chemicals such as bioplastics, food flavours, pharmaceuticals and nutraceuticals. Based on the model of a petroleum refinery, Pacific Northwest National Laboratory (PNNL) and National Renewable Energy Laboratory (NREL) identified 12 building block chemicals that can be derived from biomass in birefinery [55]. An increasing interest in the development of biorefinery systems of both researchers and policy makers has also been acknowledged through various policy initiatives [15] founded on research attempts aiming at minimizing the dependence on fossil fuels.

Further, the second generation biofuelshave produced as truly carbon negative energy source. However, the progressively increasing use of biomass for producing a spectrum of products (materials as well as energy security) need to be examined for their overall sustainability [14]. Overall sustainability here means considering the environmental trade-offs of entire life cycle starting from cultivation of biomass crops to its conversion process and use stage. Consideration of all upstream and downstream processes while incorporating all the environmental trade-offs/impacts would provide an unbiased picture of their sustainability in comparison with fossil based systems. LCA is an appropriate tool for such comparisons.

2.2 Biofuel Policies in India

The energy crisis of 1970 compelled the policy makers worldwide to set up policies for development and evolution of renewable energy sources including biomass [50]. India is the third largest importer of crude oils,industry and transport sectors together account for half of the total energy consumed (Fig. 1). The high energy demand is predominantly constituted by coal (in industry), petroleum (in transport), and electricity (in buildings, industry, and agriculture). Considering a 10% annual growth in number of vehicles, petroleum use will continue to expand, particularly in road transport, which account for significant share of passenger (90%) and freight movement (60%). Currently, the transportation fuel demand is mainly shared by diesel (46%) and gasoline (24%). The average demand for transport fuels is estimated to rise from 134 billion liters in 2015 to 225 billion liters in 2026. The current growth in transportation and consequent increase in petroleum consumption aggravate the environmental concerns. Government of India (GoI) is targeting EURO-III and IV as reference emission norms for vehicles, which in turn necessitate fuels to be clean and green [4]. The biomass based fuels have shown to be a promising alternative to curb the crude oil dependency and thus biomass based policies have received great attention in recent years.

In India, the major policy development in the area of biomass energy started in 1980s with small scale technologies when focus was to improve the efficiency and quality of traditional biomass in form of improved cook stoves and biogas. A medium-scale focused policy development referred to biomass gasification technology. It was aimed at providing the conventional energy sources from biomass, i.e. electricity. The evolution of long term policy goals started in 1990s with aim of creating institutional support for the formulation and implementation of biomass energy technologies at both micro and macro levels. Department of Non-conventional Energy Sources (DNES) was upgraded to Ministry of Non-conventional Energy Sources (MNES). This new institution set up provided more financial support to the widening scope of renewable energy promotion activities as well as the research and development. The reformation of MNES as Ministry of New and Renewable Energy in 2006 speeded up the progress and became highest institution in the renewable energy sector formulating and implementing policy strategies in all sectors including biomass.

An important point of policy evolution related to biomass energy was the setting up National Policy on Biofuels in 2009. The overarching goal of the policy was to ensure biofuels (bioethanol and biodiesel) availability in the market to meet the demands of transport fuels at any given time. The policy indicated a target of replacing 20% of petroleum fuel consumption with blending biofuels by the year 2017. Biofuels are viewed as a means to reducing dependence on imported fossil fuels and meeting energy needs through the use of non-food feedstocks. With the aim of increasing biofuels production GoI is promoting and encouraging: (a) ethanol derived from sugar molasses/juice for blending with gasoline, (b) biodiesel derived from non-edible oils and oil waste for blending with diesel, and (c) bio-methanol and biosynthetic fuels [4].

To meet the policy objectives, blending level of 5% ethanol in petrol was made mandatory by GoI in 2003 under the Ethanol Blending Programme (EBP). Ethanol is mainly produced from sugarcane molasses, a by-product of sugar production. The supply of ethanol has been controlled by cyclic production of sugarcane. Low availability of sugarcane molasses raise their price and therefore impacts the cost of ethanol production which in turn interrupt the supply of ethanol for EBP. Although the GoI has taken multidimensional steps to promote the biofuels production, the targets of achieving 20% blending appear far away [7]. India's current ethanol production in the year 2017 allow blending of only 2% [4].

GoI started National Mission on Biodiesel in 2003 to reduce the burden on ethanol production and to address the environmental concerns. Two phases were proposed in the mission: first, a demonstration project in Phase 1 by 2006–2007 and second, a self-sustaining expansion in phase 2 by 2011–2012. Jatropha was identified a most suitable tree borne non-edible oilseed for biodiesel production. The central government and several state governments provided incentives for supporting jatropha cultivation. Biodiesel purchase policy was also launched in 2006 as a potential tool to achieve socio-economic and environmental benefits. However, the ambitious target of achieving 20% blending remained unattainable due to insufficient feedstock (jatropha seeds) and lack of high-yielding drought-tolerant crop cultivars. Ultimately, a solution for reducing the dependence on imported fuels with associated socio-economic and environmental benefits can be seen in the promotion of second and third generation biofuels production. Government's support, subsidies, and fuel blending mandates would be crucial for the improving the competitiveness and scale of economies in the biofuels industry [7].

2.3 Challenges to Biofuel

Biofuel production has received huge attention of policy makers as well as scientific community to combat the challenges of limited supply of fossil fuels and growing deficit of energy. The strong commitment has been made visible in the policy initiatives, institutional set-ups and articulated via persuasive research efforts in this direction. Government's subsidies, fuel mandates and targets have been supportive to great extent in protecting the biofuels industry. However, the biofuels production in India has not yet achieved the desired targets in term of techno-economics as well as social aspects. The biofuel policies being promoted with assertion have failed in execution. In addition, the environmental sustainability of biofuels (first-generation) has often been misleadingly presented as carbon neutral. This section give description of different challenges to biofuels that needs to be tackled for meeting the goals of reduced dependence on fossil fuels.

Biofuels in India are mostly first-generation fuels and sugarcane being the most common feed stock followed by initially successful jatropha. The rising renewable energy market and ambitious ethanol blending goals (20% by 2020) seek increased production of sugarcane which in turn require more water, agriculture land and has competition with food industry. Jatropha based first generation biofuel production has also been hindered by the lack of availability in from of inadequate infrastructure for seed collection, transport and treatment [7]. Second generation biofuels from biomass have been identified as an answer to the challenges of first generation biofuels as biomass is anyway produced as a by-product of food production. The quantity of biomass produced in India is sufficient to meet the target of 20% biodiesel blending by 2030. However, lack of proper mechanisms for collection, storage and transport of biomass are important barriers preventing to achieve the desired levels of bioenergy production. Thus, management of the biomass supplies and transport for industrial operation makes an important hotspot of improving the bioenergy production. Providing incentives and infrastructure support for collection of biomass feedstocks can be considered as a first step by the policy makers [38]. Another hindrance in the second generation biofuels is high capital investment associated with large risks. According to an estimate, achieving the targets of national policy on biofuels would require an investment of US$ 32 billion by 2020 [38]. The required investment is blocked by different barriers in form of immature technology, uncertainty in market and policy support for second generation biofuels [20]. The advanced biofuel technology for producing second generation biofuels is very young and it need large scale demonstration of projects to attract the large investments. Besides the government support, there is an immediate need of investment from private companies like petroleum companies. Hindustan Petroleum Corporation Limited (HPCL) in 2016 has set India's first second generation ethanol based biorefinery in Punjab. As Punjab is rich source of biomass feedstock, the biorefinery anticipates to meet 26% requirement of ethanol blending for Punjab, reduce GHG emissions while creating around 1200 jobs throughout the supply chain. The successful implementation of second generation biofuel based refinery can reduce GHG emissions as compare to the first generation biofuels. In achieving the goals of national policy on biofuels employing second generation biofuels would save 53 million tons of CO_2 eq. by 2020 [38].

2.4 Biomass to Power Policies in India

India has been able to achieve a great progress in advancing the access to energy in recent years. Electric form of energy has become an integral part of the socio-economic and infrastructural development of the country in agriculture and industry. India's power generation capacity has shown a significant rise while grappling with the risky financial situation of local distribution companies and transmission and distribution losses. The total installed capacity of power generation (as on 31 March 2017) is 329.23 GW. Of the total power generation capacity, ~67% is contributed by fossil fuel based sources, 17.4% by renewable energy sources (solar, biomass and wind) and 13.6% by hydro sources (Fig. 2). GoI in its Intended Nationally Determined Contribution (INDC) towards United Nations Framework Convention on Climate Change (UNFCC) has aimed higher by setting a target of reaching 175 GW (40%) of renewable energy capacity by 2030 (MNRE, 2017). This appears very ambitious goal in perspective of today's level of 37 GW.

Though 240 million people still remains without access to electricity, this number is almost half of that in year 2000. Most of population without access to electricity reside in rural areas and the demand for electricity in rural areas is increasing at 7% growth rate [9]. The key factor which restrict the electrification of remote villages is localization of fossil energy based generation of electricity, necessitating huge transmission network. Further, the transmission and distribution losses would reduce the efficacy of capacity addition. Therefore, using the locally

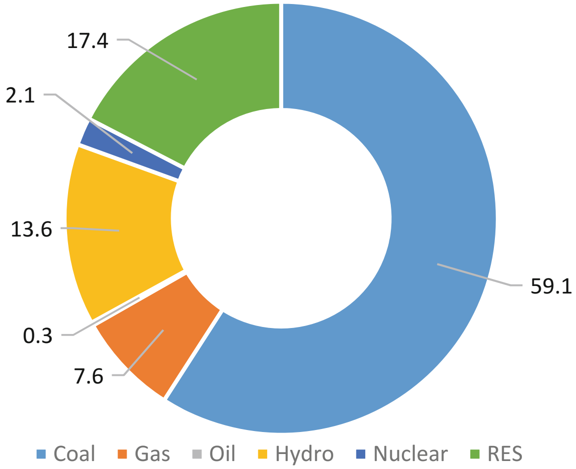

Fig. 2 Power generation capacity in India through various sources, 2017 (*Source* Ministry of power, GoI)

available renewable energy sources for decentralized electricity generation is apparently viable option for electrifying the remote villages [9]. The National Electricity Policy (NEP) announced by Government of India along with other rural electrification programmes such as Rajiv Gandhi Grameen Vidyutikaran Yojana (RGGVY) have been centred around improvement of rural electrification. The RGGVY launched in 2005aimed at providing electricity to villages with 100 or more residents and free electricity to people from economically weak section (below the poverty line). After the difficulties in implementation, the program was resumed in 2015 within a new scheme of Deen Dayal Upadhyaya Gram Jyoti Yojana (DDUGJY) [21].

The NEP emphasize on using renewable energy sources in all the villages including those having grid connectivity. This intends to reduce the load of grid provided the decentralized electricity generation is economically viable. Sustainable energy supply can be foreseen through energy conservation and increased use of renewable energy [27]. Potential renewable energy sources for decentralized electrification include solar photovoltaics, wind mills, small-scale hydropower plants and biomass gasifiers. The selection of optimal renewable energy source is dependent on the geography and the source available. Biomass, more than any other renewable energy source, has uniform and abundant availability at low rates. The desired potential of biomass for meeting the energy demands can be validated through the estimations of potential of surplus biomass for power production in India which is about 18 GW [9]. Many other advantages that come into sight from the substitution of fossil fuels with biomass for power generation include low cost, low environmental emissions, improved security of supply and employment opportunities.

Even though large potential estimates for biomass to power conversion indicate a win-win situation by curbing fossil fuel consumption and using renewable sources, the actual conversion of biomass to power is limited by inadequate collection, handling and transport. The lack of proper collection and transport mechanisms and incentives often leave farmers with the option of burning the crop residues. Further, the biomass produced at manufacturing industries are mostly found with high moisture levels which require drying before conversion. Lack of a functional market for biomass render farmers and several small to medium industries discard their biomass as waste. Both open biomass burning in farms and industrial biomass wastes cause environment pollution. There is an urgent need of proper collection and transport systems for economic and environment friendly operation of decentralized biomass conversion plants. The need appropriate collection mechanism and incentives calls for an action from policy makers in increasing the share of biomass resources in India’s energy mix. Optimizing the biomass feedstock’s supply would become a turning point in aspect of energy security and combating the climate change.

Buragohain et al. [9] indicated two possible technologies for electricity production from biomass: (1) biomass gasification coupled with an IC engine operating on producer gas, and (2) boiler-steam turbine route or cogeneration. GoI has undertaken several programs to realize the biomass potential through two major schemes: (1) grid interactive and off-grid, and (2) distributed renewable power. Under the grid interactive and off-grid scheme MNRE implemented Biomass Power/Cogeneration Program in the mid 1990s with a macro level focus on sugar mills. It was aimed at promotion of large-scale technologies and provided incentives (financial and fiscal) to the participating sugar mills for power generation and cogeneration. In the scheme of distributed renewable power, MNRE implemented a sector oriented program named Biomass Energy and Cogeneration (Non-Bagasse) in 2005. The program promoted medium- to large-scale biomass technologies such as biomass gasifier and biomass co-generation (non-bagasse). The focus of the program was broad covering pulp and paper, textiles, fertilizers, petroleum, petrochemicals, and food processing industries. It had twin objectives i.e. to supply heat and electricity for industrial operations and to feed the surplus power in the main grid, therby reducing its load. Ultimately, it was aimed at reducing the GHG emissions from industrial operations and the overall sector. The Biomass Gasifier Program, another program in distributed biomass power scheme, was implemented through collective efforts of government and non-government bodies. The program focused on both micro and macro levels. At micro level, this program aimed at promoting and increasing the biogas power generation capacity at small scale such as meeting the electricity demands of households and small-scale industries. At the macro level, it aimed at promoting distribution projects for engines running on biogas, paired with biomass gasifier for off-grid and grid power operation. In addition to these programs, several other initiatives have been taken by central and state government bodies to harness the biomass energy potential. Biomass power generation sector is expanding day by day, with annual investment of 600 crores INR and generation of 5000 million kWh of electricity along with total employment of 10 million man-days in rural sector [1, 9].

Overall, the biomass energy policies adopted and implemented by the GoI have led to significant outputs in the form of energy infrastructure. With the support of various enabling mechanisms, India’s bioenergy sector is expected to contribute 10 GW in its INDC targets of 175 GW from renewable energy sector. Several ongoing efforts have resulted in enhancing the biomass based installed capacity from 3 GW in the year 2012 to about 5 GW in year 2015. Presently, 5 GW of total installed capacity of power has been reached from 500 biomass (power and cogeneration) projects which is used for feeding to grid (as on December 2015). In addition, around 30 biomass power projects and 70 biomass cogeneration projects aggregating to 350 and 800 MW capacity, respectively are under various stages of implementation [48]. These achievements have contributed in increasing the energy supply and usage at both micro and macro levels. Furthermore, the policy implementation has resulted in capacity building of biomass based plants [50]. The government through its policies and strategies, therefore, has been an important factor for reaching so far in tapping the biomass energy potential and there is much more to capture. Capacity building programs and commercialization activities have contributed in human resource and knowledge development. Establishment of Sardar Swaran Singh National Institute of Renewable Energy (SSS-NIRE) by MNRE is an important achievement in the perspective of capacity building. It is an autonomous institute focussed on carrying out state of the art research and development and activities oriented on commercialization of renewable energy technologies in India. An example of latest initiative taken by MNRE in this direction is SSS-NIRE Bioenergy Promotion Fellowship convened by institute.

3 Solar Enrgy in India

The government of India (GoI) is aiming at increasing the access to clean and affordable energy through renewable energy sources. Considering the topography of Indian states, solar based energy technologies can be effectively utilized for meeting the demands of per capita energy consumption by harnessing the solar energy. Solar based energy technologies would save the transmission and transportation cost, thereby making it an economic and versatile energy alternative for developing countries including India. Government is actively participating to make the solar alliance partner where around 121 countries participating to share technology and finance for achieving the aim of poverty elimination [58]. Promoting the solar energy technologies has contributed in socio-economic development and poverty elimination by providing jobs and cheap electricity [59]. For example, recently 12,000 solar pumps were distributed to farmers in Chhattisgarh with subsidized rate under the scheme called “Ujjwala Yojna” [60]. Another identified area of potential application of solar energy is in public transportation as highlighted by the Indian Railway’s interest in installing solar panels at the top of 250 trains in order to reduce the fuel cost [61, 62].

Solar energy can be utilized either in direct or indirect manner: Direct application of solar energy includes utilization of solar radiations for photovoltaic devices and indirect application includes utilization of solar energy in apparent form such as wind, mini hydro, biomass etc. Direct application of solar energy involves utilization of thermal component of solar radiation through solar water heaters, solar cookers etc. whereas the energy component of solar radiation gets utilized in solar photovoltaics (PV). Solar PV devices convert solar energy into electricity and later this energy can be utilized for various application in industrial and residential sectors. The solar insolation received in the form of $\sim$3000 h (equivalent to 5000 trillion kWh) of sun light supports industry and service sector to utilize this technique [46]. Geographical coordinates of India ensures maximum availability of solar radiation for different application. Most of the Indian states’ received typically 1500–2500 kWh solar radiation/m^2 with significant bright illuminating sunny days (Fig. 3). It is worth to mention that western Indian region receives greater amount of solar radiation compared to eastern parts, which justifies the higher attention given by solar companies to the western India, potentially in Rajasthan and Gujarat. Ministry of New and Renewable Energy (MNRE), Department of Science and Technology (DST) along with their associated partners and stakeholders, such as Indian Renewable Energy Development Agency (IREDA) etc., are diligently promoting research and development (R&D) and commercialization in solar energy

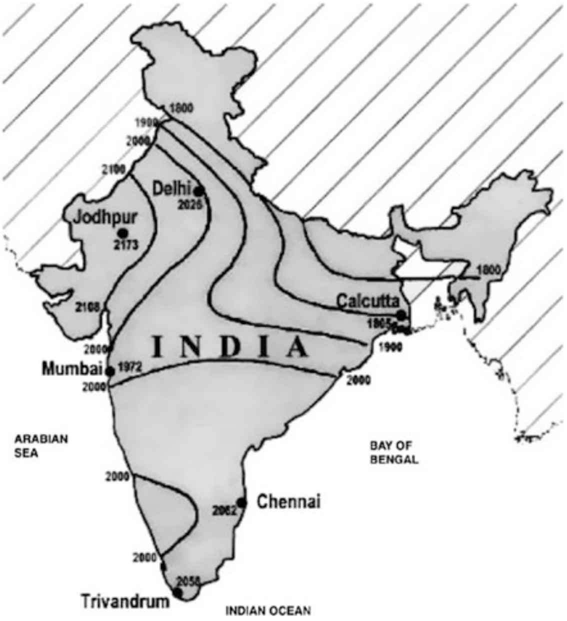

Fig. 3 The distribution of annual solar irradiation, kWh/m^2 (*Source* Muneer et al. [32]) (Reprinted from Publication "Muneer et al. [32]" with permission from Elsevier)

technologies in India. The scheme launched by GoI called-"National Solar Mission" is specifically designed for promotion of solar energy in India aiming to accelerate the solar cell manufacturing with indigenous technology. This mission also aims to develop a skilled manpower for promoting solar energy application. For example, programme called, "Surya Mitra" is one of the scheme of Indian government operated under the flagship of National Institute of Solar Energy (NISE) who runs this scheme with the collaboration of various states' nodal agencies and other partners which comes under MNRE support [63]. This scheme indirectly supports National Solar Mission by developing skilled manpower for promotion and growth of solar PV market in India. Expansion of job market in solar energy and maintaining job opportunities is essential to make the scheme sustainable in long term. There are various provisions and action plans has been designed under the National Solar Mission which needs to be explored to get a clear understanding about the India's solar action plan, therefore in the next section, we will be discussing about the National Solar Mission plan of India in detail.

3.1 National Solar Mission

In India, about 20% population living without electricity access because of the large energy deficit, which was around 11% in 2009 and dropped down up-to 2.9% during 2015–16 [64]. It should be highlighted that per capita energy consumption of India is less than one third of that of world and it is lowest as compared to other BRICS countries. Figure 4 depicts the current status of power generation and surplus for Indian states.

As discussed earlier, being a growing economy power demand in all the sectors is increasing continuously. Thus, to meet growing demand of power, GoI has aimed high in solar power due to its supportive geographical positioning of India, which supports in getting significant solar radiation. In November 2009, GoI launched Jawaharlal Nehru Solar Mission, which was designed to support National Action Plan for Climate Change and supports the other schemes which are currently being operated simultaneously. Under the solar mission, India aims to increase its grid connected solar power capacity up to 100 GW by 2022 whereas earlier the target was to increase the capacity up to 20 GW [64]. The mission was designed in 3 phases, currently transiting from phase two to phase three. The first phase of solar mission was finished in 2013 which was considered as shortest phase in the mission. The phase 3 would run from 2017 to 2022. It is worth to highlight that

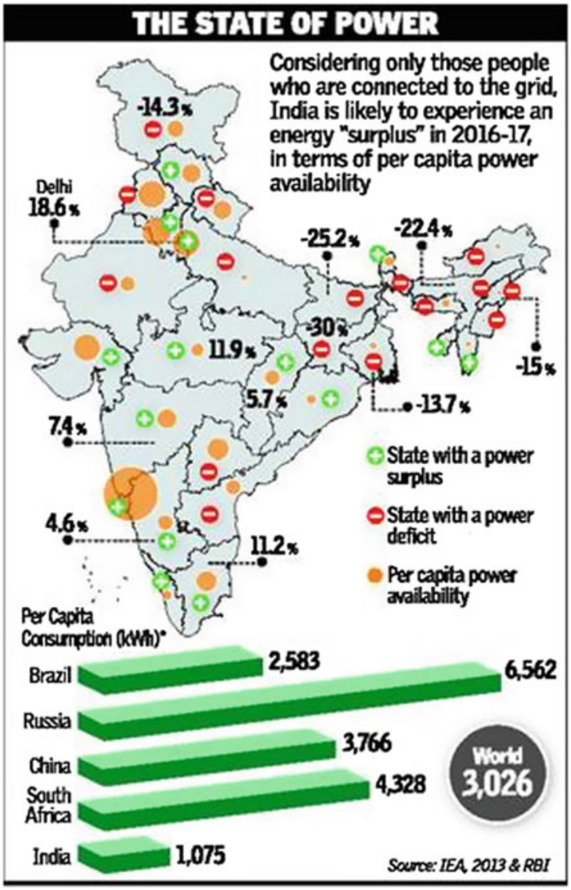

Fig. 4 Indian states position (2013) for power surplus condition (*Source* IEA and RBI) [64]

readjustment in pre-decided target is possible under this scheme and can be done based on the various operating situations. Each phase in solar mission has specific targets and provides flexibility to renew or update the new or existing targets based on the progress made in earlier phases. As delineated earlier, important component of the program is to encourage indigenous manufacturing and production of solar energy appliances. Here in this section, we will briefly discuss about some of the targets set up for all three phases of the 'National Solar Mission'.

Phase one of solar mission was devoted to the solar roof top and grid connected small solar plant installation cum power generation. Government has allocated around 4337 crores to achieve the target. Precisely it was decided to achieve 1000 MW power generation from grid connected solar power plant [65] [26]. The first phase of solar mission promoted roof top and small grid connected power sources and was designed in a way that these power generating devices get efficient power from distribution system. Provision of low interest rate and subsidy was affirmed by regulating body of national solar mission. No specific plan was designed for specific type of solar cell modules such as crystalline solar cell, amorphous solar cell and thin film solar cell. Also, manufacturing of solar cell modules contained less attention in the 1st phase, whose impact was clearly shown in the upcoming stages of the mission. Now the scheme called "Surya Mitra" etc. is compensating the damages.

The phase two aimed to achieve 10 GW power generation. Unlike phase one, the responsibilities of state and central government were divided in this phase. The central and state governments was assigned to achieve 4 GW and 6 GW of power generation target [66, 67]. Development of solar cities, skilled human resource development, solar parks, promotion of solar cookers and solar water pumps including solar water heating system are other promising characteristics of the second phase of the scheme. In the summary, phase two was fully devoted in designing a program which affects the common people of India through providing low cost energy service and generating jobs. Although the jobs were not created as it was expected because of global economic slowdown. Further, uncertain market condition and unestablished tax policies made the scenario worst for solar energy [68]. Readers should note that jobs creation was not among the priority in the first stage of the solar mission, therefore the skilled labors were not developed at the initial stages of the mission. This made an adverse effect on installation of solar power plants because investors were lagging with the supply of labors [69]. The solar mission of India is implemented through various mechanism which is described schematically in Fig. 5, which can be divided in 4 parts.

3.2 Implementation of National Solar Mission

The long term policy explains the use of step by step designing of policy which provides flexibility to correct the errors (that were occurred in earlier stages). The step by step policy designing also provided the time to examine the existing

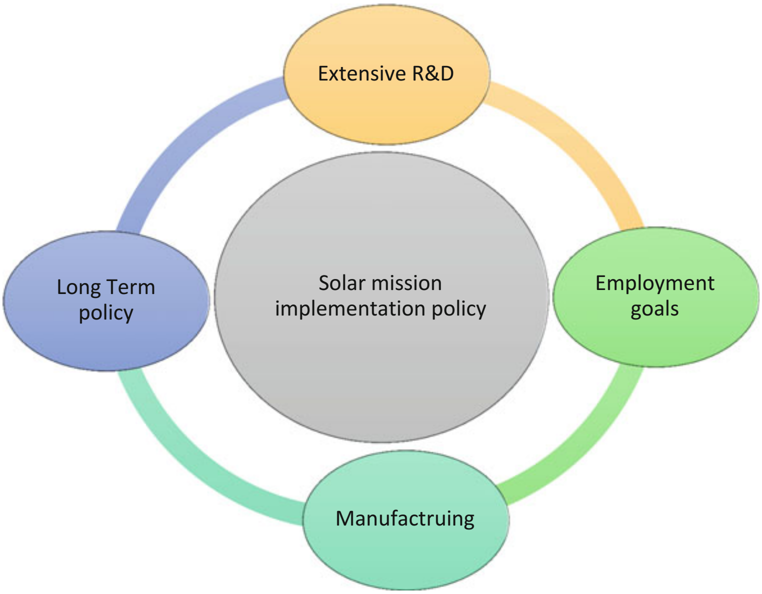

Fig. 5 Schematic of implementation mechanism of National solar mission in India

policies' results and to understand the flaws in each stages. Readers should be cautious that flaws could have been occurred either due to the policy failure or due to the unavoidable circumstances generated due to the global economic conditions. Policy paralysis may also include the human error such as improper human resources etc. could be a prominent factors for failures.

The analysis of each step would tell about the time period where maximum and minimum efficiency of implemented policy has been achieved and the factors responsible for it. The component of R&D involved research fund allocation under the flagship of MNRE and DST. The government aims to support research in solar PV for promoting new developments and innovation in this area and to make those innovations accessible for the common and poor people. The academic institutes are encouraged to participate in the existing program. This strategy will support in the knowledge and database generation and also encourage students and university to develop sound research infrastructure for conducting research. These fellowships are also supporting National Solar Mission policy indirectly because if researchers availing these government supported fellowships may get involved with PV based research. These fellowships encourage them to choose their area of interest which could be range of fields such as Si solar cells, thin film solar cell, policy design etc. Bhaskara advanced solar energy fellowship program has also been launched which allows Indian students and scientists to get exposed to USA based labs, working in solar energies [70].

Solar PV module manufacturing is another area which needs sound policy design. The manufacturing sector's policy must be designed in a way that it promotes solar PV manufacturing and installations in India. This can be done through supporting the development of solar parks across India. As delineated earlier, employment generation is an important component of the solar policy of India and that is interlinked with policies designed for manufacturing sectors. Figure 6 elucidates the types of jobs which will be generated by 2022 in solar energy sector but still sufficient job creation remain a challenge for India's solar mission.

Therefore government of India has decided to develop various solar parks which are designed to support in job creation and to enhance the existing manufacturing capacity in solar energy sector. Government of India has sanctioned 34 solar parks across the country to achieve the power generation capacity of about 20,000 MW. It should be noted that the notification issued by MNRE on 16.06.2016 [72] sanctioned the highest capacity solar park in Karnataka (2000 MW) whereas the lowest capacity solar park was allocated to Meghalaya (20 MW).

3.3 Challenges in National Solar Mission

The initiatives taken by Indian govenrment have received great applaud by national [73] and international media [74, 75]. The article published in New York Times articulated that solar energy prices per kWh electricity generation in India would go down up to 2.44 INR from the current price of 7 INR approximately. Such great fall in price would be worthy enough for the poor people in a developing country like India. Therefore, the application of solar energy would be advanced if solar power

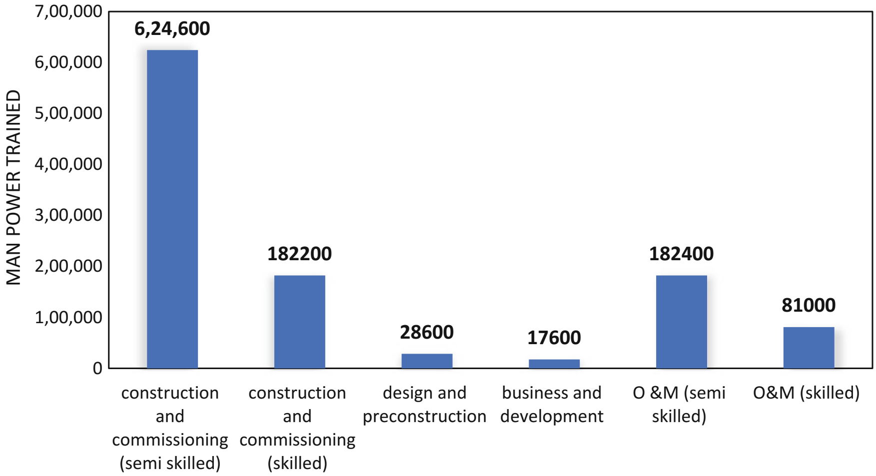

Fig. 6 Number and types of job creation in solar sector by 2022 [71]. [Reprinted from "CEEW and NRDC [11]" with permission from Council on Energy, Environment and Water (www.ceew.in)]

price gets cheaper than those of coal based power. The price reduction will bring down the cost to grid supply and will attract investors to invest in grid connected solar PV plant, an opportunity for more job creation. However, there are several challenges which would come across during the policy implementation and also in designing the future policy. The next sectionis illustrating these challenges briefly.

3.3.1 Awareness and Encouragement Among People

Illiteracy rate in India is a major hurdle for the National Solar Mission. The majority of population lives in the villages and without motivating farmers, children and youth to indulge themselves with solar appliances in their life, it will be difficult to achieve the real goal of the mission. Therefore it becomes essential to educate them about the benefits of solar power and solar energies role in their daily life application. For example, heavy farming states such as Punjab and Chhattisgarh are currently facing a problem of disturbance in rain fall pattern as a result of global warming. It is worth to mention that India has been recognized as 3rd largest GHG emitter [42]. The strategies elucidated in Table 1 could be adopted for the purpose of awareness and encouragement among people. However, it cannot be denied that in a developing economy like India it is hard for the consumers to afford roof top PV, solar cookers etc. due to high cost.

