Nuclear power plants in India: achieving clean and green energy

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Abstract: With the increasing demand in electricity and rising temperature of Earth due to global warming, nuclear power plants can address the current needs. Development in the realm of nuclear energy has become a necessity in order to fulfil the present need. The present paper will summarise the basic knowledge regarding the nuclear power plant and current status of nuclear energy in India. Moreover, the paper presents some limitations to nuclear energy. This review paper will be helpful for the beginners in the field of nuclear power plant.

Keywords: nuclear power plant; nuclear energy; India's nuclear power program; India's nuclear energy limitations.

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1 Introduction

The Paris Agreement has brought all nations to combat against the climate change and to develope a consensus to control the global temperature rise below 2°C by

2100. Moreover, efforts were employed to further restrict the temperature to below 1.5°C (Xiao and Jiang, 2018) but the methods required to fulfil this 1.5°C target have not yet been much studied. Some scholars have researched the possibility to achieve this target i.e., 1.5°C and concluded that the target could only be achieved when the global carbon emission will tend to zero within 2050–2060 and become negative thereafter which is actually impossible (Van Vuuren, 2016; Breeze, 2016). The International Energy Agency has pinpointed that nuclear power can be one among the deciding technologies that will be required in order to achieve the prescribed target of limiting the global temperature rise to 2°C (Iea and Nea, 2018). Nuclear energy has played a significant role in decreasing emission of greenhouse gases in the atmosphere. Moreover, these power plants do not release SO_2, particulate matters, and other air pollutants. IPCC has mentioned that total greenhouse gas emission per kWh in a nuclear power plant is around 100 times less than those being emitted from the fossil-fuelled electricity generation and thus it is tantamount to most renewable sources of energy production. It can, therefore, act an effective way to mitigate the greenhouse gas emission (Intergovernmental Panel on Climate Change, 2001). Table 1 shows the different countries and their operating nuclear reactor capacity in MWs.

Table 1 Installed nuclear capacity by country

Country	*Operating reactor capacity (MW)*
Argentina	1627
Armenia	376
Belgium	5943
Brazil	1901
Bulgaria	1926
Canada	13,553
China	26,967
Czech Republic	3904
Finland	2741
France	63,130
Germany	10,728
Hungary	1889
India	5302
Japan	40,480
South Korea	23,017
Mexico	1600
Netherlands	485
Pakistan	725
Romania	1310
Russia	26,053

Table 1 Installed nuclear capacity by country (continued)

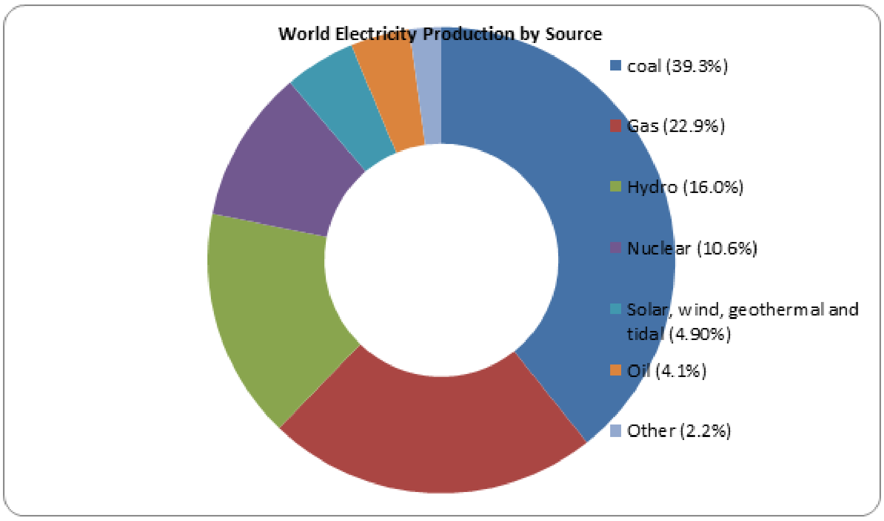
Country	*Operating reactor capacity (MW)*
Slovakia	1816
Slovenia	696
South Africa	1830
Spain	7121
Sweden	8849
Switzerland	3333
Ukraine	13,107
UK	8883
USA	98,990

Source: World Nuclear Association (2018)

Nuclear Power Plants (NPPs) operate in around 31 countries of which most are in northern America, Europe, East Asia and South Asia. France has the largest proportion of its electricity generated by nuclear power. From the Table 1, it is clear that the USA has the largest operating reactor capacity. China has the fastest growing nuclear power program with 28 new reactors under construction.

