

# Possible Challenges of Nuclear Power Plants under Climate Change Scenarios

Javed Akhter<sup>1</sup>, Lalu Das<sup>2\*</sup> and Argha Deb

<sup>1</sup>Department of Physics, Jadavpur University, Kolkata – 700032

<sup>2</sup>Department of Agricultural Meteorology and Physics,  
Bidhan Chandra Krishi Viswavidyalaya, Mohanpur, Nadia – 741252, West Bengal  
✉ daslalu@yahoo.co.in

*Received November 20, 2017; revised and accepted December 30, 2017*

**Abstract:** Along with other low carbon technologies, Nuclear power plants are given immense importance to mitigate greenhouse gas (GHG) emission from the energy sector. Nuclear power provides 11% of the global electricity production. However, like other thermo-electric plants, nuclear plants are also vulnerable to the different impacts of climate change. Increase of ambient temperature would reduce the efficiency of the nuclear plants. Water stress in different locations under changing climate would affect the coolant water supply to the plants. Warming of coolant water is also a major concern for the plants. Many authors have reported reduction of output of the nuclear plants under future warming scenarios. Additionally, sea-level rise, cyclones and hurricanes possess severe threats to the coastal plants. Therefore, it is necessary to incorporate climate change risks and formulate long-term strategies for sustainable power generation. Planning and utilization of new generation technologies is required to protect the plants from the possible impacts of climate change and avoid unexpected disruption of generation.

**Keywords:** Nuclear plants; Climate change; GHG mitigation; Water stress.

## Introduction

As a consequence of climate change, global mean air and water temperature would continue to rise and other attributes of climate would also be affected resulting in sea-level rise, frequent floods, cyclones etc. The frequency, intensity, duration and spatial extent of heat waves, droughts, storms and other extreme weather events may be altered due to climatic change. These changes might have a considerable impact on the energy sector, including nuclear power plants (IAEA, 2016). Efficiency and outputs of nuclear plants would be decreased as rise of ambient temperature will increase the temperature of cooling water. Long lasting spells of very high temperature will exacerbate the decline of conversion efficiency and increase the cooling challenge.

During the 2003 summer heat wave in Europe, more than 30 nuclear power plant units in Europe were forced to shut down or reduce their power production (IAEA, 2004; Zebisch et al., 2005; Rebetez et al., 2009; Koch and Vögele, 2009; Linnerud et al., 2011). The regions where precipitation and stream flow has been projected to decrease may face issue with availability of cooling water. The shortage of water supply due to drought, river run-off due to glacier retreat (Kibria et al., 2016) may affect inland nuclear power reactors and nuclear power supply in India, where currently 22 nuclear reactors are operating and six reactors are under construction (Kibria, 2017). Longer and more intense drought conditions will add to these problems. The major challenge will be associated with water and cooling (IAEA, 2016). In addition, extreme events like

\*Corresponding Author

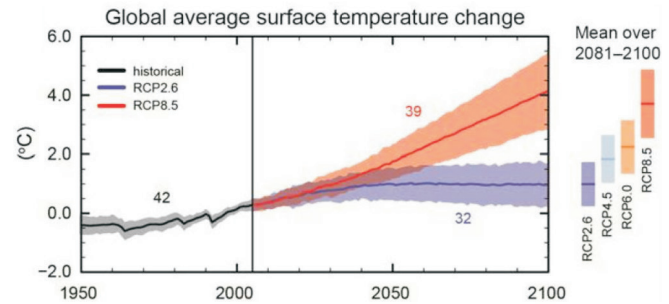
storm, flood may impact on the safety and durability of the plants. In coastal regions, a gradual rise in sea level may increasingly affect power plants located at a low elevation.

### Global Climate Change Scenario

Several assessment reports published by Intergovernmental Panel on Climate Change (IPCC) at different time interval provide an account of global climate change and their impacts. In 1996, the Second Assessment Report (AR2) has shown the evidence of anthropogenic effect on global climate. After a decade, Fourth Assessment Report (AR4) published in 2007, has concluded that warming of the climate system is unequivocal and most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations. In its Fifth Assessment Report (AR5) published in 2013, the IPCC Working Group I confirmed the human influence on the observed warming since the mid-20th century with higher confidence (95% to 100% probability). They have shown that globally averaged surface temperature increased by 0.85°C during 1880–2012. Warming of ocean has affected the upper layer of the ocean causing the Greenland and Antarctic ice sheets to lose mass and shrinking of glaciers. The global mean sea level has found to be risen by 0.19 metres between 1901 and 2010 (IPCC, 2013).