The only way which would enable people to get indulge with solar based devices is through bringing public awareness about the benefits of solar energy application and the government support in form of subsidies. Though, solar energy prices are coming down but initial cost of installation is still very high and making solar technology less attractive specifically for farmers and below poverty line families. It is worth to note that less efficient (cheaply available) solar panels make the energy output less effective than the application of costly and efficient panels and therefore poverty is an important factor for India's solar energy policy [35]. The only way which would enable people to get indulge with solar based devices is through bringing public awareness about the benefits of solar energy application and the government support is in form of subsidies. Apart from these circumstances, few other factors such as illiteracy and inadequate understanding in pay back process have also been identified as barriers for India's solar energy sector. Illiteracy is the biggest threat for India's solar growth plan including the growth of solar mission and other development programs. UNESCO's report has pointed out the illiteracy problem in Indian adults which postulated about the illiteracy of one out of four Indian adult [52]. Therefore, educating the adults about solar power becomes essential to achieve the desired goals of India's solar mission. Other important components include education and training [8]. Higher education may not be required in this regards whereas basic secondary education including vocational training about solar energy may serve the purpose in efficient manner. Solar mitra (described later in this chapter) is an exclusive example and success of this program may lead to significantly positive results. Lack of understanding about the pay back process including accelerated depreciation, unavailability of unified electricity

Table 1 Possible strategies suggested for solar PV promotion

Youth	Farmers	Children
• Help them to get skilled. "Surya MItra" program is currently helping in this regards. Launching more community based programs would help youth to get involved with the solar mission. (specifically rural youth who do not have much access to good education institutes near the vicinity of their villages) • Design of higher education program which are entirely focused on solar energy science and policy. That can be either a degree program or a post graduate diploma program which will support youths to acquire knowledge about the basics of solar PV. By providing scholarship etc., one can attract bright young minds in this field • Involvement of universities (state and central) to promote research and development (lab based). Most of the universities are currently promoting research in solar PV but the institutions such as polytechniques and ITIs etc. should not be remained untouchable and therefore course development plan should be decided for them • Promote industry to offer internship etc.	• Organizing a program which is specifically designed for the farmers, must aim to provide an introduce the benefits for solar energy to the farmers • Helping them to get fund with minimal interest rate either from Govt or from public private partnership agencies. List must be made available to the farmers easily about the possible loan grant agencies and NGOs who can support them with the funding • Encourage farmers through various schemes. For an example offering subsidy in seeds etc. if they use renewable energy sources in their farming activity would be a promising method to promote solar energy • Encourage agricultural based research activities where solar energy could play a vital role • Allocate an award money for farmers who promotes renewable energy in their farms and glorify them	• Through organizing the slogan, essay, speech etc. which is being currently organizing by Govt. on various occasion such as on national renewable energy day • Organizing an event to visit solar station for school children, organizing a forum to explore their ideas about renewable energy and provide help them to understand and explore it more • Renewing the current education curricular and incorporating major sections of renewable energy in science where the need and the principles of solar devices and Govt's mission needs to be discussed. The social aspect of policies which are made for different solar agencies needs to be discussed in social science subjects • Encourage students to participate in solar based projects during their school practicals

regulatory committee, etc., are few other hurdles in making solar mission vibrant. Accelerated depreciation benefit has become prominent after demonetization and assumed that it has led to increased investments in solar energy (effects of other factors may not be neglected at the same time). Analysis of recent studies have indicated that the researchers are aiming to achieve 6–8 KWh/day/KWp, for both grid and off grid photonic energy based system. It is realized that capital expenditure of 1–5 KWp scale grade's solar unit requires about 1 lakhs/ KWp and this cost should bring down for the developing countries like India [36].

3.3.2 Indigenous Manufacturing of Solar Appliances

Goel [16] illustrated about the contribution of India in manufacturing of solar appliances and also delineated its role in the global scenario. Study praised "Make in India" policy and speculated that it would bring investors in solar appliance manufacturing sector. The biggest obstacles identified for the investors include land acquisition, foreign investment policy and skilled employee cum leadership. Although government is boosting them through providing various subsidies and loans with low interest rates but still foreign investors are yet to come with significant investment amount. "Start-up India" is another program which motivate people to set-up their own firm. This scheme may support solar appliance manufacturing strategy of government of India but the lack of education and training about solar energy based device manufacturing and knowledge related to policy making could be assigned as hurdle. These hurdles could be sorted out through offering a degree or diploma courses as described in detail in earlier section of this chapter. There must also be a management course on solar policy making which must cover the thorough analysis of different countries' solar energy policies. Courses can be designed for various lengths such as either 6 month diploma or a year (or two) depending on the institutions' governing body and academic councils' decision. It is easy for the institutes such as IITs, NITs and IIMs to introduce these courses as most of the IITs are currently consisting energy oriented research centre and offering related courses too. Surya Mitra, launched in 2015 has targeted to trained 0.05 million workers for solar energy during the 2015–2020 time period. RBI has also revised the guidelines and kept renewable energy under the category of priority sector, which provides a luxury of accessing easy loans approval for roof top system with significant tax reduction [76].

3.3.3 Research and Development

Global research and development expenditure in renewable energy was around 9.66 billion USD in 2012 with 51% share allocated to solar based research. USA, Japan and China are the biggest research and development hubs in this area. It is worth to mention that china is currently investing large amount of public money in solar based research and development activities. There are lot of solar based research activities are currently being carried out which are not only concentrated on improving the efficiency of existing solar based PV materials but also focused on the development and innovation of new materials for future application, Device fabrication techniques, cost reduction through design engineering and solar grid based research including solar energy policy based research etc. India is lagging behind in research and development expenditure as also reported by Goel [16]. Figure 7 gives a comparison of R&D expenditure in India and other parts of the world.

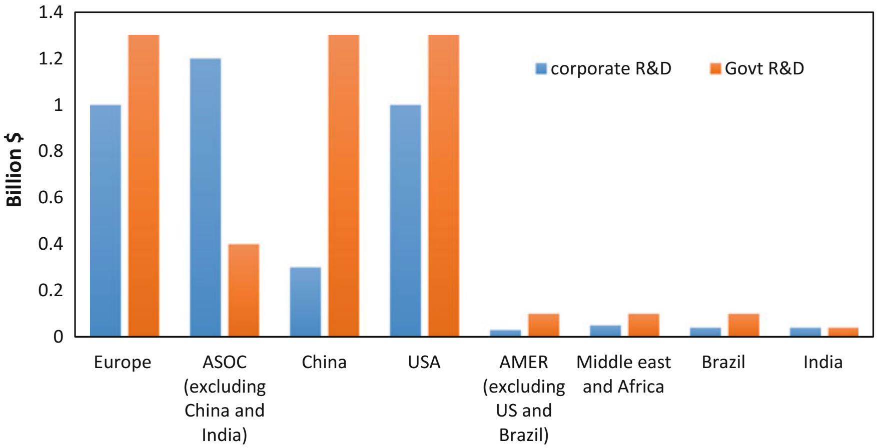

Fig. 7 Comparison of R&D investment of India with other countries [16]

It is essential for government to provide financial support for solar energy based research to public, private and deemed universities and encourage skilled people to get involved with the research activities. A positive sign in this direction can be seen in the government's call for researchers to develop international collaboration in solar based research. International collaboration allowed Indian researchers to get an access of international labs. UKIERI (UK India Education and Research Initiative) is one of the program which is currently being operated with the support of UK and India governments [77]. Bhaskara program (as discussed earlier), DST clean energy research initiative [78] are some other examples of initiatives/schemes which supports solar India mission directly or indirectly.

3.3.4 Human Resource Development

Study conducted by National Resources Defence Council (NRDC) and Council on Energy Environment and Water (CEEW) has highlighted various important skills which are required in Indian solar industries such as solar PV manufacturing, Solar based research and development etc. Study also suggested about the possible number of skilled workers required by the end of 2022 for the success of National Solar Mission and solar PV plant installation cum operation. Findings are illustrated in Tables 2 and 3.

Under the flagship of MNRE, various human resource development focused programs are currently required. For instance, villagers' centred program with provision of stipend in solar based short term courses would enable villagers to indulge themselves with solar energy based activities.

Design of bachelor courses: modification in current bachelor programs (such as BSc or BTech) is another efficient way where interdisciplinary engineering program

Table 2 Key skills required for different respective sections of solar PV industry

Manufacturing	Business development	Design and preconstruction	Construction and commissioning	Operation and maintenance
• Research and product development (patents) • Machine operating • Sales and marketing	• Market and opportunity tracking • Bid drafting and pricing • Site selection and leasing	• Plant design engg and architecture • Procurement and EPC planning • Project management	• Site engg (civil, electrical and mechanical) • Project management • Logistic management	• Performance and data monitoring • Equipment management • Technical management for grid integration

Source CEEW and NRDC [11]

Table 3 Number of skilled labour and employee required by 2022 in solar sector

Function	Skill	Key skill	Number of trained persons to achieve 40GW of solar rooftop (by2022)	Degree required
Manufacturing	Highly skilled	Research and product development	–	Photovoltaic engineering
Business development	Highly skilled	Market analysis, project finance	15,200	Business administration
Design and preconstruction	Highly skilled	Plant design	18,400	Civil, mechanical or electrical engineering
Construction and commissioning	Highly skilled	Site engineering	154,000	Civil, mechanical or electrical engineering
	Semi-skilled	Electrical and PV installation	338,400	–
Operation and maintenance	Highly skilled	Performance data monitoring	48,000	Electrical engineering
	Semi-skilled	–	92,400	

Source CEEW and NRDC [11]

focused on photovoltaic engineering can be designed. Photovoltaic has been proved to be a field which involves various engineering and science based approach such as electrical, electronics, materials science, mechanical, physics and chemistry, etc.

Counselling centre: Solar and PV technology is still new to most of the Indian and therefore it is worth to set up a counselling centre which would lead a common man to the best possible option related to their careers.

3.3.5 Policy Barrier

Development of effective PV growth model either through involving private sector or through public private partnership is a need currently. Efficient solar policy must incorporate certain essential elements such as R&D, commercialization, manufacturing, promotion, government support either through tax reduction, making installation policy flexible or through providing subsidy in terms of excluding GST charges. The policy must be open for international collaboration Involvement of many nodal, state and central agencies would often demoralize PV companies and foreign investors and therefore making this system (for all necessary legal clearance) centralized (removing multi step clearance process) would help in fast processing of applications. Govt. has initiated the plan by encouraging the solar park development to mitigate and overcome these policy barriers as mentioned earlier in this chapter, whereas its outcomes must be regularly examined. Solar park area would become the easily accessible option for the investors to invest comfortably.

3.3.6 Accessibility of Manufacturing Hub

There are various solar PV technologies currently being used (crystalline Si, amorphous Si, thin film solar cell, perovskite and dye sensitized solar cell) and offer different efficiencies. Table 4 gives compares the pros and cons of all solar PV technologies. Recently announced “make in India” policy may provide desired atmosphere for the manufacturing units to start solar PV manufacturing in India. Establishing India as solar PV equipment manufacturing hub would made the nation an emerging exporter and can help us to capture the market of SAARC countries such as Bangladesh etc. where manufacturing of solar PV is not well organized as also highlighted by Rahman [40, 41].

3.3.7 Randomness in Energy Generation Capacity

An expansion of safe transmission network is sought for in the states which does not get enough solar radiation flux throughout the year such as Sikkim, Meghalaya and other North-Eastern states. These transmission lines must get connected through each states of India. Grid connectivity and stability are major problems for power generating units [17]. Considering the importance of inter-regional transmission capacity, the green corridor project has been implemented from 2012. ‘Green energy corridor’ (GEC) program involves about 7 billion $ investment to make the renewable energy linked up with national grid network [6]. The report of power grid corporation of India limited, Gurgaon (July 2012) described the attention paid in this perspective during the 12th plan [79]. The high capacity transmission corridor plan (under 12th plan scheme) decided for India, is portrayed in Fig. 8. Power grid selected by MNRE for green corridor development help in regulating transmission line infrastructure and paving the strategic future pathways

Table 4 Current and future options of solar technology for India

Technology	Advantages	Disadvantages
Amorphous Si Technology	• Simple technology • As compare to crystalline Si technology, amorphous Si absorbs more solar energy than the crystalline (provided both are having the similar layer thickness and size) • Less expensive, low weight, less material required • Flexible in terms of deposition, variety of substrates can be used such as curved, rolled etc.	• Prone to degradation • Increased light soaking or illumination time because introducing a light, the association of hydrogen with 4th Si breaks and causes creation of dangling bond which is nothing but a defect, this effect is known as Staebler Wronski effect and can be assigned as a function of manufacturing technology • Fluorinated—amorphous Si cell is another possible option which could be adopted.
Mono crystalline Si technology	• Comes among the highly efficient technology • This technology is space efficient and requires least space Efficient life time with less degradation • Effectively suitable for warm whether	Most expensive technology
Poly crystalline Si solar cell	• Processing of polycrystalline Si is less expensive than the monocrystalline Si • Higher temperature coefficient than the monocrystalline modules and therefore increment in heat outputs is lesser than the monocrystalline cell.	• Not as efficient as monocrystalline due to the involvement of impurity • As compare to monocrystalline, large space is required to achieve the electricity generated from monocrystalline
Thin film technology	• Large Scale production is effective and simple • Flexible technology and therefore can be deposited in any substrate, made them available for emerging application such as space mobiles etc. • Lesser impact of temperature than the other technology • Cheap technology	• Although, they are cheap but needs lot of space and therefore do not convenient for roof top • As illustrated, large space is required but poor efficiency • Requirement of support structures such as cables etc. increases the overall cost apart from thee land cost • Their degradation rate is faster than others. As illustrated earlier in this chapter, problems of appearance of cracks at the interfaces between transparent conducting oxide and absorber layer material degraded the quality and efficiency

(continued)

Table 4 (continued)

Technology	Advantages	Disadvantages
Bio hybrid solar cell	• Economic and easily accessibility of materials whereas some of the solar PV technology such as thin film, involves the application of rare earth metals [82]	• Structural and functional degradation of bio material involved in making bio-hybrid material is a serious threat (Ravi and Tan [43]) • Specifically life span of bio hybrid solar cell is less
CdTe	• Low cost thin film technology • In 2013, CdTe shared half of the thin film market worldwide [83]	• Use of rare earth element is preventing this technology to get commercialized • Toxicity of Cd is another major disadvantage
Dye Sensitized (3rd generation)	• Flexible, simple in construction and low cost • Price to performance ratio is good	• Practically it involves application of expensive material, such as platinum and ruthenium which can be eliminated
Hybrid-solar cell (organic-inorganic solar cell)	• Potential to get used in commercial manner • Possible to make it low cost (through roll by roll processing)	
Perovskite solar cell	• Processing of this cell is simpler than the conventional Si solar cell which requires multi step processing at high temperature • Can be synthesized through wet chemical method even at lab scale • Process cost is cheaper and wide varieties of techniques such as vapour deposition, spin coating etc. can be adopted	• Degradation with time is the major drawback as organic compound used to get decomposed in the presence of sunlight • Involvement of toxic elements such as Pb is a major problem to get it scale up

for promoting renewable energies such as solar energy etc. The report proposed certain future mechanism to promote renewable energy sources such as application of flexible generators which would help in submitting a bid during low frequency during the surplus capacity. It was suggested that power system security and reliability must be maintained. The actions undertaken during the 12th action plan are expected to add 41,000 MW of renewable energy and therefore energy evacuation is required through developing grid infrastructure which can be sufficient enough to transport renewable energy to load centres. In future, states would not be able to purchase and consume the entire amount of produced renewable power and it would require them to transfer energy to another state in need. Therefore power evacuation system through grid connected transmission is necessary and development of this system would not only empower solar energy based power generation but would also help empowering other renewable energy sources.

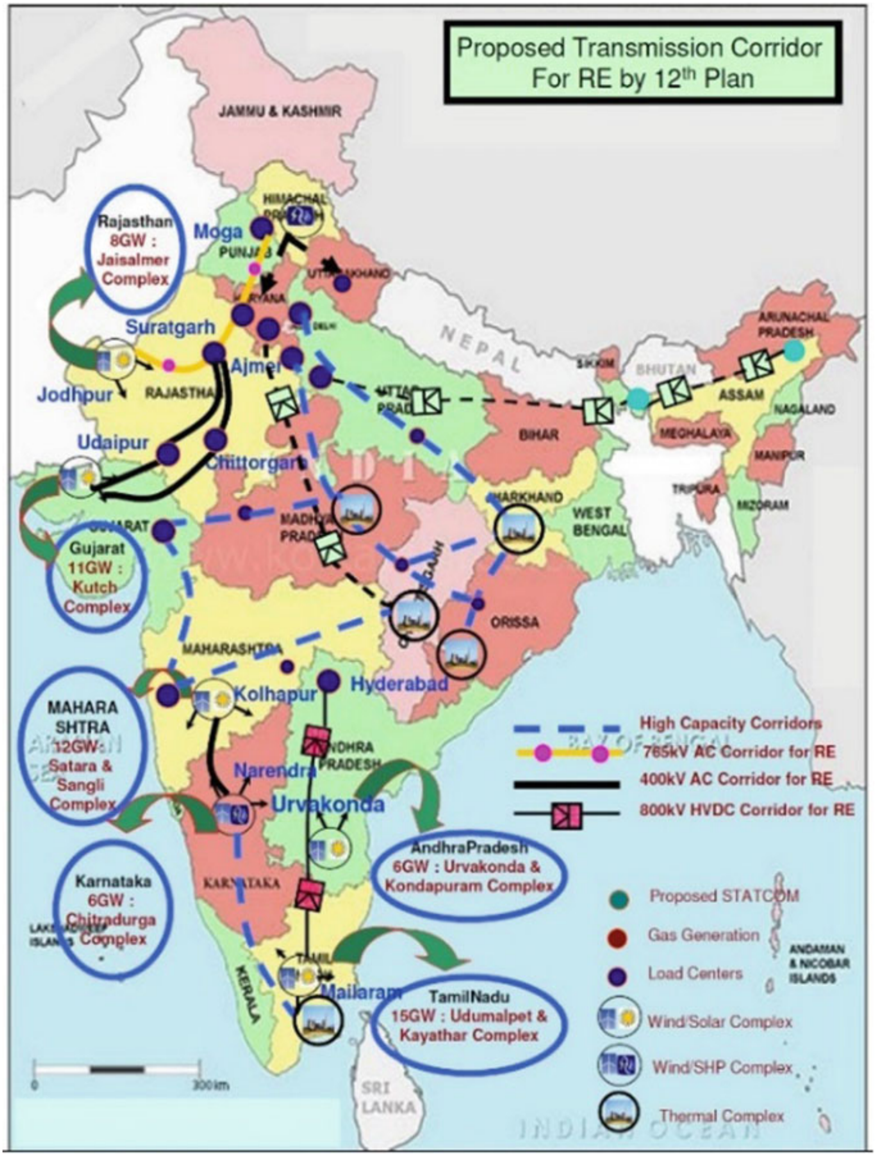

Fig. 8 Proposed green energy corridor for 12th plan (*Source* Bana [6]) (Reprinted from Publication "Bana [6]" with permission from Elsevier)

3.3.8 Strong Innovative Policy

Succinct government policies on harnessing the potential of renewable energies, have showed the results in increasing share of renewable energy capacity being reached up to 12% from 2% (9th plan) but solar mission is one of the few areas where policy could have been more dynamic and supportive. For an example, the data up to year 2012 suggests the grid interactive capacity for solar power was 45% whereas 70% grid interactive capacity was alone for wind energy. The growth pattern for solar energy was significantly higher from 3 to 941 MW during 10th to 11th action plan which certainly was an inclusive result of strong policy implementation and clear vision of introducing the solar mission. Though it was way below the maximum capacity expected (100 GW), but it paved a path to structure the mission. MNRE document titled—"Renewable energy in India Progress, vision and strategy" describing the government vision for 13th plan and aimed to achieve the capacity of solar power up to 20,000 MW (for 2022, 13th plan). Currently India has third largest installed capacity of concentrated solar power and therefore government aims to promote solar power by achieving a target of 175 GW renewable energy power (where 100 GW would be from solar energy). This document established the solar energy and PV technology as emerging source of energy in India as compare to wind and other renewable energies [79]. GoI has decided to connect solar power by grid and therefore annual solar installations growth will be 4 times by the end of 2017 with 10–50 GW power capacity (Including roof top and utility scale). Foreign Direct Investment (FDI) is another way of promoting the solar energy to reach its optimum potential. The electricity act 2003, allows 100% FDI in renewable energy sector [24] and according to commerce and industry department's statement, India has received 1.77 billion USD as FDI during April-2014 to September 2016 [80]. Although it would be interesting to observe and analyze the effect of newly launched Goods and Services Tax (GST) on FDI in renewable energy sector as different opinions have been floated in recent past. It is likely that GST implementation would change the indirect tax slab and may affect adversely in foreign investment [81].

Certain amount of monetary support has been provided by government of India under the budget of 2016–17 which includes the exemption of excise duty tax on copper wire and alloys used in solar PV manufacturing. The other supports include the concession on PV equipments, guaranteed market for solar PV manufactures, and special support under the renewable energy special economic zone and loans etc. Various state specific supports are also available, for example, Government of Rajasthan is willing to set up solar manufacturing facility at their solar park. GoI has also created an institution known as National institute of Solar Energy which aims to support research and development activity in solar energy and contributing in the solar energy progress in India. The current example is the setting up a 1 MW solar thermal research and development power project with their collaborator, IIT Bombay. It is worth to mention over here that NISE is an autonomous body under the flagship of MNRE and it has been established in September 2013. The state governments have also setup their state solar policy and established solar agencies at state level such as CREDA for Chhattisgarh is such agency.

3.3.9 Biased Policy in National Solar Mission

The policy about thin film under the national solar mission was little biased. 1st stage and 2nd stage policy implementation include the promoting the application of crystalline Si technology (cells and modules manufactured in India). But the case for thin film PV technology was different as the efficiency of thin film solar cells are lesser than the Si technology. Although researchers (from India and abroad) are working in this area to make this technology efficient. Si technology can generate power with less space requirement whereas the same equivalent power generation with thin film would need much larger space (area) which means that more labour cost would be associated with thin film solar PV station installation. Also low cost of Si PV made thin film technology not so appealing to investors. Reliability and degradation of thin film solar cell over the period of time, are also major concern for the investors to install PV station with this technology [29] whereas recent views and news article published in Nature [12] expressed the importance of thin film technology. Conventional Si solar panels are rigid and bulky whereas thin film technology can be used in various fields such as mobiles, watches, indoors etc. Therefore it is required to find solution to the problems associated with thin film PV technology and promote research and development activities specifically towards new efficient material development, effective manufacturing technology development and technology commercialization. Arent et al. [5] cautioned that outsourcing thin film PV technology could be a risky job because the chances of supply of degraded materials are huge as also highlighted by various researchers [44].

As already highlighted, succinct and innovative policies are required in solar component manufacturing. Government has provided various dividends on excise duty and taxes as illustrated earlier, lag behind in bringing desired attention of investors in manufacturing. Around 80% of our solar panels comes from abroad and it costs huge burden on nation's economy. Some of our Indian solar panel manufactures are Vikram solar (https://www.vikramsolar.com/), Moserbaer (http://moserbaer.com/products/solar/), Tata power (http://www.tatapowersolar.com/) and Lanco solar (http://www.lancosolar.com/).

Currently world has a large dependency in thin film technology where majority of elements used in thin film module manufacturing are rare earth elements. China's mining policy for rare earth has great influence on thin film PV technology market price. It is also worth to mention that thin film technology largely involves hazardous elements, therefore while promoting and deciding our policy towards thin film PV technology, one must take care about this important facts. Therefore, addressing the concerns of underdeveloped policy in context to thin film PV technology is an important attention seeking area. Recent article published by Johnson [22] highlighted various drawbacks in policy. For an example, biased policy towards foreign thin film technology manufactures as reported earlier in this chapter, caused a huge loss to our local manufactures. The interviews conducted by Johnson [22] with the manufactures suggested that the modules produced by local manufactures between 2011 and 2012 was 10–15% (in terms of operating capacity) but 0% in terms of cells. Around 50% of work force lost their job because of the severe conditions of companies such as Indo solar who stopped manufacturing completely though Moserbaer successfully restructured themselves. Similarly Tata BP became reluctant towards solar manufacturing. The article also highlighted about the lack of research and development activities. Although it was highlighted that solar manufactures were optimistic towards government policies and believed that policies could support them during stormy market conditions. However the threat of China's manufacturing capabilities was clearly highlighted in the study. As illustrated earlier in this chapter, extensive rely on thin film technology could be a dangerous steps (considering lack of rare earth mining sources within India). CEEW and NRDC [11] report suggested about the generation of about 23,884 jobs in solar market between 2011–2014 but the study done by Johnson [22] suggested nominal impact on the existing solar PV manufacturing in India during the stormy market conditions. It is also worth to mention that the data were taken during 2011–2014 where the 1st phase of National Solar Mission was being carried out and was extremely successful in terms of achieving targets as illustrated earlier but this remain a question that how can we provide maximum support to indigenous solar PV component manufacturing which should be sustainable enough even during the stormy market condition?

Lack of transparency in the ongoing policies [22] and needs for an extra attention were highlighted in various studies [44]. Therefore, based on the analysis, we can design a probability/possibility chart for future policy implementation strategies (Fig. 9), although policy designing is a complex phenomenon for a diverse field like solar energy and technology.

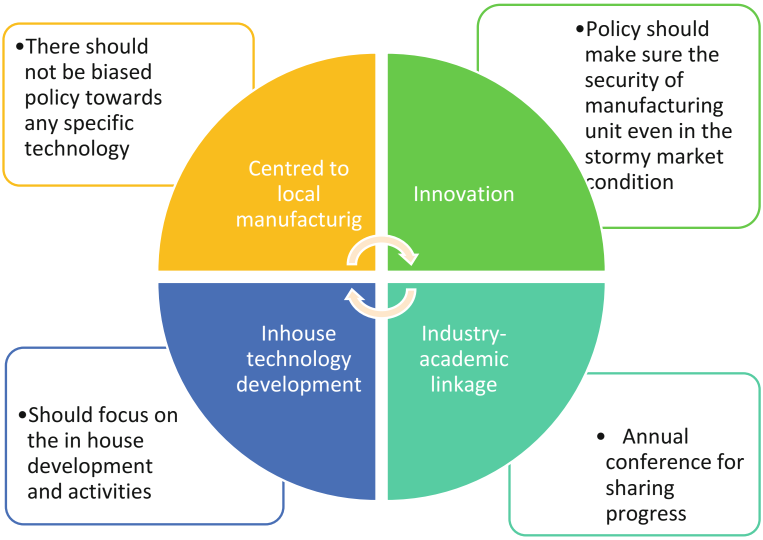

Fig. 9 Recommended future policy design and implementation policy

4 Sustainability Assessment of Renewable Energy Sources

The centralized energy systems based on fossil fuels represent the prevalent energy paradigm globally. The fossil fuels based energy systems have been regarded as damaging to environment and health [2]. The limited availability of fossil fuels, increasing energy demands and concerns of environmental and health impacts associated with their use have compelled the search for alternative energy sources. Renewable energy sources have been identified as an optimal solution for making transition to sustainable energy supply [37]. Renewable energy systems provide twin benefits in the form of reduced load on conventional energy sources and saved environmental emissions. Several governments including GoI have promoted the development and commercialization of renewable energy systems. The selection of renewable energy sources and conversion routes has been mostly dependent on techno-economic feasibility of the renewable energy systems [10]. Choosing one technology over the other has associated subjectivity because it often consider the use stage and overlook the trade-offs related to the entire life cycle [45, 53, 54]. For instance, the biomass based energy systems are mostly advocated for being as carbon neutral [27]. However, this is mostly so when only the use stage of renewable energy is taken into account. A major driving force for the political support to biomass substituting the fossil fuels comes from their environmental benefits [47, 49]. There are several studies supporting biomass based fuels over fossil fuels in terms of greenhouse gas (GHG) emissions. Similarly, solar PV based systems are viewed as environmentally clean in converting the solar energy directly into electricity but there are material and energy inputs as well as environmental emissions related to manufacturing and decommissioning of PV module. Therefore, the increasing use of renewable energy systems need to be assessed for entire life cycle and not only for the use stage [7]. The long term viability of renewable energy systems as a mean to provide sustainable energy supply have been questioned by several studies [13, 53, 54].

Life cycle assessment (LCA) is an internationally recognized methodology able to uncover the environmental performance of any product or process [25]. In biomass based energy systems, since the characteristics and conversion routes are biomass specific, an LCA based evaluation requires a reference system which can be used for comparison. Further, the second generation bioenergy systems have been promoted by several governments through technological advancements, but questions are raised on their accurate comparison with fossil based energy systems. Santoyo-Castelazo and Azapagic [45] used integration of all three sustainability dimensions using life cycle approach for identifying the most sustainable energy alternative for future electricity supply in Mexico. The study framework comprised scenario analysis, life cycle assessment, life cycle costing, social sustainability and multi-criteria decision analysis. 11 scenarios were assessed considering different technologies, electricity mixes and climate change targets up to the year 2050. The results showed a trade-off depending on the preference given to a sustainability criteria, particularly for social impacts. However, all the scenarios having renewable energy component were found sustainable as compare with business-as-usual scenario. Kumar et al. [28] carried out an LCA for assessing the GHG emissions and energy balance for 1 ton of jatropha based biodiesel system. The results were compared with petroleum based diesel system. The functional unit for GHG balance was 1 ton of jatropha. The results clearly indicated a strong influence of the criteria used for allocation the inputs-outputs between multiple products and irrigation in the agriculture stage. Therefore, decision making through sustainability assessments of renewable energy systems would require addressing the methodological complexities using tools like LCA.

5 Conclusions

Renewable energy systems with environmental benefits can significantly reduce the dependence on fossil fuels. Wide-ranging adoption of renewable energy sources and technologies in developing countries has been recognized as an essential solution to climate change challenges. India has emerged as potential market for renewable energy systems. With increasing support from government initiatives, public private partnerships and research the renewable energy sector has something to offer to every stakeholder. The estimations of fall in price for renewable energy are likely to give a setback to fossil fuel reliance.

India is responsible for 4.5% of global GHG emissions. In order to achieve "Intended Nationally Determined Contribution" of India in Paris agreement, India is expected to increase share of renewables in meeting total primary energy demand up to 40% by 2027. As highlighted in the chapter, transportation fuels along with electricity are the major forms in which energy is consumed. Growing demand of transportation fuels can be fulfilled by employing biorefinery concept, using biomass as a precursor in its various forms and electricity can be generated in decentralised as well as centralised manner using solar PV technology. GoI is also promoting the application of renewables by providing subsidies and making appropriate policies.

This chapter is an effort to highlight the importance of biomass and solar based renewable energy systems in India. The chapter attempted to provide account of present settings in policy and research perspectives for both. It has also emphasized on taking a holistic approach for growing the renewable energy share in India incorporating the aspects of economic feasibility, environmental friendliness and societal welfare into account.

