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Nuclear energy: A pathway towards mitigation of global warming

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ABSTRACT

Global warming is the ongoing rise in the average temperature of Earth's climate system. Over the past 50 years, the average temperature has increased at the fastest rate in recorded history due to uncontrolled generation of greenhouse gases. Nuclear power is low carbon energy, and it is contributing on a large scale to a low carbon economy and a green energy grid. 442 nuclear power reactors are operating worldwide generating 393 GWe of electricity providing continuous and reliable low carbon power. Nuclear electricity accounts for 11% of total global electricity generation, and this amounts to a third of the low-carbon electricity produced in the world. New innovations are taking place which make nuclear power a more affordable and attractive energy option. These include advances in large reactors, emerging technologies such as advanced fuel and small modular reactors, engineering breakthroughs extending the operational lifetime of existing reactors, and new developments in materials and better waste management. Fast breeder reactor technology has become a commercial reality and it helps not only in generating electricity, but also in producing more fuel than it consumes, besides burning nuclear waste more efficiently compared to any of the existing commercial reactor technologies.

The Sun's energy is generated by nuclear fusion. Mastering nuclear fusion technology can guarantee energy security in terms of clean, safe and affordable energy. Nuclear fusion, and plasma physics research of very complex nature are being carried out in many countries. Fusion reactions have been successfully demonstrated although for a fraction of a second and without demonstrating a net gain of electric power. The world's largest international fusion reactor facility called ITER is in an advanced stage of construction with the aim of demonstrating the scientific and technological success of fusion energy research for commercial production. Fusion fuel is plentiful and easily accessible. It is expected that fusion energy is the pathway towards energy security for thousands of years. Nuclear fission and fusion reactors do not emit greenhouse gases into the atmosphere and play a major role in mitigating climate change.

1. Introduction

Energy is essential to support everyday life and to drive human and economic development. In 2019, globally, over 26,000 TW-hours of electricity was produced from a range of energy sources, - fossil fuels, nuclear power and renewables such as solar, hydro and wind. Production of energy and its use are the largest source of greenhouse gas emissions and cause for global warming around the world. Global Warming, also called *Climate Change,* is one of the most difficult issues that the world is facing today. The Intergovernmental Panel on Climate Change (IPCC) has defined global warming as the increase in the combined land surface, air, and sea surface temperatures, averaged over a 30-year period. The increase in warming from pre-industrial levels to the decade 2006–2015 is estimated to be 0.87 °C (Masson-Delmotte et al., 2018). Currently, surface temperatures are rising by about 0.2 °C per decade. At this rate, global warming is projected to reach 1.5 °C above the pre-industrial levels by 2037 (Fig. 1) (Global Temperature report, 2020). IPCC in its latest studies has predicted that the Earth's average temperature will reach 1.5 °C above preindustrial levels around 2030, earlier than projected, having already reached a level of 1.1 °C.

According to NASA studies, global temperature has already breached the global average in several parts of the globe (Why Global Temperatures m, 2019). The consequences of global warming are being felt everywhere, from rising sea levels to more extreme weather conditions, more frequent wildfires and heat waves, and increased drought, disintegrating ice sheets holding enough water to raise seas a dozen metres, to name a few. Arctic Ocean is expected to become essentially ice-free in summer before the middle of this century. Antarctica has been losing about 134 billion metric tons of ice per year since 2002 (Fig. 2) (Greenhouse effect and report). Ocean currents that help to maintain

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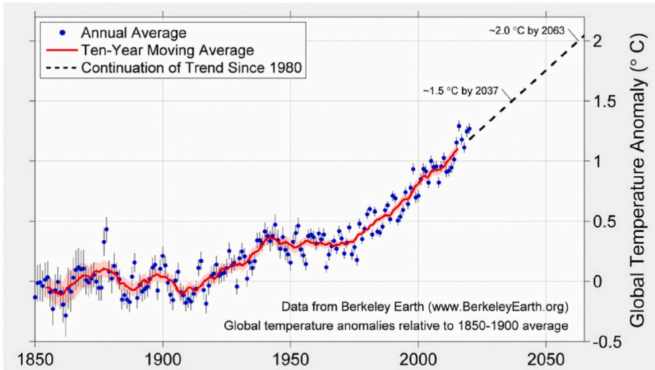

Fig. 1. Increase in global warming from pre-industrial levels to the decade 2006–2015 and projection till 2050 (Global Temperature report, 2020).

Fig. 2. Consequences of global warming. Polar bears have become a symbol of global warming. Melting polar ice and warm temperatures force animals like the polar bears to move farther south in search of food and other resources (Greenhouse effect and report).

temperature across the continents are becoming unstable. All these events call for drastic actions to save our planet.

1.1. Greenhouse gases

It is now well understood that global warming occurs due to the effect of greenhouse gases (GHG)s (Global Climate change – v, 2021; Greenhouse Gases and report, 2020; Greenhouse effect and report, 2021). Radiation coming from the Sun and which is not absorbed or reflected by the atmosphere, would normally reach the Earth and escape from the Earth back into space. The presence of greenhouse gases in the Earth's atmosphere traps the heat radiation and prevents it from escaping, and instead re-radiates the energy into all directions. This causes the Earth to get warmer, just as the Greenhouse in a botanical garden traps the Sun's energy and keeps warm inside in order for the plants to grow during the winter season. Hence, the invisible gases that surround the earth are able to trap heat just as the greenhouse that is surrounded by glass.

