Energy Sustainability Through Nuclear Energy

A. Shukla

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

Keywords Energy · Sustainability · Nuclear · Treatment · Carbon emission

1 Introduction

In the present era, when energy demand is increasing day by day and is likely to increase even with faster pace (International Energy Agency 2010), with increase in proportion of population supplied by electricity, nuclear energy remains on top agenda for all concerned stakeholders. Along with the primary question—how to cope up with ever-increasing energy demand and achieve energy sustainability—there are secondary questions too, such as whether the electricity demand will

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A. Sharma and S.K. Kar (eds.), *Energy Sustainability Through Green Energy*,
Green Energy and Technology, DOI 10.1007/978-81-322-2337-5_19

continue to be served predominantly by extensive grid systems, whether there will be a strong trend to distributed generation (close to the points of use), and whether increase in energy production will keep on increasing carbon emission or we can have enough clean energy resources. These are important technological-cum-policy questions interwoven with the major question of exploring possible resource itself. Either way, it will not obviate the need for more large-scale grid-supplied power, especially in urbanized areas having domestic as well as industrial requirements, over the next several decades. Currently, much demand is for continuous, reliable supply of electricity on a large scale, and this will continue to dominate.

Currently, our energy requirements are mainly fulfilled through fossil fuels. There are three major forms of *fossil fuels*: coal, oil, and natural gas. It is predicted that these resources may reach on the verge of depletion after about six decades. Moreover, the carbon emission from these resources is so high that it has already started affecting biosphere and can be seen in terms of climate change and global warming which may put serious threats to mankind. In such a scenario, it is of paramount importance not only to achieve energy sustainability but energy sustainability through clean energy resources. However, there are many channels to produce clean energy, namely solar, wind, and geothermal. On the basis of bulk requirement versus fuel availability, impact on climate, land use, costs, and technology transfer, nuclear power is the only energy option that can help globally in achieving energy sustainability. Hence, to achieve energy sustainability along with reduced carbon emission, nuclear energy production is bound to contribute heavily (Grimes and Nuttall 2010).

Nuclear energy: facts at a glance	
Total power production through nuclear energy	About **370,000 MWe**
Number of operational commercial nuclear power reactors	430 in 31 countries
Largest nuclear power plant	Bruce Nuclear Generating Station, Canada
Worldwide electricity production through nuclear energy (in %)	Approximately 12 %
Country which has largest share of nuclear energy	France
Cost of nuclear power production	(60–80) USD/MWh

At present, all the nuclear power plants producing electricity are based on the process of nuclear fission. Nuclear fission is a nuclear process where a heavy nucleus fragments into lighter nuclei along with producing energy. When a neutron passes near to a heavy nucleus, for example, uranium-235 (U-235), the neutron may be captured by the nucleus and this may or may not be followed by fission. Capture involves the addition of the neutron to the uranium nucleus to form a new compound nucleus, which further breaks into lighter nuclei along with emission of neutrons and energy. These emitted neutrons give rise to further process of nuclear fission, and hence, chain reaction takes place, which could be controlled for producing desirable amount of energy. Currently, nuclear fission-based reactor technology is in quite advanced stage and is being used considerably for power production. There is one another possibility to produce energy via nuclear fusion—the process through which Sun and other stars generate energy. This process has its own benefits in terms of fuel and nuclear waste in comparison with nuclear fission-based power plants. Consider this to be ideal for energy production; attempts are on to develop power plants based on nuclear fusion.