As India is inching towards its goal of achieving clean and green energy, it is required to replace some of the plants which are fuelled by coal with the nuclear power plants. Moreover, under the Paris climate change agreement, India has aimed to increase the share of electricity generation using non-fossil sources to 40% of its total electricity produced by 2030. Thus, it is quite necessary to start thinking towards nuclear energy and implement and establish it as soon as possible (Gupta, 2017). Figure 1 shows the proportions of the world's electricity produced by the solar, wind, geothermal, and tidal sources.

Figure 1 World electricity production by different sources



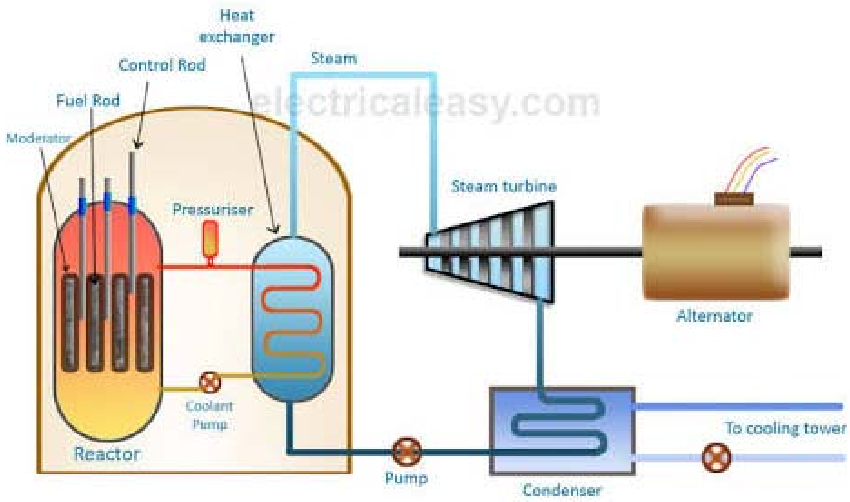
Source: IEA and NEA, 2018

2 Basic description of nuclear power plant

A nuclear power plant is a type of power station where electrical energy is generated from the nuclear energy of the atom. Its operation is somewhat similar to that of a thermal power plant where heat is obtained from a particular source of energy and this heat generates steam from water. This steam is allowed to expand in the turbine and drives the turbine to generate electricity.

Heat energy in the nuclear power plant is derived from the process of nuclear fission where a particle usually a neutron strikes a heavy fissile element and starts a series of fission chain reactions. These chain fission reactions occur in a controlled way within the nuclear reactor core. The fissionable element which is actually a nuclear fuel can be natural uranium, enriched uranium, plutonium etc. Enriched uranium is natural uranium with a higher uranium-235 isotope ratio. The U-235 isotope is around 0.7% in natural uranium. Besides the reactor, the power station has a steam turbine which is coupled to an alternator via an output shaft. One or more cooling towers are provided to extract heat from the steam at turbine exhaust. The cooling tower has water as a condensing fluid. The net efficiency of a typical nuclear power plant ranges between 30% and 40%. Figure 2 shows the basic operation of a nuclear power plant.