The primary greenhouse gases in the Earth's atmosphere are carbon dioxide (CO_2), methane, nitrous oxide and fluorinated gases. Since 1970, power generation, and industrial activities have contributed roughly 70% of the total greenhouse gas emissions. Globally, 76% of the total greenhouse gas emissions is on account of CO_2 and 24% from other GHGs (Fig. 3) (Global Emissions and report, 2015). Annually, around 43

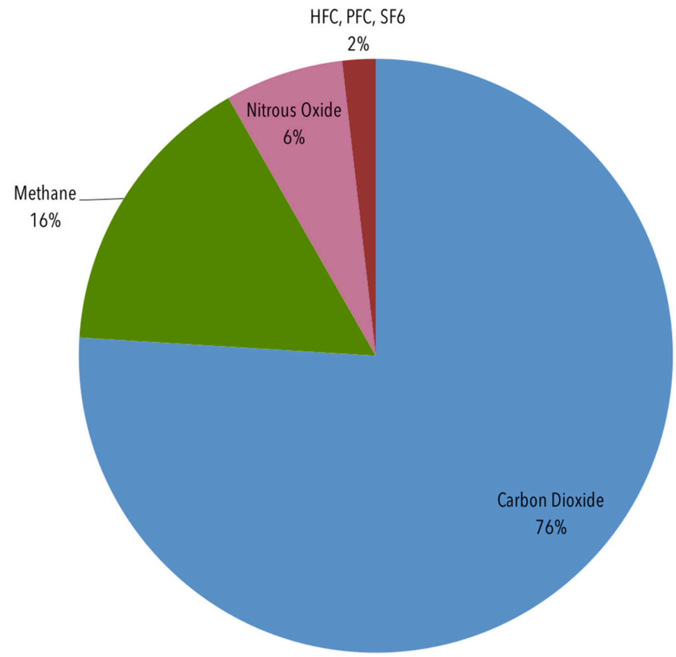

Fig. 3. Globally, 76% of the total greenhouse gas emissions is on account of CO_2 (Global Emissions and report, 2015).

billion tons of CO_2 is generated by the combustion of fossil fuels such as coal, natural gas, and oil for power production and transportation needs. Increase in the demand for electric power is responsible for about half of the increase in greenhouse gas emissions since 1990. Global population is expected to grow by 25% during 2017–2050 period (Fig. 4). The growth in global GDP is projected to be much faster than the population growth rate, and it may increase by 200% during the same period (Fig. 4) (Climate change and nuclea, 2020a, 2020b). Since GDP growth rate and per capita consumption of electricity are directly related, global electricity demand is also projected to nearly double by 2050. Emissions from electricity generation are growing rapidly and have more than tripled since 1970. Although electricity is clean at the point of consumption, over 40% of all energy-related carbon emissions is produced during its generation. In the United States, the transportation sector generated the largest share of greenhouse gas emissions in 2019 (29%). 25% of greenhouse gas emissions came from electricity production, out of which 62% of electricity was produced by burning fossil fuels, mostly coal and natural gas (Sources of Greenhouse Gas, 2020). Industrial activities accounted for 23% (Fig. 5). Decarbonising the electricity generation is essential to combat climate change.

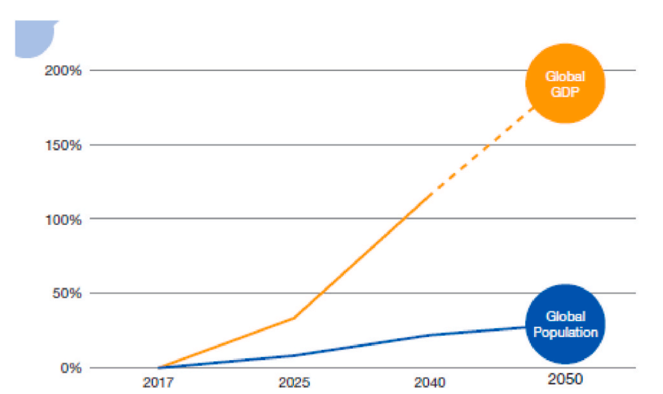

Fig. 4. Projection of global electricity demand by 2050 (Climate change and nuclea, 2020a, 2020b).

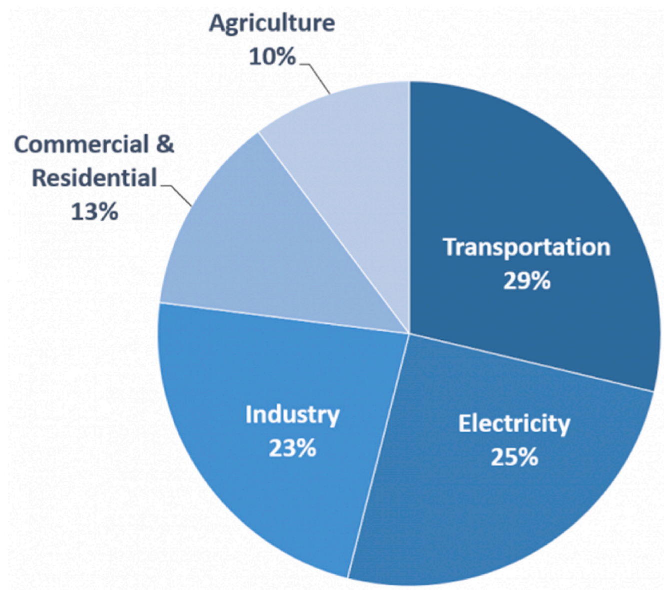

Fig. 5. Total greenhouse gas emissions in US in 2019 by economic sector (Sources of Greenhouse Gas, 2020).

The United Nations Framework Convention on Climate Change (UNFCCC) is an action plan to drastically reduce greenhouse gas emissions that allows a gradual transition to clean energy. This agreement was concluded in the year 2015 in Paris among 196 countries. The agreement mandates member nations to take effective steps to reduce greenhouse gas emissions to achieve the target of limiting the increase in global average temperatures to well below 2 °C, preferably 1.5 °C relative to the pre-industrial levels (1850–1900 period) by encouraging the use of low carbon energy sources to reduce greenhouse gas emissions. Reaching these climate goals by 2050 will require at least 80% of electricity to be shifted to low carbon sources, according to the International Renewable Energy Agency.