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Planning to Mainstream Distributed Electricity Generation from Renewables

S. P. Gon Chaudhuri and Rekha Krishnan

Abstract Decentralised renewables in India have evolved over the years, from solar lanterns to solar home lighting systems and further from multi-purpose power packs to mini and micro grids powered by various renewables to the modern-day smart grids to optimise the integration of DER. Does DER (distributed electricity generation from renewables) have a future in a scenario with 100% grid connectivity? What niche applications of DER can provide substantial developmental benefits? How will the roles of various models of DER evolve and how may these be integrated sustainably? These are some of the questions that this chapter addresses with a view to essaying a plan to sustainably integrate DER as a reliable mode of electricity service provision/expansion in grid-connected and/or stand-alone modes employing renewable forms of energy. The focus is on ways to tap the strengths and address the limitations of various forms of distributed electricity generation. The chapter explores hybridisation, grid connectivity, smart metering and load planning and management as important technical elements of the way forward.

Keywords Distributed generation · Renewables · Indian context

1 Background: India's Continuing Electrification Challenge

India's electrification efforts have been dominated by grid extension programmes. Several schemes of the government have focused on rural electrification but India's electrification shows many gaps and challenges as outlined below:

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- 41 million households are yet to be electrified[1]
- Nearly 50% of "electrified" households have low levels (less than four hours per day) of reliable and affordable electricity access in some states[2]
- 65 million Indians who live in slums have irregular electricity supply
- 32 million children study in schools which have no electricity[3]
- 50% of rural primary schools in India are unelectrified[4]
- 33 million Indians rely on unelectrified primary health centres[5]
- Electrified hamlets, households, schools and healthcare centres are faced with frequent power outages and voltage fluctuations
- 25% of school toilets are not working or not usable partly due to lack of lighting or water connection.

It is evident that providing electricity for all Indians for all their basic, welfare and economic needs will remain a daunting challenge. The conventional approach of reaching the unelectrified by extending the grid has not always yielded desired results. Here, distributed electricity generation might offer enormous possibilities to relieve the pressure off the grid.

2 Decentralised Electricity from Renewables: Options and Benefits

DER options may be broadly categorised as:

- RE (renewable energy) devices for lighting such as solar lights and RE power packs for a range of applications such as lighting, powering computers, chillers etc.; in a sense, powering essential devices without depending on the grid
- RE based mini and micro grids leading to distributed or decentralized generation of electricity from various renewable energy sources.

The relevance of DER, particularly vis-à-vis its role as an alternative or complement to the grid arises out of the following:

- Establishment of new generating plants and transmission networks is capital-intensive

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[1] https://garv.gov.in/garv2/dashboard/garv accessed on August 27, 2017.

[2] http://ceew.in/pdf/CEEW-ACCESS-Report-29Sep15.pdf

[3] https://www.oxfamindia.org/sites/default/files/WP-Solar-for-Powering-Health-and-Education-in-India-EN.pdf

[4] https://www.oxfamindia.org/sites/default/files/WP-Solar-for-Powering-Health-and-Education-in-India-EN.pdf

[5] https://www.oxfamindia.org/sites/default/files/WP-Solar-for-Powering-Health-and-Education-in-India-EN.pdf

- At some locations, grid extension costs are too high and energy demand insufficient to justify the high investments
- Remote areas, inaccessible terrain, forested areas pose logistic challenges in setting up and maintaining electricity transmission networks.

Gaps in grid electrification in the form of frequent outages and unelectrified households have been traditionally bridged by diesel generators. However, switching to renewables-based decentralised generation has numerous positive features:

- Reduces dependence on centralized utilities such as electricity or gas grids and LPG distribution networks
- Is carbon-neutral or low carbon
- Can flexibly match local demand for electricity, heat, and other energy services
- Requires less capital investment and is easier to set up through small start-ups
- Generates employment opportunities for the local community
- Can provide reliable energy for critical community or economic activities.

An important limitation of some renewable energy technologies (not limited to decentralised renewable energy) is their intermittency of supply, resulting in a failure to meet fluctuations in demand (such as diurnal or seasonal fluctuations). While biomass-based technologies are not characterised by diurnal variations, there could be seasonal issues with timely feedstock availability of suitable quality. Technology offers various solutions to these issues through hybridisation with multiple energy sources, integration with the grid, energy storage etc.

3 Deploying DER for Development

Both categories of DER–RE devices/power packs and RE-based mini/micro grids can be designed to deliver a range of energy services like lighting, water pumping, cooling, water purification. While straightforward applications like solar lanterns, solar pumps and solar street lights are well-known, there are several other innovative DER examples that have successfully delivered a range of energy services reliably. A few of these are described below (Fig. 1).

3.1 Micro Solar Dome (Surya Jyoti): An Affordable Lighting Device for Mass Application

Many households in rural areas and urban slums in India (as in many other developing countries) have neither electricity connection nor do they have proper access to sunlight within their rooms during daytime. These households use kerosene lamp or electric lamp by borrowing electricity from local shops or from diesel

Fig. 1 Micro Solar Dome

generator operators. Absence of sunlight and use of kerosene lamp in homes, both result in unhealthy living conditions (Figs. 2 and 3).

To eradicate the darkness in these households, an innovative concept of Micro Solar Dome (Surya Jyoti), has been developed by Kolkata based NB Institute of Rural Technology (NBIRT). The Micro Solar Dome (MSD) is a day and night lighting single device with unique features:

- Has a transparent semi-spherical upper dome made of acrylic material which captures the sunlight and the light passes through a sun-tube having a thin layer of highly reflective coating on the inner wall of the passage.
- Contains a lower dome made of acrylic.

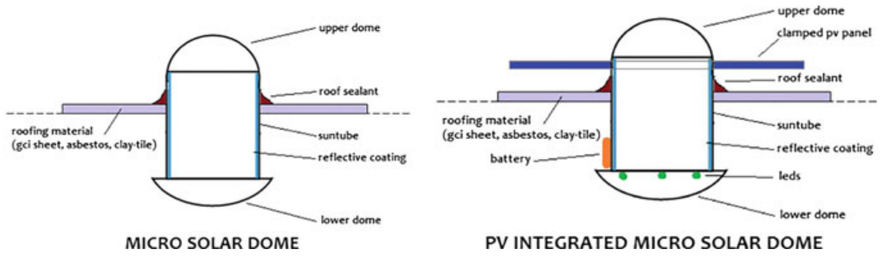
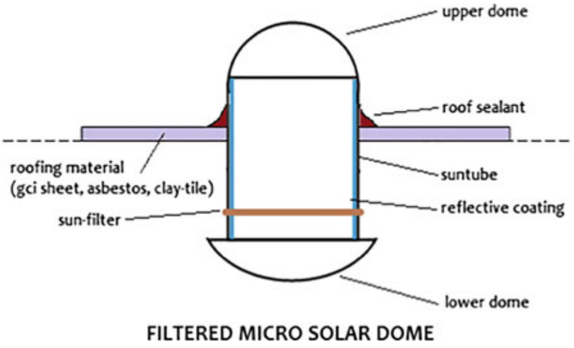


Fig. 2 A components of a PV integrated solar dome

Fig. 3 Components of a filtered solar dome



- Is fitted with a shutter in the bottom of the lower dome which can be closed, if light is not required in the daytime.
- Is leak proof and works throughout the day and 4–5 h after sunset depending on the season and location.
- Is the world's first hybrid solar lighting device, using a combination of passive and active energy.
- Has additional feature for mobile charging in some models.

Use of the micro solar dome at various times of the day helps to optimise radiation, temperature and illumination. Following the demonstration of the efficacy and reliable working pattern of the MSD, Department of Science & Technology, Govt of India supported the concept and entrusted NBIRT to install Surya Jyoti in different metro cities as well as in remote rural and tribal belts. NBIRT has initially installed 1000 such devices in urban slums on experimental basis.

MSD is now being field tested in different agro-climatic conditions under a network project involving S&T based Core Support Groups working with Science for Equity, Empowerment & Development (SEED) Division of Dept of Science & Technology, GoI.

Technical specifications of micro solar dome				
Item	Rating			
PV module O/P power	2 × 3 W			
PV module O/P voltage	10 V Voc, 8 V Vmp			
PV module rated current	375 mA			
Battery type	Li-Ion			
Battery capacity	2 × 4000 mAh			
Battery voltage	7.4 V (2nos 3.7 V connected in series)			
Luminary type	3 W LED			
Circuit used	Electronic driver circuit			
Hours of operation		Daytime (h)	Night time (h)	Total (h)
	Summer	12	5	17 (minimum)
	Winter	8	5	13 (minimum)

Types of Dome There are four types of Micro Solar Dome (Surya Jyoti) developed after prototype testing under field conditions and consequent product evolution:

(1) **Normal Micro Solar Dome**: Dome type day-lighting device has a transparent semi-spherical upper dome made of acrylic material which captures the sunlight and the light passes through a sun-tube having a thin layer of highly reflective coating on the inner wall of the passage. The light output varies from 3 to 15 Watts (electrical equivalent) Watt from morning to evening.

(2) **PV Integrated Micro Solar Dome**: It is the latest version of the Micro Solar Dome. The integrated PV module fitted in the dome charges a battery during day time which in turn provides light during night time from the MSD for 4–5 h through LED fitted in the lower dome.

(3) **PV Integrated or Non-PV Filtered Micro Solar Dome:** In both of these types of domes, Sun Filter has been used to reduce illumination during summer, if required

(4) **PV Integrated Micro Solar Dome with USB port:** This version of MSD can also charge mobile phones in addition to providing day and night solar light.

3.2 Powering 24 × 7 Running Water to Rural Toilets and Drinking Water with Solar

An estimated 1.4 lakh children die due to diarrhoea in India annually,[6] and a major cause for this is the lack of access to clean drinking (potable) water and proper sanitation facilities. It is common for rural households and urban slums to have

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[6] http://cghealth.nic.in/ehealth/2016/Instructions/IDCF_Guideline_2015.pdf

toilets that are dark and do not have running water for hand-washing and cleaning the facilities.

To alleviate these problems, a unique combination of technologies has been developed into a solution package as follows:

(i) Pumping sufficient water from ponds or underground reservoir to an overhead tank which cater daily needs through a solar pump. The capacity of the solar pump will be higher (1000–3000 W) if a submersible pump is installed for drawing ground-water and costs will also be higher than in situations where surface water is available.
(ii) Using the solar power to run a RO Water purifier to provide purified drinking water by using an intelligent controller (this will be possible because the solar pump will operate only for 2–3 h to fill up the overhead tanks of the toilet)
(iii) The RO system capacity may be of 200 litres per hour (costing Rs 15,000) or 600 litres per hour (costing Rs 35,000).

Running water is an important facet of effective sanitation. Even dry toilets need running water for hand-washing. Ensuring water availability in and near toilets has been made possible in unelectrified areas by using micro solar pumps. For instance, at a maternity home in a remote village in the Indian state of West Bengal, pregnant women often had to carry buckets of water because the toilets at the home did not have a water connection despite there being a water body next to the home. Incorporating a micro solar pump and a water tank (with five days' storage), ensured running water in the toilets. This system is already running in 2 girls schools and 1 maternity home in West Bengal and in Tripura 10 schools have this system now (Source: NBIRT, Kolkata) (Figs. 4 and 5).

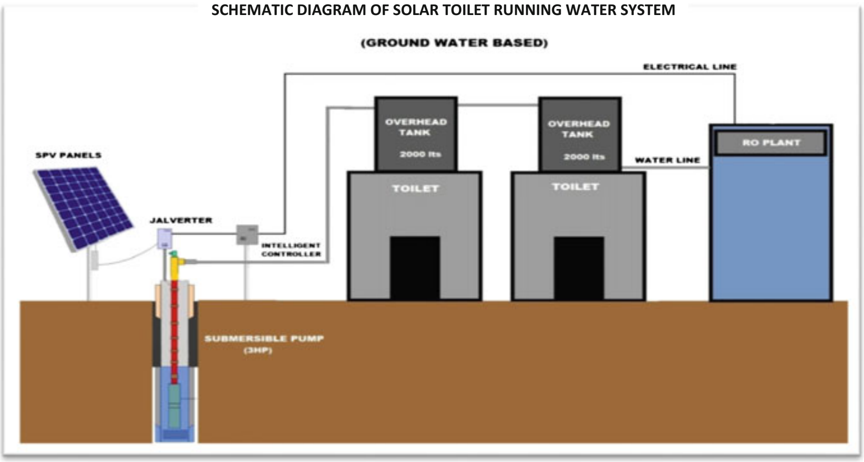


Fig. 4 Solar-powered toilet running water and drinking water module (ground-water based)

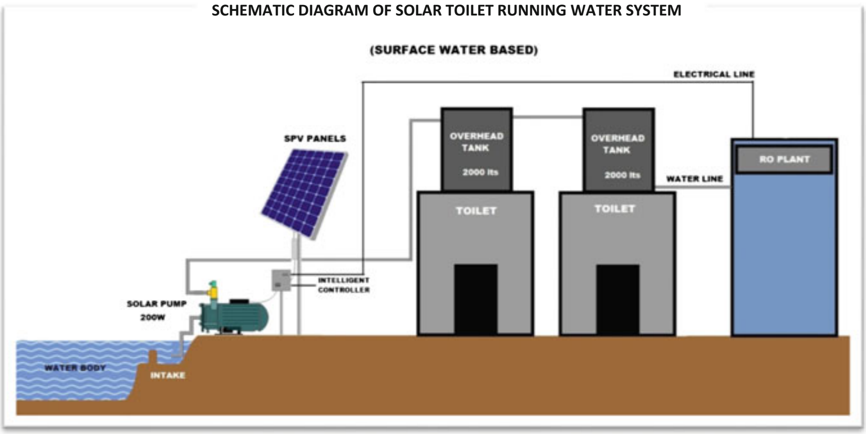


Fig. 5 Solar-powered toilet running water and drinking water (surface water based)

3.3 Floating Solar: Averting the Search for Land and Rooftops

The ambitious plan to deploy 100 GW of Solar Power by 2022 requires about 500,000 acres of land. While taking this quantum leap in solar capacity, one of the major challenges is of finding adequate non-arable land resources without disturbing the ecological balance at any location. Against this backdrop, floating solar which involves setting up solar panels on static and sweet water bodies, has enormous potential. It is estimated that utilizing just 5% of the water bodies of India, the country can generate 130 GW of Solar Power.

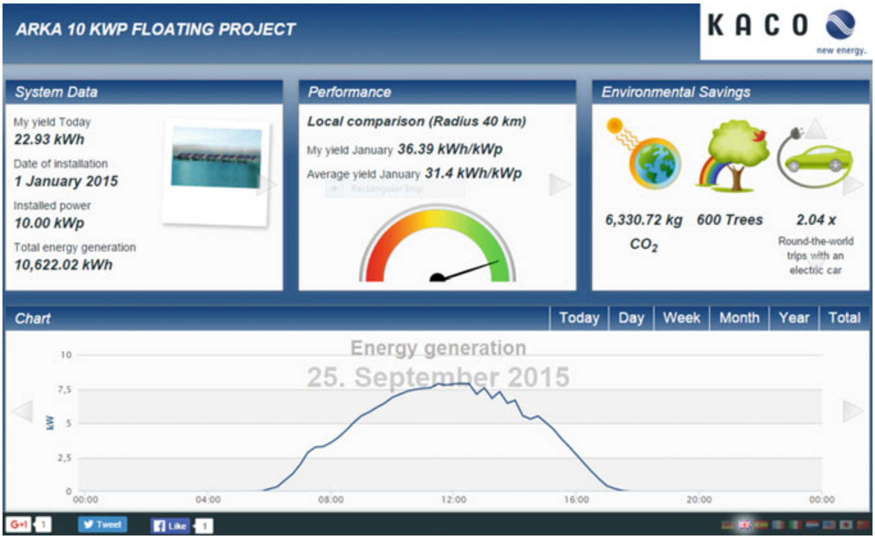
In 2014 India's first pilot Floating Solar Power Plant of 10 kWp capacity was set up at New Town, West Bengal. The performance of the plant has been found to be excellent (Figs. 6 and 7).

Floating solar projects comprise an array of PV Panels supported on light structural frames which are mounted on a floating platform with access walkways for maintenance. The principal components of the power plant are:

a. 40 nos. PV Panels @ 250 W per Unit to generate 10,000 Watts.
b. Structures to support PV Panels.
c. Walkways and their supporting structures.
d. Inverter.
e. A Floating Platform to carry all the above.
f. Anchoring arrangement for keeping the Platform in place.

Floating solar offers several advantages, some of them are as follows:

- Surrounding temperature is low in summer ensuring higher generation of power from PV modules.



ARKA 10 KWP FLOATING PROJECT

System Data

My yield Today
22.93 kWh

Date of installation
1 January 2015

Installed power
10.00 kWp

Total energy generation
10,622.02 kWh

Performance

Local comparison (Radius 40 km)

My yield January 36.39 kWh/kWp

Average yield January 31.4 kWh/kWp

Environmental Savings

6,330.72 kg CO_2

600 Trees

2.04 x Round-the-world trips with an electric car

Fig. 6 Benefits and features of floating solar project

Fig. 7 First floating solar plant of India at New Town, Kolkata inaugurated on 5th January, 2015

- Precious land is not required and the additional cost of floating solar (nearly four times on-land solar PV) is offset if avoided land cost is factored in.
- No cement, concrete or elaborate construction required; DC power output is converted to AC using an inverter kept on the floating structure and the AC power can be fed to the local grid using underwater cables.
- Dust accumulation is much less when the modules are installed on water bodies.
- Conservation of water due to less evaporation.
- Algae formation in the water body will be less due to continuous maintenance of the Solar Floating System.

Some precautions needed in the installation of floating solar are as follows:

- Stability of the platform is important. It must be anchored from all four sides and the distribution of loads needs to be fairly uniform. Proper anchoring is also required to ensure the panels do not move with rain and/or high-speed winds as any change in the direction or orientation of the PV panels will affect power output.
- In grid connected inverter, frequency control is necessary, If the grid frequency exceeds the tolerance band, the project goes into islanding mode for protection, but this results in energy losses.
- Possible negative impact on aquatic life (flora and fauna) needs to be monitored.

3.4 Bio Solar Automated Teller Machine (BS-ATM):: To address the Need of the Rural Unlettered Masses of India

With the advent of cashless economy and digital banking, it has become necessary for everyone to be able to use ATMs. So the number of ATMs has been growing steadily. However, for ATMs to be useful, they need to be easy-to-use even for the illiterate and those unaccustomed to digital transactions.

An innovation in the form of a Biometric-based Solar-powered ATM (BS-ATM) has a huge potential to change the lives of rural masses. A prototype of the BS-ATM (figure of model is illustrated below) based on an audio-video-touch interface avoids the use of cards, PIN and paper. Apart from reducing the use of plastic (in cards) and paper, this ATM is green also because it is powered by solar. This also makes the ATM functional in areas where grid electricity is unavailable or unreliable. The BS-ATM is also energy-efficient with 300 W peak consumption and 50 W consumption in standby-mode. One BS-ATM has been commissioned and another is being fabricated.

The potential for replication of this model is enormous as there are already over 2 lakh ATMs in the country with an average electricity consumption of 5.5 kWh daily and associated annual CO_2 emissions of 8.1 lakh tonnes (Fig. 8).

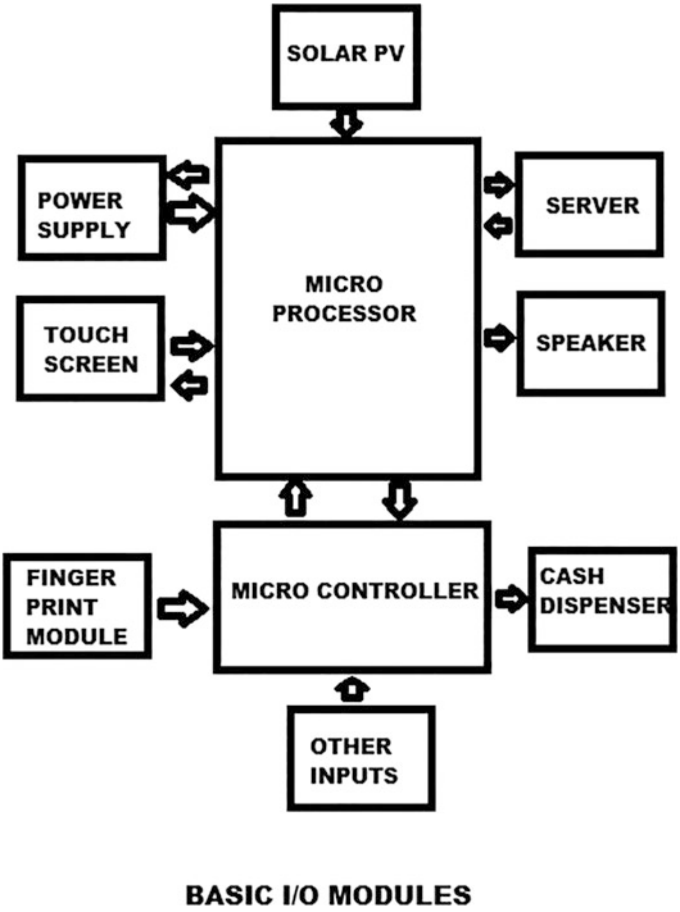


Fig. 8 Schematic representation of a BS-ATM

4 Important Factors to Catalyse and Strengthen DER Deployment[7]

DER solutions are often misunderstood as solely household-level energy technologies. As a result, the potential of DER for several commercial/productive and social/community applications is underutilised in India. Water purification, water pumping, cold storage or drying of vegetables, fruits and fish, milk chilling, aeration of ponds, or powering of boats are just some of the energy services that can be

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[7] This section draws extensively on two briefing papers prepared by the authors available at http://shaktifoundation.in/wp-content/uploads/2014/02/Paper-12-FINAL-Revised-13-1-14.pdf, http://shaktifoundation.in/wp-content/uploads/2014/02/1FINAL-Overview.pdf

powered by solar, biomass, or other renewable energy or hybrid renewable energy systems. The examples above demonstrate numerous possibilities and the table below summarises the costs of some of these systems that can effectively be deployed across various settings.

Technology	Cost (indicative —September 2017)	Applications/potential users
Micro solar dome (PV integrated with mobile charging facilities	Rs 1600	Households particularly in slums, small shops
24 × 7 running water to toilets and drinking water—both powered by solar	Rs 80,000	Typical module for a school with 100 students
24 × 7 running water to toilets and drinking water—both powered by solar (with submersible pump)	Rs 200,000	Typical module for a school with 100 students
Bio-solar automated teller machine (BS-ATM)	Rs 800,000	For ATMs in rural and remote areas
Floating solar power plant (10 kW)	Rs 70,000/kW	Electricity generation

Ironically, some of the strengths of DER also represent intrinsic limitations. For instance, because they are decentralised and are of small-scale, DER systems typically do not achieve the economies of scale of large or grid-scale projects. Also, as the systems are numerous and scattered, there are higher transaction costs associated with project management and coordination. Community engagement can also be a challenge, especially if the projects are not conceptualised with community involvement from the beginning.

An important limitation of some renewable energy technologies (not limited to decentralised renewable energy) is their intermittency of supply, as mentioned above.

In addition to the inherent limitations of DER, there are several external or ecosystem-related factors that hinder its large-scale adoption. DER technologies tend to be costlier than their centralised large-scale counterparts as they typically entail higher upfront and in some cases costlier and/or more cumbersome operations than conventional energy solutions. This poses challenges on various fronts: affordability for consumers, viability of operations, and the need for entrepreneurial and end-user finance or subsidy support. Poor data on operations, business prospects, and lack of standards can reduce user and investor confidence in these systems.

Lack of relevant technical expertise for operation and maintenance is another impediment to DER adoption. The DER practitioners must also cope with regulatory and policy uncertainty, as well as the absence of a level playing field resulting from deep subsidies to large-scale centralised energy providers, which tend to be fossil fuel-based and are not penalised for their environmental impacts or neglected energy access gaps.

Some important pointers for DER planning and mainstreaming for meeting various energy services:

- Understanding and customizing to suit the context: Perhaps the most important feature of a DER project is its distributed nature, making it a local solution. Thus DER requires us to think and plan for a specific community, integrating local energy needs and resources.
- Address intermittent supply: Power storage is usually conceded to be the weakest link in DER, both technically and organisationally. Energy storage is an area of intense research with various options being explored to address intermittency associated most notably with solar and wind energy.
- Hybridisation: One way of addressing intermittency is hybridisation within and across technologies (e.g., combining solar mini grids with solar home systems or solar mini grids with biomass gasifiers or wind turbines). This can help overcome diurnal variations in energy demand and supply. It can also provide flexibility in meeting rapid growth in demand, especially in households enjoying their first-time access to electricity.
- Grid interactivity: Commercial viability of off-grid power is always a challenge, given its low levels of affordability to many rural Indians, and diseconomies of scale. Decentralised micro grids can also be threatened by the grid. Grid-connected (or grid-compatible) projects are better equipped to deal with this risk. However, grid interactivity requires a regulatory framework that accommodates three DER options: (1) continue off-grid; (2) sell surplus power into the grid, and (3) buy from the grid a portion of the total power requirement (which could be a mix of conventional and non-conventional energy).
- Smart metering and load management: For the integration of DER systems across various renewable energy sources and/or the grid and to meet a range of energy demands (that have diurnal and seasonal variations), smart controls are necessary to ensure safety and to minimize energy losses. Such smart meters and controls are integrated into some of the systems described above.

In the past, DER in the form of devices and mini grids have been deployed as a quick-fix for energy access gaps. In the absence of proper planning, some systems that have worked well in the short term have failed in the medium- to long-term.

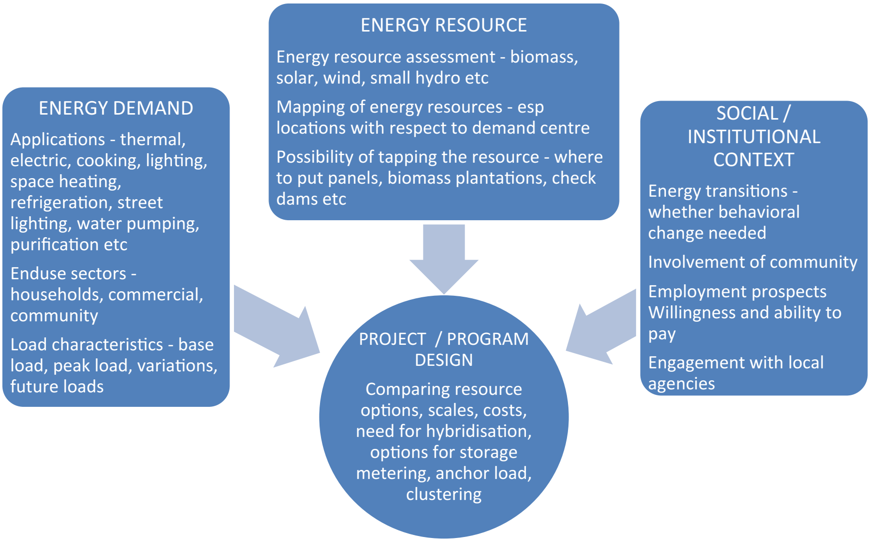

Fig. 9 Local multi-aspect planning for DER projects. *Source* http://shaktifoundation.in/wp-content/uploads/2017/06/1FINAL-overview.pdf

The examples above show the need for detailed planning to be able to integrate intermittencies (Fig. 9).

Institutionally, DER planning must be integrated with the responsibilities of local development agencies so that systems can be better integrated with existing infrastructure in a planned manner. For instance, fitting upcoming community centres and primary health centres with solar PV integrated domes, pumps and water purifiers ensures that basic needs of lighting, running water and drinking water are met at the outset with low or no dependence on the grid.

Virtual Power Plants: How Far Is India from This Reality

Tanmoy Mondal and Deb A. Mukherjee

Abstract Integration of renewable energy, which is distributed and intermittent by nature, calls for harnessing the inherent flexibilities in the supply and demand side. Experiences across the world have shown that Virtual Power Plant is an important intervention in tapping redundancy and bringing it logically through the market mechanism into the utility's scheduling process. With a major push towards de-carbonization in capacity addition, we may find Virtual Power Plants in India faster than expected. Is the country prepared for it?

Keywords Renewable integration · Intermittent power · Virtual power plant
Global context · Indian context

1 A Case Study

1.1 Current State

New housing in Indian cities is characterized by large societies with thousands of residential units within a gated community. For the electricity supply, each of the units would have a grid connection from the local distribution company ("Discom" henceforth). The Discom puts their own transformers and provides Low voltage ("LV" henceforth) individual connections and meters to each of the residential units. Since the reliability was not expected to be of the desired level, a backup source in the form of a diesel generator with enough capacity to either meet the entire requirement or at least the essentials would have to be included. The builder/developer builds a partial or complete parallel network for the power from the diesel generator. This is what most of us are used to seeing.

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Green Energy and Technology, https://doi.org/10.1007/978-981-10-8393-8_15

However, some changes to this established norm started happening in the last decade. In the new practice the society avails a single high voltage ("HV") connection from the Discom. In most cases, the electricity utility is rather too happy to provide a HV connection. HV tariffs are higher and provide a much higher recovery for the utility for the electricity sold. Moreover, the connection requires much lesser commitment of resources and lesser service. The consumer cluster on the other hand receives power which is somewhat better in quality—higher reliability, better voltage profile etc. Instead of individual residential units being individual consumers, the entire consumer cluster becomes one single consumer. The grid reliability would still fall short of the desired level and the solution would still be a diesel generator. The builder/developer, on the other hand, puts up a consolidated network to provide a connection to each of the residential units. It would provide power from the grid as well as the backup source depending on the situation. The developer would implement a common metering and billing solution with differentiated tariff for different sources. Moreover the same billing system may also include the charges for all the other services provided, which need to be paid for (*example. Water, Gas, Internet/WiFi, Satellite Television, Cleaning & Maintenance* etc.). These solutions would be an overall asset management ERPs or just a part of it. The metering and billing solutions are fairly efficient and provides a consolidated bill for the entire set of services.

1.2 Winds of Change

However, the winds of change are already blowing and can clearly be felt right on the face. Let us consider some of the emerging drivers which are likely to influence the shape of things in the decades to come.

One of the most important drivers influencing the energy consumers is the focus on cleaner and sustainable sources of energy. With increasingly smaller space left for CO_2 emissions to prevent a catastrophic climate change, renewables have caught the imagination of the world. Consumers are not just looking for quality power but also cleaner (less polluting, less carbon intensive) power. More often than not, consumers are even willing to pay more for cleaner power. Over the years, the technology of the fossil fired power plants have improved and are much less carbon intensive as compared to what it used to be years back. But the real transformative change is that of renewables like wind and solar achieving grid parity. The falling prices, availability of unused rooftops, ease of implementation and maintenance and the modular structure of rooftop solar makes it attractive for its usage as small captive facilities. In most cases, the levelized cost of electricity from the rooftop solar is less than the retail tariff for the residential consumers, which makes it attractive to consumers.