Figure 2 Operation of a nuclear power plant



Source: http://electricaleasy.com

The heat energy in nuclear power plants is derived from the nucleus of fissile atoms using the process of nuclear fission. In the nuclear fission, a high-energy particle at a certain speed, usually a neutron, is bombarded on the fissile atom which is radioactive and has high-atomic mass. The element inside the core, that fission, is a nuclear fuel, which is usually a rare isotope of uranium or plutonium. The atoms have internal cohesion bonds that unite their sub-particles i.e., electrons, neutrons and protons as a single entity. As the neutron strikes the atom, these bonds get collapsed and liberate the internal binding energy that bonded the separated particles. This is an exothermic reaction and thus a large amount of energy is released in form of heat.

In order to achieve output energy to be more than the input energy supplied to neutron, the nuclear reaction must be a chain reaction. Once a chain reaction is initiated properly, the reaction goes on its own without any extra energy to be supplied. The products of the chain reaction are some radioactive products, two or three neutrons and a large amount of energy. The neutrons liberated are responsible for continuation of chain reaction. Chain reactions occur in the core of the nuclear reactor. A moderator is present inside the reactor which slows down the speed of newly developed neutrons and makes it thermal neutron suitable for continuation of chain reaction. A cladding of metal (steel) is present which separates the coolant from the region where reaction takes place. The coolant flows through a circuit of tubes and gains the thermal energy from the reactor.

The heat from coolant is transferred to the water and thus the water boils and is transformed into very high-pressure steam. The steam under high-pressure forces the blades of the turbine to move. The water as well as the coolant is pumped back to its initial position to complete the cycle. In this way, the nuclear energy is transformed into mechanical energy due to the rotation of turbine. The turbine is connected to an alternator via a shaft that transforms mechanical energy into electrical energy (or electricity) (UNFCCC Process | UNFCCC, 2018).

3 Types of reactor

On the basis of the type of fuel, coolant, moderator, availability of fuel nearby etc. there are different types of reactor. Each reactor has its own specifications and different working requirements. Some of the most common reactors are briefly discussed below.

3.1 Pressurised water reactor (PWR)

The PWR is the most popular reactor prevailing in the world. The function of moderator and coolant is fulfilled by water. In a PWR, it is necessary to have a coolant pressure well above its saturation pressure so as to prevent the boiling of the coolant. A major drawback of the PWR is the lower critical temperature of the coolant (water), i.e., 374°C. Thus, to keep the coolant in liquid form, the temperature should be below 374°C and in practice, it is around 300°C to allow a margin of safety. Enriched uranium in the form of plates or thin rods is used as a fuel. The cladding of the reactor is made either of stainless steel or zircaloy.

3.2 Boiling water reactor (BWR)

In this reactor, the steam is formed directly when water comes into contact with the reactor core thus rejecting the need of separate heat exchanger with lower pressure water system as done in PWR. The obtained steam is extracted and superheated (dried) by some mechanical equipments installed in the upper section of the pressure vessel assembly. The steam is, thereafter, sent directly to the high-pressure turbine. The water besides being a coolant and moderator also serves the purpose of working fluid.

3.3 Gas-cooled reactors

For such reactors, the purpose of coolant is served by a gas such as CO_2 or helium and the moderator is graphite. Because of high-melting point of graphite, these can be used effectively even at elevated temperatures and the conditions at which steam is generated is tantamount to that of in modern coal-fired power plant.

3.4 Liquid metal fast breeder reactor

These reactors are equipped to generate new fissile fuel from a fertile material while producing useful electricity at the same time. The most common reaction involves the production of fissile plutonium (Pu-239) from fertile uranium-238. The core region is provided with fuel rods that contains a well proportionate mixture of fissile Pu-239 and U-238. A blanket of fertile U-238 surrounds the active core region. As the neutrons are bombarded, the blanket and gets converted into fissile material, thus producing additional fuel. Such reactors do not have moderator.