2. Renewable energy

The effective way to reduce CO_2 emissions is to reduce fossil fuel consumption and shift to renewable energy resources. Renewable energy, also called as *clean energy*, comes from natural resources or processes that are continuously replenished such as solar, wind, hydroelectric, biomass, geothermal, tidal waves etc.. Solar and wind energy are the fastest growing and most affordable resources of clean electricity (Renewable Energy and report, 2020; World Adds Record New Ren, 2021). By end of 2020, the total installed capacity of renewables was 2799 GW, with hydropower contributing to 1211 GW, followed by wind (733 GW) and solar (714 GW) according to the International Renewable Energy Agency (Renewable capacity highli, 2021). Since the cost of solar energy continues to drop significantly benefitting from advances in processes, materials and technology, more industries are deploying solar power. One of the world's busiest airports, the Cochin International Airport in India, operates completely on solar power with an installed capacity of $40MW_p$ and is projected to avoid generation of 900,000 metric tons of CO_2 over a period of 25 years. Among other renewables, geothermal energy derives the heat below the Earth's surface which can be harnessed to generate clean renewable energy with very little greenhouse gases. Biomass is an organic renewable energy source which can be converted into biofuels. Nuclear power is a very low carbon emitting source of electricity and contributes nearly 11% of the global electricity generated.

Share of renewables in global electricity generation in year 2020 has reached 29% thereby offering the benefit of lower carbon footprint. That's expected to rise to 45% by year 2040. Most of the increase will likely come from solar, wind, and hydropower (ManfredLenzen, 2008). The pathway for the world to achieve the Paris Agreement goals towards transforming the global energy landscape is by phasing out coal and reducing investments in oil and gas, so as to achieve a quick decline in the carbon footprint.

Another major step to reduce GHG emissions and mitigate climate change will be the widespread adoption of electric vehicles (EVs), by replacing automobiles using combustion technology and oil as fuel. Pure electric vehicles produce no carbon dioxide emission when driving. EVs can drastically reduce GHG emissions. All the major automobile manufacturers of the world are developing and manufacturing EVs in recent years.

3. Nuclear energy

Nuclear energy is released from the nucleus, the core of an atom, which is made up of protons and neutrons. Nuclear energy can be produced in two ways: nuclear fission – when a heavy nucleus of an atom splits into several parts, or nuclear fusion when two light nuclei of different atoms fuse together. The nuclear energy harnessed in the world today to produce electricity is through nuclear fission (What is Nuclear Energy? T, 2021). The technology to generate electricity from fusion is at an advanced stage of realization. During nuclear fission, the nucleus of a heavy atom splits into two or more smaller nuclei, and releases energy (Fig. 6). When bombarded by a neutron, the nucleus of an atom of Uranium-235 splits typically into a barium nucleus and a krypton nucleus, and two or three neutrons, plus a certain amount of energy is released. These extra neutrons will cause nuclear fission in surrounding Uranium-235 atoms, thereby initiating a chain reaction. The reaction is accompanied by release of energy in the form of heat. The heat can be converted into steam and then into electricity in a nuclear power reactor just as heat from fossil fuels such as coal, gas and oil is converted to generate electricity (Fig. 7). Thus, in a nuclear reactor, energy is produced by initiating and controlling a sustained nuclear chain reaction. This electricity is low-carbon electricity.

3.1. Clean energy transition

The clean energy transition means shifting from fossil energy to energy resources that release little or no greenhouse gases such as nuclear power, hydro, wind and solar. About a third of the world's carbon-free electricity comes from nuclear energy.

Nuclear power has a great potential to contribute to the 1.5 °C Paris climate change target. Nuclear power plants produce no greenhouse gas emissions during their operation; only very low emissions are produced over their full life cycle. Even after accounting for the entire life cycle from mining of nuclear fuel to spent fuel waste management, nuclear power is proven to be a low carbon electricity source. During operation and maintenance, nuclear power plants produce different levels of solid and liquid waste and are treated and disposed-off safely. While conventional fossil-fueled power plants cause emissions almost exclusively from the plant site, the majority of greenhouse gas emissions in the nuclear fuel cycle are caused in processing stages upstream (exploration and processing of the uranium ore, fuel fabrication etc.), and downstream from the plant (fuel reprocessing, spent fuel storage etc.). Over the course of its life-cycle, the amount of CO_2-equivalent emissions per unit of electricity produced by nuclear power plants is comparable with that of wind power, and only one-third of the emissions by solar. The greenhouse gas emissions correspond to 10–15 gm of CO_2 per kilowatt hour electricity produced in comparison with the emission from a fossil fueled plant of 600–900 gm, 15–25 gm from wind turbines and hydroelectricity, and around 90 g from solar power plants (Fig. 8) (Carbon Dioxide Emissions, 2021).

Nuclear power delivers reliable, affordable and clean energy to support economic growth and social development. Without a larger role for nuclear energy, it would not be possible to combat climate change.

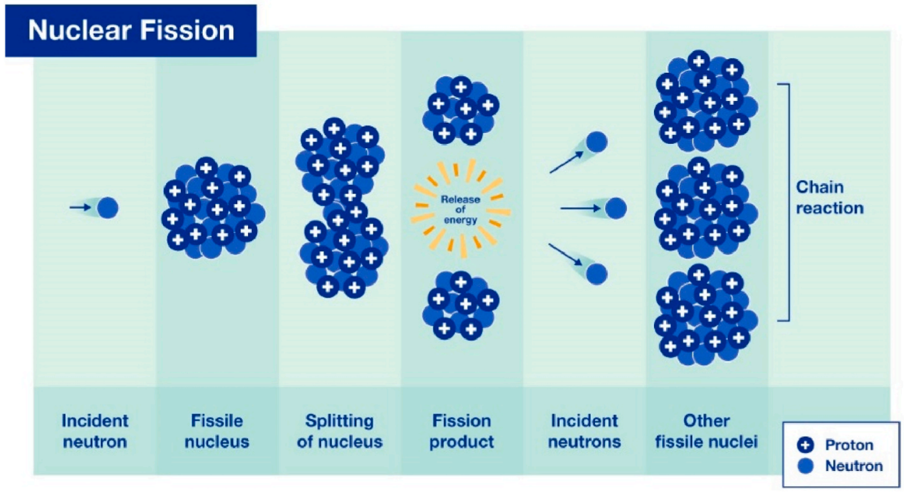

Fig. 6. Nuclear fission is a reaction where the nucleus of an atom splits into two or more smaller nuclei, while releasing energy (What is Nuclear Energy? T, 2021).