The latest IPCC scenarios are dependent on four representative concentration pathways (RCPs) for exploring near and long term climate change implications of different paths of anthropogenic GHG emissions, aerosols and other climate drivers (IAEA, 2016). The four RCPs present approximate total radiative forcing values such as 2.6, 4.5, 6.0 and 8.5 watts per square metre ( $\text{W/m}^2$ ). Except RCP 2.6, all RCPs have projected more than 1.5°C increase (upper limit of increase as per Paris agreement) in global surface temperature by the end of this century relative to the 1850–1900 periods. The global surface temperature may increase between 0.3°C and 1.7°C (RCP2.6) at the low end, and between 2.6°C and 4.8°C (RCP8.5) at the high end of the scenario spectrum (Figure 1).

Working Group II of AR5 has assessed the possible risks from global climate change. The livelihoods in low lying coastal zones and on small islands are in risk due to storm surges, coastal flooding and sea level rise. Inland flooding is a possible threat for large urban populations. Increase of extreme weather events



**Figure 1: Change from 1950 to 2100 in global mean surface temperature relative to the 1886–2005 mean values from the CMIP5 concentration driven experiment. Time series of projections and a measure of uncertainty (shading) are shown for scenarios RCP2.6 (blue) and RCP8.5 (red). (Source: IAEA, 2016)**

may have severe impacts through the breakdown of infrastructure networks and critical services such as electricity, water supply, and health and emergency services; loss of livelihoods, insufficient access to drinking and irrigation water and reduced agricultural productivity; and loss of terrestrial, marine and coastal ecosystems, biodiversity, and ecosystem goods, functions and services (IAEA, 2016). These key risks would create lot of difficulties for the least developed countries and for vulnerable communities owing to their limited ability to adapt. Without stringent climate action, more than 100 million additional people may fall back into poverty by 2030 (Hallegatte et al., 2016).

In order to maintain 1.5°C limit, enormous mitigation effort is required throughout the world in response to fast increasing GHG emissions in recent decades and the possible future emissions as depicted by the RCPs. Since 1750, the largest contribution to total radiative forcing has been caused by the increase in the atmospheric concentration of  $\text{CO}_2$  (IAEA, 2016). To a large extent, these  $\text{CO}_2$  emissions have resulted from fossil fuel burnt in the energy sector. In order to reduce the potentially severe risks of climate change, global GHG emissions and, in particular,  $\text{CO}_2$  emissions, will need to peak in the next few years and then be reduced at an accelerating rate. Nuclear power and other low carbon technologies will be fundamental in putting the world on this ambitious mitigation pathway (IAEA, 2016).

### Nuclear Power Plant Scenario over World

Nuclear technology has been developed during 1940s and in the initial stage nuclear research was focused to develop weapons. But in the next decade of 1950s,

nuclear power has been started to be used for electricity generation. Today 11% of the world's electricity has been supplied by nuclear power (<http://www.world-nuclear.org/>). Worldwide 448 reactors in 31 countries are operating with 391.744 GW total net electric capacities (Table 1). Besides, many other countries are dependent on nuclear power through regional transmission grids.