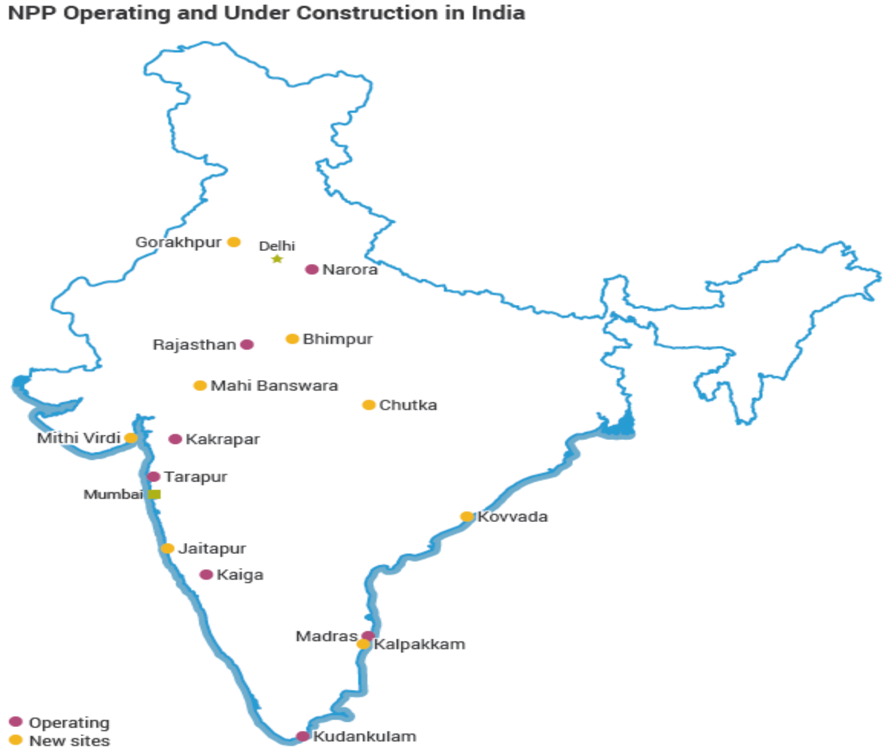
3.5 Pressurised heavy water reactor (PHWR)

The very low neutron capture cross-section of heavy water makes it an excellent moderator and coolant and permits the use of natural uranium (0.7% U-235) as fuel. It has good breeding ratios, high-fuel burn up and reduction in fuel cost. These reactors were first developed in Canada and are popularly called CANDU-PHW (Canadian Deuterium Uranium Pressurised Heavy Water). These reactors are majorly used in India under the India's nuclear power program.

4 India's nuclear power programme

Nuclear power is the fifth largest source of electricity in India. India has at present a total of 22 nuclear reactors in operation at seven nuclear power plants which have an installed capacity of 6780 MW. In 2017, nuclear power stations produced 35 TWh of electricity. Six reactors are under construction in India as at January, 2018. In 2017, the government of India has emanated a proposal of building 10 new nuclear plants which would target to grow the share of nuclear energy in its total electricity generation (List of Nuclear Powerplants in India – Wordpandit, 2018). Tarapur is the largest nuclear power station in India. Nuclear Power Corporation of India Limited (NPCIL) is a government owned corporation of India based in Mumbai which supervises the generation of nuclear power for electricity. It is administered by the Department of Atomic Energy, Govt. of India. The Atomic Energy Regulatory Board (AERB) is the regulatory body in India which takes the responsibility of prescribing and implementing certain parameters and safety measures which would ensure that the use of radioactive elements in nuclear power plants would have no adverse effect on the health of workers working in the plants, members of the public living in nearby areas and the environment (Kumar et al., 2017). Figure 3 shows the NPPs operating and under construction in India.