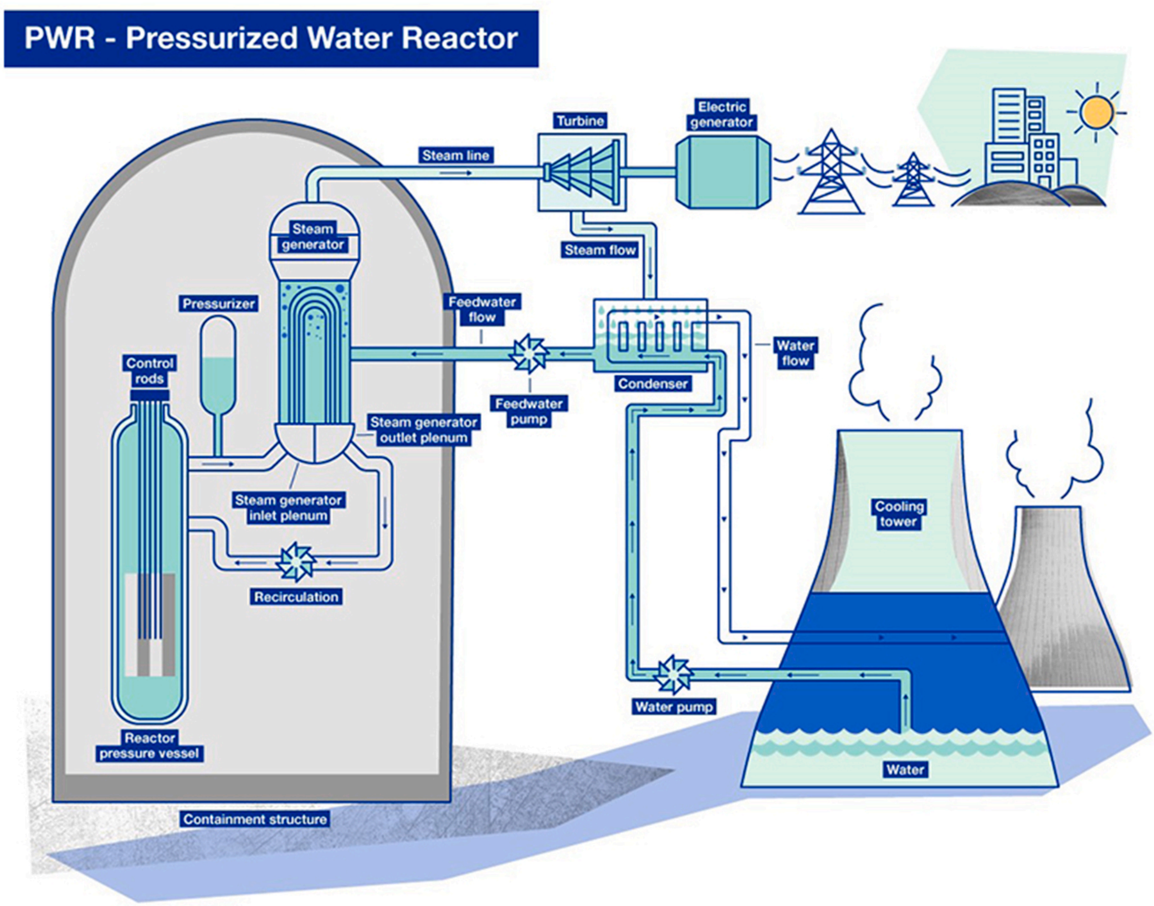

Fig. 7. Inside nuclear power plants, nuclear reactors and their equipment contain and control the chain reactions, most commonly fueled by Uranium-235, to produce heat through fission. The heat warms the reactor's cooling agent, typically water, to produce steam (What is Nuclear Energy? T, 2021).

Nuclear power can be deployed on a large scale. So, nuclear power plants can directly replace fossil fueled power plants. As of end December 2020, global nuclear power capacity was 393 GW(e) and accounted for around 11% of the world's electricity and around 33% of global low carbon electricity. Currently, there are 442 nuclear power reactors in operation in 32 countries. There are 54 reactors under construction in 19 countries, including 4 countries that are building their first nuclear reactors according to the IAEA reports (Nuclear Power Proves its, 2021; Climate Change and Nuclea, 2020a, 2020b). Nuclear power is reducing CO_2 emissions by about two gigatons per year. Therefore, nuclear power will be imperative for achieving the low carbon future. In France, nuclear power plants accounted for 70.6% of the total electricity generation in 2019, the largest nuclear share for any industrialized country. About 90% of France's electricity comes from

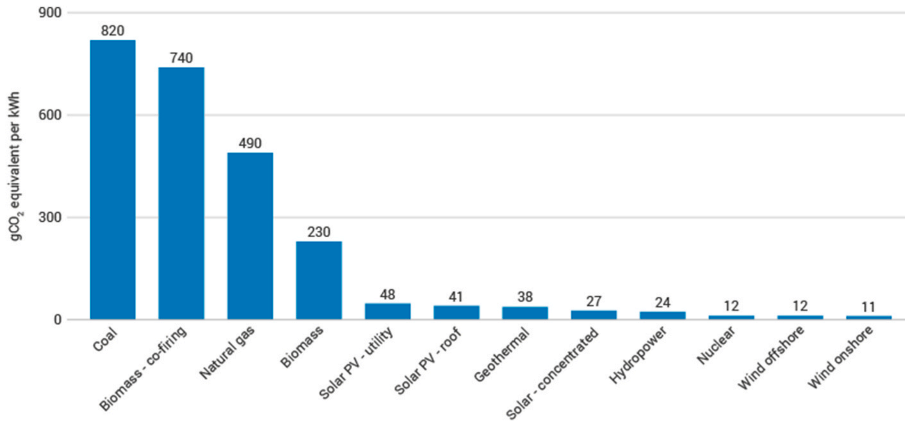

Fig. 8. Over the course of its life-cycle, nuclear power plants produce about the same amount of CO2-equivalent emissions per unit of electricity produced as wind power, and only one third of the emissions by solar power (Carbon Dioxide Emissions, 2021).

low carbon sources (nuclear and renewable combined). Nuclear power contributes 20% of electricity generation in the United States over the past two decades and it remains the single largest contributor of non-greenhouse-gas-emitting electric power generation out of 1,117, 475 MWe total electricity generating capacity of which 60% is from fossil fuel.