Nuclear fusion is a process whereby two hydrogen nuclei collide and join together to form a heavier atom, usually deuterium and tritium. When this happens, a considerable amount of energy gets released at extremely high temperatures: nearly 150 million °C. At extreme temperatures, electrons are separated from nuclei and a gas becomes plasma—a hot, electrically charged gas. A plant producing electricity from a nuclear fusion reaction could well replace nuclear fission plants. The fuel for nuclear fusion is abundant (deuterium, lithium, and tritium), with very little radioactivity and low radioactivity of the components with a short half-life, no need for underground storage, and no environmental risk in case of accident, as plasma cannot exist without being confined in a chamber under high pressure. Fusion is arguably one of the major research challenges of the twenty-first century. It is an option to provide environmentally benign energy for the future without depleting natural resources for next generations. Therefore, fusion scientists from the European Union, India, China, Japan, Korea, Russia, and the United States are proceeding with the construction of a 500-MW (thermal power) experimental plant (ITER—the International Thermonuclear Experimental Reactor). Although further research and development work needs to be done on materials and on concept improvements, ITER is expected to be the last major step between today's experiments and a demonstration power plant. The Fusion Power Coordinating Committee (FPCC) provides a platform to share results of fusion activities worldwide: the ITER project, the International Atomic Energy Agency, the European Commission (EURATOM), the International Tokamak Physics Activity (ITPA), and the Nuclear Energy Agency. The FPCC also coordinates and oversees the activities of fusion-related multilateral technology initiatives, or Implementing Agreements, that carry out R&D on the physics, technology, materials, safety, environmental and economic aspects, and social acceptance of fusion power (Intergovernmental Panel on Climate Change 2007).

2 Current Status

The generation of electricity using nuclear energy started in early 1950s, and the first commercial nuclear power plants started operation in the early 1960s. Electricity production through nuclear power grew rapidly in the 1970s and 1980s as countries sought to reduce dependence on fossil fuels, especially after the oil crisis of the 1970s. By 1990s, nuclear power emerged a strong contributor in the field of energy supply, though the growth stagnated slightly due to increasing concerns about safety operations following accidents in the Three Mile Island (1979) and Chernobyl (1986) (Talbott et al. 1979). The delays along

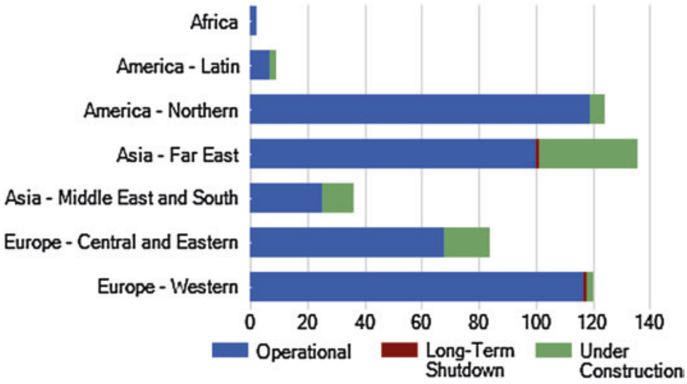

Fig. 1 Geographical distribution of operational/long-term shutdown/under construction nuclear power plants (Talbott et al. 1979; http://www.nei.org/Knowledge-Center/Nuclear-Statistics/World-Statistics)

with higher-than-expected construction costs at some nuclear plants, and a return to lower fossil fuel prices, also contributed to the stagnation of nuclear energy growth chart. However, from 2000, there was a renewed interest in nuclear power, and the pace of construction accelerated after 2005. At the end of 2010, there were 65 reactors under construction, and 60 new countries had expressed interest in launching a nuclear program to the International Atomic Energy Agency (IAEA). As of May 2014, 30 countries worldwide are operating 438 nuclear reactors for electricity generation and 72 new nuclear plants are under construction in 15 countries. Figure 1 shows the geographical distribution of nuclear power plants which are either operational or under construction. It is evident that Asia overall has chosen nuclear power plants for its energy supply in considerable fashion. Moreover, Africa is on the lowest side to adopt nuclear technology and certainly has big opportunity due to large energy requirements. The USA and Europe are undoubtedly leading the nuclear energy production, but their future plans to enhance nuclear capacity are under question due to raising concerns over treatment of nuclear waste disposal and safety operations. Nuclear power plants provided about 375,504 MWe of power which is about 12.3 % of the world's electricity production in 2012 (http://www.nei.org/Knowledge-Center/Nuclear-Statistics/World-Statistics). In total, 13 countries relied on nuclear energy to supply at least one-quarter of their total electricity. Tokyo Electric Power Co.'s (TEPCO) Kashiwazaki-Kariwa plant in Japan is currently the world's largest nuclear power plant, with a net capacity of 7,965 MW but is operating only at 48 % of capacity due to earthquake damage and decommissioning. Hence, currently Bruce Nuclear Generating Station, located in Canada, is the largest nuclear facility in the world with a net capacity of 6232 MWe. As of now, there are more than 400 nuclear reactors which are operational in about 30 countries. Countrywise list of same is given in Fig. 2 along with number of operational reactors. France is one among the leaders in energy production through nuclear energy having more than 50 operational nuclear reactors and relying mainly on nuclear