Figure 3 Nuclear power plants operating and under construction in India



Source: World Nuclear Association (2018)

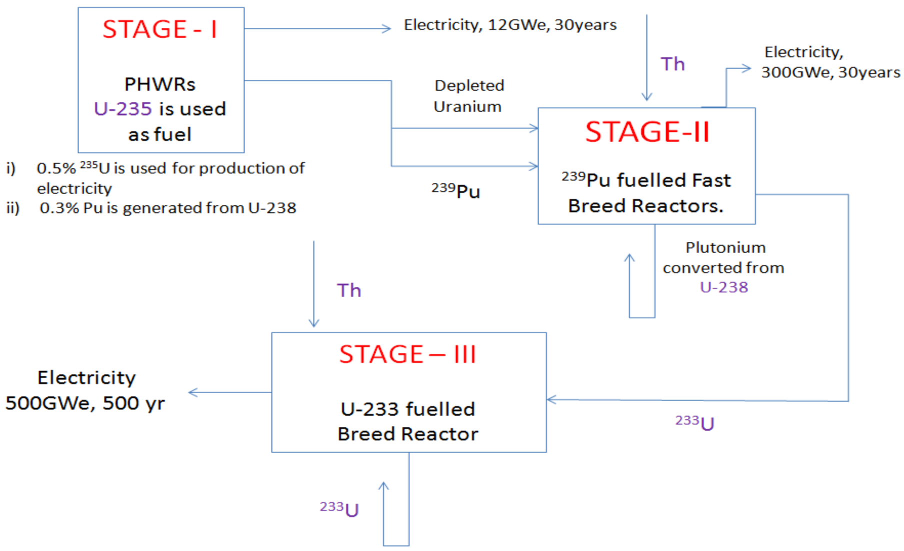
Since India is not a member country of the Non-Proliferation Treaty (NPT) due to its weapons programme, it was debarred from import of uranium until 2009 which reduced the scope of nuclear energy based power in India. This ban imposed over India no doubt hampered the growth of nuclear energy until 2009. But even after all such restrictions, India has managed to generate electricity from nuclear energy by exploiting the thorium reserves due to its strong will power and determination (World Nuclear Association, 2018).

India's nuclear power programme is a three stage programme devised by eminent scientist Dr. Homi Jahangir Bhabha in the 1950s. Since India has insufficient uranium reserves but huge thorium reserves, the current programme would ensure the utilisation of thorium reserves of India to produce electricity so as to meet the country's energy requirements. Figure 4 shows the three stage program of nuclear power plants in India.

4.1 Stage I: Pressurised heavy water reactor

The programme initiates with the stage I in which the Pressurised Heavy Water Reactor (PHWR) is fuelled with the natural uranium. The natural uranium has a minor portion of U-235 and is mainly composed of U-238. When neutron strikes the natural uranium, the U-235 being a fissile element produces heat and neutrons while the U-238 being a fertile element absorbs the neutron to form plutonium-239. Thus, the electricity is produced due to fission of U-235 and plutonium-239 is obtained as by-product.

Figure 4 Three stage nuclear power program in India



Source: (IEA and NEA, 2018)

4.2 Stage II: Fast breeder reactor

The second stage of the Indian nuclear power programme involves the use of fast breeder reactors. The reactor uses mixed oxide of plutonium-239 and natural uranium, i.e., PuO_2 – UO_2 as a fuel. The intriguing fact is that the plutonium oxide in the mixture is the one which is obtained as a by-product in the first stage. Thus, the by-product of the stage I acts as a fuel for stage II. In the reactor, plutonium-239 undergoes fission to produce heat and thus electricity, while the fertile uranium-238 present in the mixed oxide fuel gets converted into additional plutonium-239. This leads to the creation of more fuel than what was consumed. Once sufficient plutonium-239 is produced, the uranium is replaced by thorium as a blanket material in the reactor. Due to this, the fertile thorium gets converted into fissile U-233 and is further used in the third stage of the program.

4.3 Stage III: Thorium based reactors

This stage involves the use of fast and thermal breeder reactors. A series of self-sustaining reactions takes place. The uranium-233, which was the by-product of the earlier stage, would act as fuel in this stage while the thorium acts as a blanket material. This leads to formation of energy from the fission of U-233 and conversion of thorium into U-233 thus producing more fuel than what was consumed (Daware, 2018).