The second-largest source of low carbon energy in use today is nuclear power, after hydropower. Nuclear power plants provide continuous and stable energy to the grid whereas solar and wind energy require back-up power during their output gaps, such as at night or when the wind stops blowing. The International Panel on Climate Change (IPCC) has proposed at least doubling of nuclear power generation by 2050 to meet the Paris agreement. Nuclear power has compensated about 60 Gt of CO_2 emissions over the past 50 years, nearly equal to 2 years of global energy-related CO_2 emissions and can help to conquer the challenges of climate change.

Existing reactors and future advanced nuclear technologies, like Small Modular Reactors (SMRs), can meet base load power needs and also operate flexibly to accommodate renewables and respond to demand. SMRs are a recent concept to accelerate the construction and commissioning of large nuclear power projects. By adopting the concept of modular manufacture of components, significant reduction in on-site construction time can be achieved. This can also help in reducing the capital costs. Several types of SMRs are currently under development and these offer improved economics, operational flexibility, enhanced safety, a wider range of plant sizes and the ability to meet the emerging needs of sustainable energy systems. Some of these reactors are designed to operate up to 700–950 °C (for gas cooled reactors) compared to LWRs, which operate at 280–325 °C. The electrical efficiency is higher and it can supply high temperature heat to industrial processes. High temperature SMRs can generate hydrogen through more energy efficient processes such as high temperature steam electrolysis or thermochemical cycles. Their smaller size and easier siting are expected to be a better fit for most non-electric applications, which require an energy output below 300 MWe.

3.2. Electric grid stability and nuclear power

Renewable energy sources are not able to meet continuous energy demands due to the intermittent nature of solar and wind power, and the absence of massive energy storage capacities. This means that the power grids often require supplementary energy sources. Nuclear power can generate low carbon energy 24 h a day, 7 days a week and can meet fluctuations in energy demand and provide stability to electrical grids, especially those grids with a high share of variable renewable sources which otherwise have to depend on fossil fuels. A typical energy demand in a 24-h cycle is shown schematically in Fig. 9. Nuclear power can provide backup capacity support for variable solar and wind generation without the need for fossil fuel. Unlike conventional electricity grids, Smart grids allow several different energy sources to be connected dynamically. Smart grids use Artificial Intelligence (AI) and the Internet of Things (IoT) technologies to automate processes. Nuclear power combined with smart power grids helps smooth transition to renewable energy sources and ensure reliable, stable and sustainable energy supplies.

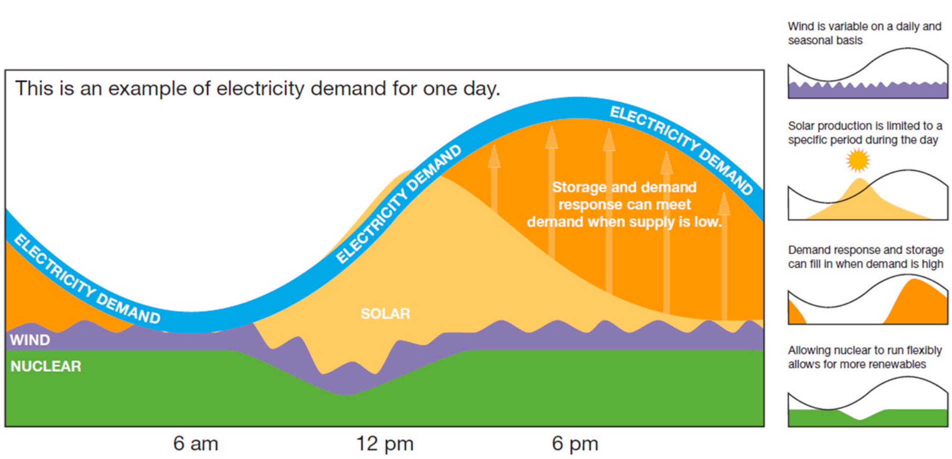

Fig. 9. Typical energy demand in a 24-h cycle (Climate change and nuclea, 2020a, 2020b).

4. Fast breeder reactor technology

Water Cooled Reactors (WCRs) have been the main source of nuclear power in the 20th century. Of the 442 reactors in operation world-wide, 96% are WCRs. Most of these plants were originally licensed to operate for 20–30 years. Because of the advances in technology and engineering, good operating history and conservatism in the design of the equipments and plants, over the years, the operating life of many of these plants is being extended up to 60 years, with a potential to keep them running still longer. The development of new materials such as duplex stainless steels, which provide better corrosion resistance along with new joining techniques such as laser beam welding and friction stir welding help to design new nuclear plants with longer life (Nuclear Power and Clean E, 2020). WCRs will continue to play a pivotal role in the 21st century. The two popular designs of WCRs are the Pressurized Water Reactors (PWRs) which produce steam for the turbine in separate steam generators (Fig. 7), and the Boiling Water Reactors (BWRs) which use the steam produced inside the reactor core directly in the steam turbine. All LWRs use uranium fuel that is enriched to 3–5% in the fissile isotope, U-235. Unlike LWRs, Heavy Water Reactors (HWRs) use heavy water (obtained by the reaction between oxygen and heavy hydrogen), an isotope of hydrogen deuterium. This heavy water is used as a moderator (for slowing down the neutrons produced in nuclear fission) and is suitable to improve the overall neutron economy and allows using uranium without any enrichment.