**Table 1: Country specific details of nuclear plants**

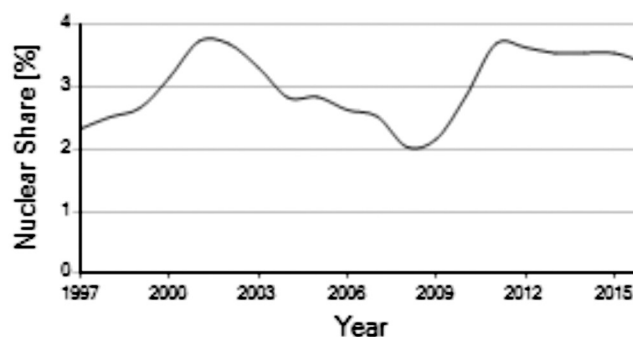
| <i>Country</i>            | <i>Number of reactors</i> | <i>Total net electrical capacity (MW)</i> |
|---------------------------|---------------------------|-------------------------------------------|
| Argentina                 | 3                         | 1632                                      |
| Armenia                   | 1                         | 375                                       |
| Belgium                   | 7                         | 5913                                      |
| Brazil                    | 2                         | 1884                                      |
| Bulgaria                  | 2                         | 1926                                      |
| Canada                    | 19                        | 13554                                     |
| China                     | 38                        | 33384                                     |
| Czech Republic            | 6                         | 3930                                      |
| Finland                   | 4                         | 2764                                      |
| France                    | 58                        | 63130                                     |
| Germany                   | 8                         | 10799                                     |
| Hungary                   | 4                         | 1889                                      |
| India                     | 22                        | 6240                                      |
| Iran, Islamic Republic of | 1                         | 915                                       |
| Japan                     | 43                        | 40290                                     |
| Korea, Republic of        | 25                        | 23077                                     |
| Mexico                    | 2                         | 1552                                      |
| Netherlands               | 1                         | 482                                       |
| Pakistan                  | 5                         | 1320                                      |
| Romania                   | 2                         | 1300                                      |
| Russia                    | 35                        | 26111                                     |
| Slovakia                  | 4                         | 1814                                      |
| Slovenia                  | 1                         | 688                                       |
| South Africa              | 2                         | 1860                                      |
| Spain                     | 7                         | 7121                                      |
| Sweden                    | 8                         | 8629                                      |
| Switzerland               | 5                         | 3333                                      |
| Ukraine                   | 15                        | 13107                                     |
| United Kingdom            | 15                        | 8918                                      |
| United States of America  | 100                       | 100351                                    |
| <b>Total</b>              | <b>451</b>                | <b>392521</b>                             |

Source: PRIS, IAEA

World nuclear association report has depicted that sixteen countries depend on nuclear power for at least a quarter of their electricity. France gets around three-quarters of its power from nuclear energy, while Belgium, Czech Republic, Finland, Hungary, Slovakia,

Sweden, Switzerland, Slovenia and Ukraine get one-third or more. South Korea and Bulgaria normally get more than 30% of their power from nuclear energy, while in the USA, UK, Spain, Romania and Russia almost one-fifth is from nuclear. Japan is used to relying on nuclear power for more than one-quarter of its electricity and is expected to return to that level. Among countries which do not host nuclear power plants, Italy and Denmark get almost 10% of their power from nuclear.

In India there are 22 operational nuclear reactors and six under construction that have produced 34,999.86 GW.h electricity which is 3.38% of total electricity production of the country. The historical trend of nuclear share in the electricity has been shown in Figure 2.



**Figure 2: Trend of nuclear share of total electricity production over India. (Source: PRIS, IAEA)**

It is clear that nuclear share has gradually increased during 1997-2002 then started to decrease till 2009 and increased afterwards.

Among 22 operational plants, maximum number of plants (six) is situated at Kota, Rajasthan while there are four plants each in Tarapur (Maharashtra) and Kaiga (Karnataka). Kakrapar (Gujarat), Narora (Uttar Pradesh), Madras and Kudankulam (Tamilnadu) have two operating nuclear plants each.

### **Impact of Water Temperature and Availability on Nuclear Plants**

Thermoelectric power plants require large amount of water for its operation. Water is mainly utilized for cooling purposes. Nuclear plants require substantially more water than other thermoelectric plants to cool or condense the coolant that is used to cool the reactor core by transferring heat from the core to the turbines. For example, a nuclear plant may require 2 billion cubic metres of water each year for cooling purposes (Vrontisi, 2013).

Based on the cooling systems, there are two types of nuclear plants. Firstly plants with once through cooling and secondly plants with recirculating cooling.

In Once-through cooling system water is extracted from nearby water body (stream, pond, lake or ocean), passed through a heat exchanger (where it absorbs heat from the condenser), then the warm water (whose temperature is now several degrees higher) is discharged back to the water body.

The heat transfer rate in the condenser ( $dq/dt$ ) depends on the heat capacity ( $C_p$ ) and flow rate of cooling water ( $Q$ ) as following (Yannick Rousseau, 2013):

$$dq/dt \leq C_p \cdot \rho \cdot Q \cdot \Delta T$$

where  $\rho$  is the density of water and  $\Delta T$  the difference in temperature between the coolant and the working fluid.

With the density of water fixed, the heat transfer rate is limited by the flow rate of the coolant, the specific heat of the coolant (itself dependent on its temperature) and the difference in temperature between the coolant and the working fluid. As the temperature of the water body source increase, higher water extraction rates are required in order to keep the efficiency of the condenser at a maximum. In locations where the water supply is adequate, this does not present any issue. In warmer areas, where water restrictions and quotas are often in place, the efficiency of thermodynamic cycles can decrease drastically. This problem is especially pronounced during summer, when both the temperature of the water and the risk of drought are higher.