Second important driver which is likely to influence the energy consumers is the emergence of low cost storage. Initially, most of the rooftop solar projects came up under the net-metering conditions, wherein the generation was either paid for or banked after setting off the own consumption. However, net-metering had its own limitations, which put a barrier on the amount of rooftop capacities which could be installed. Emergence of battery storage as a economically viable option addresses this barrier. It technically removes the limitation on the amount of rooftop solar which can be integrated and harnessed economically.

Third important driver to influence is the digital control and integration. The inter-networking of physical devices, (also referred to as "connected devices" and "smart devices"), and other items embedded with electronics, software, sensors, actuators, and network connectivity which enable these objects to collect and exchange information along with the ability to analyze large volumes of data have opened up the possibility where the operations are smarter and often without any manual intervention. The concept of Internet of Things ("IoT" henceforth) indicates that it is possible to receive and send data in real-time across all components of the entire ecosystem, enabling more sophisticated and comprehensive management on a real time basis.

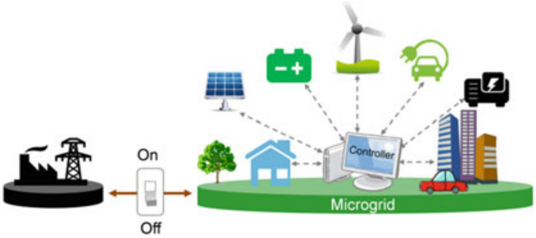
These three important developments may look rather innocuous but have profound effect on the future. It is likely to influence the way we live and think. Let us consider the impact of these changes on the mundane issue of our electricity supply of the housing societies as considered above.

1.3 Green Shoots

Today, it is not uncommon to find a few rooftop solar installations in some of the housing societies. They are either for complete captive consumption or on net-metering scheme. Over a period of time, the increasing focus on cleaner energy, sheer economics and technical ease will push all such housing societies to install more and more solar rooftop as an alternate source of electricity. In future, perhaps, maximizing the solar generation will become one of the key criteria for building designers and architects.

Moreover, there are interesting trends appearing in the horizon. Research in material science has led to development of flexible solar panels which can be used on any surface as covering material and at the same time generates electricity. Also there are solar panels available in the market which can be used as building facades. The possibilities do not end here. There would be many more on the drawing board tapping energy, not just from sun but from other renewable natural resources like wind, water etc. as well. Suddenly the prospects seem to be enormous and limitless. In future we may be able to generate a substantial portion of the energy requirement, if not entirely, from the everyday set up we live in. The overall reliance of the grid may become lesser and lesser as the distributed renewable energy sources take control.

Along with captive distributed renewable energy sources let us consider low cost battery storage and a digitally connected smart system. Interestingly, we already have a "microgrid" in place beyond the utility's meter. Though an abridged version, the "microgrid" has its own electricity distribution systems containing loads and distributed energy resources, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded. It opens up enormous possibilities. Let us consider some of the simpler ones.



The diesel generator, as we know, is a necessary evil. It is inefficient, costly and certainly not clean. Depending upon the situation and application, the distributed generating sources along with the battery may provide enough backup to reduce the capacity or even eliminate the diesel generator altogether. I am sure the diesel generator manufacturers are taking note.

In the electricity bill, the High Voltage consumers are subject to at least two (actually there are other parameters as well) different charges—(a) demand charges, which is payable on the maximum demand (peak load) recorded by the consumer within a specified period, (b) variable charges, depending on the amount of energy consumed at within a specified period. There is a certain benefit, in terms of reduction of the demand charges, if the maximum demand can be reduced. Utilized intelligently, the captive generation along with the battery storage can be used to chop off the maximum demand and hence reduce the demand charges. So utilities stand to immediately lose a part of their revenue even with the same or may be higher energy consumption.

Most of the High Voltage consumers are also subject to the peak hour tariffs, called the Time of Day ("ToD" henceforth) tariff, for the part of the consumption during the peak hours. It is a demand management tool used by the utility wherein the consumers are charged a higher tariff for the energy consumed during the system peak. The battery storage, if in place, can be used to cut down the drawal from the grid during the peak hours and charged back in the off-peak hours. Eventually, such a measure will reduce the overall energy costs by reducing the effective rates without really affecting the consumption pattern.

Though far-fetched, Policy-Regulatory framework permitting, the housing society can also earn some revenue by selling surplus or stored energy during high demand periods by selling the power. The case becomes much more dynamic and complex if we further add the consideration that Electric Vehicles ("EV" henceforth) would be a way of life in sometime. Each of these EVs is nothing but battery storage of electricity, which can be used for other purpose when they are not plying on the roads. However, those discussions are not taken up as a part of this scope.

The discussion so far is fairly simple and intuitive. Evidently, we are approaching a situation where technology is outpacing regulations and rates. But there are inherent flaws in these arguments. Distributed renewables are intermittent by nature. Though predictable by nature, there would be cloudy days or partially sunny days, when the reliance on the grid would go up substantially. With higher demand on the grid, the electricity price in the grid is likely to go up. Will it create a situation wherein, all the value created in the above paragraphs would be destroyed?

2 Changes at Grid

The electricity systems, as we have known for more than a century, are going through a paradigm shift. So far it had been characterized by a few, large, centralized (fossil-fuel fired or nuclear or hydro) power plants providing electricity for bulk of our needs and a set of transmission and distribution systems conveying the power to the point of consumption. However, there are certain fundamental changes which are taking place in the energy industry—the grid is becoming Distributed, De-carbonized and Digital. These changes are fairly disruptive and likely to bring about a paradigm shift in the industry as a whole.

Coal and natural gas fired power plants form the backbone of the source mix for electricity systems across the world. A shift from the conventional fossil fuel-driven generation to renewable (RE) generation is likely to have a profound effect. As compared to the predictable and controlled operation of the conventional power plants, renewable energy is distributed and intermittent by nature. Moreover, unlike the conventional power plants which have variable and fixed costs of operation, renewable energy has high capital cost but very low (almost zero) variable cost. These two simple differences have a big impact on the established techno-commercial models and the principles of grid operations. Suddenly the concepts of base load power plants, merit order dispatch appear to lose their relevance as we have known them so far.

Studies have shown that, so long as RE contributes <3% of the overall energy input to the grid, the system is able to accommodate without any perceptible impact. The input is small enough to lay hidden within the supply side redundancies. When the RE contribution is >3% but <15%, the existing system can still handle, but with modifications—mostly utilizing the flexibility on the generation side. It is the situation we are currently observing in India. However, once the share of RE is >15%, there is a need for thorough overhauling of the techno-commercial arrangement of the whole sector. The imminent challenges in energy supply can no longer be met solely by actively managing generation. Load flexibility must also be actively included in planning and operation. The old principle that "generation will follow consumption" is changing as demand adapts to supply. The focus of interventions turns towards aggregation and utilization of the inherent flexibilities both in the demand and supply side in order to achieve a balance in the grid.

Some of the means by which, the utilities across the world are trying to address the changes include dynamic pricing (signals indicating the shortage or glut in the market), large scale distributed generation to reduce reliance on centralized power plants, demand response to manage load during trying times and improve grid balance/reduce shortage, leveraging the wholesale market to tap demand response and localized small scale distributed generation. All of these measures offer tremendous opportunities but also pose difficult challenges in implementation. The interventions chosen have to be appropriate to the specific electricity system—there is no common solution that suits all.

The Indian grid, which sources most of the electricity from the coal fired power plants, is likely to have more issues and costs in integration of the renewable. The flexibility on the supply side is fairly limited. Harnessing the demand side redundancies may be crucial for balancing and grid stability. Demand Response and eventually organized Virtual Power Plants would be a key factor in harnessing the demand side opportunities.

3 Virtual Power Plant—A Solution?

It is a fairly complex game for the utility to roll out a model for dynamic pricing, demand response and tapping distributed energy resources in the scheduling process. One of the ways of addressing the problem is to use the concept of Virtual Power Plant (“VPP” henceforth). VPP is a logical aggregation of one or more consumers under a single profile, which mimics the characteristics of the traditional generation plant. It can be forecasted and scheduled in the utilities portfolio.

The overall idea of a VPP is to use a combination of technology and connected grid which can be remotely controlled, to monetize the inherent flexibility in the consumption and generation patterns of the distributed renewable energy resources, trading it on energy markets or using it on-site to reduce the net energy charges.

In the long run, VPP generate value by relieving the stress on the system, allows more renewable to be cost-effectively integrated into the grid and helps to secure energy supply. It goes a long way in achieving energy affordability, grid reliability and resilience.

As of now, the changes have elicited different kinds of VPP models depending on the techno-commercial and policy-regulatory environment the stakeholders are operating in. Most of them can essentially be categorized into 3 broad types with minor variations here and there.

The first is a supply-side system, which is more prevalent in Europe, where small-scale renewable energy projects already abound. In this model, operators coordinate the output of independent solar and wind farms with hydropower, biogas, and other low-carbon resources, thus simulating the output of a 24-h power plant. Some of the major technology giants and the utilities are in the process of jointly building the technology backbone of a mass-market virtual power plant that will coordinate hundreds of megawatts’ worth of distributed energy projects such as wind and solar farms.

The second model focuses primarily on “demand response”—cutting consumption, through energy efficiency systems and software, during hours when electricity demand is highest. Such models, focusing on harnessing consumption flexibilities, are most relevant in industrial parks and large conglomeration of commercial and residential units.

The third model of virtual power plants is a mixed bag of assets such as battery storage, some renewable power sources and energy efficiency systems that both reduce consumption and supply clean power in targeted ways. This is the model, which is likely to see maximum growth in India, particularly as the cost of battery systems continue to plummet and solar panels proliferate across rooftops.

4 Preparedness for VPP

In the above case of the residential societies, it is evident that the consumers are ready for a change so long as it helps in furthering their objectives of moving to a cleaner environment and sustainable sources of energy, reducing energy bills and improving the overall quality of life. They are ready to adopt technology, new business models, which add efficiency and quality to their energy portfolio.

The Residential Societies have moved from individual metered units to a clustered format, using technology to improve the quality of their supply and reduce their overall cost of energy. It would not be unreasonable to assume that they are smart enough to adopt smart solutions like Virtual Power Plants (or at least Demand Response to begin with) as and when there is an enabling environment. The transformation can happen fast.

It would be interesting to extend the same logic to other organized consumer groups like (a) Industrial establishments/parks/conglomerate, (b) large commercial buildings/complexes. Along with the large residential societies, these two groups form a large and growing component of the electricity consumers of modern India. Industry as well as the large Commercial establishment are conscious and have already made good progress under different initiatives of energy conservation and efficiency enhancement. It is evident in the overall trend of the falling curves of the energy intensity of the GDP growth.

In the short to medium term, a larger shift to distributed renewable generation, mostly in the form of rooftop solar looks inevitable. With falling prices of solar panels, it makes good sense for the industries, commercial buildings, parking lots, bus/railway stations, schools etc. to utilize their unused rooftops to install solar panels. Many of the institutions have already gone for such installations. The installed rooftop capacity in India is about approximately 1400 MW (Industry c.a. 800 MW, Commercial and Residential around 300 MW each), and another likely addition of 1200–1300 MW by the end of the year. As discussed earlier, we are likely to see a flood of technologies and material for other-than-rooftop applications, which with further accelerate the rate of capacity addition.

The reliability and resilience of the grid is not comfortable across the country. Almost all the Industries and Commercial establishments are dependent on costly, inefficient and fossil fuel based diesel generator alternatives for backup power. So strong is the trend that finding an Industrial setup or commercial establishment without a diesel generator would be more of an aberration. In addition, almost all of them use some or the other form of inefficient storage systems euphemized as Uninterruptible Power Supply ("UPS" henceforth) to provide uninterrupted supply of electricity for critical electronic appliances and computers, which otherwise will get affected. UPS is costly and inefficient; there is hardly any possibility of using it for anything other than emergencies or backup for extremely critical equipment which otherwise will get spoilt with power cuts. Once the large scale economic and efficient battery storage becomes a reality, which the trends definitely indicate, both these categories of customers will perhaps waste no-time in adopting and applying the technology on a mass scale.

In order to manage and control all the connected devices, distributed generating resources and one or multiple battery storage units, there is need for a technology solution. It could start with a rudimentary form of IoT and then upgraded over time to a powerful IoT, depending on the business case, with the capability to acquire, analyze data and control the connected devices and embedded smartwares. Eventually the systems would get upgraded to have machine learning capabilities and Artificial Intelligence ("AI" henceforth).

It is easy to conclude that a large section of the organized consumers (residential clusters, industrial and commercial) either have already adopted or ready to adopt all/most of the essential ingredients of a Virtual Power Plant. The current state as discussed assures their preparedness for migrating to smart systems as and when the technology becomes economically viable. Evidently, the preparedness of stakeholders "after-the-meter" appears confirmed.

The bigger question for implementation of VPP is the preparedness on the part of the stakeholders "before-the-meter"—(a) **policy makers** in terms of their ability to understand, appreciate, foresee and provide direction to the industry, (b) **Regulators** in terms of their ability to provide effective enablers facilitating efficiency and at the same time ensure adequate control, and (c) **utilities** in terms of their infrastructure and institutional capacity building to effectively manage such a change. Some of the macro issues around the preparedness of the stakeholders "before-the-meter" are taken up in the subsequent section.

Importantly, it is necessary that the stakeholders "before-the-meter" get their acts together in order to facilitate the change. The smart consumers will anyway adopt "distributed captive generation + storage + technology" solutions and device effective demand responses in order to optimize their energy bills. In case, these demand responses are not taken into account, it could have serious impact on the demand forecasting, scheduling and planning of the utility, leading to sub-optimal utilization of the assets and the Power Purchase Agreements ("PPA" henceforth) portfolio of the utility. In turn, it would affect the stability and reliability of the grid. Moreover, It would also adversely affect the finances of the utility questioning their financial viability in future.

5 Barriers to Successful Implementation

From the policy perspective, the country has taken up massive initiative of adding renewable capacity. As a response to counter Global Warming, it is altogether fitting and proper, that the country takes effective measures to shift from carbon intensive energy source to more sustainable and lesser carbon intensive sources. However, it is not a one-to-one shift. The renewable are fundamentally different in their generation characteristics from the large fossil-fired power plants. It calls for adopting new commercial models, business processes and different set of capabilities. The paradigm shift in the grid management calls for two basic interventions —(a) grid infrastructure and (c) capacity building.

5.1 Grid Infrastructure

The implementation of Virtual Power Plant calls for an enabling infrastructure, technology enabled business processes and adequate supervisory mechanism for governance and control. Essentially, the enabling infrastructure means development of a Smart Grid or at least a part thereof with some of the key components. A Smart Grid calls for (a) Advanced Metering Infrastructure ("AMI" henceforth), (b) communication network and (c) Data Acquisition and Management Systems which are capable of receiving, storing and analyzing large volumes of data. Obviously, this calls for an integrated infrastructure consisting of intelligent devices—smart meters, smart distribution, smart transformers, smart substations etc. For a grid of the size of India, it is a fairly elaborate task and calls for phenomenal investment in terms of investment and resources.

Several pilot Smart Grid projects have been organized under the sponsorship of Ministry of Power, Government of India. Besides, the utilities themselves have made investments, though in bits and pieces, to make the grid smarter. The initial results are encouraging. But it is a big task with lots of challenges. It would be interesting to see, how soon the Indian utilities can make that paradigm shift from the traditional grid to a smart grid. Without a technology enabled smart grid, it may not be possible to implement VPP.

5.2 Capacity Building

The monolithic electricity utilities, characterized by inefficient cost-plus attitudes, received the first major push for change with the enactment of the Electricity Act 2003. It separated the key functions of policy making, regulations and utility operations into independent entities. In order to usher competition and improve efficiencies, the integrated utilities were unbundled to separate the natural monopolies from the portions which could compete. It called for a complete change in the mindset and capability building. There have been some improvements—investments in capacity additions, reductions in the losses, enhancement of the collection efficiency, lesser political interferences. However, a lot remains to be done even after one and a half decades of reforms.

Though the policy makers at the Central Government level have been somewhat reasonable in their vision and outlook, that of the States have left much to be deserved. In many of the States, the utilities have degenerated and become weaker because of lack of a long term vision and political will. With mounting losses it is a financial quagmire which will take significant pains to extricate. Some of the loss making utilities will face a real challenge in raising resources and attracting talent to implement the changes required in the new environment.

Regulators also need a major push for institutional capacity building. Most of them are constrained in their capacity to annual tariff setting and occasional regulations. For the Regulators, more often than not, caution and conservatism prevails over prudence, because of their lack of resources and institutional capacity. Significant amount of capacity enhancement programs would be required to get the Regulators to a level where they can effectively regulate a market which is much more dynamic.

Besides, the infrastructural issues, the institutional capability enhancement requirement at the utilities would be the most daunting task. With people used to handling flat tariff (except for some customers being subject to fixed TOD tariffs) across the year, to a situation wherein there could be a dynamic pricing is a tall task. The saving grace, much of the task would be taken up by technology once they are implemented.

6 Conclusion

As the electricity sector embarks on this massive task of de-carbonization, it will become more and more distributed and digital. Distributed renewable energy by nature is intermittent. In order to be economically harnessed the grid needs to tap on the inherent flexibilities on the demand and the supply side. VPPs offer both. In spite of the issues, VPP in some form would have to be essentially implemented. It is not a choice.

Laminar Burning Velocity of Biomass-Derived Fuels and Its Significance in Combustion Devices

Atmadeep Bhattacharya and Amitava Datta

Abstract Biomass is considered to be an alternative and renewable energy resource for the sustainable development in future. The most conventional way of deriving energy from biomass is through direct combustion of the fuel. However, the combustion devices directly burning biomass are highly inefficient and result in emission of significant pollutants. Generation of secondary fuels, called biofuels, from biomass and their utilization in various applications can circumvent these limitations. The second generation biofuels can be derived either in liquid or gaseous forms and can be used in devices like engines and burners. When the fuel is burned with oxidizer as a premixed flame, e.g. in a spark ignition engine or on a premixed burner, the laminar burning velocity plays a major role in the propagation or the stabilization of the flame. The structure of the fuel and its reaction kinetics influence the laminar burning velocity. Laminar burning velocity also depends on the equivalence ratio, pressure and temperature of the reactant mixture. In recent times, research is being conducted on laminar burning velocity of biomass-derived fuels or their blends with petro-fuels and oxidizer mixture. Information regarding this fundamental combustion characteristic is essential in designing combustion devices burning biofuels or for retrofitting fossil-fuel based devices using biofuels. The present chapter aims towards reviewing the literature of laminar burning velocity of biomass derived fuels and also explaining the significance of laminar burning velocity in some important combustion applications.

Keywords Laminar burning velocity · Premixed flames · Biofuels
Engine · Burner

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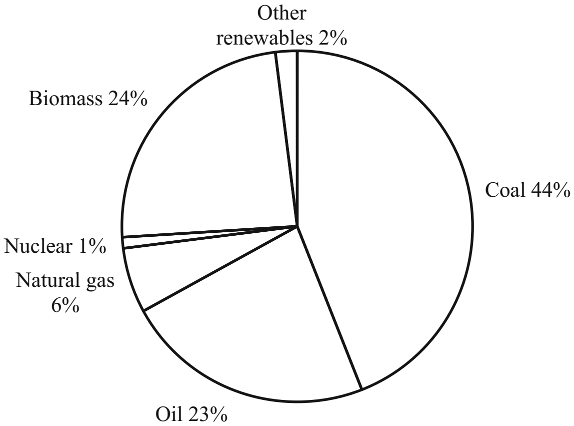
1 Introduction

Laminar burning velocity (LBV) is a fundamental combustion characteristic for premixed flames in various applications. It characterizes the propagation of flame through the premixed fuel/air mixtures and influences the shape, structure and stabilization characteristics of the flame on a burner. It has relevance in all applications involving premixed flames, like spark ignition engines, lean burn gas turbine combustors, premixed burners etc. LBV of a fuel-air mixture depends on the fuel used, the reactant mixture quality, pressure and temperature of the reactant mixture and introduction of additives in the reactant mixture. It is an important combustion parameter for the fuel retrofitting in an existing device as also for the design of new devices with novel fuels.

In recent times, the depletion of fossil fuels and the strict environmental norms in different applications have led to an intense investigation on the novelty in the fuel market. However, the human society is still largely dependent upon the fossil fuels. As a consolidation of this fact, the share of energy resources for Indian energy sector is shown in Fig. 1 [1]. It may be seen from the figure that the sector is dominated by the fossil fuels, like coal, petroleum oil and natural gas. The share of biomass, as depicted in the figure, is mostly due to its traditional use in rural households, which is quite inefficient and harmful towards the health [2]. The ever growing population of India is causing the energy demand to rise. The dual pressure of increase in demand and decrease in reserve is causing the rise in the price of the fossil based fuels. This fact is evident in Fig. 2, where the demand of petrol (million tons) and its price (INR) have been plotted over the fiscal year range 2002–2014. Therefore, the role of renewable fuels in controlling the fuel price is inevitable in the near future. Moreover, it is an established fact that the renewable energy resources have to play a dominating role in stabilizing the greenhouse gas emission and limiting the global warming to the 2 °C target above the pre-industrial level.

Fig. 1 Share of different fuel resources in the Indian energy sector [1]



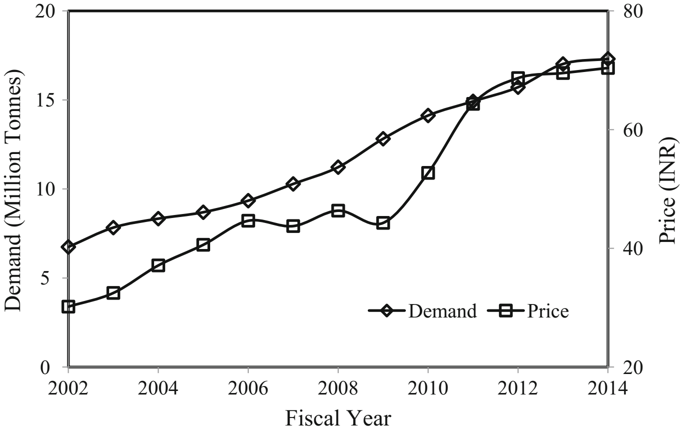


Fig. 2 Variation in petrol demand and price during the fiscal years 2002–2014 in India (*source* Petroleum Planning and Analysis Cell, Govt. of India)

The energy from biomass (i.e. bioenergy) is considered to be renewable, due to the abundance of perennial bio resources, and carbon neutral, due to their ability to re-absorb the carbon emitted from combustion of the same. Moreover, unlike some other renewable resources, the temporal variability of biomass resources is limited. Thus fuels derived from biomass can be important in the future to replace the fossil fuels, at least in some application sectors.

Biomass is presently the fourth largest energy resource behind petroleum, coal and gas and the market of biomass fuel is fast growing around the world. Some literature predicts the share of bioenergy in total primary energy to be as high as 35% of the total primary energy by 2050 and 50% by 2100 [3]. The transportation sector, which is the second largest carbon dioxide emitter behind electricity and heat [4], has a high potential to use biomass based fuels. At present, the sector is almost entirely driven by the petroleum products. However, in the past decade, there has been an impetus among the scientific community regarding the exploration of novel biomass derived transportation fuels (i.e. biofuels) and studying their properties [5–7]. Various studies have been done to investigate the in-vehicle performance of biofuels in comparison to the conventional petro-fuels and to evaluate the carbon savings [8]. In this respect, laminar burning velocity is an important combustion property for the development of fuels for the existing engines and also in the design of the new engines for novel fuels. The flame propagation and abnormal combustion in spark ignition engines are guided by the laminar burning velocity. On the other hand, in case of gas turbine combustors and flame burners the flame stabilization is influenced by the laminar burning velocity of the reactant mixture.

2 Bioenergy Resources and Biofuels

The bioenergy resources are diverse in nature as depicted in Fig. 3 [9]. From a broader perspective, the biomass used for producing transportation fuels can be classified into first generation, second generation, third generation and fourth

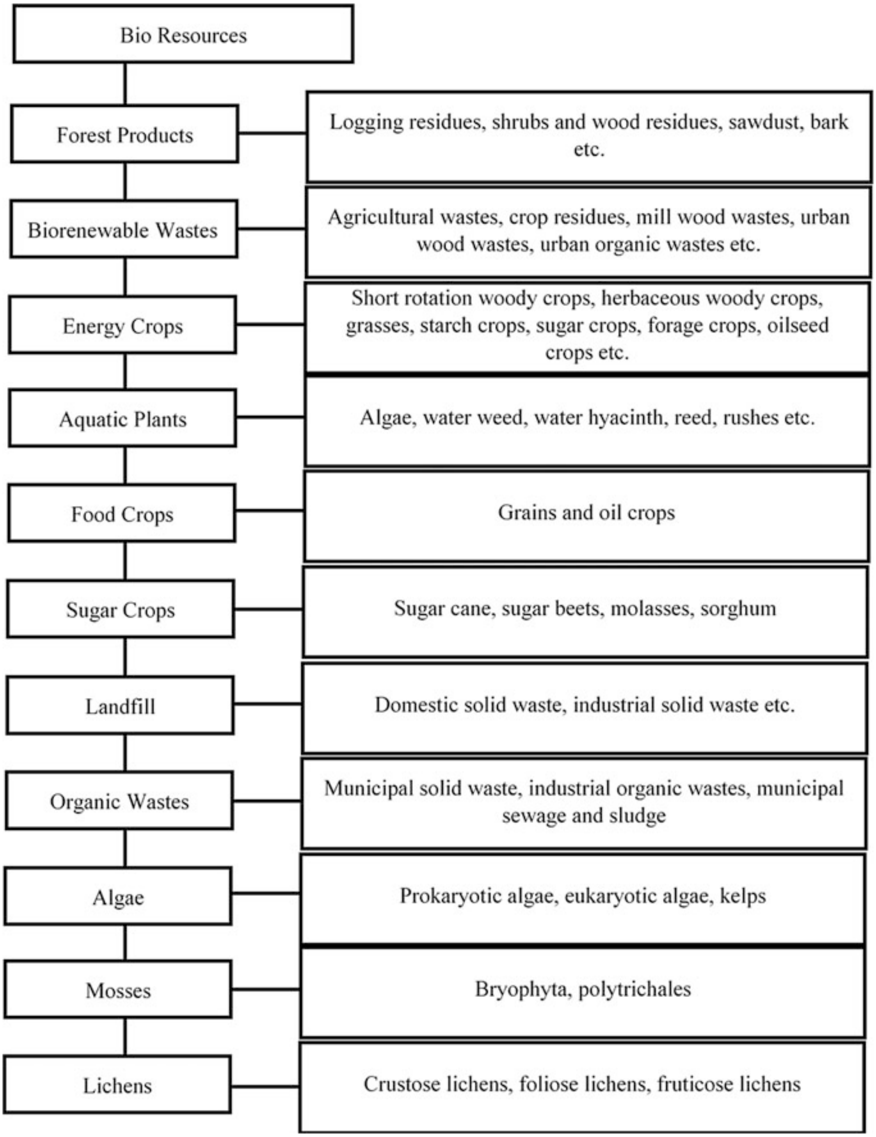


Fig. 3 Diverse resources of biomass based fuels [9]

generation bio resources [10]. The first generation bio resources are also food sources, like starch, sugar, animal fats and vegetable oil. Two of the most popular contemporary first generation biofuels are bioethanol and biodiesel. For the production of bioethanol, the starch in food grains, like wheat, is fermented. On the other hand, the transesterification of vegetable oil, like sunflower oil and soyabeen oil, is the common method to produce biodiesel [9]. Bioethanol is blended with gasoline to use in spark ignition engines as it is a high octane product. Biodiesel in general can be used in compression ignition engines mostly as a blend with diesel. However, the first generation bio resources have a direct conflict with the food supply and increase considerable carbon footprint [11]. Hence, a better option lies in the second generation bio resources, which are primarily inedible biomass resources like switchgrass, jatropha, rice straw etc. The third generation bio resource, which is aquatic algal biomass that does not occupy land, is another viable option. A very useful review about this topic can be found in the work of Alaswad et al. [12]. The algal biomass can be classified into two categories, viz. seaweed and microalgae. In their natural habitat, seaweeds grow on rocky substrates and sometimes on sand particles. They have multi-cellular structures and exhibit land based plant like characteristics. Their cultivation is easy and cost effective and with higher production rate than microalgae. On the other hand, microalgae are microscopic organisms, which are smaller than 0.4 mm in size. The photosynthetic efficiency for microalgae is much higher than most of the land based crops [13]. For the fourth generation bio resources, the lipid content and the carbon absorbability of the algae are enhanced using genetic modifications. The higher lipid content is utilized for biodiesel production. The life cycle of fuel production for the fourth generation bio resource is the shortest among all four variants of bio resources [14].

Since there are numerous types of biofuels processed from a variety of bio resources, a summary of them is given in Table 1. The conversion of the bio resources to biofuels can be done either through biochemical or thermochemical routes. The biochemical conversion process involves the use of bacteria, microorganisms and enzymes for converting biomass into gaseous or liquid fuels (like biogas and bioethanol). Biogas is commonly produced by anaerobic digestion of animal manure mixed with water as the input. The mixture is stirred and warmed inside an airtight container, which is known as a digester. Inside the digestor, the anaerobic

Table 1 Different types of biofuels [9]

Type	Biomass feedstock	Example
1st generation	Sugar, starch, vegetable oils, animal fats	Bioalcohols, biodiesel, biosyngas, biogas
2nd generation	Non-food crops, wheat straw, corn, wood, solid waste, energy crops	Bioalcohols, bio-DMF, biohydrogen, bio-Fischer–Tropsch diesel, wood diesel
3rd generation	Algae	Biogas, biodiesel
4th generation	Genetically engineered algae	Bioisoprene, bioethanol, biodiesel

microorganisms digest the raw biomass and generate methane and carbon dioxide as the output. Bioethanol is produced through fermentation of biomass feedstock that is rich in starch. Bioethanol can also be produced from lignocellulosic biomass following a pre-treatment to separate the carbohydrate polymers (cellulose and hemicelluloses) from lignin. However, delignification of the lignocellulosic raw materials is the rate-limiting and the most difficult task in the process. A state of art review on the subject of bioethanol production can be found in [15, 16].

The thermochemical conversion route of biomass fuel can be sub divided into categories like direct combustion, pyrolysis, liquefaction and gasification. It is believed that globally about 2.8 billion people rely on the direct combustion technique of biomass [17]. However, the direct combustion of biomass is associated with low efficiency of conversion and numerous health hazards [18–20]. In pyrolysis, the biomass is heated in absence of air to produce a liquid biofuel with high conversion efficiency. The bio-oil, thus produced, can be used in engines and turbines. However, the process is restricted due to poor thermal stability and high corrosivity of the fuel. Liquefaction is the conversion of the biomass resource into a stable hydrocarbon liquid fuel at low temperature and high hydrogen pressure. Gasification of biomass is a developed technology where the feedstock is converted into a gas mixture by partial oxidation at high temperature. The gas mixture, known as producer gas or syngas, contains hydrogen and carbon monoxide as the major combustible components and can be used as a fuel in engines and gas turbines.