Fast breeder reactors (FBRs), also called fast breeder neutron reactors, are a class of advanced nuclear reactors that have some key advantages over WCRs in terms of safety, sustainability, and nuclear waste disposal. FBRs breed more fuel than they consume which is a basic feature of renewable energy sources. FBRs use fast neutrons to cause nuclear fission; neutrons produced immediately after fission have high kinetic energy of the order of million electron volt (MeV) and are called fast neutrons. The fast neutron spectrum allows FBRs to increase the energy yield from the nuclear fuel as compared to thermal reactors (where nuclear fission is caused by neutrons having energy of the order of electron volts (eV)). FBRs can utilize uranium 60 times more efficiently than LWRs. As the coolant, fast reactors use liquid metal sodium instead of ordinary water that is used in LWRs, and heavy water coolant in HWRs. Use of liquid sodium allows for the coolant to operate at higher temperatures up to 650 C, and also at lower pressures than WCRs. In fast reactor design, coolant choice is an important technical issue since it determines the design approach, safety, technical and economic characteristics of the system. Lead and lead-bismuth eutectic, are under investigation as coolants in place of sodium in FBRs. However, FBRs require fuel which is very rich in fissile material (Uranium-235 and Plutonium).

Fast reactor technology was first developed in the 1950's. Over the years, sodium cooled fast reactor technology has evolved and attained maturity in design, construction, operation and decommissioning of experimental, prototype, demonstration and commercial reactors. It has accumulated more than 400 reactor-years of experience. India, France, Germany, China, Japan, the Russian Federation, the United Kingdom and the United States are the leaders in fast reactor technology. Table 1 lists the countries having FBRs, and details of the FBRs in operation/closed/under construction (Fast Neutron Reactors and Re, 2021). It is recognized that long-term development of nuclear power as a part of the world's future energy security will necessarily require FBR technology with closed fuel cycle. The distinguishing characteristics of FBRs include long design life, high temperature of operation leading to improved thermal efficiency, high neutron flux and high fuel burnup (Mathew et al., 2013; Mannan et al., 2013; Baldev et al., 2002). A typical flow diagram of a fast breeder reactor is shown in Fig. 10. Fast reactors represent a technological leap beyond WCRs, and are poised to become the mainstream. Fast reactor technology enables more efficient use of uranium resources and the ability to burn long-lived actinides. Using the currently known uranium resources, it is projected that fast reactor technology can extend nuclear power for thousands of years, and also provide significant improvements in nuclear waste management (Fast Reactors Provide Sus, 2013).

Table 1
Details of FBRs in operation/closed/under construction in different countries.

Country	Coolant	MWe	MW (thermal)	Operation/status
USA				
EBR 1	Sodium-potassium	0.2	1.4	1951–63
EBR II (E)	Sodium	20	62.5	1963–94
Fermi 1 (E)	Sodium	61	200	1963–75
SEFOR	Sodium		20	1969–72
Fast Flux Test Facility (E)	Sodium	–	400	1980–93
ARC -100 (D)	Sodium	100	260	Working with GEH
PRISM & Natrium (D)	Sodium	311	840	From 2020s
UK				
Dounreay FR (E)	Sodium	15	65	1959–77
Protoype FR (D)	Sodium	250	650	1974–94
France				
Rapsodie (E)	Sodium		40	1967–83
Phenix* (D)	Sodium	250	563	1973–2009
Superphenix (C)	Sodium	1240	3000	1985–98
Astrid (D)	Sodium	200		Delayed, after 2050
Germany				
KNK 2 (E)	Sodium	20	58	1972–91
India				
FBTR (E)	Sodium	13	40	1985-
PFBR (D)	Sodium	500	1250	under const.
FBR 1&2 (C)	Sodium	600		
Japan				
Joyo (E)	Sodium		50, 75, 140	1978–2007 may be restarted in 2021
Monju (D)	Sodium	280	714	1994–96, 2010.
JSFR (D)	Sodium	750	3530	From 2025?
Kazakhstan				
BN-350 (D)	Sodium	135	750	1972–99
Russia				
BR 5 Obninsk (R)	Sodium		5	1958–71
BOR 60 Dimitrovgrad (R)	Sodium	12	60	1969-
BR 10 Obninsk (R)			8	1973–2002
BN-600* Beloyarsk 3 (D)	Sodium	600	1470	1980-
BN-800 Beloyarsk 4 (E)	Sodium	864	2100	2014-
BN-1200 (C)	Sodium	1220	2800	From 2030
MBIR (E)	Sodium	40	150	From 2020, under const.
BREST (D)	Lead	300	700	(2026)
China				
CEFR (E)	Sodium	20	65	2010-
CFR600 (D)	Sodium	600	1500	under const.
CDFR-1000 (C)	Sodium	1200		From 2034
South Korea				
PGSFR (D)	Sodium	150	392	From 2028
Belgium				
MYRRHA (E)	Lead–Bismuth		57	Early 2020s

E = experimental, D = demonstration or prototype, C = commercial, R = research.