Bartos and Chester (2015) have shown that the required water withdrawal of a thermoelectric plant can be expressed as:

$$\dot{W}_{ap} = P_{ap} \cdot \frac{1 - \eta_{net} - k_{as}}{\eta_{net}} \times \frac{1}{\rho_w \cdot C_{p,w} \cdot \max(\min(Tl_{max} - T_w), \Delta Tl_{max}, 0)}$$

$P_{op}$  is the installed capacity of the plant,  $\eta_{net}$  is the net plant efficiency, and  $k_{os}$  is the fraction of heat lost to heat sinks other than the cooling system (for nuclear plants it is assumed to be zero).  $Tl_{max}$  is the maximum permissible intake water temperature ( $^{\circ}\text{C}$ ),  $T_w$  is the ambient stream temperature ( $^{\circ}\text{C}$ ), and  $\Delta Tl_{max}$  is the maximum permissible temperature rise of the water ( $^{\circ}\text{C}$ ).  $\rho_w$  is the density of liquid water and  $C_p$  is the heat capacity of water.

When due to increase of ambient temperature difference between  $T_w$  and  $Tl_{max}$  reduces, power plant

has to withdraw additional water to maintain the same generating capacity. If sufficient additional water is not available, then the usable capacity of the plant would be reduced as following:

$$P_{rc} = \frac{\min(yQ, \dot{W}_{op}) \cdot \rho_w \cdot C_{p,w} \cdot \max(\min(Tl_{max} - T_w), \Delta Tl_{max}, 0)}{1 - \eta_{net,i} - k_{us}} \eta_{net,i}$$

Plants with recirculating cooling require much less amount of water compared to once-through cooling plants. Here heat is rejected to atmosphere through evaporation of water instead of discharging the warm water in the water body. Water that is not evaporated during cooling process is re-used. Cooling water requirements are mainly dependent on atmospheric parameters like air temperature and humidity. The intake temperature of water has not much importance here.

Electricity generation capacity of recirculating plants can be formulated as function of water circulation rate and meteorological parameters:

$$P_{rc} = \frac{\rho_w \dot{W}_{circ} \left[ \frac{h_{a,out} + T_c c_{p,w} (\omega_{out} - \omega_{in}) \tau}{-T_{mu} c_{p,w} (\omega_{out} - \omega_{in}) - h_{a,in}} \right]}{\sigma \cdot \frac{1 - \eta_{net,i} - k_{us}}{\eta_{net,i}}}$$

Here  $\sigma$  is the water-air mass flow ratio,  $\dot{W}_{circ}$  is the flow rate of water circulating through condenser ( $\text{m}^3/\text{s}$ ),  $\omega_{out}$  is the humidity ratio of air exiting the tower, and  $\omega_{in}$  is the humidity ratio entering the tower,  $h_{a,out}$  and  $h_{a,in}$  are the enthalpies ( $\text{MJ/kg}$ ) of the hot air exiting the tower and cool air entering the tower, respectively.  $T_{mu}$  is the temperature of the makeup water, and  $T_c$  is the temperature of the cool water.  $\tau$  is the ratio of blow down water to makeup water entering the condenser.

To account for constraints on water availability, an expression is developed by Bartos and Chester (2015) to relate makeup water requirements to the total rate of water recirculating through the system as following:

$$\frac{\min(\dot{W}_{mu}, yQi)}{\dot{W}_{circ}} = \sigma (\omega_{out} - \omega_{in})$$

Thus, when the makeup water requirement ( $\dot{W}_{mu}$ ) is greater than available streamflow ( $yQi$ ), the volume of water passing through the condenser ( $\dot{W}_{circ}$ ) decreases such that the ratio of makeup water to recirculating water remains the same for a given set of humidities. Accordingly, as  $\dot{W}_{circ}$  decreases, the available capacity decreases accordingly.

In a warming world (the rise in water temperature, scarcity of water resources, hot summer and heat waves), the nuclear cooling system would require more water and therefore power plants may operate less efficiently. In fact, when cooling systems cannot operate efficiently, power plants may be forced to shut down or reduce its output (Kibria, 2017).