3 Laminar Burning Velocity

Laminar burning velocity (LBV) is an important intrinsic property of a combustible reactant mixture, producing a laminar premixed flame. It is the velocity of the reactant mixture with respect to the flame at the flame surface in a direction normal to the flame surface. Thus in a one-dimensional flame assumed to be established in a tube with the reactant flowing at a velocity v_u and the flame moving with a velocity v_f, both towards the exit of the tube, the laminar burning velocity (S_L) is given as, $S_L=(v_u - v_f)$. The LBV is a function of the flame stretch, fuel molecule structure, oxidizer, equivalence ratio (which defines the quality of the mixture), pressure and temperature of the reactant mixture etc. Thus the stabilization or movement of the flame in the tube is entirely dependent on the velocity of the reactant mixture. When the reactant mixture flows with a velocity equal to the LBV (i.e., $v_u = S_L$) the flame becomes stationary in the tube and v_f is equal to zero. On the other hand, when $v_u \neq S_L$ the flame moves either towards the entry or the exit side of the tube, depending upon the velocity which is greater. However, the actual mechanism of stabilization and propagation of flame in the tube is not so simple as the velocity of the reactant mixture flowing through the tube bears a profile and the burning velocity near the tube wall drops down to zero due to quenching. Likewise, the shape and structure of a flame on a burner (e.g. Bunsen burner) is also dependent on the laminar burning velocity of the fuel-air mixture issued from the burner. The stabilization of the flame is characterized by the comparison of the flow velocity and the burning velocity. When the flame does not stabilize due to mismatch of the two velocities, it can either flash back inside the burner tube or blows off above the burner.

The mass burning flux in a premixed flame is directly proportional to the laminar burning velocity. Hence, a high laminar burning velocity represents higher mass burning flux, i.e. higher reactivity of the fuel/air mixture and vice versa. Theoretical analyses of different complexities show that the laminar burning velocity is a proportional function of the thermal diffusivity of the reactant mixture and the volumetric mass burning rate of the fuel in the flame zone. Higher laminar burning velocity of a mixture reduces the flame thickness for a fuel-air mixture. There are different methods for measuring the laminar burning velocity. For example, in the combustion bomb method [21, 22], a free, spherically propagating flame is established inside an optically accessible constant volume chamber. The rate of change of flame radius is measured with respect to the flame stretch. Then the unstretched LBV is evaluated using extrapolation to zero flame stretch. In counter flow flame method [23, 24], a twin flame is established between the closely spaced opposed flow burners. As the flow velocity is decelerating near the stagnation flame region, a reference flow speed is defined as the minimum axial velocity upstream of the flame. At the location of this reference flow speed the radial velocity gradient is obtained. This radial velocity gradient "*a*" is related to the axial velocity gradient "*K*" through the relation $K = 2a$. The axial velocity gradient "*K*" is also the flame stretch rate. Based on the variation of the reference flow speed with K, the stretchless LBV can be determined by either linear or nonlinear extrapolation to zero stretch rate. In the diverging mesoscale channel method [25], a planar 1-D flame obtained in the diverging channel is considered for the determination of LBV of certain fuel/air mixture. The flame position is recorded using a camera and the velocity of propagating flame is obtained by the mass conservation equation for the fuel/air mixture. This velocity can be termed as the laminar burning velocity given the flame is adiabatic and stretchless. In the heat flux burner method [26], a stretchless 1-D laminar flame is established for the determination of the adiabatic laminar burning velocity. Egolfopoulos et al. [27] compared the merits of the experimental methods for the study of laminar burning velocity. It was mentioned that the accuracy of the heat flux burner method is by far superior to the other methods.

In the heat flux burner method, a flat flame is established on the burner plate. A schematic top view of the burner plate is shown in Fig. 4a. It may be seen from the figure that the burner plate consists of a fine mesh and about 8 thermocouples at different diametric positions. A hot water jacket of about 80 °C is wrapped around the burner plate. A schematic diagram of the side view of the heat flux burner is shown in Fig. 4b along with the heat balance across the burner plate. In order to obtain the adiabatic laminar burning velocity, the heat loss from the flame (q_f) to the burner plate has to be compensated by the heat gained by the unburnt gases from the burner plate (q_b). The heat flux from the burner to the unburnt gas (q_b) is aided

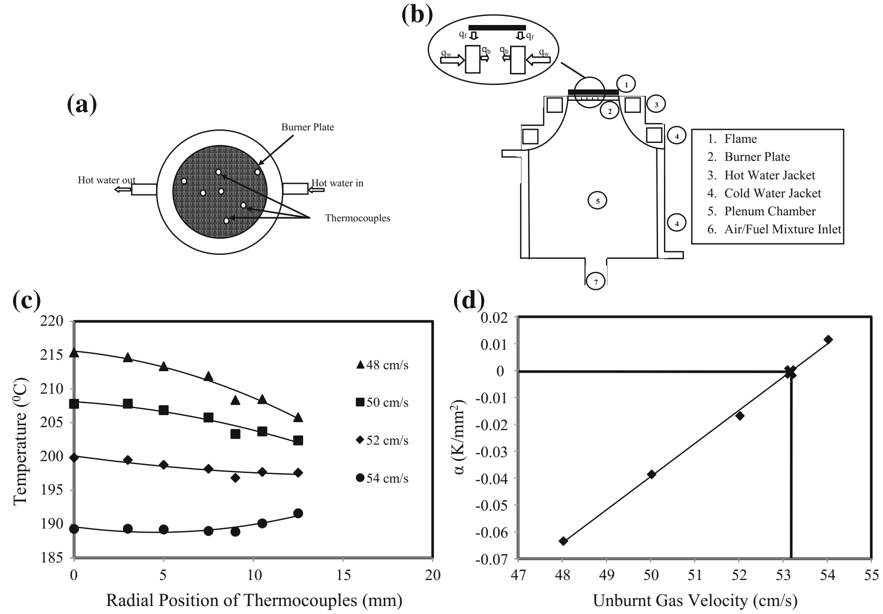


Fig. 4 **a** Top view of the heat flux burner plate, **b** side view if the heat flux burner, **c** variation of the temperature distribution on the burner plate surface for different unburnt gas velocities, **d** variation of "α" with unburnt gas velocity for the determination of the adiabatic laminar burning velocity

by the heat flux from the hot water to the burner plate (q_w). When the unburnt gas velocity is lower than the adiabatic LBV, the flame is established near the burner grid and the heat loss from the flame to the burner plate (q_f) is high. This heat loss (q_f) equals the sum of the heat flow to the jacket water (q_w) and to the unburnt gas mixture (q_b). On the other hand, when the unburnt gas velocity is higher than the adiabatic LBV, the flame remains significantly away from the burner and the heat loss from the flame to the burner plate (q_f) is comparatively lower. In this case, the heat gain by the unburnt gas (q_b) is more than the heat loss from the flame to the burner grid and equals the sum of the latter (q_f) and the heat flow from the heating jacket to the burner grid (q_w). Hence, when q_f is equal to q_b, the net heat loss from the system is zero and the unburnt gas velocity is considered as the adiabatic laminar burning velocity. The difference between the heat loss by the flame and heat gain by unburnt gas is responsible for temperature distribution on the burner plate. This temperature distribution is recorded by the thermocouples. The diameter of the thermocouple tip equals the diameter of a single hole in the burner plate.

For the purpose of determining the adiabatic LBV, different unburnt gas flow velocity has to be set and the temperature distribution across the burner grid is noted for each case. The recorded temperatures have to be fitted in a function: $T(r) = T_c + \alpha r^2$, where $T(r)$ denotes the temperature on the burner plate at any radius *r*, T_c denotes the temperature at centre and α is the parabolic coefficient (Fig. 4c). It can be proved mathematically that "α" is directly proportional to the net heat loss from the flame [26]. Next, the values of α evaluated for different temperature distributions are plotted against the corresponding unburnt gas velocities (Fig. 4d). The value of the unburnt gas velocity corresponding to $\alpha = 0$ is obtained by interpolation. This condition reflects zero heat loss from the system and theoretically corresponds to a horizontal temperature profile. Hence, the unburnt gas velocity corresponding to $\alpha = 0$ is the adiabatic laminar burning velocity.

It may be mentioned, however, that in most of the practical combustion devices the flame establishes as a turbulent one. A turbulent premixed flame has wrinkled structure with the formation of several twists and bends at the flame front. The propagation of turbulent flame is also much faster compared to the laminar one. Literature correlates the burning velocity of a turbulent flame as a function of the laminar burning velocity of the reactant mixture and the intensity of turbulence in the flow [28]. Therefore, laminar burning velocity has its relevance in the turbulent premixed flame propagation and stabilization as well.

3.1 Laminar Burning Velocity of Different Biofuels

The determination of laminar burning velocity of different biofuels is a popular field of research among the combustion fraternity in recent time. The gaseous biofuel that has been studied most extensively with respect to laminar burning velocity is the syngas. A useful review on this subject may be seen in the work of Lee et al. [29]. The primary constituents of syngas include hydrogen and carbon monoxide. Since syngas is obtained through the gasification of different types of biomass or coal, its composition varies. Therefore, in the above mentioned review work, it has been observed that the laminar burning velocity also varies over a wide range depending upon the composition of the syngas. The variation of the laminar burning velocity of syngas with varying hydrogen and carbon monoxide ratio and equivalence ratio (φ) are shown in Fig. 5a. The experimental data have been taken from the work of Bouvet et al. [30] for the H_2 mole fraction varying between 0.05 and 0.5 in the H_2/CO blend. Moreover, the experimental data for H_2 mole fraction 0.6 and 0.8 have been taken from the work of Fu et al. [31]. The experimental data of Bouvet et al. [30] have been compared with the numerical simulation results using the chemical kinetic mechanism proposed by Goswami et al. [32]. Figure 5b shows the variation of the LBV of syngas/air mixture with equivalence ratio at different unburnt gas temperature and atmospheric pressure. The composition of the syngas has been assumed to be an equimolar mixture of H_2 and CO. The experimental data have been taken from the work of Natarajan et al. [33]. In this case also the experimental results have been compared with the numerical predictions made by using the above mentioned chemical kinetics [32]. It may be seen from both Fig. 5a and b that the kinetic mechanism performs quite well in predicting the laminar burning velocity except for the high temperature region where there is a

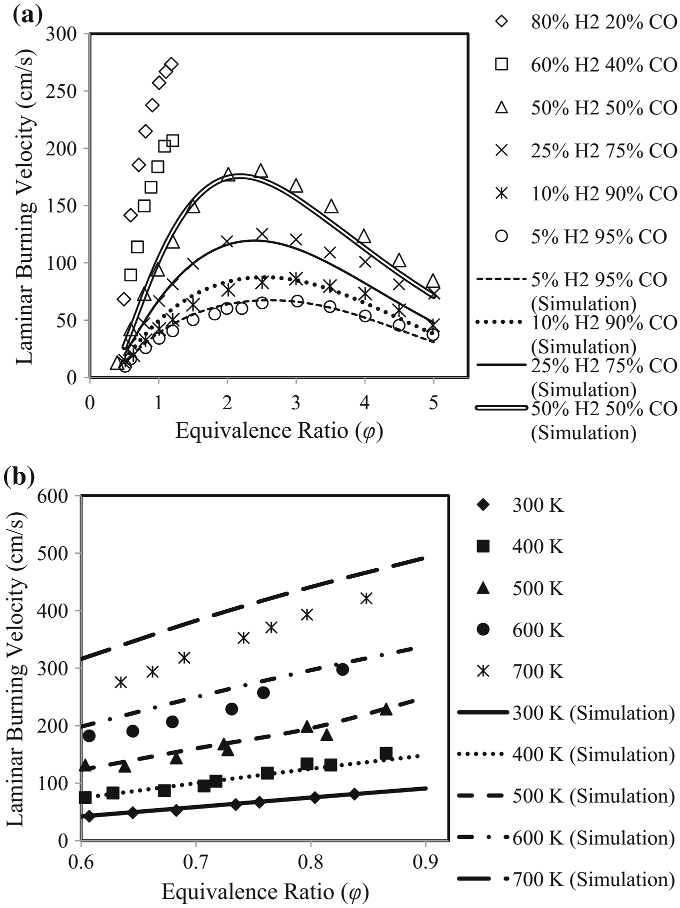


Fig. 5 Variation of laminar burning velocity with equivalence ratio for **a** different composition of syngas in air [30, 31]. The unburnt gas temperature and pressure are 298 K and 1 atm respectively. **b** Different unburnt gas temperatures at atmospheric pressure for syngas (H_2:CO 1:1) in air. The symbols represent experimental data [33] and the lines numerical simulation results

slight over prediction. The LBV of a particular fuel in air is also dependent upon the pressure. The literature shows that the LBV decreases with increase in pressure for almost all fuel/air mixtures at a particular unburnt gas temperature. The temperature, pressure, equivalence ratio, fuel type and the amount of diluent gas dependence of LBV has been summarized in the following correlation by Metghalchi and Keck [34].

$$LBV = LBV_0\left(\frac{T_u}{T_0}\right)^{\alpha}\left(\frac{p_u}{p_0}\right)^{\beta}(1-\gamma Y_{dil}) \qquad (1)$$

where the subscript “0” refers to the reference condition, T_u and P_u are the unburnt gas temperature and pressure respectively and Y_{dil} is the mole fraction of the diluents in the combustible mixture. The variables α, β and γ are fuel specific functions of equivalence ratio and fuel composition [35].

For syngas/air mixture, it is worth mentioning that hydrogen as a fuel shows the highest reactivity among the gaseous fuels at a particular unburnt gas temperature and pressure. This fact can be attributed to the high thermal diffusivity of the gas. Hence, it may be seen from Fig. 5a that the laminar burning velocity of the fuel/air mixture increases with the increase in hydrogen content in the fuel. However, since gasoline burns far more slowly than hydrogen [36], the hydrogen based fuels, like syngas, can be unsuitable for the state of art gasoline engines unless some corrective measure is taken. As a result of this fact, the alcohol based fuels have lately gained popularity.

The comparison of the laminar burning velocity at different equivalence ratios of some alcohols up to C_4 are shown in Fig. 6 along with that of gasoline/air mixture. The experimental data are taken from the works of Veloo et al. [37], Veloo and Egolfopoulos [38] and Dirrenberger et al. [39]. It may be seen from the figure that in the lean stoichiometry region, the laminar burning velocity of all four alcohols is quite close to the corresponding values for the gasoline/air flame. This fact, along with the miscibility with gasoline and the ease of production are the driving forces behind the popularity of ethanol as an SI engine fuel. On the other hand, the laminar burning velocity of methanol—having the simplest molecular structure among

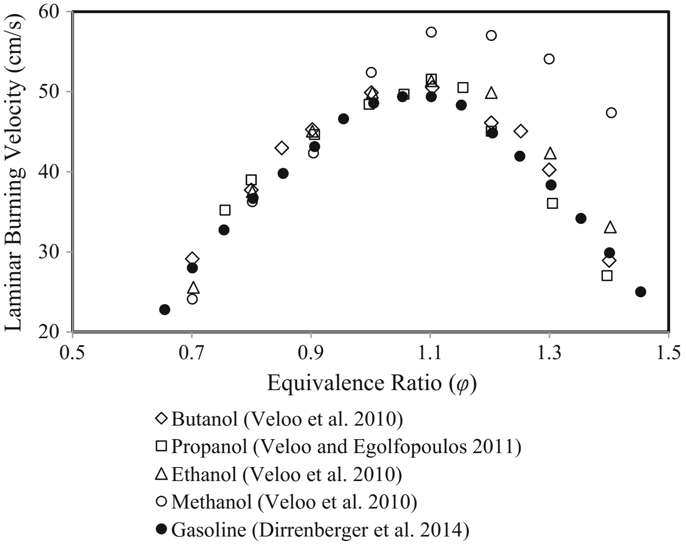


Fig. 6 Variation of laminar burning velocity of alcohol/air and gasoline/air flames with equivalence ratio at atmospheric pressure. The unburnt gas temperature is 343 K for alcohol and 358 K for gasoline. The experimental data are taken from three different literatures [37–39]

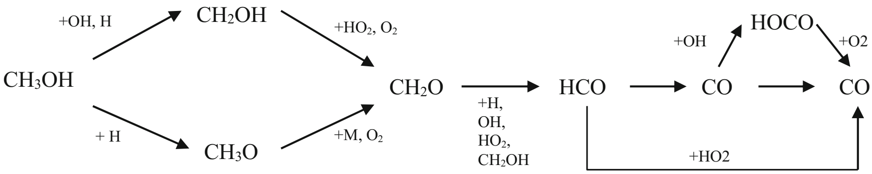


Fig. 7 The high temperature reaction path diagram for methanol oxidation [41]

biomass derived alcohol fuels—is relatively higher than gasoline, particularly in the richer side of the stoichiometry. It has been clearly mentioned by Sarathy et al. [40] that the laminar burning velocity is governed by the high temperature chemistry of the fuel/air mixture. Aranda et al. [41] have demonstrated a relevant reaction path diagram, which is recreated here in Fig. 7, in this regard. It may be seen from the reaction path diagram that the methanol molecules readily break down to formaldehyde. The primary cause behind the formaldehyde formation is the β-scission breakup of the initial methanol decomposition products like hydroxymethyl (CH_2OH) and methoxy (CH_3O) radicals. The formaldehyde radical gives rise to the highly reactive H and OH radicals. These radicals are believed to increase the laminar burning velocity of the fuel/air mixture in general [36].

As mentioned earlier, the alcohols, especially ethanol, are the first generation biofuels. Moreover, all the alcohols have a tendency to get diluted through absorption of water. This factor along with the low calorific value of alcohols is considered to be strong drawbacks of these fuels. The state of art literature considers furan derivatives to be the better candidates to replace gasoline due to their higher calorific value than alcohols and almost zero propensity towards water. In Fig. 8, the laminar burning velocities of four furan derivatives are compared against gasoline (isoocatne). The experimental data are taken from four different literatures [42–45]. It may be seen from the figure that the laminar burning velocity of 2,5-dimethylfuran/air mixture is the closest to that of gasoline/air mixture in the near stoichiometric region. Hence, this particular furan derivative is gaining attention in the engine research community.

3.2 Significance of Laminar Burning Velocity

The laminar burning velocity as a combustion parameter has many significant aspects. It is a key parameter in the design and simulation of the combustion devices such as internal combustion engines, gas turbine combustors and various gas burners. Most engine combustion models assume the flame structure inside the combustion chamber to be that of a stretched laminar flame, with the effects of the in-cylinder turbulence that stretches and wrinkles the flame. Hence the flame area is increased. Therefore, data on the laminar burning velocity and its dependence on pressure, temperature, mixture composition and stretch rate are prerequisites for the

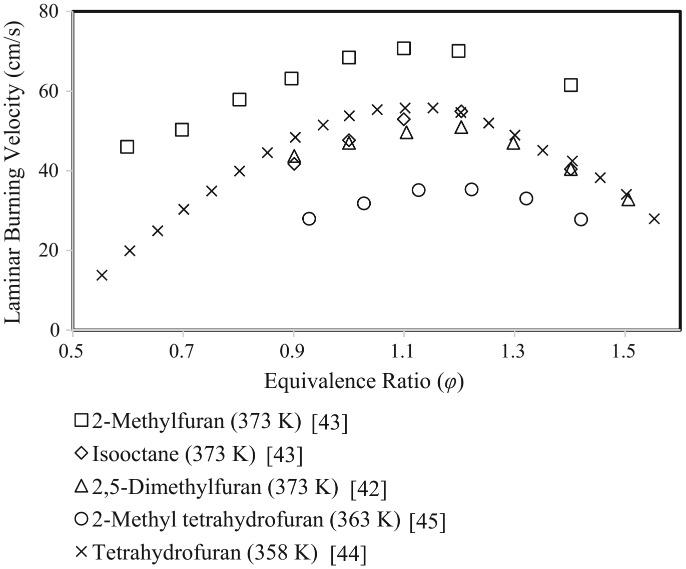


Fig. 8 Variation of laminar burning velocity of furan derivatives in air and isooctane/air flames with equivalence ratio at atmospheric pressure. The experimental data are taken from four different literatures [42–45]

engine combustion models. As mentioned earlier, an increased laminar burning velocity results in the faster burning of the fuel/oxidizer mixture inside the combustion chamber and the vice versa. As a consequence of this, Bayraktar and Durgun [46] observed that the liquefied petroleum gas resulted in higher cylinder pressure and temperature compared to gasoline when used in the same SI engine. Pourkhesalian et al. [47] developed a model to predict the performance and emission of an SI engine running on alternative fuels like hydrogen, propane, methane, ethanol and methanol. In this work, the authors pointed out that it is mandatory to use correlations for the laminar burning velocity of the respective fuel/air mixture for the model to produce acceptable results. If the laminar burning velocity is higher, the possibility of heat dissipation from the flame is lower and the heat loss from the flame is reduced. Abedin et al. [48] studied this aspect for the application of fuels like alcohols, hydrogen and liquefied petroleum gas in the internal combustion engine. In their study, it was observed that blending hydrogen with gasoline reduces the heat loss from the engine. The cause of this fact can be attributed to the higher laminar burning velocity of hydrogen compared to gasoline. Similar effect was seen for alcohol based fuels and liquefied petroleum gas due to the same reason as above. Moreover, the lower heat dissipation due to faster burning velocity causes the equivalence ratio range for stable combustion to widen.

In the same manner, higher laminar burning velocity provides greater tolerance for exhaust gas recirculation. Park et al. [49] have shown that the laminar burning velocity of the fuel/air mixture contributes significantly towards the hydrocarbon and NO_x emissions. In this study, a blend of biogas and hydrogen was investigated as the fuel. The results showed that the higher laminar burning velocity of hydrogen contributed towards better combustion stability in the presence of inert gas dilution when the exhaust gas is recirculated. However, inert gas dilution slows down the laminar burning velocity of a particular fuel/air mixture. Therefore, it was reported in the work by Razus et al. [50] that the inert gas dilution increases the heat loss from the engine. On the other hand, there are certain drawbacks for the increase in laminar burning velocity as well. In this regard, it is worth mentioning that super knock is a phenomenon that causes higher engine damage compared to conventional knock due to higher pressure fluctuations. During super knock, pre-ignition of the fuel/air mixture occurs prior to the actual sparking in the cylinder [51]. The cause of the pre-ignition can be attributed to the presence of hot spots inside the cylinder. Therefore, pre-ignition cannot be suppressed by conventional knock prevention measures like spark retardation. Some of the key components considered as potential hot spots are the spark plug, exhaust valves, piston edges etc. [52]. It can be easily comprehended that the decrease in the heat loss due to high laminar burning velocity can result in the generation of hot spots inside the combustion chamber. As a consolidation of this fact, Kalghatgi and Bradley [53] have shown a reciprocal relationship between the pre-ignition rating, which signifies the resistance to pre-ignition, and the maximum LBV for fifteen different fuels in air. The data are plotted in Fig. 9. The authors have collected the experimental data on pre-ignition rating from three different literatures [54–56]. The laminar burning velocity data correspond to unburnt gas pressure of at 3 bar and unburnt gas temperature of 450 K. It may be seen from the figure that the relationship is quite linear with $R^2 = 0.85$.

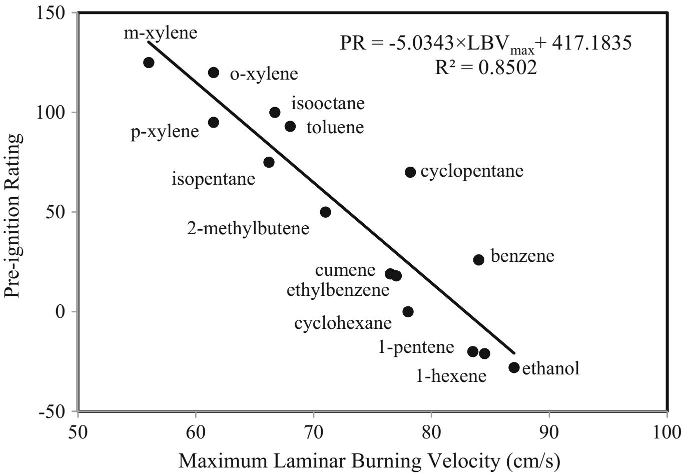


Fig. 9 Variation of pre-ignition rating with the maximum laminar burning velocity for different fuels in air [53]

The laminar burning velocity is an important parameter for gas turbine combustors as well. The flame height above the burner inside the combustor is greatly influenced by turbulent burning velocity, which in turn is a proportionate function of the laminar burning velocity [57]. For lower burning velocity, the flame tends to stabilize at a greater distance from the burner surface. As a result, the heat loss to the solid burner surface gets reduced. Therefore, it may be understood that the heat load on the solid surfaces of the combustor and the recirculating zone is a function of the laminar burning velocity of the fuel/air mixture. A common method to shorten the flame length by inducing more turbulence in the combustion chamber is to use swirlers. A shorter flame results in a more compact design of the combustor. However, the introduction of the swirler significantly slows down the axial velocity of the fuel/air mixture. Moreover, the turbulence caused by it increases the burning velocity. The combination of these two factors can lead to flashback [58]. Flashback is said to take place when the flame propagates from the combustion chamber to the premixing part of the combustor. The phenomenon significantly increases the temperature inside the premixer beyond its endurance limit. It is believed that the fuels with high laminar burning velocity (e.g. hydrogen) are more prone to cause flashback. A proof of this fact can be comprehended from Fig. 10 [59]. In this figure, the equivalence ration corresponding to flashback is plotted as a variable of unburnt gas temperature at 10 bar pressure. The fuel considered in this case is syngas with composition H_2:CO 1:1 by mole. The linear decrease in the equivalence ratio signifies the increase in flashback tendency with the increase in unburnt gas temperature. It has already been shown on Fig. 5b that the increase in the unburnt gas temperature results in the increase in the LBV also. Therefore, from Figs. 5b and 10, it can easily be concluded that the increase in flashback tendency is primarily due to the increase in the LBV of the syngas/air mixture when the unburnt gas temperature increases.

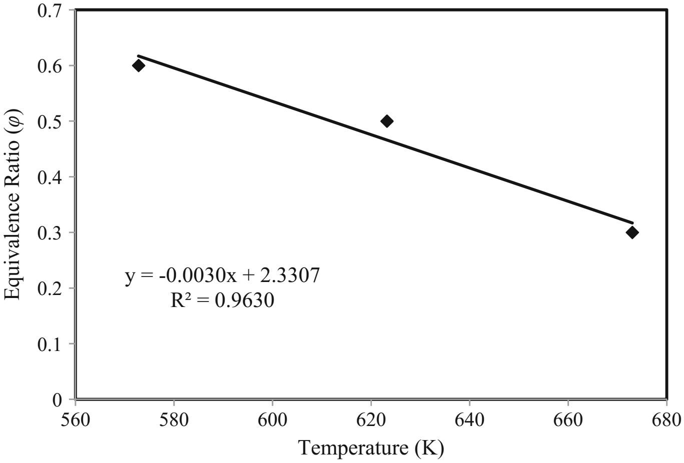


Fig. 10 Variation of the equivalence ratio corresponding to flashback with the unburnt gas temperature at 10 bar pressure. The experimental data have been taken from Daniele et al. [59]

Apart from being a highly influential parameter for practical combustion devices like internal combustion engines, gas turbine burners etc., the laminar burning velocity is considered as one of the key parameters for the purpose of validation of combustion chemistry of different fuel/oxidizer mixtures. For example, the well-known GRI-Mech 3.0 [60] mechanism for the simulation of the natural gas/air flames has been validated against eight sets of experimental values of laminar burning velocity data [61–64]. The Chemical Reaction Engineering and Chemical Kinetics group at Politecnicodi Milano, Italy have recently validated their gasoline surrogate mechanism [65] with different sets of experimental data on laminar burning velocity. Cai and Pitsch [66] have validated their gasoline surrogate mechanism against the experimental laminar burning velocity data from three different works [67–69]. Zhou et al. [70] have recently proposed a combustion kinetic mechanism for isobutene. In this work, the mechanism has been compared with the laminar burning velocity data at different unburnt gas temperature and atmospheric pressure. Among the biomass based fuels, Frassoldati et al. [71] proposed a chemical kinetic mechanism for the simulation of syngas/air flames. This mechanism was validated using experimental data on laminar burning velocity at different unburnt gas temperatures and pressures from a wide range of works. In the work of Ranzi et al. [72], comparison of the proposed kinetic model prediction and experimental data on laminar burning velocity of different liquid biofuels, like methanol and ethanol, can be found. Dooley et al. [73] proposed a kinetic mechanism for the oxidation of methyl formate, which is an intermediate during the combustion of dimethyl ether combustion in air. This chemical kinetic mechanism has been validated against the laminar burning velocity data at unburnt gas temperature of 295 K and atmospheric pressure.

4 Conclusion

The importance of biomass as a fuel resource is increasing with time. However, the utilization of biomass as a fuel resource should be done in a way so that the food security remains intact. Therefore, the bio resources have been divided into four categories, viz. 1st, 2nd, 3rd and 4th generation bio resources. Different types of biofuels that are gaining popularity among the combustion community include syngas, alcohols, furan and its derivatives etc. Before a fuel is applied to the engine, its combustion characteristics need to be evaluated. The laminar burning velocity is one of the most important combustion parameters in premixed flame applications. The state of art literature shows numerous works on the evaluation of laminar burning velocity of different biofuels. While syngas shows high values of laminar burning velocity due to the presence of hydrogen in it, the corresponding values for the C_1-C_4 alcohols are quite close to the gasoline laminar burning velocity. In particular, the laminar burning velocity of ethanol is the nearest to that of gasoline. Similarly, among the furan derivatives, the laminar burning velocity of 2,5-Dimethylfuran is the closest to the corresponding values for gasoline. There is no reported experimental data on the laminar burning velocity of furan/air mixtures till date. The laminar burning velocity strongly influences the heat loss, super knock and flame stability characteristics in an internal combustion engine. For the design of burners, the flame height above burner and the flash back phenomena are heavily dependent upon the laminar burning velocity of the fuel/oxidizer mixture. Apart from this, the laminar burning velocity is considered to be a mandatory parameter in evaluating the performance of the chemical kinetic mechanism for a particular fuel/oxidizer mixture.

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An Unsteady Model to Study the Effects of Porosity and Temperature in All-Vanadium Redox Flow Battery with Mass Transfer and Ion Diffusion

H. M. Sathisha and Amaresh Dalal

Abstract The crossover of vanadium ions through membrane in vanadium redox flow battery after many cycles leads to capacity loss of the cell. Different membrane materials show different diffusion behavior which results in variation in the cell potential response. The diffusion coefficients of the membrane is temperature dependent, therefore, concentration profile varies with temperature. The model has considered the effects of crossover of vanadium ions through membrane and mass transfer. The present model predicts the capacity loss for different membrane materials. The simulation results show that reaction rate constants and diffusion coefficients depend on temperature and these affect the cell performance. The results show that for Selemion AMV and Selemion CMV membranes capacity loss increases linearly at different temperatures and porosity with increase in number of cycles. In the case of Nafion 115 membrane the capacity decays up to 77 cycles and then it stabilizes.