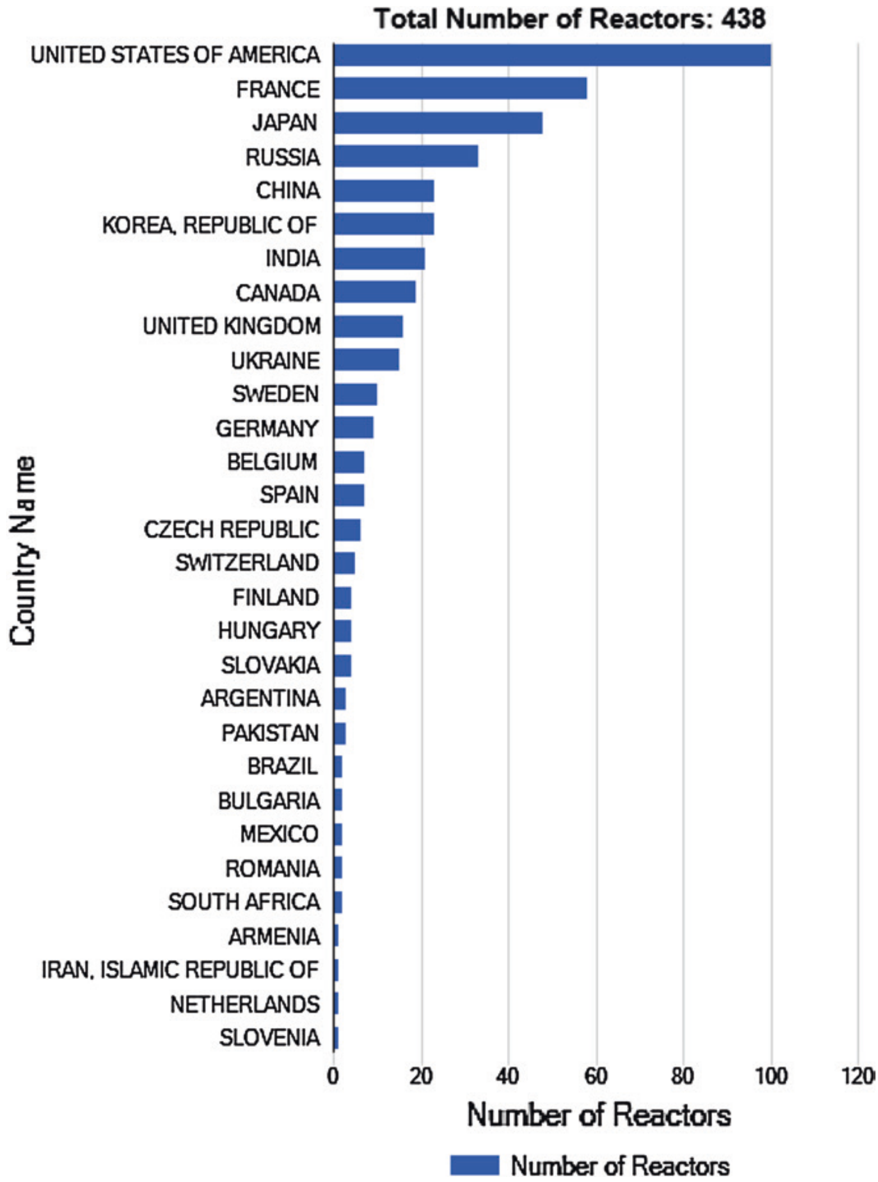

Fig. 2 List of countries along with number of operational nuclear reactors (Talbott et al. 1979; http://www.nei.org/Knowledge-Center/Nuclear-Statistics/World-Statistics)

power only for major part of its energy needs (ref. to Figs. 2 and 3). The situation of countrywise share of power production through nuclear energy is expected to enhance in Asia phenomenally, with