### Impact of Ambient Air Temperature on Nuclear Plants

Increase of ambient temperature would reduce the efficiency of nuclear power plants. Linnerud et al. (2011) have shown the relationship between ambient temperature and plant efficiency through regression analysis. They have used hourly data on actual capacity (MW) of a European power plant (identity of the plant was kept anonymous) and ambient temperature (°C) at the plant site from January to November 2007. Following equation has been used:

$$Y_t = b_0 + b_1D + b_2T_t + b_3DT_t + b_4DT_t^2 + \varepsilon_t$$

where  $Y_t$  is capacity utilization,  $T_t$  is the ambient temperature at the plant site,  $D$  is a dummy variable for full load,  $\varepsilon_t$  is the error term (white noise), and the subscript  $t$  denotes the time (hour).

The analysis has been performed in two conditions firstly for full load ( $D = 1$ ) and secondly for reduced load ( $D = 0$ ). Under full load condition, if fuel use is kept constant 1°C rise in ambient temperature resulted in reduction of output by about 0.4% as a result of decreased thermal efficiency. Under reduced load condition, 2.3% decrease in output has been found due to combined impacts of reduced efficiency and reduced load (Figure 3).

Increase of ambient air temperature will in turn increase the temperature of water required for cooling purpose. Therefore, the production of nuclear power has to be reduced to meet the laws of thermodynamics. This is the major concern for nuclear plants under global warming scenario.

### Impacts of Sea Level Rise and Extreme Events on Nuclear Plants

To meet the requirements of water supply, nuclear reactors are often located along the coasts. The International Atomic Energy Agency database ([http://gcmd.nasa.gov/records/GCMD\\_GNV181.html](http://gcmd.nasa.gov/records/GCMD_GNV181.html)) indicates that significant number of nuclear plants are located along coastlines.