Keywords Mass transfer · Crossover · Porosity · Temperature
Cell potential

1 Introduction

Redox flow batteries are more popular because they offer various advantages. The advantages are high energy efficiency, elimination of electrolyte cross-contamination, long cycle life, active thermal management, low cost for large energy storage systems, etc. [1, 2]. One more important feature of redox flow batteries is that the flexibility of power and capacity design of a battery are not

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coupled which makes it efficient design of the battery configurations. Therefore, the redox flow batteries are suitable for the applications of peak shaving, load leveling, grid integration and frequency regulation [1–5]. Compared to other flow batteries, all-vanadium redox flow battery (VRFB) is more popular because there is no problem of electrolyte cross-contamination due to the fact that both the half cells of the battery employ different species of vanadium in the electrolyte. As a result electrolyte lifetime is considerably increased. Also it is found that from VRFB the disposal of vanadium ions will not create any environmental issues in comparison with conventional lead acid battery.

A VRFB has vanadium ions reacting in two half cells of the battery, each cell being separated by an ion exchange membrane which only allows proton ions to pass through to make charge balance. An ideal proton exchange membrane should possess chemical stability, good conductivity, and also control the flow of vanadium ions from negative half cell to positive half cell or vice versa.

After using VRFB for many cycles the performance reduces due to ion diffusion of vanadium ions pass through membrane. Therefore, a lot of research is going on to improve performance and maintain the capacity for long term cycling. It was found that no membrane gives 100% performance [6], there will be vanadium ions diffusion through membrane from negative half cell to positive half cell and vice versa. Due to diffusion of vanadium ions, the vanadium concentration of one half cell increases and the other half cell vanadium concentration decreases, which results in performance loss of the cell. Due to self discharge reactions, capacity of the cell decreases and this can be restored by remixing the vanadium ions to both half cells periodically. Also there is oxygen and hydrogen evolution side reactions taking place inside the cell, which results in capacity loss, to restore the capacity it requires electrochemical rebalance. Several researchers proposed few approaches to overcome the performance loss for different operating conditions of the cell. Studies have shown that crossover of vanadium and water through membrane reduce the coulombic efficiency and capacity. Numerical model has been developed to study the effect of self-discharge for VRFB [7]. Two-dimensional isothermal numerical model including the effect of crossover and water through membrane shows the capacity loss of the battery [8]. Tang et al. [9] developed a model in which the approach is based on molar mass balance simplified equations for studying self discharge process and they studied the effect of diffusion coefficients, flow rate and concentration of hydrogen ions. Same model is extended by adding the energy balance equation, model predicts capacity loss and temperature of electrolyte for a Nafion 115 membrane [10]. The model employed Arrhenius equation to model the temperature dependent diffusion coefficients of membrane. Badrinarayanan et al. [6] studied the model for ion diffusion and the effects of temperature and electrolyte transfer. One more model is developed for the self discharge process of the vanadium redox flow battery [11], the model includes mass transfer and vanadium ions crossover through the membrane, they showed the effects of temperature on crossover.

The present simulation is based on model developed by Yu and Chen [11], including the effects of mass transfer and crossover of vanadium ions through membrane. The effects of temperature on diffusion coefficients and effects of porosity on concentration for different membrane materials using this model have not been studied so far. Three membranes are used in the simulation which includes Selemion CMV, Selemion AMV and Nafion 115 membrane. These membranes are available in the market and most of the researchers are used in their experiments and numerical simulation [9]. The main difference between these membrane materials is the difference in diffusion coefficients. Due to the variation in diffusion the crossover of vanadium ions also varies for different membrane materials.

2 Principles of Operation and Model Assumptions

VRFB includes three major components as shown in Fig. 1a: (i) two porous electrodes that act as active sites for redox reactions, (ii) liquid electrolytes that include of different vanadium ions dissolved in sulphuric acid solution, and (iii) a proton exchange membrane that serves as a separator to prevent the cross-over of the vanadium ions from both the positive and the negative half-cells.

The following main electrochemical reactions taking place at each electrode

At the negative electrode

$$V^{3+} + e^{-} \rightleftharpoons V_2^{+} \tag{1}$$

At the positive electrode

$$VO^{2+} + H_2O - e^{-} \rightleftharpoons VO_2^{+} + 2H^{+} \tag{2}$$

The following are the self-discharge reactions occurred at each of the electrode

At negative electrode

$$V^{2+} + VO^{2+} + 2H^{+} \rightarrow 2V^{3+} + H_2O \tag{3}$$

$$2V^{2+} + VO_2^{+} + 4H^{+} \rightarrow 3V^{3+} + 2H_2O \tag{4}$$

$$V^{3+} + VO_2^{+} \rightarrow 2VO^{2+} \tag{5}$$

At positive electrode

$$2VO_2^{+} + V^{2+} + 2H^{+} \rightarrow 3VO^{2+} + H_2O \tag{6}$$

$$VO_2^{+} + V^{3+} \rightarrow 2VO^{2+} \tag{7}$$

$$VO^{2+} + V^{2+} + 2H^{+} \rightarrow 2V^{3+} + H_2O \tag{8}$$

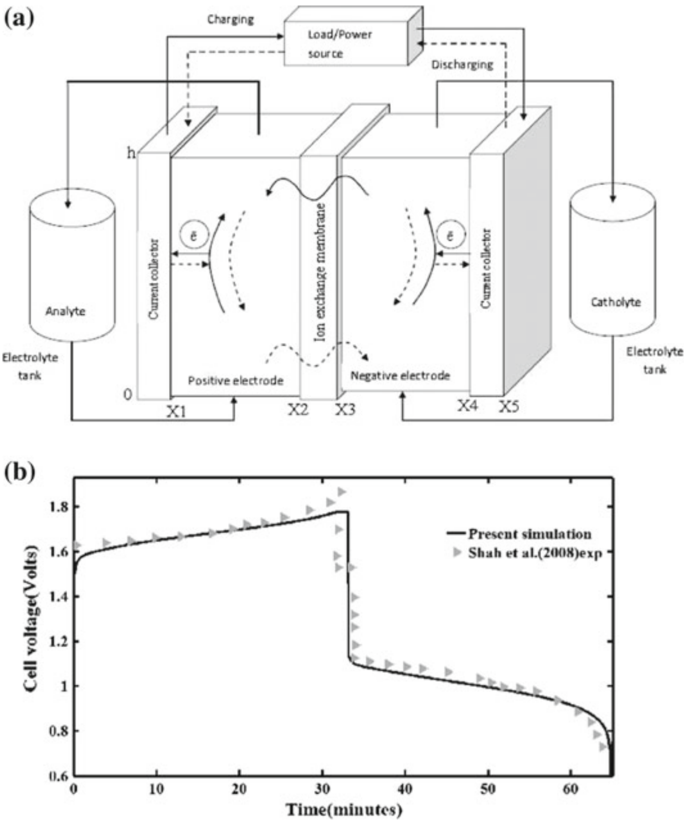


Fig. 1 **a** Schematic of the all-vanadium redox flow battery showing the components, current collectors, porous electrodes, membrane and reservoirs. **b** Comparison between simulated and experimental cell voltage variation. The vanadium concentration was 1200 mol/m^3, the current density was 1000 A/m^2, the cell temperature was 297 K and the flow rate was 1×10^{-6} m^3/s

After many cycles, concentration imbalance takes place in the battery due to difference in diffusion rates of vanadium ions. Vanadium crossover occurs between two half cells through membrane which results in loss of performance of cell [9]. Water crossover affects on the overall concentration of vanadium in both half of cell. Here water crossover is neglected and this can be overcome by approximating the effective diffusion coefficient of vanadium species.

The following are the assumptions considered for simplifying the equation.

1. Apart from oxidation-reduction reactions there will be hydrogen and oxygen gas evolving reactions occur under normal conditions [12, 13].
2. Vanadium ions are diffused through the membrane and react instantaneously; therefore side reactions are considered.
3. Water crossover is neglected due to difficulty in predicting the electro-osmatic drag and osmosis by lumped model.

3 Model Equations

The equations are based on law of conservation of mole for vanadium species in the electrodes and reservoir volumes of each half cell. Due to diffusion in the membrane, the concentration of vanadium changes in the porous electrode by recirculation of electrolytes between the reservoir and electrode and externally applied current. The model contains total eight unknowns of concentrations, four for positive and negative porous electrodes and four for concentrations in the external reservoirs. Therefore, the mass balance of species i in the reservoir can be written as,

$$\frac{dC_i^{res}}{dt} = \frac{Q}{V_{res}}\left(C_i - C_i^{res}\right) \tag{9}$$

where C_i^{res} and C_i are the respective concentrations in the reservoir and cell of species $i \in$ [2–5] corresponding to V^{2+}, V^{3+}, VO_2^+ and VO^{2+}, respectively, V_{res} is the volume of electrolyte in the reservoir, Q is the electrolyte flow rate.

The mass balance for species includes electrochemical reaction, recirculation and diffusion of species through membrane and these are expressed as,

$$\frac{dC_2}{dt} = \frac{Q}{\varepsilon V_e}\left(C_2^{res} - C_2\right) + \frac{A_m j}{\varepsilon V_e F} - \frac{A_m}{w_m}\left(D_2 c_2 + 2D_5 c_5 + D_4 c_4\right) \tag{10}$$

$$\frac{dC_3}{dt} = \frac{Q}{\varepsilon V_e}\left(C_3^{res} - C_3\right) - \frac{A_m j}{\varepsilon V_e F} - \frac{A_m}{w_m}\left(D_3 c_3 - 3D_5 c_5 - 2D_4 c_4\right) \tag{11}$$

$$\frac{dC_4}{dt} = \frac{Q}{\varepsilon V_e}\left(C_4^{res} - C_4\right) - \frac{A_m j}{\varepsilon V_e F} - \frac{A_m}{w_m}\left(D_4 c_4 - 3D_2 c_2 - 2D_3 c_3\right) \tag{12}$$

$$\frac{dC_5}{dt} = \frac{Q}{\varepsilon V_e}\left(C_5^{res} - C_5\right) + \frac{A_m j}{\varepsilon V_e F} - \frac{A_m}{w_m}\left(D_5 c_5 + 2D_2 c_2 + D_3 c_3\right) \tag{13}$$

where V_e is volume of the electrode, A_m is the contact area of the membrane, j is the applied current density, ε is the porosity of the electrode, w_m width of the membrane, and D_2, D_3, D_4 and D_5 are the diffusion coefficients of membrane corresponding to respective vanadium species.

The diffusion coefficients depend on temperature and these are approximated using Arrhenius law given by,

$$D = D_0 e^{\frac{E_a}{R}\left(\frac{1}{298} - \frac{1}{T}\right)} \tag{14}$$

where D_0 is the diffusion for each vanadium species at temperature 298K, E_a is the activation energy. Also K_2, K_3, K_4, K_5 are the diffusion coefficients of membrane material at reference temperature 298K, corresponding to respective vanadium species, the values of diffusion coefficients are given in Table 1. It is understood

Table 1 Values of diffusion coefficients for three different membrane materials [9]

Membrane	k_2 (dm/s)	k_3 (dm/s)	k_4 (dm/s)	k_5 (dm/s)
Selemion AMV	3.53×10^{-8}	2.18×10^{-8}	0.91×10^{-8}	2.57×10^{-8}
Selemion CMV	3.17×10^{-7}	0.716×10^{-7}	2×10^{-7}	1.25×10^{-7}
Nafion 115	6.9×10^{-7}	2.54×10^{-7}	5.37×10^{-7}	4.64×10^{-7}

from Eq. 14, the diffusion coefficients of membrane varies exponentially with temperature, this phenomena explained elaborately in results and discussion section. The value of E_a is 1.663×10^4 J/mol taken from literature [14] based on experimental data.

The open circuit voltage is calculated from the Nernst equation given by,

$$E_{OC} = (E^0_{pos} - E^0_{neg}) + \frac{RT}{F} ln\left(\frac{c_2 c_5 c^2_{H+}}{c_3 c_4}\right) \tag{15}$$

where E^0_{neg} and E^0_{pos} are the standard cell potentials for the reactions for negative and positive electrodes, F is the Faraday constant, T is the cell temperature, R is the gas constant and c_{H+} is the concentration of protons in the positive half cell. Due to complex ionic equilibria it is very difficult to model accurately the dynamics of proton concentration. However, the small changes in proton concentration will not affect on cell voltage significantly, therefore proton concentration is assumed to be constant, the value is taken to be 4M for simulations.

The cell voltage E_{cell} is determined by deducting the voltage losses due to ohmic resistance, and activation overpotential to the open circuit voltage, which is given by

$$E_{Cell} = E_{OC} - \sum E_{ohm} - \sum E_{act} \tag{16}$$

Ohmic losses associated with current collector, membrane and electrolyte can be calculated by,

$$E_c = j_{app} \frac{w_c}{\sigma_c} \tag{17}$$

$$E_m = j_{app} \frac{w_m}{\sigma_m} \tag{18}$$

$$E_e = j_{app} \frac{w_e}{\varepsilon^{3/2} \sigma_e} \tag{19}$$

where, σ_c,σ_m, and σ_e are the conductivities and w_c, w_e and w_m are the widths of the current collector, electrode, and membrane respectively. The effective conductivity of electrolyte $\varepsilon^{3/2}\sigma_e$, is obtained by using a Bruggeman correction. For Nafion 115 membrane conductivity can be calculated using the following empirical relationship given by [15],

$$\sigma_m = (0.5139\lambda - 0.326)\exp\left(1268\left[\frac{1}{303} - \frac{1}{T}\right]\right) \tag{20}$$

The membrane conductivity depends on membrane water content λ and temperature of cell. The membrane is assumed to be fully saturated (λ) since, there is constant contact with liquid electrolytes on each side of the cell.

To drive the electrochemical reaction requires overpotential which is calculated from the current-overpotential equation at a given current density assuming equal charge coefficients ($\alpha = 0.5$) [16]

$$\frac{j}{j_0} = \left(1 - \frac{j}{j_{1,c}}\right)\exp\left(-\frac{F\eta}{2RT}\right) - \left(1 - \frac{j}{j_{1,a}}\right)\exp\left(\frac{F\eta}{2RT}\right) \tag{21}$$

Here, j_0 is the exchange current density and η is the overpotential can be expressed as,

For negative electrode

$$j_0 = Fk_{neg}\sqrt{c_2 c_3} \tag{22}$$

For positive electrode

$$j_0 = Fk_{pos}\sqrt{c_4 c_5} \tag{23}$$

Reaction rate constant at the positive electrode k_{pos} can be calculated by using Arrhenius law,

$$k_{pos} = k_{pos,ref}\exp\left(-\frac{FE^0_{pos}(T_{ref})}{R}\left[\frac{1}{T_{ref}} - \frac{1}{T}\right]\right) \tag{24}$$

Reaction rate constant at the negative electrode k_{neg} can be calculated by using Arrhenius law,

$$k_{neg} = k_{neg,ref}\exp\left(\frac{FE^0_{neg}(T_{ref})}{R}\left[\frac{1}{T_{ref}} - \frac{1}{T}\right]\right) \tag{25}$$

Here, $k_{neg,ref}$ and $k_{pos,ref}$ are reaction rate constants at 293 K (reference temperature). The anodic and cathodic currents, $j_{l,a}$ and $j_{l,c}$, consider the rate at which the consumed species can be brought to the electrode surface from the bulk electrolyte solution and are associated to the bulk concentration and mass transfer coefficient given by, For negative electrode

$$j_{1,a} = -Fm_3c_3 \tag{26}$$

$$j_{1,c} = Fm_2c_2 \tag{27}$$

For positive electrode

$$j_{1,a} = -Fm_4c_4 \tag{28}$$

$$j_{1,c} = Fm_5c_5 \tag{29}$$

Where m_2, m_3, m_4, and m_5 are the mass transfer coefficients. It is assumed that mass transfer is same for each vanadium species and it is denoted by m_v. The mass transfer coefficient depends on electrolyte flow velocity v can be calculated by the following empirical equation [11]

$$m_v = 1.6 \times 10^{-4}\, v^{0.4} \tag{30}$$

Solving the nonlinear overpotential Eq. (21) requires numerical methods. If the current density is very small compared to the limiting current density so that the concentration of consumed species in the bulk solution and at the electrode surface are approximately equal, then Eq. (21) reduces to the ButlerVolmer equation [16].

$$\frac{j}{j_0} = \exp\left(-\frac{F\eta}{2RT}\right) - \exp\left(\frac{F\eta}{2RT}\right) \tag{31}$$

Above equation can be inverted to calculate the overpotential at each electrode. For negative electrode

$$\eta = \frac{2RT}{F}\sinh^{-1}\left(\frac{j}{2Fk_{neg}\sqrt{c_2c_3}}\right) \tag{32}$$

For positive electrode

$$\eta = \frac{2RT}{F}\sinh^{-1}\left(\frac{j}{2Fk_{pos}\sqrt{c_4c_5}}\right) \tag{33}$$

If the mass transfer effects are not important then Butler-Volmer equation is computationally most efficient method of approximating the overpotential. Yu and Chen [11] first time proposed new model by introducing mass transfer coefficient into the overpotential equation of the lumped model gives significant increase in overpotential, which is important in predicting the cell potential variation accurately. This model gives closed form piecewise equations to approximate current-overpotential equation over the entire range up to the limiting current.

If the current density is small with respect to limiting current density, the Butler-Volmer equation is accurate in predicting the overpotential. If the current density is high, the Butler-Volmer equation is less accurate in predicting the overpotential because it fails to capture the mass transfer effects which contributes to overpotential. Yu and Chen [11] proposed new approximations called mass transfer-limited (MTL) approximations to calculate overpotential by adding the mass transfer effects into the overpotential equation.

At high positive current densities overpotential approximations can be found by neglecting cathodic component (right side) of Eq. (21). This can be proved if the current density approaches $j_{1,a}$ at large negative overpotentials. Therefore, MTL approximations to calculate overpotential for an anodic reaction can be expressed as

$$\frac{j}{j_0} = -\left(1 - \frac{j}{j_{1,a}}\right)\exp\left(\frac{F\eta}{2RT}\right) \tag{34}$$

$$\eta = \frac{2RT}{F}\left[ln\left(\frac{j_{1,a} - j}{j}\right) + ln\left(\frac{j_{1,a}}{j_0}\right)\right] \tag{35}$$

Similarly, the MTL approximations to calculate overpotential for an cathodic reaction are

$$\frac{j}{j_0} = \left(1 - \frac{j}{j_{1,c}}\right)\exp\left(-\frac{F\eta}{2RT}\right) \tag{36}$$

$$\eta = \frac{2RT}{F}\left[ln\left(\frac{j_{1,c} - j}{j}\right) + ln\left(\frac{j_0}{j_{1,c}}\right)\right] \tag{37}$$

It is found that if the Butler-Volmer equation and MTL approximations under predicts the overpotential then larger of the two approximations should be considered for simulation [11]. In all of our simulations MTL approximations are used to calculate overpotentials.

4 Results and Discussion

All simulations are conducted by using the inhouse code. In the code, ordinary differential equations (ODE) are solved as mentioned in earlier sections. The structural dimensions of the VRFB are based on the experimental setup taken from Ref. [17]. The other parameters related to diffusion coefficients are given in Table 1 and these are reported by Tang et al. [9].

Figure 1b shows comparison between simulated and experimental cell voltage variation. The cell temperature was 297 K, initial vanadium concentration was

1200 mol/m^3, the flow rate was $1 \times 10^{-6}\ \mathrm{m^3/s}$ and the current density was 1000 A/m^2. The model simulated result shows very good agreement with the experimental result taken from literature for validation.

4.1 Effects of Temperature on Diffusion Coefficients and Reaction Rate Constants

Figure 2 shows variation of diffusion coefficients with temperature for Selemion AMV, Selemion CMV and Nafion 115 membranes. The variation of diffusion coefficients with temperature is based on the model of Arrhenius. Here the assumption is that the activation energy is same for all vanadium species. It is observed that diffusion coefficients increase with temperature, therefore change in concentration of vanadium ions takes place in both half of the cell.

The reaction rate constants also depend on temperature for both negative and positive electrode. Variation of reaction rate constant with temperature for negative and positive electrode is shown in Fig. 3a and b, respectively. The temperature dependent variation is based on Arrhenius model. It is understood from Fig. 3a that

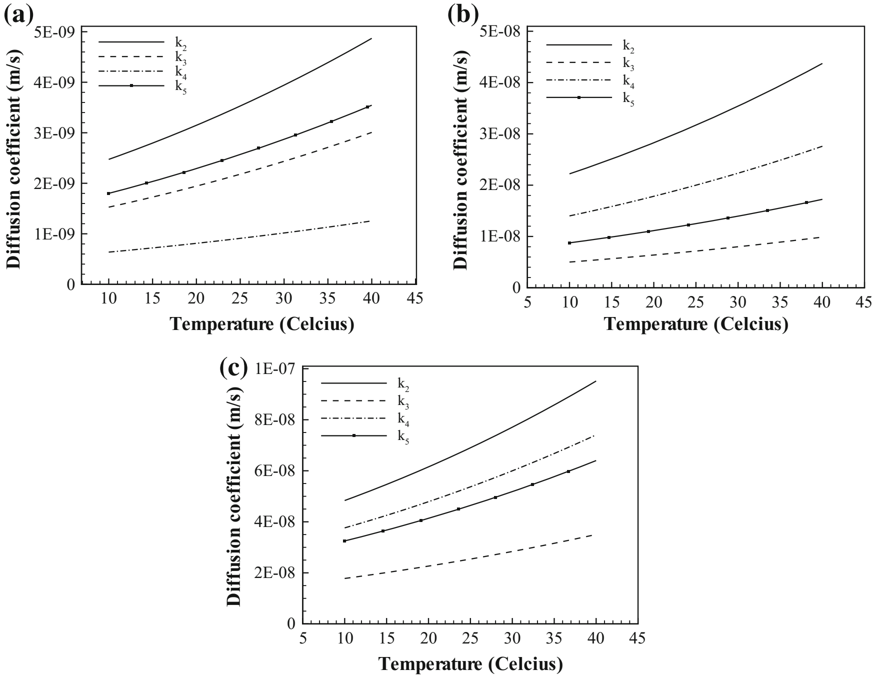


Fig. 2 Variation of membrane diffusion coefficients at different temperatures **a** Selemion AMV **b** Selemion CMV **c** Nafion 115

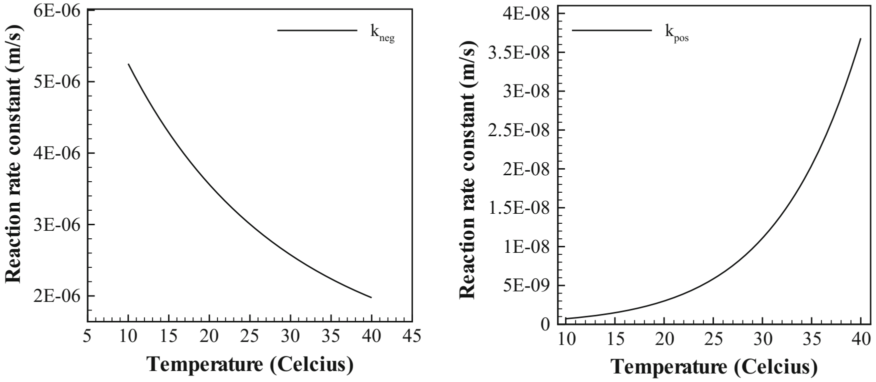


Fig. 3 Reaction rate constant at different temperatures **a** Negative electrode **b** Positive electrode

for negative electrode if temperature increases, reaction rate constant decreases, for positive electrode (see Fig. 3b) if temperature increases, reaction rate constant increases. The reaction rate constants are useful in predicting the overpotentials accurately.

4.2 Cell Potential Response for Butler-Volmer and MTL Approximations

Figure 4a shows cell potential variation with time and comparison for Butler-Volmer and MTL approximations. Higher cell voltage variation for MTL approximations is observed in comparison with Butler-Volmer equation approximations. Also it is understood that there is small difference in cell voltage between two approximations, because of adding the mass transfer term in the overpotential equation. Considering the effect of mass transfer in the model, it leads to prediction of overpotential accurately. Yu and Chen [11] showed that Butler-Volmer approximation predicts overpotential accurately for small current densities in comparison with the limiting current density. In present simulations value of current densities is high in comparison with limiting current density, therefore, MTL approximations are used.

4.3 Cell Voltage Response Due to Mass Transfer Effects

Figure 4b shows the comparison of cell potential with and without mass transfer effects state of charge (SOC) of 80% and 40 minutes discharge. If the mass transfer

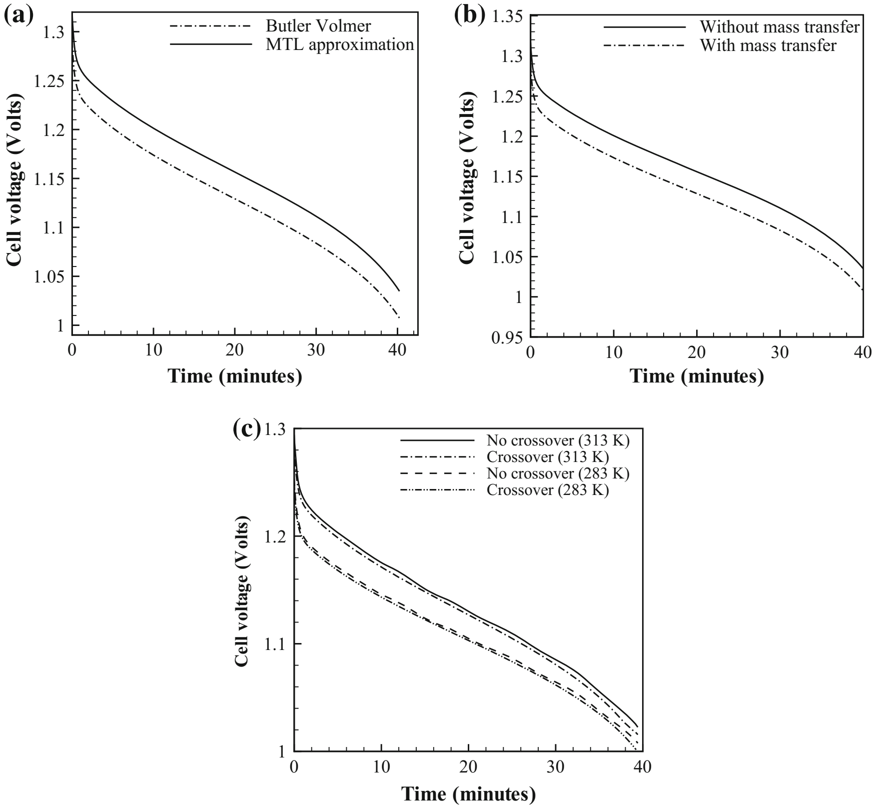


Fig. 4 **a** A comparison of Butler-Volmer equation and MTL approximation to the cell voltage. The flow rate was 1×10^{-6} m^3/s and the SOC were set to 80%. **b** Simulated discharge cell potential response with and without mass transfer effects, current density and SOC are 1000 A/m^2 and 80% respectively. **c** Simulated discharge voltage response with and without crossover at 283 K and 313 K. The flow rate and current density were set to 1 mL/s and 1000 A/m^2. The initial soc were set to 80%

effects are added and MTL approximations or Butler-Volmer equations are employed to calculate overpotential, the cell potential depends on the density ratio. When the mass transfer effects are not considered, then Butler-Volmer equations are employed to determine overpotential. It is observed that there is 2.74 mV difference between the two curves because Butler-Volmer equation used for without mass transfer effect and MTL approximations used for with mass transfer effect. The deviation is almost same till the end of discharging process. Also it is understood that cell voltage decreased by 2.74 mV due to mass transfer effect.

4.4 Cell Voltage Response Due to Crossover Effects

Figure 4c shows the comparison of cell voltage variation response with and without crossover for discharging conditions. The flow rate and current density were set to $1 \times 10^{-6}\ \mathrm{m^3/s}$ and $1000\ \mathrm{A/m^2}$, respectively. The difference in cell potential between two cases is less for higher SOC but increases considerably for lower SOC. After discharging process, the differences in cell potential are 6 and 6.86 mV at 283 and 313 K, respectively. The difference is considerably higher for higher temperature due to increase in diffusion coefficients with temperature and it results in increase of self discharge rate. Using the cell for long term, capacity of cell decreases due to crossover and this can be overcome by electrolyte rebalancing [18]. It is observed that voltage efficiency increases with temperature because of lower activation overpotential.

4.5 Concentration Response Due to Temperature

Three different membranes such as, Selemion AMV, Selemion CMV and Nafion 115, are considered for temperature dependence solution. The upper voltage limit is assumed to be 1.7 V and lower voltage limit is 0.95 V. The vanadium species concentration for V^{2+}, V^{3+}, V^{4+} and V^{+5} are analyzed at 1.7V and temperatures ranging from 10 to 40 °C. The vanadium ion concentration variation with number of cycle trends is consistent with those diffusion model of Badrinarayanan et al. [6]. Four different vanadium ion concentrations are plotted by calculating the difference in diffusion between 10 to 40 °C as shown in Fig. 5a, b and c for three membranes (Selemion AMV, Selemion CMV and Nafion 115). Figure 6 describes the difference in vanadium concentration change between 40 and 10 °C.

The variation of concentration difference with number of cycles between 10 and 40 °C is shown in Fig. 5 for 200 charging/discharging cycles. From Fig. 5a for Selemion AMV membrane based cell, the difference in diffusion does not reduce with number of cycles but it increases with number of charging/discharging cycles. It is understood that relative difference varies linearly with number of cycles and the difference increases with the number of charging/discharging cycles. The temperature dependence characteristics curves of Selemion AMV look similar to that of Selemion CMV (Fig. 5b), but the diffusion of vanadium ion species is different.

Figure 5c shows the concentration difference with number of cycles between 40 and 10 °C for Nafion 115 membrane. It is observed that difference in diffusion increases up to 77 cycles then decreases as the number of charging/discharging cycles progresses. The diffusion of Selemion AMV and Selemion CMV does not vary linearly as it depends on the diffusion coefficient of the membrane.