number of reactors under construction (http://www.nei.org/Knowledge-Center/Nuclear-Statistics/World-Statistics, http://www.eia.gov). As evident from Fig. 3, currently European countries are

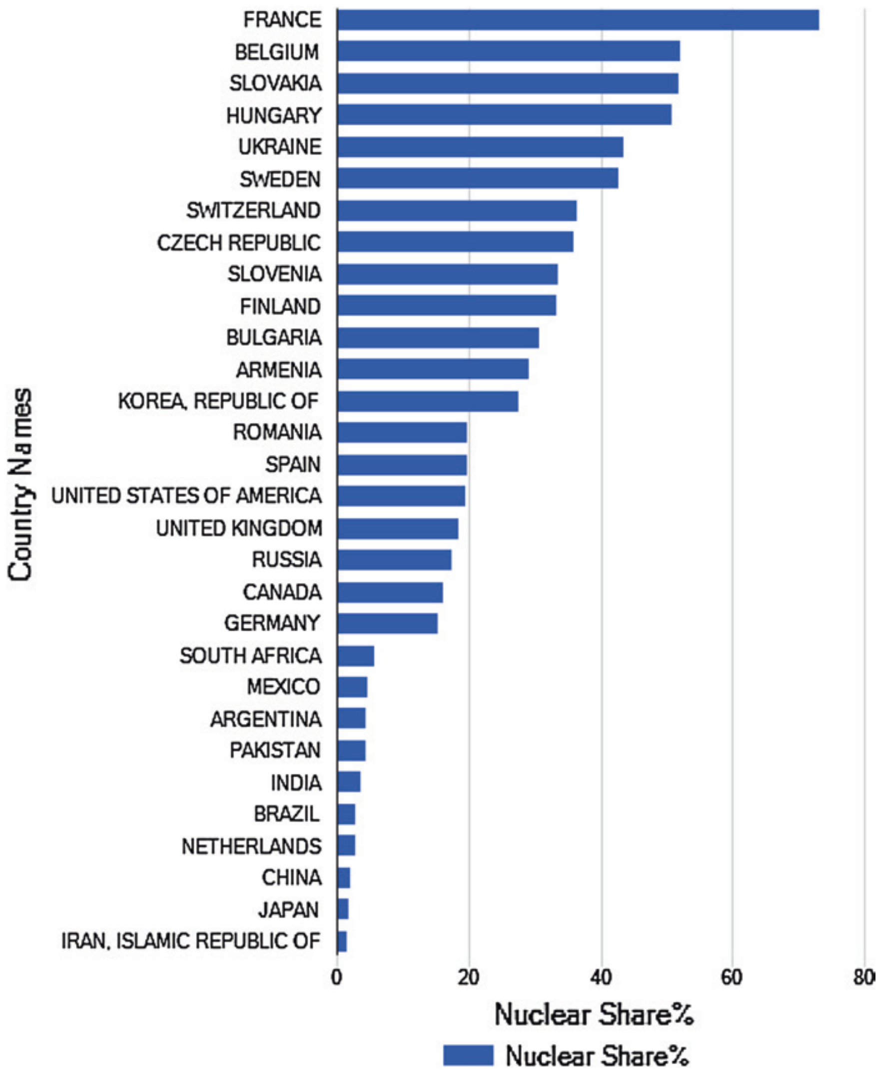

Fig. 3 Countrywise share of power production through nuclear energy (in %) (Talbott et al. 1979; http://www.nei.org/Knowledge-Center/Nuclear-Statistics/World-Statistics)