One can note that the India's current nuclear power program mainly utilises a large number of PHWRs instead of other types of reactors like PWRs, BWRs and gas-cooled reactors etc. There are certain reasons which justify the India's choice of opting for PHWRs. The biggest and dominating reason behind this is the ability of the PHWRs to use the unenriched natural uranium unlike LWRs which make use of enriched uranium. Since natural uranium is available in India, it saves a large investment in importing enriched uranium which in itself is a very difficult task amid several restrictions imposed over its import to India. Moreover, the PHWRs are more efficient than comparable LWRs as they develop more energy per kg of the mined uranium. Thus high cost of heavy water is justified. Besides, the PHWR core containing natural uranium is safer with its lower reactivity and excellent neutron economy resulting in large yield of plutonium (Gupta, 2017).

The installed electricity generating capacity in India as of March 2016 is 298 GW (Source: CEA, India (Central Electricity Authority, 2018)) which places India among the top five producers of electricity around the globe. But, it is perplexing to find that the share of nuclear energy among the overall installed capacity is merely about 2% which is a subject of deep discussion. To uplift the contribution of nuclear energy in its overall power capacity, India is undergoing process of establishing Pressurised Light Water Reactors with foreign collaboration while continuing its own programme of PHWR based NPPs and indigenously designed light water reactor based NPPs (Kumar et al., 2017).

5 Limitations of nuclear power plants

Even though the nuclear power plants inherit a large number of advantages, they also have certain disadvantages which impede their growth rate. The by-products formed as a result of these nuclear processes are immensely hazardous, toxic and fatal, and proper techniques of disposing such hazardous waste in a safe, secure and congenial manner is yet to be discovered by the nuclear industry. The measures required to protect the public interest are insufficient and thus serve as a major reason in differentiating public acceptance to this technology (Annual Report of China Institute of Atomic Energy, 2011). The threat of exploiting nuclear energy for making weapons instead of utilising it for power generation is a complicated issue which can't be ignored. The incidents of nuclear bombing in Hiroshima and Nagasaki during world war II has instilled fear in the minds of public which makes it very difficult to separate one from the other.

Another deciding factor which has widened the gap between the nuclear energy and the public is the fear of a nuclear accident. The repercussion of such a mishap would result in the liberation of radioactive elements into the surrounding environment. The fateful incident that took place at the Fukushima Daiichi nuclear power plant as a result of the disastrous undersea earthquake and tsunami in 2011 left the city in pain and distress. The earthquake and tsunami caused in repeated fires and three core meltdowns in the power plant resulting in the loss of $166 billion (Slodkowski and Saito, 2013) and around 575 immediate deaths from the evacuation. Furthermore, due to the release of radioactive isotopes, many people died due to cancer related disease (Ten Hoeve and Jacobson, 2012). Such failures of nuclear power plant had a severe impact on the people who were compelled to loss their faith in nuclear power. Such incidents have also questioned the government's policy in several countries (Chaturvedi, 2014).

In the wake of achieving 63 GW in 2032 (Srivastava, 2011), India planned to raise the numbers of nuclear reactors in 2010 but after the nuclear disaster in Fukushima nuclear reactor, the dwellers around the proposed site of that power plant launched protests and agitation, asking questions from the authorities regarding the credibility of atomic energy as a clean and safe energy resource and as substitute for fossil fuels (Nag, 2003). Massive protests were organised by the residents and the activists against the French backed 9900 MW Jaitapur nuclear power project in Maharashtra and the Russian backed 2000 MW Kudankulam nuclear power plant in Tamil Nadu. Moreover, West Bengal also declined to permit six Russian reactors near Haripur considering safety norms (Nag, 2003).

The government must ensure that the nuclear power plants are setup keeping in mind the safety of the nearby dwellers. Awareness programmes must be organised regarding the boons and banes of nuclear power plants to eliminate the misconceptions present in the minds of people. The Atomic Energy Regulatory Board must be vigilant about whether the prescribed rules and regulations are being followed by the power plants or not so as to prevent any mishap. The combined efforts of authorities, government and people would make it possible for India to achieve a large portion of its electricity from nuclear power plants thus reducing the burden over the coal-based power plants.