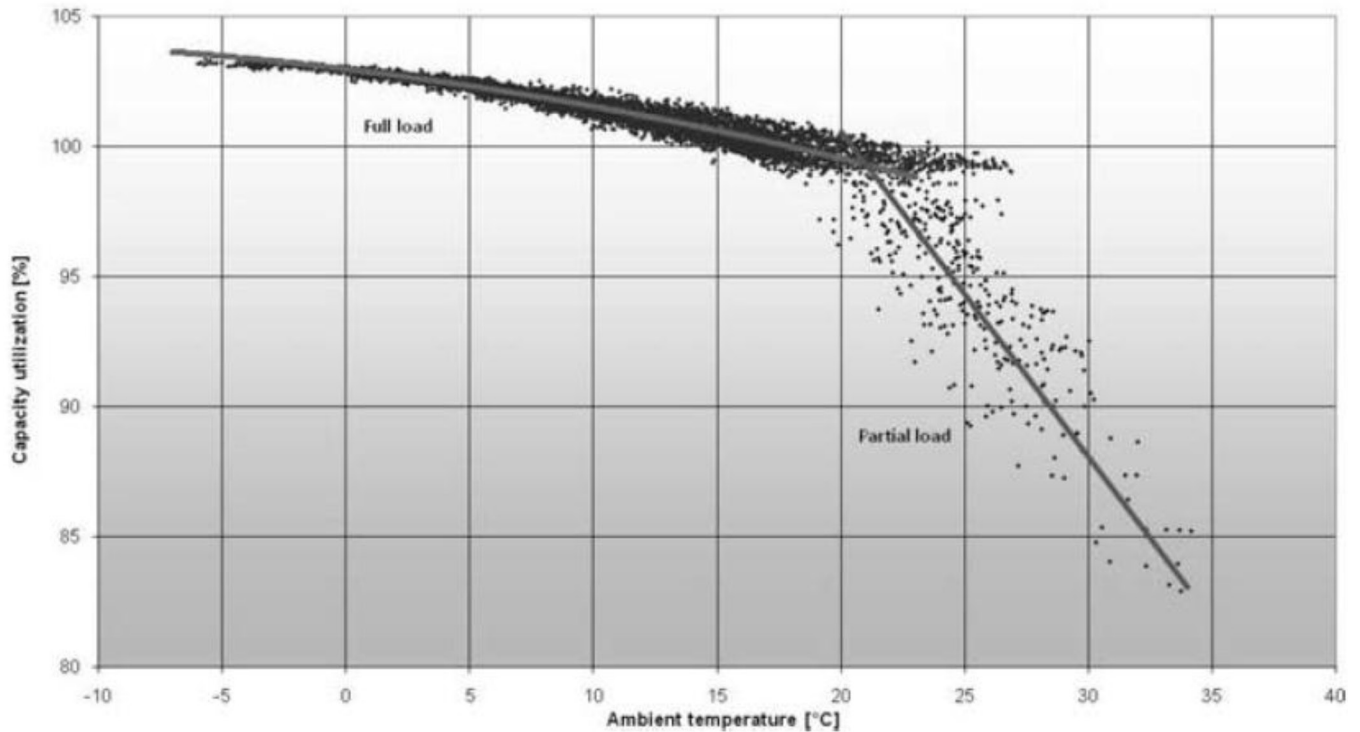


Figure 3: Scatter plot of capacity utilization and ambient temperatures for a given nuclear plant. (Hourly observations, 2007)

Sea level rise is also a major concern for the coastal plants. Although power plants are usually located a few metres or tens of metres above the sea, the mean sea level rise is not expected to reach that magnitude. But the rise of sea level may be responsible for erosion and inundation at reactor sites thus damaging the infrastructure of plants.

Extreme events like storms and hurricanes possess major threats to coastal plants through flooding and wind damage. For example Fukushima plant in Japan was affected by Tsunami waves after earthquake.

Floods can also affect inland nuclear plants by submerging installations, damaging equipment etc. Flooding events at Le Blayais nuclear plant in France (1999, 2003) caused damage to the cooling system of the plant through mud and debris in the water used for cooling purposes (Kopytko and Perkins, 2011) and eventually triggered the shutting down of the plant.

Overall, sea level rise or other extreme events may not affect the production of nuclear plants but these may damage the infrastructure of the plants. Coastal plants are more vulnerable to sea-level rise and cyclones whereas river side plants may face floods during heavy rainfall events.

### **Future Projection on Nuclear Power Production**

Most of the authors have reported reduction of nuclear power production under future warming scenarios. Forster and Lilliestam (2010) have shown that there may be 1.6-11.8% reduction in production for once-through plants due to 1K-5K increase in river water temperature assuming unchanged stream flow. If stream flow would also simultaneously reduce, the situation would be worsening. For 1 K increase in temperature, power production may reduce 8.4-26.2% for 10-50% decrease in stream flow whereas reduction may be 27.8-39.2% for 5 K scenario with reduced stream flow.

Hoffmann et al. (2013) have shown vulnerability of thermo-electric plants including nuclear plants for both once-through and closed circuit cooling systems over Germany. They have found power reduction will be comparatively lesser for closed circuit plants. Under A1B scenario 0.10 MW decrease per year has been projected for closed plants whereas reduction has been 0.33 MW per year for once through plants during 2011-2070. Under A2 scenario, power output of OTC units can be reduced down to 66.4% of the nominal capacity during 2041-2070.

Ganguli et al. (2017) have found that about 27% thermo-electric power production over United States including nuclear power may be severely impacted due to warmer and scarcer water during 2030s. Van Vliet et al. (2012) calculated a reduction between 6.3% and 19% for European power plants. Greis et al. (2010) found a decrease in power production of 0.36% for a closed circuit unit during the summer months.

### **Summary**

Nuclear power plants are considered as a mitigation option to reduce greenhouse emissions. However, from above discussion it is clear that like other thermoelectric plants nuclear plants are also vulnerable to different impacts of climate change. Therefore, it is necessary to incorporate climate change risks and formulate long-term strategies for sustainable power generation. Planning and utilization of new generation technologies is required to protect the plants from the possible impacts of climate change and avoid unexpected disruption of generation. Preventive investments are required for coping with extreme events like storms, floods as well as the danger of sea level rise.

Policymakers and governments are also required to take appropriate action plans. Disruptions in electricity supply may have far reaching consequences for society in terms of sudden electricity price hikes, sectors having conflicting interests with respect to water consumption, negative implications on river biodiversity if regulation on return water temperature is relaxed, etc. (Linnerud et al., 2011). Energy disruptions may also have consequences for a wider region through its impact on water management and exchanges of electricity across countries (Vogele, 2010; Koch and Vogele, 2009).