utilizing nuclear power as major energy resource. Earlier Lithuania was global leader among the countries utilizing nuclear energy, fulfilling more than 80 % of its requirements through nuclear power. By the end of 2009, Lithuania closed its last nuclear reactor, which had been generating 70 % of its electricity.

In March 2011, a major earthquake and tsunami ravaged the Pacific coast of northern Japan and damaged the cooling system at the Fukushima Daiichi nuclear power plant, resulting in a severe accident. No deaths have been attributed to the accident (while the tsunami and the earthquake killed about 20,000 people), but serious releases of radioactive material resulted in contamination of the surrounding environment and led to the evacuation of several thousand inhabitants from neighborhood. This accident forced to rethink about the safety concerns related to nuclear power plants. In reaction, most nuclear countries announced safety reviews of their nuclear reactors and the revision/improvement of their plans to address similar emergency situations.

One of the advantages enjoyed by nuclear power plant operators is the abundance of fuel. Uranium, the main material for fueling nuclear power plants, is plentiful and available in many parts of the world. Although, at present, annual uranium production provides only some 60 % of reactor consumption, secondary sources, such as inventories of producers, utilities and governments, and ex-military materials, are sufficient to cover demand. The current global demand for uranium is about 68,500 tU/year (tons uranium per year). The vast majority is consumed by the power sector with a small amount also being used for medical and research purposes, and some for naval propulsion. At present, about 53 % of uranium comes from conventional mines (open pit and underground), about 41 % from in situ leach, and 5 % is recovered as a by-product from other mineral extraction. Kazakhstan produces the largest share of uranium from mines (38 % of world supply from mines in 2013), followed by Canada (which long held the lead) (16 %), and Australia (11 %) as shown in Table 1. Thus, the world's present measured resources of uranium (5.4 Mt) in the cost category a bit above present spot prices and used only in conventional reactors are enough to operate nuclear power plants for more than a century

Table 1 Production of uranium through mines in last five years (in tons U per year)

Country	2009	2010	2011	2012	2013
Kazakhstan	14,020	17,803	19,451	21,317	22,451
Canada	10,173	9783	9145	8999	9331
Australia	7982	5900	5983	6991	6350
Niger (EST)	3243	4198	4351	4667	4518
Namibia	4626	4496	3258	4495	4323
Russia	3564	3562	2993	2872	3135
Uzbekistan (EST)	2429	2400	2500	2400	2400
USA	1453	1660	1537	1596	1792
China (EST)	750	827	885	1500	1500
Malawi	104	670	846	1101	1132
Ukraine	840	850	890	960	922
South Africa	563	583	582	465	531
India (EST)	290	400	400	385	385
Brazil	345	148	265	231	231
Czech Republic	258	254	229	228	215
Romania (EST)	75	77	77	90	77
Pakistan (EST)	50	45	45	45	45
Germany	0	8	51	50	27
France	8	7	6	3	5
Percentage of world demand (%)	78	78	85	86	92

http://www.eia.gov

(http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Mining-of-Uranium/World-Uranium-Mining-Production/). This represents a higher level of assured resources than is normal for most minerals. Other resources are known to exist and could be made available with further exploration and development efforts. Moreover, the introduction of advanced reactors and fuel cycles could multiply the lifetime of those resources by 30 or more and allow for a sharp rise in demand. Indeed, breeder reactors could eventually make nuclear energy a quasi-renewable source. Further exploration and higher prices will certainly, on the basis of present geological knowledge, yield further resources as present ones are used up. In the long term, we are confident that ample natural resources and progress in technology can ensure nuclear fuel supply, whatever the development of nuclear energy may be.