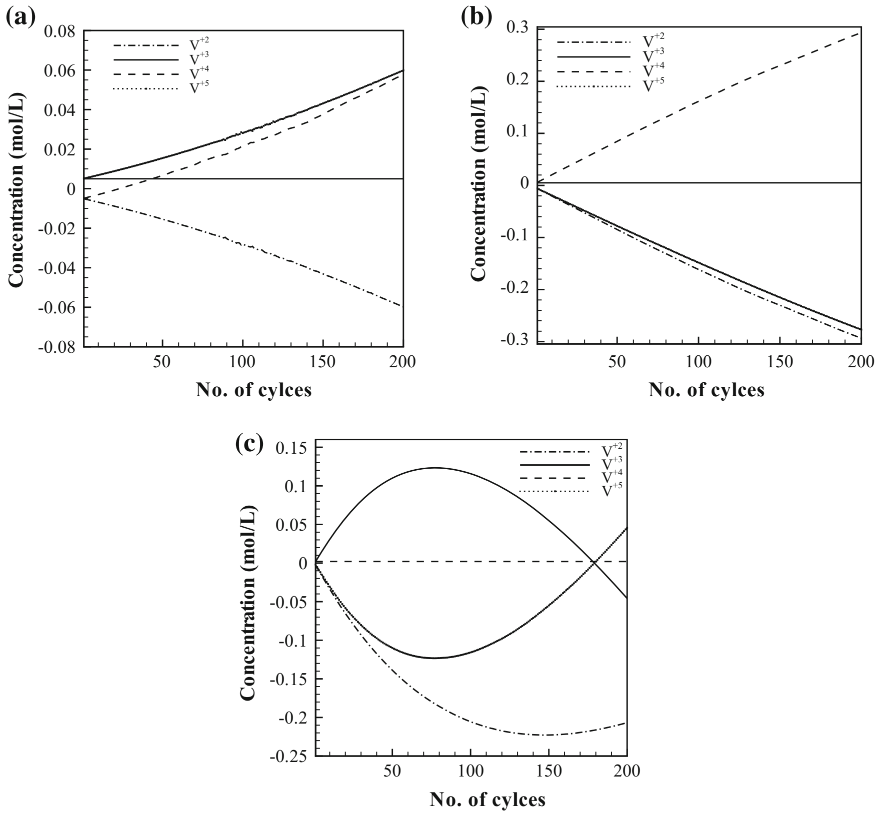


Fig. 5 Variation in diffusion trend due to temperature at 1.7 V **a** for AMV membrane **b** for CMV membrane **c** for Nafion 115 membrane

4.6 Concentration Response Due to Porosity

The variation in concentration depends on the porosity of the electrode as seen from Eqs. 10 to 13. If the porosity of the electrode varies, there is variation in the concentration which leads to changes in difference in diffusion of vanadium ions. Here three different membranes such as, Selemion AMV, Selemion CMV and Nafion 115, are also considered for porosity dependence solution. The upper cell potential limit is assumed to be 1.7 V and lower cell potential limit is 0.95 V. The vanadium species concentration for V^{2+}, V^{3+}, V^{4+} and V^{+5} are analyzed at 1.7 V at porosity values ranging from 0.6 to 0.8.

Figure 6a shows difference in diffusion variation for Selemion AMV membrane based cell, the diffusion difference increases with number of charging/discharging cycles. It is observed that for both Selemion AMV membrane and Selemion CMV

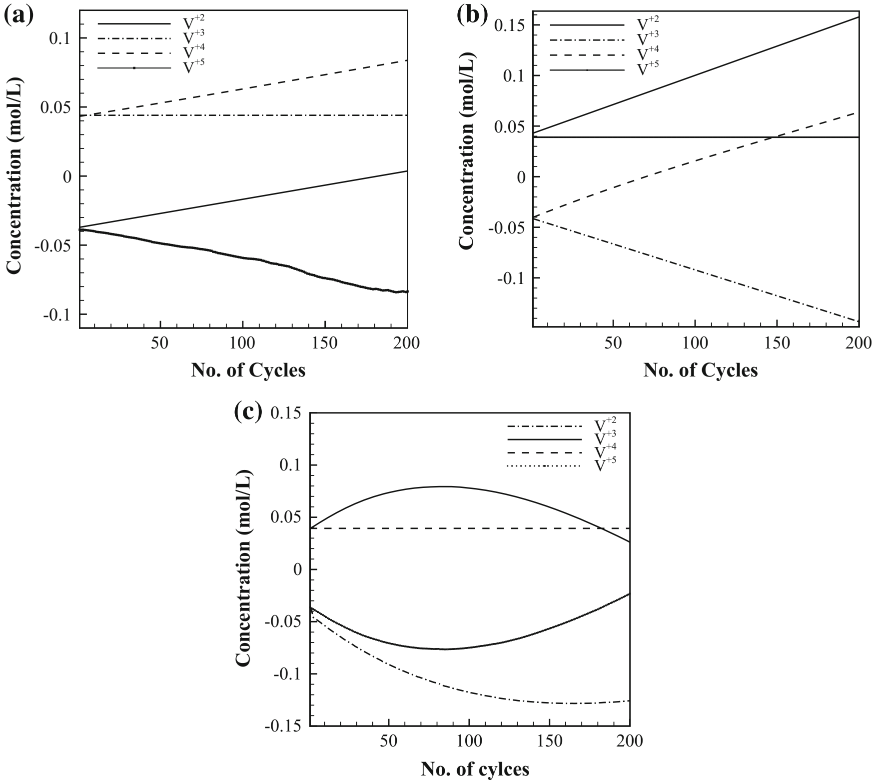


Fig. 6 Difference in diffusion trend due to porosity at 1.7 V **a** for Selemion AMV membrane **b** for Selemion CMV membrane **c** for Nafion 115 membrane

membrane (from Fig. 6b) relative difference of diffusion of concentration varies linearly with the number of cycles. The porosity dependence characteristics curves of Selemion AMV looks similar to that of Selemion CMV (Fig. 6b).

Figure 6c shows the concentration difference with number of cycles between 0.6 and 0.8 for Nafion 115 membrane. It is understood that difference in diffusion increases up to 77 cycles then decreases as the number of charging/discharging cycles increases. Also, it is observed that for current diffusion coefficient values of Nafion 115 membrane the diffusion trend is not linear compared to the other membranes (Selemion AMV membrane and Selemion CMV membrane). The cell voltage variation for 11 cycles (starting from 50 to 61) is shown in Fig. 7 for Nafion 115 membrane. It is understood that capacity of the cell decreases with charging/discharging cycles due to the effect of vanadium ions cross over through the membrane. Figure 8 shows the capacity loss of the cell variation with number of cycles for Nafion 115 membrane. It is observed that the capacity of the cell linearly

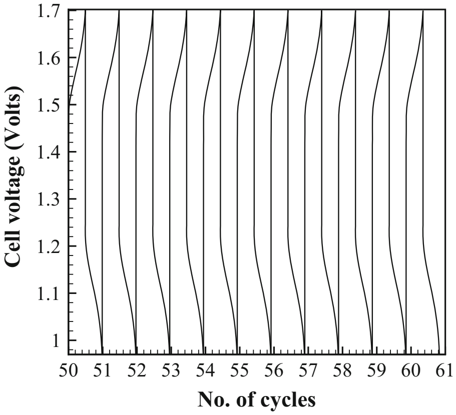
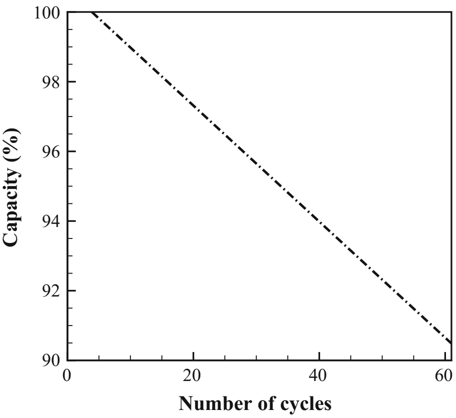


Fig. 7 Cell voltage plot for different cycles for Nafion 115 membrane for 11 cycles

Fig. 8 Capacity versus number of cycles for Nafion 115 membrane for 60 cycles. The flow rate and current density were set to 1 mL/s and 1000 A/m^2 respectively



decreases to 90.5% after 60 cycles. Also it is noted that initial four cycles the crossover effect is very small (negligible), then decreases with number of cycles. The capacity decay is mainly due to the effect of crossover of vanadium ions through the membrane.

5 Conclusions

The present model considers the effect of mass transfer and crossover of vanadium ions through the membrane. The model is used to predict the capacity loss of the battery due to the crossover of vanadium ions through the membrane over many cycles at different temperatures. The effect of temperature and porosity on concentration change is studied for three membrane materials such as, Selemion AMV membrane, Selemion CMV membrane and Nafion 115 membrane, the temperature ranging from 10 °C and 40 °C. Also effects of temperature on diffusion coefficients and reaction rate constants has been studied. It is observed that for Selemion AMV membrane and Selemion CMV membrane capacity loss shows linear variation with number of cycles but there is no sign of stabilizing. In the case of Nafion 115 membrane capacity loss experienced initial 77 cycles then stabilized with increase in number of cycles. The simulation results have shown that crossover and mass transfer effects have significant impact on the performance of the cell potential response. The new MTL approximations are used and predicted well the cell voltage response for higher density ratio.

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Energy Efficient Future Generation Electronics Based on Strongly Correlated Electron Systems

Abhijit Chanda, Sudipta Goswami and Dipten Bhattacharya

Abstract Three major developments in three decades are quietly changing the whole spectrum of 'electronics' (as it is conventionally known) making it ready for a major revolution. At the heart of this lies the 'electronics based on strongly correlated electron systems'. The broad canvass of 'strongly correlated electron systems'—especially the ones assuming importance for future generation electronics—covers primarily transition metal ion based complex oxide compounds exhibiting superconductivity at a record high temperature (cuprate superconductors); gigantic change in electrical resistivity under tiny magnetic field (CMR manganites); and coexisting ferroelectric and magnetic orders within a single phase with an extraordinary cross-coupling (multiferroics). Thanks to these developments, apart from charge of an electron, its spin and orbital degrees of freedom are now being shown to offer tremendous manoeuvrability for developing not just electronic but spintronic and orbitronic devices as well. Larger coherence length and stability of spin and orbital spectra can be exploited for bringing functionalities hitherto unknown. Using up and down spins and different patterns of orbital occupancy of the electrons, it is now possible to design and develop spintronic and even orbitronic devices by exploiting esoteric effects such as spin-transport, spin-tunnelling, spin-Hall, spin-Seebeck or switching of orbital orders under optical illumination. These nanoscale devices are energy efficient and ultra-sensitive. They are expected to perform more complex jobs in a vast arena which includes even bio-electronics.

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In this article, we introduce the area of strongly correlated electron systems and explore the advancements already made and possibilities emerging in developing future generation electronic-spintronic-orbitronic devices based on complexities which till now stubbornly defied complete understanding in spite of intense efforts worldwide—a classic example of which is the mechanism of high temperature cuprate based superconductors.

1 Introduction

With the discovery of superconductivity at a record high temperature of $\sim$35 K in Ba-doped La_2CuO_4 in 1986 [1], a new chapter in the area of oxide electronic materials began. The importance of ABO_3 perovskite systems and its higher order derivatives including layered Aurivillus phase, double perovskite $A_2B_2O_6$ or Ruddlesden-Popper systems $A_3B_2O_7$ in yielding complex functionalities within the domain of electronic, magnetic, and optical properties started unfolding slowly. After three decades since 1986 and many seminal discoveries in the meantime with this class of compounds, the situation seems well poised to change the entire area of ‘electronics’—as it is conventionally known since the era of Si-based devices—though full scale commercial usage is still a few years away. Apart from the ‘charge’ of an electron, ‘spin’ and ‘orbital’ degrees of freedom are also now accessible for utilization in new generation ‘electronic’ devices. Three decades saw development of three new areas: (i) high temperature superconductivity [2], (ii) colossal magnetoresistivity [3], and (iii) multiferroicity [4]. The high temperature copper oxide based superconductors were projected to revolutionize the power transmission, storage, and generation besides having large scale applications in electronic circuitry as fault current limiters and Joesphson devices. The gigantic magnetoresistivity (orders of magnitude drop in resistivity under a magnetic field) in perovskite manganites was found to be promising for applications such as magnetic read/write heads allowing enormous jump in the data storage density, magnetic memories, other field-effect devices, and even in detection of infrared radiation. The multiferroics, on the other hand, with coexisting ferroelectric and magnetic phases and a cross-coupling between the order parameters offer an additional handle for writing the memory devices electrically and reading magnetically which, in turn, reduces the power consumption drastically while enhancing the storage density of a memory device. The era of new generation electronic, spintronic, optoelectronic, optospintronic, or orbitronic devices is about to begin. These perovskites and their derivative systems possess complex crystallographic and electronic structure and often described as ‘strongly correlated electron’ systems. In spite of diversity in them, there are certain commonalities as well.

It is important to point out here that much of the new generation electronic and spintronic devices such as bipolar switches, filters, spin valves, memories, read/write heads etc. would possibly be developed from even metallic magnetic multilayers (e.g., ferromagnetic layers sandwiching a nonmagnetic layer) and dilute magnetic semiconductors [5] which do not fall into the category of 'strongly correlated electron systems'. We keep them out of our discussion as we focus on the energy efficient devices based on 'strongly correlated electron' systems alone.

In this article, we shall first introduce the physics of these complex oxides and underline how they are different and more complex from conventional metal, semimetal, semiconductor, and insulator and how this complexity can be fully exploited for novel applications. We shall then highlight the advancements made in real-life device fabrications using this class of compounds.

2 Strongly Correlated Electron Systems

Based on the electronic band structure and electrical properties, the entire class of materials can be categorized as metal, semiconductor, and insulator. While metals do not possess a gap in the electron band near Fermi level, semiconductor and insulators contain small to large band gaps of the order of even few eV. The Fermi energy (E_F) or Fermi velocity (v_F) is orders of magnitude higher than the lattice Debye energy (E_D). The electron-phonon coupling is generally weak. The effective mass (m*) of free electrons at the Fermi surface in a metal is comparable with free electron mass (m_e), i.e., $m^* \approx m_e$. The Coulomb interaction among the electrons is much smaller than the other energy scales such as kinetic and electron-phonon interaction energy. Therefore, it is treated as a perturbation leading to negligible renormalization of the effective electron parameters such as velocity, mass, momentum, energy etc. The situation changes completely in a certain class of compounds where the Fermi energy is an order of magnitude smaller and the density of states at the Fermi level is large. The electron-electron Coulomb interaction energy becomes no longer negligible. These compounds are categorized as 'strongly correlated electron systems'. The effective mass of an electron (m*) in these cases turns out be varying from $\sim 10\ m_e$ to $\sim 1000\ m_e$. The perovskites and their derivatives—pointed out above—containing transition metal ions belong to this 'strongly correlated electron' class and as such form the heart of the new generation electronic devices. This strong correlation among the electrons gives rise to novel phenomena such as metal-insulator transition, colossal magnetoresistivity, and even superconductivity at a very high temperature [6]. The onsite electron-electron repulsion appears to be primarily responsible for the development of gap in the band structure near Fermi level (Fig. 1) which, in turn, leads to insulating ground state. Interestingly, one electron band structure in the absence of Coulomb interaction predicts metallic state. This Mott insulating state undergoes metallic transition upon doping which creates mobile charge carriers for hopping from site to site. Instead of band conduction, these systems, therefore, exhibit hopping conduction with formation of polarons. The polarons form due to the change in polarization of the ion sites in presence of hopping charge carriers. The properties such as electrical resistivity, thermoelectric power, specific heat, thermal

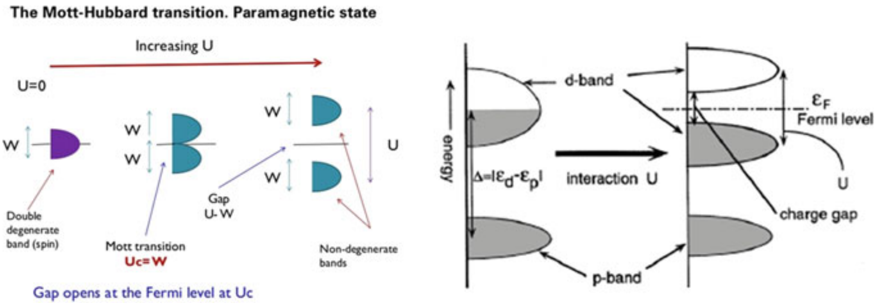

Fig. 1 The schematic of band gap at the Fermi level as a result of electron correlation (i.e., Coulomb repulsion)

conductivity, optical conductivity etc. exhibit completely different pattern and dependence on parameters such as temperature, pressure, magnetic field or optical pulse is nontrivial. The electrons (better called quasiparticles as the mass, momentum, energy etc. vary around their mean values) of these systems with large renormalization of the parameters such as mass, momentum, velocity, energy cannot be described by conventional Fermi liquid formalisms. They are described by different non-Fermi liquid theories [7]. In such systems, the Fermi surface deviates from the conventional spherical shape and becomes more anisotropic with even rather blurred edges. An important aspect of the strongly correlated electron systems is the interplay among different degrees of freedom of the electrons—such as charge, spin, and orbital—with the lattice. This interplay, in fact, gives rise to the formation of different ordered pattern of the charge, spin, and orbital degrees of freedom of the electrons. Another important feature of this class of materials is the intrinsic structural and/or electronic phase segregation and consequent coexistence of ordered and disordered or metal and insulator phases. This enormous complexity makes this class of materials an extremely fertile ground for observing and/or engineering newer phenomena. We shall now discuss the essential physics of the cuprate superconductors, magnetoresistive manganites, and multiferroics.

2.1 *Cuprate Superconductors*

We shall restrict our discussion within three families of cuprate superconductors: (i) $YBa_2Cu_3O_{7-x}$ (YBCO), (ii) $Bi_2Sr_2CaCu_2O_8$ (BSCCO2212), and (iii) $Bi_2Sr_2Ca_2Cu_3O_{10}$ (BSCCO2223). We leave out the Tl- and Hg-based compounds because of their toxicity and consequent smaller chance of finding real-life applications. The salient features of the cuprate superconductors are given here: (i) the superconducting transition temperatures T_C (below which electrical resistivity becomes zero and magnetic flux is excluded from the bulk of the sample) for these compounds are ∼90 K [8], ∼85 K [9], and ∼110 K [10], respectively;

(ii) above T_C, they exhibit metallic resistivity pattern though the normal state resistivity of these systems is quite high (of the order of few milli-Ohm.cm); the conductivity (σ) is smaller than even Mott's minimum metallic conductivity σ_m ($\sim a/l_{mfp}$; l_{mfp} is the electron mean free path and a is the lattice constant) [11]; (ii) the normal state resistivity (ρ) follows linear temperature (T) dependence (i.e., $\rho \sim T$) which is unusual for a metal and signifies non-Fermi liquid character of the electron fluid at the Fermi level; (iii) linear T dependence of the normal state ρ influences the optical conductivity $\sigma_1(\omega)$ across a large frequency (ω) range up to microwave frequency; in fact, $\sigma(\omega)$ is given by $\rho(T)$ and the Drude conductivity spectrum; of course, while YBCO system exhibits large frequency dependence of σ_1 in the low temperature range, it is absent in BSCCO system [12]; (iv) the thermoelectric power (S) follows $\sim A + BT$ temperature dependence in the high temperature region; (v) large anisotropy with conducting Cu–O layers sandwiched between charge-reservoir layers comprising of other elements of the compound; the anisotropy depends on the number of Cu–O layers in the unit cell; while YBCO and BSCCO contain two Cu–O layers, BSCCO2223 contains three layers (Fig. 2); anisotropy, accordingly, in creases from $\sim 10^2$ in YBCO to $\sim 10^5$ in BSCCO2223; (vi) transition temperature T_C depends strongly on the doping level (x) of the Cu–O plane; it increases initially with the increase in 'x' and then reaches maximum and finally drops off (Fig. 2); three regions are marked as 'underdoped', 'optimally doped', and 'overdoped'; T_C fits $T_C/T_{C,max} \sim 1 - 82.6(x - 0.16)^2$ relation well [13]; (vii) in almost all the cases of the cuprate superconductors, the parent undoped compound is antiferromagnetic and insulator; doping induces spin fluctuations and breaks the long-range magnetic order and drives insulator to metal transition; eventually, at a critical doping level $x = x_C$, the superconductivity sets in; prevalence of spin fluctuations is considered a vital ingredient for inducing pairing of electrons necessary for superconductivity to set in; (viii) a pseudogap opens up far above T_C in the electron spectrum (which could as well be a gap in the spin spectrum) of the cuprate superconductors whose presence is reflected in NMR data,

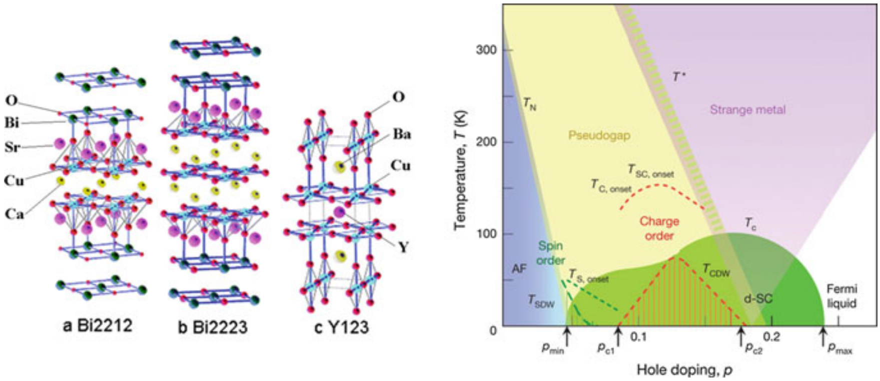

Fig. 2 The crystallographic structures of **a** BSCCO2212, **b** BSCCO2223, and **c** YBCO; right panel shows the generic electronic phase diagram of the cuprate superconductors

infrared reflectivity, dc resistivity, thermoelectric power etc.; (ix) the paired electrons assume anisotropic d-wave symmetry resulting from higher order spin triplet formation; (x) importantly, the magnetic phase diagram is extremely complex [14] comprising of vortex solid, glass, and liquid phases in different regions of the field (H)—temperature (T) diagram; giant vortex creeping [15] across a wide region of the magnetic phase diagram—which gives rise to finite electrical resistivity by destroying superconductivity—actually is responsible for rather limited application potential for these cuprate superconductors.

2.2 Colossal Magnetoresistive Manganites

Within a few years of the discovery of cuprate superconductors, another surprising discovery was made in 1992 in ABO_3 type compounds $RMnO_3$ (R = La, Pr, Nd, Sm) (Fig. 3). In a thin film of $La_{0.7}Ca_{0.3}MnO_3$, a gigantic decrease in electrical resistivity (of the order $\sim 10^6$) was observed under a magnetic field of few tesla [16]. Such a large drop in resistivity under magnetic field, i.e., magnetoresistivity was unprecedented. In the subsequent years, the full spectrum of the properties and phase diagram was explored. This class of compounds provides a classic playground to demonstrate close relationship between magnetic and electrical properties. While antiferromagnetic order gives rise to insulating behaviour, ferromagnetism is found to be concomitant to metallicity. The salient features of this class of compounds are given here. (i) The parent $RMnO_3$ (R = La, Pr, Nd, Sm) compound is antiferromagnetic and insulating; the antiferromagnetic order is A-type where spins are aligned ferromagnetically within a Mn-O plane and antiferromagnetically across the plane; depending on the average R-site radius $\langle r_R \rangle$, the phase diagram and the transition temperatures change dramatically; this offers a tool for tuning the properties [17]; (ii) with the increase in doping by alkali ions such as Ca^{2+}, Sr^{2+}, Ba^{2+} at the R-site, the antiferromagnetic order melts and antiferromagnetic to ferromagnetic and insulator to metallic transition sets in (Fig. 3); the

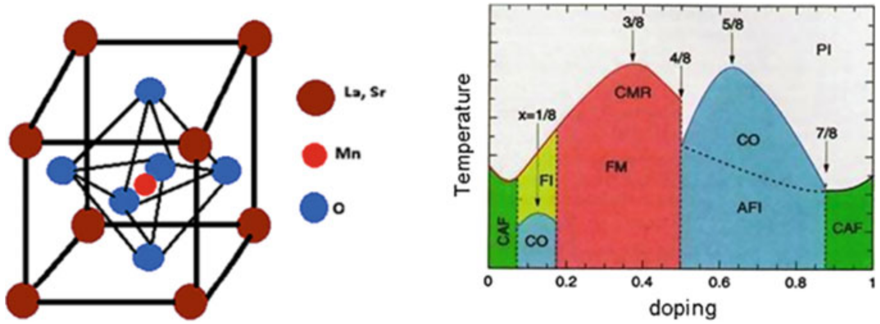

Fig. 3 The crystallographic structure of perovskite $LaMnO_3$; right panel shows the generic electronic phase diagram of the manganites

critical doping level x_C varies within $\sim$0.17–0.20; higher the $\langle r_R \rangle$ smaller is the x_C; the ferromagnetic and metallic behaviour is governed by double exchange interaction across Mn^{3+}–O^{2-}–Mn^{3+} bonds where exchange coupling between the spins at the Mn sites develops as a result of hopping of electrons from site to site; (iii) the entire electronic phase diagram comprises of, primarily, antiferromagnetic insulating, ferromagnetic metallic, and, again, antiferromagnetic insulating phases as the doping level ‘x’ increases from zero to 1.0. The structure of antiferromagnetic order, of course, changes from low doping to higher doping range—from A-type (mentioned above) to C-type (one-dimensional spin chain), to CE-type (two-dimensional zigzag), to E-type (spin chain with rotation), and eventually to G-type (three-dimensional antiferromagnetic); (iv) the intermediate doping range $x \sim 0.2$–0.4 exhibits the ferromagnetic and metallic properties where colossal magnetoresistivity is also observed; (v) this class of materials also exhibit, at different regions of the phase diagram, real-space ordering of charge and orbital degrees of freedom; the charge/orbital order too assumes different patterns such as C, CE, or E type [18]; (vi) importantly, like magnetic order, the change/orbital order too melts under different external stimulations such as magnetic field, electric field, and optical pulses [19] and gives rise to gigantic change in the physical properties such as electrical resistivity, magnetization, thermal and optical properties; (vii) an important aspect of these manganites is the intrinsic structural and/or electronic phase segregation which leads to the formation of coexisting metallic and insulating phases; the colossal magnetoresistivity was shown as outcome of percolation of the metallic phase under magnetic field in an effective medium type theory.

2.3 Multiferroics

Although first observed [20] in early 1960s, the resurgence of the area of multiferroics took place in the new millennium because of two important observations—one theoretical and another experimental. The multiferroics harness different ferro orders such as ‘(anti)ferroelastic’, ‘(anti)ferroelectric’, and ‘(anti)ferromagnetic’ orders within a single phase. More importantly, there exists a cross-coupling among the order parameters which makes polarizing the sample by magnetic field and vice versa possible. In 2000, based on theoretical calculations it was argued [21] that a transition metal ion with partially filled 3d levels cannot give rise to covalency driven instability necessary for structural off-centering, i.e., ferroelectricity. This is because of centrosymmetric distortion (Jahn-Teller) associated with magnetic ions. Only $3d^0$ ions (observed in Ti^{4+} in $BaTiO_3$ or $PbTiO_3$) can give rise to off-centric distortion. As a result of this, multiferroic compounds are rare in nature. The ferroelectric instability arises in a different sublattice in compounds which exhibit coexisting ferroelectric and magnetic phases. This observation triggered renewed search for new set of compounds with such characteristics. In 2003, another group showed [22] in an experimental work that epitaxial thin film of $BiFeO_3$—a compound known to be multiferroic since early 1960s—does exhibit large ferroelectric polarization and magnetization at room temperature. In fact, the ferroelectric and magnetic transition temperatures are ~ 1103 and ~ 650 K, respectively. This work initiated rigorous attempts to explore and exploit the multiferroicity in $BiFeO_3$ in various forms—single crystal, epitaxial thin films with a design to observe host of different characteristics, and nanosized particles. Given the knowledgebase generated so far, it appears that $BiFeO_3$ could well be the most important material for fabrication of devices for commercial usage. But the search for new compounds with superior properties is also on. The salient features of the single phase multiferroic compounds are given here: (i) depending on whether ferroelectric and magnetic orders develop on identical or different sublattice, the entire class of materials is divided into Type-I and Type-II categories [23]; in Type-I systems, the ferroelectric and magnetic order sets in two different sublattices and the transition temperatures—T_C (ferroelectric) and T_N (magnetic)—are also different; the coupling between the order parameters is weak; in Type-II systems, ferroelectric order emerges out of nontrivial magnetic structures (Fig. 4) and therefore, both the transitions are simultaneous; the coupling between the order parameters is large in these cases; (ii) in most of the cases, the origin of ferroelectricity is different; it emerges either from magnetic structure, charge/orbital order, or geometric effect; in these cases, the ferroelectricity is not the primary instability; these systems are called improper ferroelectrics [24]; $BiFeO_3$, $BiMnO_3$, $PbVO_3$ and few other systems, where ferroelectricity is driven by stereochemical activity of A-site ion lone pairs (Fig. 4), exhibit proper displacive ferroelectricity; improper ferroelectric systems exhibit smaller polarization (<1 μC/cm^2) whereas the proper ones exhibit large polarization (>10 μC/cm^2). It will not be out of place here to mention that from the point of view of applications, composite systems where ferroelectric and magnetic layers form multilayered or other designed structures including one of nanosized columns of one compound embedded within a thin film matrix of another are also quite attractive [25]. The coupling between the order parameters in such composite systems has also been found to be useful for many applications.