### **References**

- Bartos, M.D. and Chester, M.V., 2015. Impacts of climate change on electric power supply in the Western United States. *Nature Climate Change*, **5(8)**: 748-752.
- Förster, H. and Lilliestam, J., 2010. Modeling thermoelectric power generation in view of climate change. *Regional Environmental Change*, **10(4)**: 327-338.
- Hallegatte, S. et al., 2016. Shock Waves: Managing the Impacts of Climate Change on Poverty. The World Bank, Washington, DC.
- Hoffmann, B., Häfele, S. and Karl, U., 2013. Analysis of performance losses of thermal power plants in

- Germany—A System Dynamics model approach using data from regional climate modelling. *Energy*, **49**: 193-203.
- Ganguli, P., Kumar, D. and Ganguly, A.R., 2017. US Power Production at Risk from Water Stress in a Changing Climate. *Scientific Reports*, **7**(1): 11983.
- Greis, S., Schulz, J. and Müller, U., 2010. Water management of a thermal power plant—A site specific approach concerning climate change. In: *Management of Weather and Climate Risk in the Energy Industry*, pp. 267-280.
- International Atomic Energy Agency (IAEA), 2016. Climate Change and Nuclear Power 2016, Vienna. (<http://www-pub.iaea.org/MTCD/Publications/PDF/CCANP16web-86692468.pdf>)
- International Atomic Energy Agency (IAEA), 2004. Operating experience with nuclear power stations in member states in 2003.
- Intergovernmental Panel on Climate Change, 1996. Climate Change 1995: The Science of Climate Change. Contribution of WGI to the Second Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge.
- Intergovernmental Panel on Climate Change, 2007. Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge.
- Intergovernmental Panel on Climate Change, 2013. Climate Change 2013: The Physical Science Basis (Working Group I: Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change), IPCC Cambridge University Press, Cambridge.
- Intergovernmental Panel on Climate Change, 2014. Climate Change 2014: Impacts, Adaptation, and Vulnerability (Working Group II: Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change), IPCC, Cambridge University Press, Cambridge.
- Kibria, G., Haroon, A.K.Y. and Nugegoda, D., 2016. Climate Change and Water Security. Impacts, Future Scenarios, Adaptations and Mitigations. New India Publishing Agency, New Delhi. ISBN: 978- 93-85516-26-9.10.13140/RG.2.1.1848.1528/2.
- Kibria, G., 2017. Nuclear Power - Pros and cons and threats of climate change. ResearchGate Online. [https://www.researchgate.net/publication/321376073\\_Nuclear\\_Power\\_Pros\\_and\\_Cons\\_and\\_Threats\\_of\\_Climate\\_Change](https://www.researchgate.net/publication/321376073_Nuclear_Power_Pros_and_Cons_and_Threats_of_Climate_Change).
- Koch, H. and Vögele, S., 2009. Dynamic modelling of water demand, water availability and adaptation strategies for power plants to global change. *Ecological Economics*, **68**(7): 2031-2039.
- Kopytko, N. and Perkins, J., 2011. Climate change, nuclear power, and the adaptation-mitigation dilemma. *Energy Policy*, **39**(1): 318-333.
- Linnerud, K., Mideksa, T.K. and Eskeland, G.S., 2011. The impact of climate change on nuclear power supply. *The Energy Journal*, 149-168.
- Power Reactor Information System (PRIS), Dec 13, 2017. <https://www.iaea.org/pris/>
- Rebetez, M., Dupont, O. and Giroud, M., 2009. An analysis of the July 2006 heat wave extent in Europe compared to the record year of 2003. *Theoretical and Applied Climatology*, **95**(1): 1-7.
- Van Vliet, M.T., Yearsley, J.R., Ludwig, F., Vögele, S., Lettenmaier, D.P. and Kabat, P., 2012. Vulnerability of US and European electricity supply to climate change. *Nature Climate Change*, **2**(9): 676-681.
- Vrontisi, Z.N., 2013. Energy Production, Conversion, Transmission and Distribution, Policy, Planning, and Mitigation Processes—General Considerations-3.14: Large Energy Projects, Efficiency, and Vulnerability.
- Yannick Rousseau, 2013. Impact of climate change on thermal power plants—Case study of France. Master's thesis, Faculty of Earth Sciences, University of Iceland.
- Zebisch, M., Grothmann, T., Schröter, D., Hasse, C., Fritsch, U. and Cramer, W., 2005. Climate change in Germany. Vulnerability and adaptation of climate sensitive sectors/Klimawandel in Deutschland—Vulnerabilität und Anpassungsstrategien klimasensitiver Systeme. Federal Environmental Agency Germany/Umweltbundesamt, Dessau, Report, 201.