6 Conclusion

The review paper briefly summarised the basic knowledge regarding nuclear energy and nuclear power plants and their present contribution to power generation in India as well as in the world, underscoring India's nuclear power programme and also introducing the readers to some of the threats caused by nuclear energy in the past. From the above discussion, we can infer that the nuclear energy is indeed a versatile source of clean energy and is a boon to the power generation sector provided that radioactive waste produced is properly treated. The government needs to divert its attention towards nuclear power sector so as to minimise the burden on coal-based thermal power plants since coal is a limited resource. In order to bridge the gap between the public and the nuclear energy, there is need of improving the nuclear technology and strengthening of safety regulations.

References

Annual Report of China Institute of Atomic Energy (2011) Available online at: http://www.ciae.ac.cn/eng/AnnualReport/2011en.pdf.

Breeze, P.A. (2016) *Nuclear Power*, 1st edition, Elesivier (accessed on 2nd August 2018).

Central Electricity Authority (2018) *Govt. of India, Ministry of Power*. Available online at: http://www.cea.nic.in/ (accessed on 1st August 2018).

Chaturvedi, A.K. (2014) *Nuclear Energy in India's Energy Security Matrix : an Appraisal*. Vij Books India Private Limited, New Delhi, India.

Daware, K. (2018) *Methods of Voltage Control in Power System*, *Electrical easy.com.* Available online at: https://www.electricaleasy.com/search/label/Power System (accessed on 2nd August 2018).

Gupta, P. (2017) *Explained: Why India Is Betting Big On Heavy Water Reactors – Swarajy*. Available online at: https://swarajyamag.com/technology/explained-why-india-is-betting-big-on-heavy-water-reactor (accessed on 1 August 2018).

IEA and NEA (2018) *Technology Roadmap Nuclear Energy*. Available online at: www.iea.org/roadmaps (accessed on 1 August 2018).

Intergovernmental Panel on Climate Change (2001) *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the 3rd Assessment Report of the Intergovernmental Panel on Climate Change – GCIS*, Technical Report. Available online at: data.globalchange.gov/report/ipcc-tar-wg1 (accessed on 29 January 2019).

Kumar, S., Harikumar, S., Varghese, C.S. and Shukla, D.K. (2017) 'Regulatory aspects of nuclear power program in India', *Progress in Nuclear Energy*, Vol. 101, pp.146–159.

List of Nuclear Powerplants in India – Wordpandit (2018) *Wordpandit*. Available online at: https://wordpandit.com/list- nuclear-powerplants-india/amp/ (accessed on 1 August 2018).

Nag, P.K. (2003) *Power Plant Engineering*, McGraw Hill.

Slodkowski, A. and Saito, M. (2013) *Special Report – Help wanted in Fukushima: Low pay, high risks and gangsters*. Available online at: https://www.reuters.com/article/us-fukushima-workers-specialreport/special-report-help-wanted-in-fukushima-low-pay-high-risks-and-gangsters-idUSBRE99O04320131025 (accessed on 1st August 2018).

Srivastava, S. (2011) *India's Rising Nuclear Safety Concerns*, Asia Sentin.

Ten Hoeve, J.E. and Jacobson, M.Z. (2012) 'Worldwide health effects of the Fukushima Daiichi nuclear accident', *Energy Environmental Science*, Vol. 5, pp.8417–8429.

UNFCCC Process | UNFCCC (2018) Available online at: https://unfccc.int/process (accessed on 2nd August 2018).

Van Vuuren, D.P. et al. (2016) 'Carbon budgets and energy transition pathways', *Environmental Research Letters*, Vol. 11, No. 11.

World Nuclear Association (2018) *World Nuclear Association*. Available online at: http://www.world-nuclear.org/ (accessed on 1st August 2018).

Xiao, X-J. and Jiang, K-J. (2018) 'China's nuclear power under the global 1.5 C target: preliminary feasibility study and prospects', *Advances in Climate Change Research*, Vol. 9, No. 2, pp.138–143.