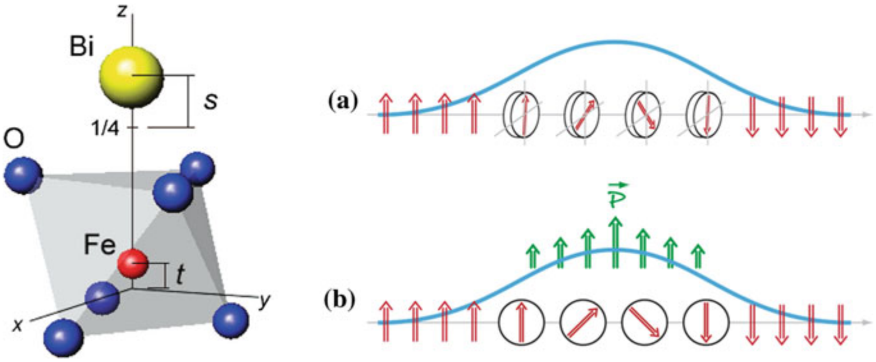

Fig. 4 The off-centred displacement of Bi and Fe ions along (001) axis in hexagonal setting; right panel shows the spiral spin structure which supports ferroelectricity (one where rotation of spin takes place along its trajectory)

3 Energy Efficient Devices Based on Cuprate Superconductors

At the advent of cuprate superconductors, euphoria was generated on the possibility of large scale applications in power transition, storage, generation, and many other electrical and electronic devices. However, it was soon realized that the cuprate superconductors because some intrinsic drawbacks cannot solve the energy crisis by a large scale. Most important drawback is the re-emergence of normal state resistivity with time. Since cuprate systems are Type-II superconductors, magnetic field (generated either by the flowing current itself or from applied external magnetic field) penetrates through the bulk of the sample in the form of quantized vortices. Each vortex line carries one flux quantum $\phi_0 = (h/2e) = 2.015 \times 10^{-15}$ Wb; the core of the vortex (of the size of coherence length $\xi = hv_F/2\pi k_B T_C$) is in normal resistive state while whirlpool of macroscopic current around the core over a length scale of penetration depth (λ) maintains the flux inside and shields the rest of the superconducting bulk. The vortices start penetrating the bulk of the sample at a lower critical field $H_{c1}(T)$ and fills the entire bulk by the upper critical field $H_{c2}(T) = \phi_0/2\pi\xi^2(T)$, the maximum field at which the superconductivity is retained. While $H_{c1}(T)$ is of the order of 100–500 Oe, $H_{c2}(T)$ is quite large (>1000 kOe). Even though the $H_{c2}(T)$ is large, in practice, superconductivity in the cuprate systems cannot be retained under large magnetic field because of weak pinning force acting on the vortices which make them flow under both thermal activation and Lorentz force. Upon entering the bulk of the sample, the vortices normally follow the crystallographic defects in a sample as these defective regions maintain their normal state (as against superconducting state) and thus offer attractive sites to the vortices. The vortices, therefore, are pinned by the lattice defects. The pinning force is higher than the inter-vortex repulsive force which force them to arrange themselves in a different geometry than the simple hexagonal one predicted by Abrikosov [26] in the absence of lattice defects. Depending on the concentration of the lattice defect (point or line or planar) and vortices within the bulk of the superconductor at a given field, the vortices form many complicated structures including even glassy structure. The magnetic phase diagram, therefore, becomes complicated. More importantly, in presence of flow of current through the sample, Lorentz force $\mathbf{F_L} = q.\mathbf{J} \times \mathbf{B}$ acts on the vortices and if the Lorentz force turns out to be greater than the pinning force $\mathbf{F_p}$—determined by the defect structure of the sample—the vortices start moving which, in turn, gives rise to resistance in the sample. The weak pinning force in the cuprate superconductors also leads to the thermal activation of the vortices because of which normal state resistance emerges over a certain span of time. The vortex flow resistivity, in general, is given by the Bardeen-Stephen formula $\rho = (B/H_{c2})\rho_n$ where ρ_n is the normal state resistivity of a superconductor at above T_C. Because of this flux flow, a superconductor looses the superconducting property and becomes resistive even when the operating temperature is well below T_C and the magnetic field is far lower than H_{c2}. In fact, detailed study of the magnetic phase diagram and the vortex dynamics under current flow and thermal activation showed that in cuprate system, the bulk superconductivity is retained up to the irreversibility field $H_{irr}(T)$ which is far smaller than the $H_{c2}(T)$. This is a serious impediment which has prevented cuprate superconductors to be used for large scale applications. The weak pinning force stems from the order of magnitude smaller coherence length ξ ($\approx$10–100 Å; whereas in low-T_C superconductors, it is $\sim$1000 Å) and also from large anisotropy ($\sim 10^2$–10^5). The strength of the thermal fluctuation with respect to the condensation energy of superconductor is expressed succinctly by Ginzburg number $Gi = 2\gamma(k_B T_C m_{ab}/\pi h^2 n\xi^2)$ where $\gamma = m_c/m_{ab}$, m = mass of an electron within ab-plane and along c-axis, and n is the Cooper pair density. In the low-T_C superconductors, the thermal fluctuation is negligible as $Gi \approx 10^{-5}$ to 10^{-6} whereas for YBCO system $Gi \approx 10^{-2}$ and for BSCCO system, $Gi \approx 1$. Higher Gi narrows down the operating zone for these cuprate systems within the magnetic field-temperature phase diagram. Another important aspect is the difficulty in fabrication of the cuprate superconducting wires. Because of brittleness, the ceramic cuprate systems cannot be fabricated in the form of wires of cables easily. In spite of this intrinsic shortcoming, power cables as well as superconducting magnets have been developed using cuprate superconducting wires for commercially use. We discuss here the fabrication technique and the devices.

In spite of the above-mentioned shortcomings, during the last decade and a half, tremendous progress has been made in the fabrication of cuprate superconducting cables for power transmission lines and other applications. The first and even second generation cables of $Bi_2Sr_2Ca_2Cu_3O_{10}$ (BSCCO) and $YBa_2Cu_3O_7$ (YBCO) clad within Cu or Ag sheaths are now being fabricated for commercial usage [27] for operating within 20–77 K. This is far above the temperature range at which the Nb–Ti and Nb_3Sn wires (low-T_C superconductors) and the magnets made of them work (<10 K). Insert magnets capable of generating 5T magnetic field within a background of 20T field, generated by Nb–Ti or Nb_3Sn based magnets, have also been developed using the cuprate superconductors. The first generation cables of the cuprate superconductors are fabricated by powder-in-tube (PIT) technique [27] in which superconducting powder is packed inside Ag tube which is then sealed, evacuated, and drawn in the form of a hexagonal rod. The rods are cut and bundled in the form of multifilaments and inserted within a second Ag tube (Fig. 5). This tube is then sealed, evacuated, and drawn in the form of a rod. The rod is rolled in the form of tape with intermediate heat treatment. The superconducting fill factor is typically 30–40%. The filamentary structure of the cables helps in reducing the ac losses. The critical current density (J_c) of the cable is measured by allowing more and more current to flow through the sample till a potential drop of 1 μV/cm develops. The corresponding current is called the critical current I_c. It is divided by the cross-sectional area of the tape to obtain the 'engineering J_c' which is quite useful a parameter for any application. The BSCCO system because of its layered crystallographic structure is amenable for forming flaky textures during processing which reduces the grain boundary misalignment angle (θ). This, in turn, improves the J_c as J_c follows exponential drop with the increase in θ, $J_c \sim J_{c0}.\exp(-\theta/\theta_c)$ [28]. The engineering J_c should attain 10^4–10^5 A/cm^2 in magnetic fields 0.1T to

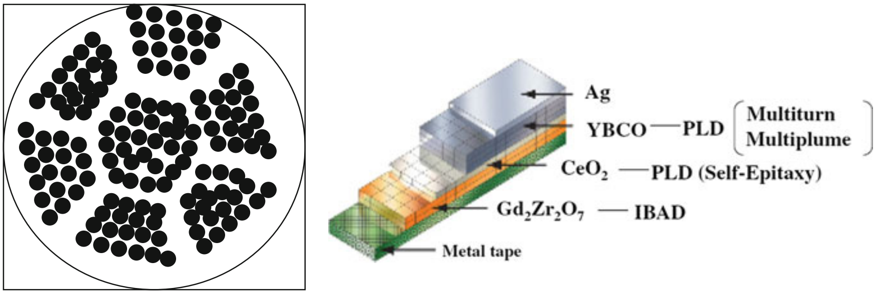

Fig. 5 The multifilamentary BSCCO2223 wires within Ag sheath in a first generation superconducting cable (after R.M. Scanlan et al. [29]); right panel shows the schematic of the second generation YBCO cable architecture. [S. Tanaka, Jpn. J. Appl. Phys. **45**, 9011 (2006) reproduced with permission from Japan Society for Applied Physics]

25T for applications as power cables and magnets. The actual superconducting J_C is given by J_c/f, where f is fill factor. In the case of BSCCO wires, steady progress has been made in improving the J_c. It has reached ~ 30,000 A/cm^2 at 77 K under 0.1T field. Understanding of the current flow path (the grain colonies which allow the current flow unhindered) and the role of the defects in pinning the vortices and improving the current carrying cross-section of the superconducting filament helps in designing the cables better.

The second generation cable technology [29] uses multiple processing routes comprising of epitaxial thin film deposition on tape-shaped templates (Fig. 5). This epitaxial texture is then replicated to form the YBCO wires with high degree of grain alignment. YBCO system with lower anisotropy and consequently higher $H_{irr}(T)$ offers higher operating temperature than BSCCO.

These first and second generation cables of BSCCO and YBCO superconductors find applications in power transmission lines, power equipment, motors, generators, synchronous condensers, transformers, and fault-current limiters for the electric utility grid.

Alongside all these, applications of cuprate superconductor based Josephson junctions are also envisaged as superconducting quantum interference device (SQUID) sensors working at 77 K. In a SQUID, single or double Josephson junctions are introduced within a superconductor circuit through which superconducting current tunnels. The circuit current changes significantly under application of a magnetic field. The magnetic field attaches to the device in the form of quantized fluxes ($\phi = n\phi_0$). The change in current, in turn, is used to measure the applied field and also magnetization of a sample. Because of substantial change in the tunnelling current under even one flux quantum ϕ_0 (= 2.07×10^{-15} Wb), a SQUID sensor is extremely sensitive.

A SQUID prepared by using Josephson junction of YBCO system (by depositing thin film of YBCO on a bicrystal to introduce the Joesphson junction) works at 77 K and has been used for magnetocardiography. Hitachi Ltd. has developed [30] an array of 51 SQUIDs for studying the human heart diseases. Of course, the sensitivity of YBCO based SQUIDs working at 77 K is about ten times lower than Nb based SQUIDs working at 4 K. An array of Josephson junctions comprising of 100 junctions with YBCO superconductors are used [31] for constructing single quantum flux (SFQ) device (Fig. 6). In this device, the quantized magnetic field under application of short pulse of current can either appear or disappear and thus render the junctions normal or superconducting. The state of the flux is designated as ‘0’ or ‘1’. The combination of generation of quantized flux and its transmission by Josephson transmission line is used for many logic operations. These logic operations use just 0.1 μW of power which is 100 times smaller than any semiconductor based logic gate device. The operation speed, on the other hand, is 100 times faster. The YBCO based SFQ devices are capable of working at 40 K.

In summary, cuprate superconductors are continuously pushing the boundary and increasingly find applications in large and small scale electrical and electronic devices. With the improvement of materials processing technology, problem of weak pinning of magnetic flux lines (vortices), brittleness of the ceramic systems, stability of the persistent mode operation, relatively low operating temperature than what was envisaged at the beginning are being solved. Great future awaits the cuprates in many diverse fields, glimpses of which have been presented here.

4 Energy Efficient Devices Based on Magnetoresistive Manganites

Large negative magnetoresistance in magnetic multilayer (comprising of two metallic magnetic layers sandwiching a nonmagnetic metallic layer) and spin valve effect opened the door of spintronics or spin-based electronics where spin of an electron (instead of charge) is used for transmission and processing of information. The spin transport with larger coherence length and precession time helps in enhancing the efficiency of information storage and communication. The

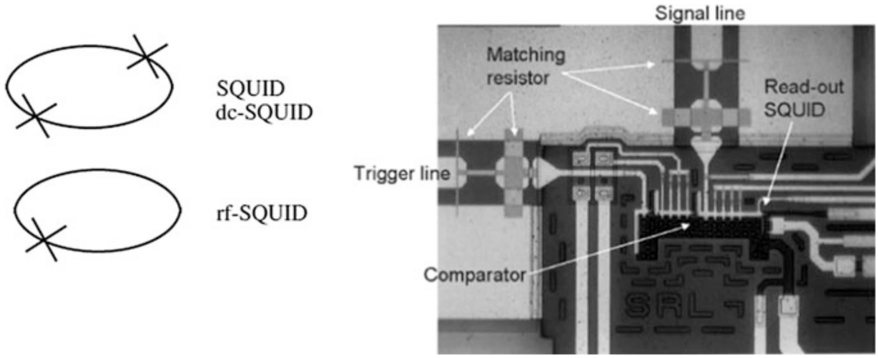

Fig. 6 The schematic of one and two Josephson junction SQUID and (right panel) the image of a sampler device associated with SFQ. [S. Tanaka, Jpn. J. Appl. Phys. **45**, 9011 (2006) reproduced with permission from Japan Society of Applied Physics]

observation of orders of magnitude decrease in electrical resistance under magnetic field in perovskite manganites ($RMnO_3$ with doping by Ca, Ba, or Sr at R-site) has created new possibilities for spintronic devices. The magnitude of magnetoresistance in doped perovskite manganites is even larger than what is observed in metallic magnetic multilayers. The charge carriers in manganites are almost 100% spin polarized (large band gap develops between up and down spins) with either up or down spins flowing through the sample [32]. These materials, therefore, are called half metals. The extent of spin polarization is given by $P = [N_{\uparrow}(E_F) - N_{\downarrow}(E_F)]/[N_{\uparrow}(E_F) + N_{\downarrow}(E_F)]$ where $N(E_F)$ is the density of electron states with either up or down spin – as the case may be—at the Fermi level (E_F). This is utilized in spin polarized magnetic tunnel junction devices.

The magnetic tunnel junctions (MTJ) are used for non-volatile magnetic random access memories (MRAM) (Fig. 7) which are superior to the dynamic random access memories (DRAM) and static random access memories (SRAM). The DRAM and SRAM systems are volatile because of leakage currents in the circuit. They need to be refreshed by frequent power supply. The MRAMs, on the other hand, do not require frequent power supply. The MTJs are constructed from two ferromagnetic electrodes and a thin tunnel barrier with fully spin polarized currents flowing across the tunnel barrier. One of the electrodes is pinned while the other is left free for the applied magnetic field to align the spins. Depending on whether the spins are aligned in parallel or antiparallel in the electrodes, spin-polarized current can flow with minimum or maximum tunnel resistance. The tunnelling magnetoresistance (TMR) is given by $2P_1P_2/(P_1 + P_2)$ where P_1 and P_2 are the spin polarizations in the two ferromagnetic electrodes. Because of nearly 100% spin polarization in $La_{0.7}Sr_{0.3}MnO_3$, the TMR is very large under moderate magnetic field. This is utilized in MRAM devices [33]. Similar effect can also be observed within a ferromagnetic layer by engineering a domain wall or defect line

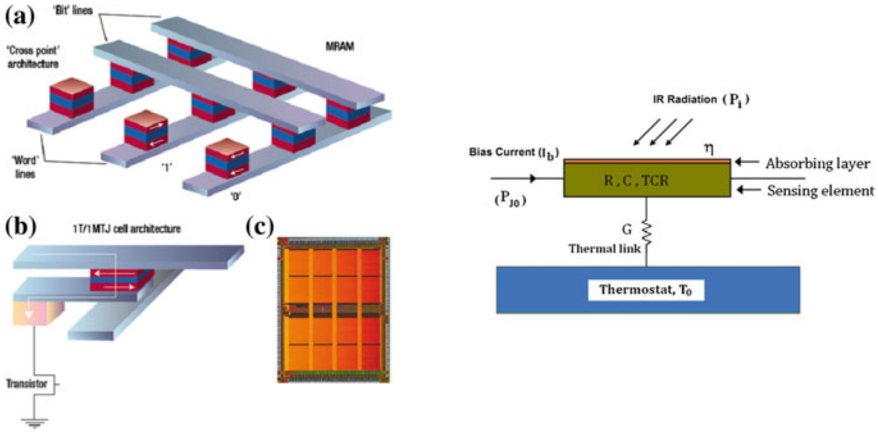

Fig. 7 Schematic of MRAM device based on magnetic tunnel junctions and also a photograph of the real device is shown in (**c**); right panel shows the schematic of the bolometer device

(grain boundary) across which the spins are rotated [34]. For perfect spin alignment across that nano-constriction, the resistance is small whereas the resistance become large for anti-alignment of the spins across the constriction. Under moderate magnetic field, the spins are aligned across the constriction giving rise to large magnetoresistance.

Another important manganites based device is the IR detector or bolometer (Fig. 7). Since the temperature coefficient of resistance (TCR) around the metal-insulator transition is large in this class of compounds, they are suitable for bolometers [35]. The typical response time is of the order of few ns which is fast enough for practical applications. The sensitivity and noise (due to fluctuations in incident energy, Johnson and phonon noise in the circuit) in the circuit could be defined in terms of normalized Hooge parameter. Large TCR and small Hooge parameter are suitable for bolometer application. Because of metal-insulator transition taking place near room temperature in $La_{0.7}Sr_{0.3}MnO_3$, this compound is suitable for room temperature bolometer devices in spite of relatively smaller TCR here than other manganites such as $La_{0.7}Ca_{0.3}MnO_3$.

The colossal magnetoresistive manganites find applications is the magnetoresistive read heads of the magnetic data storage medium. Sharp change in electrical resistivity under tiny magnetic field—observed in CMR systems—is exploited for reading a magnetic bit stored in a medium of nanosized domains. With such read heads, the data storage density enhances manyfold than conventional inductive head where current is induced in the head in the vicinity of magnetic storage medium. The CMR manganites are expected to achieve as high a storage density as 1 Tbit/in^2. Of course, the intrinsic magnetoresistance in the manganites is colossal only under a higher field (of the order of 1 to 2T) whereas for read head application, large magnetoresistance should be observed under few tens of Oersted. This is achieved in granular CMR system where spin polarized intergranular transport exhibits large magnetoresistance under low field. The granular structure is developed [36] by artificially etching out grain boundaries in thin film of CMR oxide (Fig. 8).

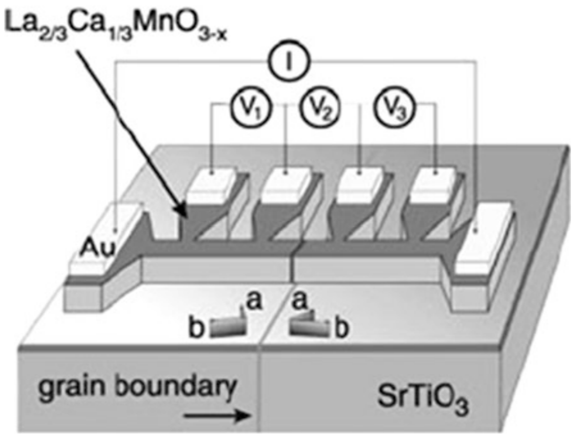

Fig. 8 Schematic of artificially etched grain boundaries in a thin film of CMR manganite

While CMR of the manganites—being exploited in MRAM, disk read head, and bolometer devices—are observed in the composition regime where the sample assumes ferromagnetic and metallic properties, the regime where long-range charge/orbital order prevails and the sample exhibits primarily antiferromagnetic and insulating behaviour is also suitable for novel spin and orbital based electronic applications. Importantly, because of closeness of the energy scales involved, the interplay among charge, spin, orbital, and lattice degrees of freedom is quite delicate in different regions of the phase diagram and this, in turn, can be exploited by switching the ordered states or order-disorder transition under external stimulation such as light pulse, electric or magnetic field. In a charge/orbital ordered system, electrons occupy specific d-orbitals which, in turn, organize in different patterns; electrons, therefore, carry their orbital degrees of freedom in such cases. Because of associated polarizability, the orbital degree of freedom couples with the applied electric field and/or optical pulse. It has been demonstrated [37, 38] that ultrafast switching of orbital states (as the orbitals and their dynamic response 'orbitons' have a typical response frequency 10–100 THz which is orders of magnitude larger than 0.1–1.0 GHz spin precession frequency) and/or melting under optical pulse can be utilized in optical devices (Fig. 9).

In summary, CMR manganites find applications as MRAM, magnetic disk read head, bolometer, and also orbitronic devices where melting of orbital order gives rise to gigantic change in physical properties such as resistivity, magnetization, thermal properties, optical constants etc. which recover slowly with time. Such changes can be utilized for ultrafast optical switches.

5 Energy Efficient Devices Based on Multiferroics

The spin and orbital based electronic devices receive a boost from the multiferroics where coexisting ferroelectric and magnetic order and their coupling expands the horizon even further. The advantages of FeRAM and MRAM can now be

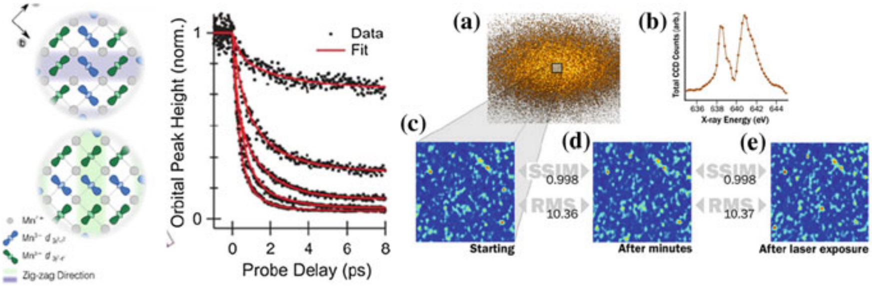

Fig. 9 Orbital domain structures with two different types of Mn 3d orbital patterns; the peak corresponding to the orbital order in $La_{1.8}Ba_{0.2}MnO_4$ melts rapidly under laser fluence of 60 mJ/ cm^2within 1–2 ps; right panel, however, shows that over a time span of few minutes the orbital order recovers fully with virtually identical speckle patterns [*source* https://upcommons.upc.edu/bitstream/handle/2117/107059]

integrated into a single multiferroic memory device which offers four independently accessible logic states [(+P, +M), (+P, −M), (−P, +M), and (−P, −M); where P and M are polarization and magnetization, respectively] – not possible to access in FeRAM or MRAM separately—and consequently exponentially enhanced computation capacity. The voltage driven multiferroic memory because of very small current flow requires an order of magnitude smaller power supply and also exhibits an order of magnitude smaller Joule heating than spin torque transfer type memories which depend on spin polarized current flow.

The major bottleneck, however, is the non availability of suitable multiferroic compound which exhibits ferroelectric and ferromagnetic orders and strong cross-coupling at room temperature itself. Very recently, of course, epitaxial thin film based device of room temperature multiferroic $BiFeO_3$ was shown to exhibit complete 180° switching of magnetic domains under electric field [39]. Energy consumption in such a device was shown to be ~ 0.5 mJ/cm^2 which is nearly an order of magnitude smaller than the energy consumption of a spin torque transfer type memory (~ 3–4 mJ/cm^2). This device or, alternately, where multiferroic $BiFeO_3$ and ferromagnetic $La_{0.7}Sr_{0.3}MnO_3$ (LSMO) are formed as multilayers, exchange coupled device (Fig. 10) could well be used as real-life multiferroic memory in near future [40]. In the exchange coupled device, the magnetic anisotropy of the ferromagnetic LSMO layer was shown to switch under electric field because of switching of anisotropy in $BiFeO_3$ under electric field and exchange coupling between antiferromagnetic $BiFeO_3$ and ferromagnetic LSMO which generates sizable exchange bias field at the interface.

The non-availability of single phase room temperature multiferroic has been circumvented by multilayers of ferroelectric ($BaTiO_3$) and ferromagnetic ($La_{0.7}Sr_{0.3}MnO_3$) systems which exhibits nearly 400% large tunnelling magnetoresistance [41]. This system also works as low energy memory device. Similar

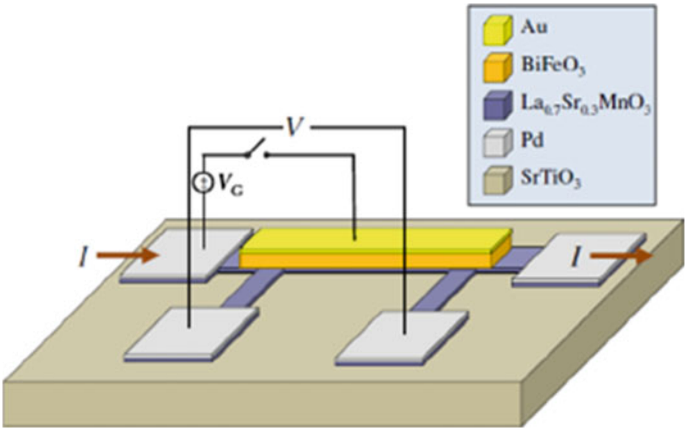

Fig. 10 Schematic of the exchange coupled multiferroic memory device comprising of $BiFeO_3$ and $La_{0.7}Sr_{0.3}MnO_3$ layers

device has been developed by using $PbZr_{0.52}Ti_{0.48}O_3$(PZT)/$La_{0.7}Sr_{0.3}MnO_3$ (LSMO). The heteroepitaxy, in fact, is currently the main theme underlying the device configuration for multifunctional device development. Heterostructures of $Co_{0.9}Fe_{0.1}$/$BiFeO_3$ and $BaTiO_3$/$BiFeO_3$ have also been developed [42] for memory and magnetoelectric sensor applications.

The piezoelectric effect and magnetoelectric coupling in composite ferroelectric/magnetic system have been used [43] for magneto-mechano-electric generator. Multilayers of PMN-PZT ferroelectric, Ni magnetostrictive, and Nd magnetic systems with Cu electrodes laminated within are used to generate as high as $\sim$9.5 V under H_{ac} of 160 mT (at 60 Hz) without any dc external magnetic field. The power density appears to be $\sim$46.3 mW/cm^3/Oe^2 which is $\sim$1600% higher than conventional devices. This device can be used as power source for wireless sensor network, low power electrical devices, and wireless charging system.

The composite of magnetic and ferroelectric systems, in fact, were shown to be useful for a variety of other low power device applications such as microwave resonator, phase shifter, delay line. The yttrium iron garnet (YIG) and PZT composite has been used [44] to demonstrate the tuning of ferromagnetic resonance (FMR) in the YIG, driven by electric field, at a signal input of 2–10 GHz and 0.1 mW power. The resonance frequency shifts from 5 GHz under zero electric field by +16 MHz under +10 kV/cm and −18 MHz under −10 kV/cm. The use of electric field as against magnetic field in all these cases reduces the power consumption by a large extent.

Single phase multiferroic systems find applications even as photovoltaic cell based devices. In a photovoltaic cell, irradiation of sunlight creates electron-hole pairs by exciting the electrons across the band gap in a semiconductor which, in turn, are separated for producing the current flow in the circuit. Normally, this is achieved in a p-n junction device. The semiconductor of small band gap absorbs more photons and creates large current while the one of large band gap absorbs lesser photons and creates large voltage. Striking a balance between the two is a problem. This requires bulk photovoltaic effect instead of the one observed at the p-n junction interface. Bulk photovoltaic effect is observed in ferroelectric systems where additional internal electric field due to large ferroelectric polarization (P) helps in photocurrent flow [45]. This, in turn, offers larger open circuit voltage than what is observed in p-n junction device. However, one disadvantage of the ferroelectric cell is large band gap (of the order of 3–6 eV) which prevents entire solar light spectrum to be used. Single phase multiferroics such as $BiFeO_3$ with relatively smaller band gap ($\sim$2.3 eV) or double perovskite Bi_2CrFeO_6 (band gap $\sim$1.4–2.0 eV) appear to be suitable for photovoltaic cells [46]. It has been argued that exchange coupling interaction associated with long-range magnetic order is responsible for reducing the band gap. The switching of ferroelectric polarization and/or turning it on by external magnetic field—as is possible in a multiferroic system—make them more attractive. The schematic of the function of a multiferroic based solar photovoltaic cell is shown in Fig. 11. The coupling among strain-ferroelectric-magnetic properties makes the multiferroics extremely attractive for photovoltaic application.

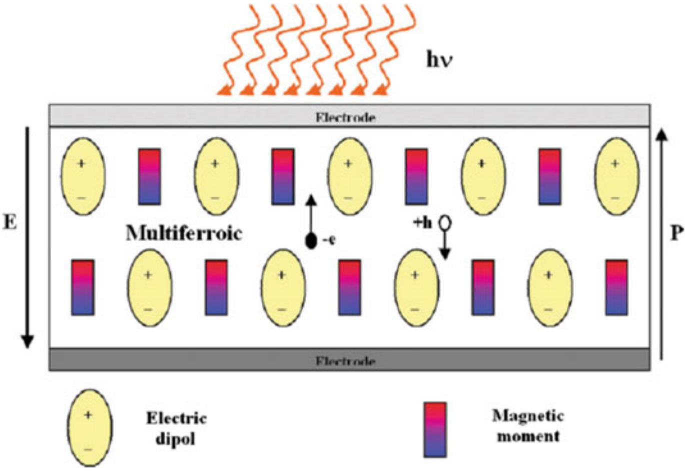

Fig. 11 Schematic of bulk photovoltaic effect in multiferroic system in presence of electric and magnetic dipoles

An extremely important upcoming application of multiferroic systems is in the biomedical field. Here, rectification of a faulty ion channel could be carried out by insertion of a nanoscale multiferroic device. This device generates electric field locally—thus operates the ion channel valves—under remote application of magnetic field [47]. The two main characteristics of the ion channels are their selectivity and their gating (process of opening and closing in response to gating variable). In the recent past, researchers have focussed on the effect of electric field on these ion channels using currently available multiferroic nanoparticles. Though it is a well accepted fact that the function of ion channel can be modified through the use of drugs, the prospect of multiferroic nanoparticles is worthy of detailed investigation. In some of the recent papers, it is reported that multiferroic particles introduced extra or intra-cellularly can modify the electric field and control ion channel gating by externally applied magnetic fields. Therapeutic use of electric or magnetic field till date has its own limitations. It includes use of high voltage (sometimes above 200 volts), exposure to large volume of tissues, direct contact with body fluids in case of percutaneous electrodes etc. In case of multiferroic composites, individual cells are proposed to be targeted, not the whole tissue. The voltage required for the stimulation is also reported to be in millivolts. Moreover cell functioning in internal organs can be controlled in a remote way. When an external magnetic field is applied, the multiferroic particles can convert it to localised electric field. If the particles are placed near cell membranes, this may lead to membrane depolarisation and accordingly, the ion channels can open. The magnetic field can be applied globally by the Helmholtz coils but the electric field will still be locally generated. This will lead to localised changes in ion channel gating. Moreover, it is also interesting that the signals generated by nanoparticles have closely similar characteristics to those of electric signals propagating in neural cells. In future, it can generate new scopes to remotely stimulate the functions of neural cells for pain management. Another important issue arising out of the use of multiferroic composites is the scope of applying magnetic field pulses with higher frequencies. The ion channels may not respond to high frequency fields, but the strength of electric fields produced by the multiferroic nanoparticles may be sufficient to cause electroporation of cell membranes and cause permanent damage which, in turn can provide a tool for cancer treatment.

In summary, a variety of spintronic based devices are possible for either single phase or composite multiferroic systems ranging from four-logic-state next generation memory, to read heads, to sensors, tunable resonators, magneto-mechano-electric generators, photovoltaic cells to even biomedical implants. In all the cases power consumption and efficiency of the devices appear to be lot better than the conventional devices.

6 Future Projection

In the previous paragraphs, glimpses of the developments made in the area of 'strongly correlated electron system' based electronic, spintronic, and orbitronic devices have been given. In spite of the great promise of the cuprate superconductor, CMR manganite, and multiferroic compounds, it is true that many issues still need to be solved in order to go for full scale commercial usage. Some of the issues are intrinsic such as giant vortex creeping in cuprates which destroys superconductivity in the long run, non-availability of single phase multiferroic system exhibiting ferroelectric and ferromagnetic properties as well as large magnetoelectric coupling right at room temperature. Some of the issues, however, are operational. For instance, interesting properties could be observed in laboratory scale on thin films prepared on single crystal substrates by sophisticated techniques such as pulsed laser deposition. However, for industrial processing low-cost chemical vapour deposition or sputtering technique and cheaper substrates are required. The heteroepitaxy, currently being explored for artificially building up novel device architecture [48] capable of exhibiting requisite functionality, needs to be simple and cheap enough to be industrially viable. While, technological development at the laboratory scale such as molecular beam epitaxy, laser based synthesis, atomic force microscopy based tailoring can certainly yield novel material properties by ingenuous lattice strain/defect engineering, greater ingenuity is required to achieve the same result in rather simple and cheaper techniques. The development of novel industrially viable processing technique appears to be a major bottleneck for commercial use of these systems.

However, as discussed above, the prospect of the 'strongly correlated electron systems' is certainly bright and in near future with the advancement in material processing technology, commercial devices will roll out for ushering in an era of 'strongly correlated electron' system based electronics.

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