3 Challenges

Like any other energy source and technology, nuclear energy has advantages and drawbacks in each of the three dimensions of sustainable development: environmental, social, and economic. Policymakers must have authoritative facts, figures, and analyses to support their decisions on energy choices. The Nuclear Energy Agency can provide expertise and help governments to assess nuclear energy on a level playing field, with alternatives. While the economic sense of nuclear energy is no longer an issue, financing the building of nuclear power plants and fuel cycle facilities remains a challenge. Recent decisions in Europe to build new plants suggest greater interest from investors, but they remain cautious about the long-term financial risks. To reassure them, governments must at least provide stable regulatory frameworks in the field of nuclear safety and radiation protection, and back this up with clear policies to limit greenhouse gas emissions.

In parallel with technical improvements, addressing public concerns about nuclear risks is a high priority. Nuclear power plants generate large quantities of highly radioactive material. This is due to the leftover isotopes (atoms) from the splitting of the atom and the creation of heavier atoms, such as plutonium, which the nuclear power plant does not utilize. It is called nuclear waste. It is necessary to isolate the waste from humans and environment for about 100,000 years before it decays to safe levels. The consensus among the nuclear power industry is that radioactive waste should be isolated by multiple barriers and placed deep underground. However, other strategies involving waste transmutation are being investigated. Another main concern to address is that of waste management and disposal. Although radioactive waste management, including final disposal, does not raise any significant technical or economic problems—it is essential to note in this regard that the cost of waste management and disposal is already integrated in the price paid by consumers of nuclear electricity—establishing repositories to hold all waste types for a considerable time has proven to be a challenge. However, experts agree that the safe disposal of radioactive waste is feasible, with due respect being given to health and environmental regulations protecting present and future generations. Advanced studies and demonstration projects have been carried out on the treatment, packaging, and disposal of the waste in deep geological formations. These provide confidence that the successive natural and engineered barriers will satisfactorily isolate waste from the biosphere for as long as its level of radioactivity requires. Several countries, such as Finland, Sweden, and the United States, are in the process of developing repositories that should be opened within a decade or so (Elliot 2007).

Safety is of paramount importance in this regard. The excellent safety records of nuclear power plants and fuel cycle facilities in operation in OECD countries demonstrate the effectiveness of stringent regulations in place and of the efforts by industry and regulators to implement a robust safety culture. As a result of these efforts and progress in technology, the impacts of nuclear energy facilities on human health and the environment are well below the levels imposed by regulators and accepted by society in general for industrial activities. Going beyond mere compliance, the radiation doses received by workers in nuclear installations have been more than halved over the past 20 years. Meanwhile, the strictly monitored radioactive releases surrounding nuclear power plant sites remain extremely low (typically between a tenth and a hundredth of natural background radioactivity) and are decreasing further still.

4 Nuclear Power: Is It Really a Sustainable Energy Source?

With all said and done, it is important to examine the question, "If nuclear power can be termed as sustainable energy source? Does nuclear power meet our current energy needs and has potential for future too without compromising the living conditions of next generations?" Let us try to answer the same in terms of some specific criteria (Pearce 2012).

4.1 Greenhouse Gases and Carbon Emission

Nuclear power complies with the international standards of carbon emission as nuclear power plants do not produce greenhouse gases. In fact, they have helped several nations to reduce their greenhouse gas emissions significantly. Moreover, it is possible only by the use of nuclear energy for all nations to meet the demand for increased energy while still reducing emissions of greenhouse gases.