5. Fusion reactor technology

Fusion reactor technology is very complex but promises unlimited energy potential. All the energy from the sun is powered by a reaction called nuclear fusion. During nuclear fusion, two light atomic nuclei combine (fuse) to form a single heavier nucleus, and in that process, release a lot of energy. For fusion reactions to take place, the atomic nuclei need to collide with each other which can happen only at temperatures exceeding millions of degrees Celsius because of the mutual

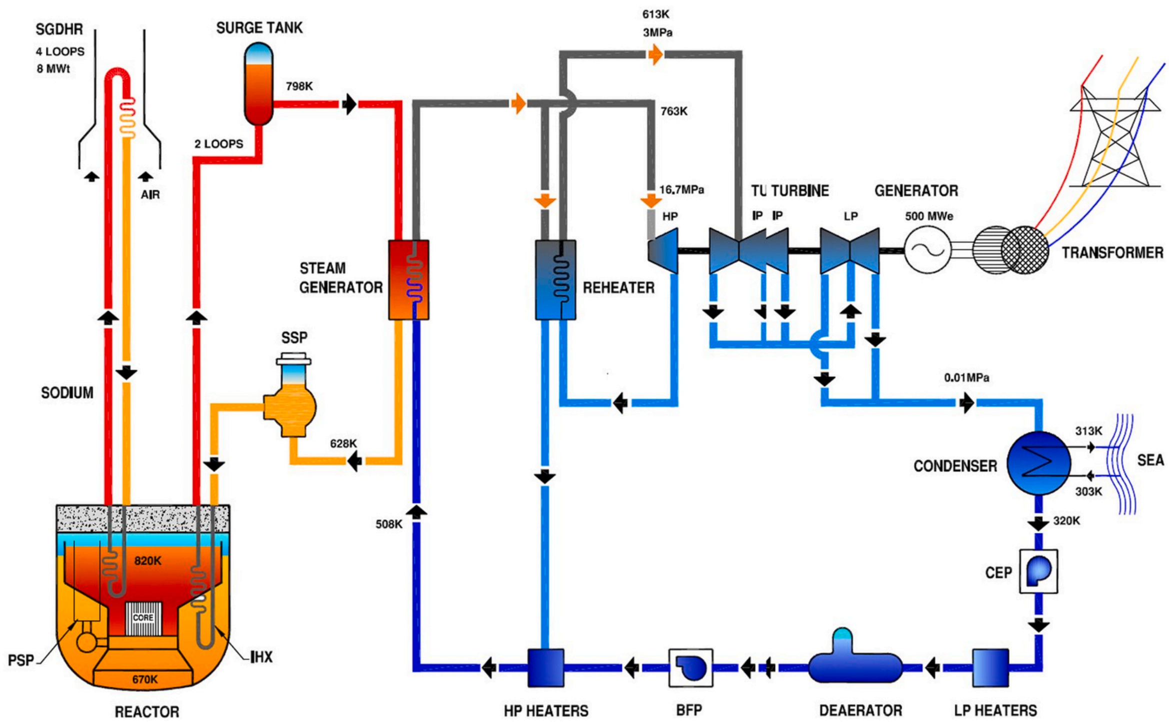

Fig. 10. Flow diagram of India's 500 MWe Prototype Fast Breeder Reactor undergoing commissioning (Mannan et al., 2013).

electrical repulsion. Once the nuclei overcomes this repulsive force, the attractive nuclear force between them will allow fusion to take place. To increase the chances of collision, the nuclei must be confined within a small space. In the sun, the high pressure produced by gravity (>3.4×10^8 atm) creates conditions favorable for fusion. Typically, the amount of energy released from a fusion reaction is more than four times the energy released from fission reactions.

Nuclear fusion can provide unlimited clean, safe and affordable energy to meet the world's energy demand. The lightest element is hydrogen. Its isotopes are deuterium and tritium (Fig. 11) (S8 and https:/). It can undergo fusion reactions (Fig. 12) (What is Fusion and and Why I, 2021) at temperatures of the order of 100 million degree Celsius. At such high temperatures, nuclear particles will have a large kinetic energy. The particles have to be confined so that they do not escape. Hence, a successful fusion reaction would need to contain the particles in a small enough volume for a long enough time so that fusion reactions can proceed. The plasma, which is a gas of charged particles, is confined using strong magnetic fields, in the absence of gravitational pressure that exists in the sun. A charged particle moving through a magnetic field can be confined to move in a circle or helix around the lines of magnetic flux. In principle, a few grams of these gases can

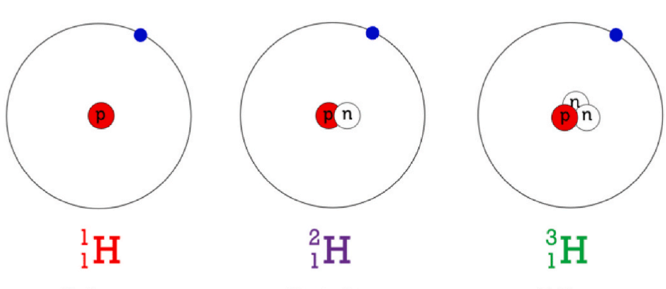

Fig. 11. Isotopes of hydrogen – deuterium and tritium. Isotopes are atoms with the same number of protons but different number of neutrons. They share almost the same chemical properties but differ in mass and physical properties (S8 and https:/).

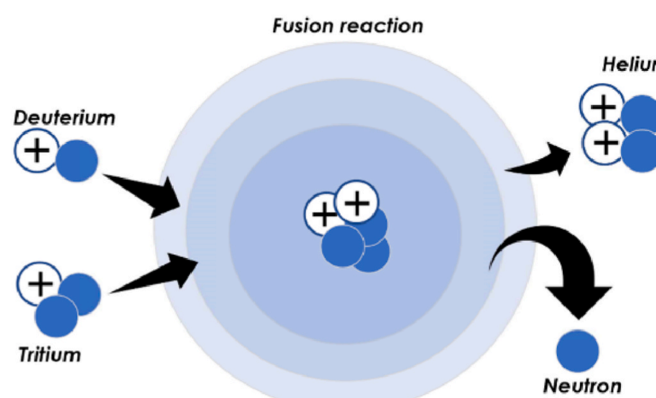

Fig. 12. Fusion reaction: one atom of deuterium and one atom of tritium fuse together, forming a helium nucleus, and releases 14.1 MeV energy neutron (What is Fusion and and Why I, 2021).

produce a terajoule of energy (What is Fusion and and Why I, 2021). Nuclear fusion and plasma physics research over the past several decades have enabled realization of fusion reactions successfully in many experiments. The fuel for fusion reactions is available in plenty and easily. Deuterium can be extracted from seawater. Lithium is naturally available in abundant amounts and can be used to produce Tritium. Therefore, the raw materials required for nuclear fusion are available naturally and in abundance.