4.2 Land Requirements

Compared to other non-carbon-based and carbon-neutral energy options, nuclear power plants require far less land area. For a 1000-MW plant, site requirements are estimated as follows: nuclear, 1–4 km^2; solar or photovoltaic park, 20–50 km^2; a wind field, 50–150 km^2; and biomass, 4000–6000 km^2. Estimates about urban civilization suggest that by 2050, half of the world's population will live in large cities (Hondo 2005). This will require concentrated energy production systems in proximity to those population masses. The use of large land areas for energy production will be impractical.

4.3 Long-lasting Reserves of Fuels

Estimates about known fuel resources suggest that nuclear power plants can easily provide for more than 250 years of consumption using current "once through" commercial reactor technology. The technology exists (though it is not yet significantly deployed), with multiphase fuel usage and fast reactors, to utilize even more energy from each fuel sample. Recycling of uranium and plutonium could extend the fuel supply for by order of magnitude of estimated years of consumption. Abundance of uranium is spread all around the globe in relatively politically stable countries. These known resources clearly provide for many future generations with strong edge over limited fossil fuel materials.

4.4 Nuclear Waste Disposal, Environmental Impact, and Personal Safety

Rather than disperse massive quantities of waste products over wide areas, as is the case with emissions from fossil fuel plants (sulfur oxides, nitrogen oxides, carbon dioxide, and toxic metals such as arsenic and mercury contained in the fly ash), nuclear power plant operators are able to consolidate the waste and sequester it safely while its radiation level drops. By comparison, some of the waste dispersed into the air from fossil fuel plants is toxic and will remain so forever. The record of the civilian nuclear power industry in safely isolating both low-level and high-level nuclear wastes has been excellent. There have been no significant releases of nuclear waste to the environment, and improved repositories such as the recently licensed Waste Isolation Pilot Plant (WIPP) in the USA offer promise of an even more secure future. Potential environmental impacts from nuclear power operations are carefully controlled and regulated. Presently, nuclear plant operations are quite standardized and are operated according to stringent safety standards, posing no threat to workers, society, or to the environment. Over the long term, the fission of nuclear fuel resources and safe isolation of the radioactive wastes generated in the plant operation process actually reduce the exposure of the biosphere to nuclear radiation through naturally occurring radioactive elements. Moreover, the quantity of fossil fuel, such as coal, required to provide equivalent amounts of energy would release chemical elements and gases which are much more contaminated resulting in greater exposure to hazardous materials than would be the case using nuclear power.

4.5 Preservation of Fossil Resources

Controlled fission of small amounts of uranium fuel can be used to generate large amounts of electricity without burning carbon-based fuel sources. The amount of fuel (mass and volume) required for nuclear power is significantly less than that required for a fossil-fueled plant. Energy produced by one ton of uranium is equivalent to 17,000 tons of coal. Nuclear power plants utilize resources of fissionable heavy metal (uranium) which has no other major use. Thus, the use of nuclear power slows the depletion rate of fossil resources significantly and helps in preserving fossil fuel resources to meet future developmental needs. Further, it frees fossil resources, so they can be used for other critical applications, such as feedstocks for chemical processes, personal transportation, and residential heating and cooking. Lowering the demand for fossil fuels in developed countries contributes to environmental equity by allowing developing countries to have vital energy supplies at lower cost (Goswami 2008).

4.6 Nonproliferation of Nuclear Weapons

From the early days of nuclear power development, there has been widespread concern that increased use of nuclear power would lead to the diversion of nuclear materials to clandestine weapon production. The system of international safeguards implemented by the IAEA, however, has been effective in preventing diversions of nuclear materials from commercial power reactors or reprocessing plants. The effectiveness of the safeguard program is aided by the extreme technical difficulties inherent in converting nuclear material produced in power reactors to weapons-grade material.

4.7 Technology Transfer

Transfer of technology to developing countries has made a major contribution to energy production in developing countries, such as Brazil, China, India, Korea, Argentina, and South Africa. This ongoing technology transfer continues to build technical capacities to manage nuclear material and the ability to regulate, oversee, and ensure its safety. As a result, the foundation is being built in the developing world for additional use of nuclear energy and promotion of the beneficial uses of nuclear science and technology in the future. Hence, overall nuclear energy can be undoubtedly termed as reliable sustainable energy source.

5 Future Prospects

Recent studies have shown that new nuclear power plants can compete favorably with alternatives, generally gas- and/or coal-fired plants, in most countries. The main factors that contribute to the competitiveness of nuclear power plants, based on new designs that may be ordered today, include cost-effectiveness of the concepts, and enhanced technical performance such as longer lifetimes, higher energy availability, and better fuel utilization. The advanced light water reactors currently available on the market are designed for 60 years of operation at an average availability factor above 90 %. They are designed to make better use of the energy content of natural uranium and to generate some 15 % less waste. Obviously, rising prices of fossil fuels and concerns for clean energy reinforce the competitiveness of nuclear-generated electricity. Furthermore, the pricing of carbon emissions in the costs of fossil fuel burning, through tradable permits and taxation for instance, will increase the competitive margin of energy sources that emit no or very little carbon.

Fast reactors, closed fuel cycles, and re-using of nuclear fuel are some of the key options in enhancing the sustainability of future nuclear systems. Fast reactors can reduce waste streams and improve efficient use of uranium. To enhance the sustainability of nuclear power globally, thorium can be used as an alternative fuel. Technology development is diversifying to meet a wide range of conditions for the deployment of new reactor designs, including small- and medium-sized reactors. These reactors may allow for expanded use of nuclear power—including on smaller grids and in remote settings, as well as for nonelectrical applications—and improve the access to nuclear energy, including for developing countries.

6 Summary and Conclusion

Nuclear energy is no more a new term to the present civilization. Today, worldwide, 68 % of total energy production comes from fossil fuels (41 % coal, 21 % gas, and 5.5 % oil), 13.4 % from nuclear fission, and 19 % from hydro and other renewable sources. In such a scenario, it is very less likely to reduce the usage of fossil fuels drastically at present; however, the impact of the usage of fossil fuels vis-a-vis the growth of nuclear generating capacity will become fully clear only in the coming years. A majority of countries have confirmed their construction plans (including China, the Emirates, France, Poland, the United Kingdom, and the United States), while a limited number of others (essentially Germany and Italy) have decided to eventually phase out nuclear power or to abandon their nuclear plant projects due to public outrage against safety concerns.

These challenges also point to the attraction of nuclear energy and demonstrate the opportunities involved. Nuclear power is a nearly carbon-free electricity generation source, with a large and diversified fuel resource base. Nuclear energy may be considered as essential part of the complete solution to energy sustainability, together with renewable energy sources. Today, nuclear energy has become a proven, mature technology benefiting from broad industrial experience. State-of-the-art nuclear energy systems in operation worldwide have demonstrated highly satisfactory technical and economic performance. Moreover, extensive R&D programs are under way in many countries, often as part of international endeavors, and aim to make even more progress to enhance safety and proliferation resistance, to reduce uranium consumption and waste, and to increase the competitiveness of nuclear energy. Construction of nuclear fusion-based reactor tokamak will be major breakthrough in this direction.

To summarize, nuclear energy complies strongly on the scale of safety, reliability, competitiveness, and efficient use of natural resources, as well as health and environmental protection, to become a part of sustainable energy solution, provided governments, industry, and civil society work together to lay out a robust policymaking framework for all options to be assessed and developed according to their respective costs and benefits for society. This also includes cooperation across the globe, so as to ensure the continuous supply of fuel, technology transfer with highest possible standards in the fields of safety and reliability, health and environmental protection, proliferation resistance and physical protection, and economics. Thus, nuclear energy could make a very unique contribution to diversification, security of energy supply, and the reduction of greenhouse gas emissions in a cost-effective way globally. Energy efficiency and savings, carbon sequestration, renewable sources, and nuclear energy are to be looked together meet the demand of growing populations and economic development while protecting the environment.

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