Nuclear fusion is forecast to be the basis of future green energy. The *International Thermonuclear Experimental Reactor (ITER)*, the world's largest and most advanced experimental nuclear fusion reactor facility, is currently being built in France for demonstrating the scientific, technological and commercial feasibility of fusion energy production. The ITER Tokamak is designed to produce 500 MW of fusion power for 50 MW of input heating power and will be the first fusion device to create net energy (Photos and https://www.). The ITER project represents a giant leap from several decades of experimental studies of plasma physics to full-scale electricity-producing fusion power plants. The fusion reaction will consist of a deuterium atom and a tritium atom, two different isotopes of hydrogen, fusing together to form a helium nucleus along with the release of 14.1 MeV energy. ITER faces huge challenges in terms of technology, cost and time. The project is funded and run by a consortium of EU, USA, South Korea, Russia, China, Japan and India. The European Union is contributing to 45% of the cost and the other countries will contribute 9% each. ITER promises to usher in the next phase of fusion energy development, namely, the Demonstration Fusion Power Plant and later the commercial fusion power plants (Fusion Energybulle, 2021). Weighing 23,000 tons and 30 m tall, ITER Tokamak reactor is at the heart of ITER plant and is an engineering and technology marvel (Fig. 13). While the laboratory physics experiments on fusion reactions have not been successful in producing more energy than is consumed to initiate the fusion reaction, ITER has been designed to demonstrate that fusion reactions can produce significantly more energy than the energy consumed, resulting in net gain in power. With the injection of just 50 MW heating power into the plasma, ITER is designed to generate 500 MW of fusion energy in pulses that are each roughly 5–10 min long. The most challenging science and engineering endeavor so far ever undertaken by scientists and engineers is nuclear fusion. Building a fusion reactor, achieving a self-sustaining fusion reaction and converting that power to near inexhaustible electricity will be a game changer to combat global warming. Technical challenges related to design of structures, and properties of fuels and materials needed to hold such complex machines together remain to be fully solved.

Developing structural and plasma-facing materials that can withstand degradation from neutrons is a priority for researchers. These materials need safety characteristics such as low neutron-induced radioactivity to minimize the production of radioactive waste and sufficient mechanical properties (ITER et al., 2014; Laha et al., 2013). There will be no emission of carbon dioxide or other greenhouse gases into the atmosphere from nuclear fusion, and so along with nuclear fission would be an abundant source of low carbon energy. It is expected that fusion could meet humanity's energy security in the future for millions of years.

6. Summary

Global Warming, also called Climate Change, is one of the most difficult issues that the world is facing today. Global warming occurs due to the effect of greenhouse gases such as CO_2, methane, nitrous oxide and fluorinated gases. CO_2 is generated by the combustion of fossil fuels such as coal, natural gas, and oil for power production and transportation needs. While electricity is clean at the point of use, its generation produces over 40% of all energy-related carbon emissions. The Paris agreement is an international treaty on climate change, and the goal is to limit global warming to well below 2 °C, preferably to 1.5 °C by 2050, compared to pre-industrial levels. The effective way to reduce CO_2 emissions is to reduce fossil fuel consumption and shift to renewable energy sources like nuclear, solar, wind, hydroelectric, biomass, geothermal and tidal waves.

Nuclear power plants do not produce greenhouse gas emissions during their operation, and only very low emissions over their full life cycle. Nuclear power contributes 11% of the global electricity generated which amounts to one-third of the world's carbon-free electricity. Nuclear power can meet fluctuations in energy demand and provide stability to electric grids with a high share of variable renewable sources which otherwise have to depend on fossil fuels. Combined with smart power grids, nuclear energy can help the transition to low carbon electricity sources and ensure reliable, stable and sustainable energy supplies. Water Cooled Reactors (WCRs) have been the cornerstone of the nuclear industry in the 20th century, with 442 reactors in operation world-wide. FBRs represent a technological leap beyond WCRs, and are poised to become the mainstream. FBRs breed more fuel than they consume and allow more efficient use of uranium resources.

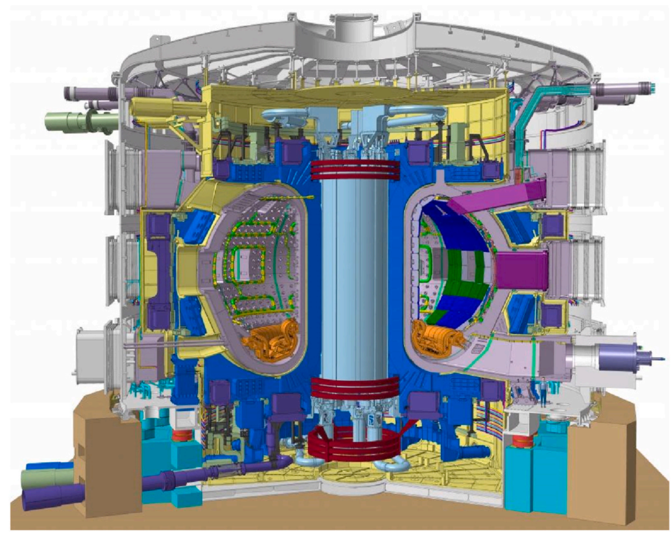

Fig. 13. ITER Tokamak reactor weighing 23,000 tons and 30 m tall (Photos and https://www.).

Fusion reactors are forecast to be the future of green energy and an unlimited resource. ITER is an international nuclear fusion research and engineering project designed as a full-scale 500 MW electricity-producing fusion power plant. Nuclear fission and nuclear fusion energy do not emit carbon dioxide or other greenhouse gases into the atmosphere, and would be an abundant source of low carbon energy for energy security. Climate change is an urgent crisis that requires greater adoption and expansion of nuclear energy.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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