Energy-Water Nexus and Efficient Water-Cooling Technologies for Thermal Power Plants in India

An Analysis within an Integrated Assessment Modelling Framework

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COUNCIL ON ENERGY, ENVIRONMENT AND WATER,
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Abbreviations

ACCESS	Access to Clean Cooking Energy and Electricity – Survey of States
BCM	billion cubic metres
CLEAN	Clean Energy Access Network
CRMM	Common Risk Mitigation Mechanism
COP	Conference of Parties
CEEW	Council on Energy, Environment and Water
CEA	Central Electricity Authority
CT	Cooling Tower Technologies
CWC	Central Water Commission
CGWB	Central Ground Water Board
CPCB	Central Pollution Control Board
GCAM	Global Change Assessment Model
GW	gigawatts
HHV	Sent-out efficiency heat rate
IEA	International Energy Agency
INDC	Intended Nationally Determined Contributions
kWh	kilo watt hours
MoEFCC	Ministry of Environment, Forest and Climate Change
NTPC	National Thermal Power Corporations
NRDC	Natural Resources Defense Council
NETL	National Energy Technology Laboratory
OTC	once through technology
PIB	Press Investigation Bureau
SGWG	Sustainable Growth Working Group
TPP	thermal power plants
UCS	Union of Concerned Scientists
USAID	United States Agency for International Development
WEC	World Energy Council

Executive Summary

India is increasingly experiencing pressure on its already scarce water resources. With increasing GDP and population, this pressure is bound to intensify in the future. A large part of the water withdrawal is for meeting irrigation needs of the agriculture sector. However, water demand from the electricity sector is continuously growing. In the electricity sector, water is required mainly for cooling during the power production process. In coal power plants, water is also required for washing coal for removing the high ash content. With electricity sector set to grow at least for the next few decades, the additional pressure that the thermal power plants are expected to put on local water resources could have significant implications on the people living in the surrounding area.

The Ministry of Environment, Forest and Climate Change (MoEFCC) recently unveiled draft rules for India's power sector, which define strong limits on the usage of water for inland thermal power plants. This clearly shows government is putting emphasis on enhanced water use efficiency in the thermal power plants. Understanding the challenges pertaining to water-energy nexus in India is an important theme adopted by the Sustainable Growth Working Group (SGWG), a group formed within the aegis of India-US partnership. The SGWG is spearheaded by the NITI Aayog, Government of India and USAID. SGWG seeks to provide a platform for researchers to undertake cutting edge research for understanding the issues related to energy-water-food nexus in India.

With this background, the Council on Energy, Environment and Water (CEEW), supported by the NITI Aayog, has undertaken this research with a focus on exploring long term scenarios on water demands from India's electricity generation sector. The study analyses the following research objectives:

(i) To understand water consumption and withdrawals from India's power generation sector under the reference scenario.
(ii) To understand water consumption and withdrawals from India's power generation sector under scenarios of domestic policy target of 175 GW of renewable energy based installed capacity by 2022 and NDC target of 40 per cent non-fossil based generation capacity by 2030.
(iii) To understand the implications of water efficient technologies, for thermal cooling, on water consumption and withdrawals.
(iv) To recommend policy interventions based on the insights from the research.

We undertake this analysis within the modelling framework of Global Change Assessment Model (GCAM), IIM Ahmedabad version. GCAM is a global energy-agriculture-emissions model that has been widely used in climate policy analysis. Within the GCAM-IIM version applied, the world is disaggregated into 32 regions, with India as a separate region. GCAM has a detailed power sector with representation of fossil and non-fossil power generation technologies. GCAM is a state-of-the-art model and has been consistently used for IPCC related exercises, and has widely published and cited literature. GCAM output gives information on electricity production by technology, energy demand of building, transportation and industrial sectors, and GHG emissions from energy as well as land use sector. Being an integrated assessment model, GCAM also has a reduced form of climate model that informs increase in global atmospheric GHG concentrations as well as temperature increase. GCAM runs till 2100 in five-year time steps, and can model energy policies as well as climate policies like carbon markets and carbon taxes.

We model five scenarios for answering our research questions:

i. Reference scenario for electricity and economic growth rate with water conservation policy failure

ii. Reference scenario for electricity and economic growth rate with successful water conservation policy

iii. Reference scenario for economic growth rate with domestic policy target of 175 GW renewable based capacity by 2022, and a scenario with NDC based target of 40 per cent non-fossil based capacity by 2030 with successful water conservation policy

iv. Low carbon scenario with 60 per cent and 80 per cent non-fossil based capacity by 2030 and 2050, respectively with successful water conservation policy

v. Sensitivity over economic growth rate with reference electricity growth and successful water conservation policy – High GDP growth rate of 7.4 per cent average between 2015 and 2050; Low GDP growth rate of 5.8 per cent average between 2015 and 2050.

For our scenario with water policy failure, we use India specific water coefficients collected from water tariff petitions for coal and gas-based generation and from Environment Impact Assessment reports for nuclear based generation. For all other scenarios, we use the coefficients as specified as limit on water consumption in the 2015 draft power sector rules.

We compare three key types of water efficient technologies- once through cooling, cooling tower based cooling, and dry cooling – across technical and economic parameters. Dry cooling is an interesting technology that saves water, but could be expensive, by up to 20-25 per cent in terms if increase in cost of electricity generation. Literature review shows that even though the technology is fairly expensive compared to its alternatives, it is being used in some other countries where water is a challenge. In fact, China's 12 per cent of China's thermal power generation capacity is based on dry cooling. Given China's huge power generation base, this is a significant number and demonstrates that another country has used this technology in a big way to address challenges of electricity-water nexus.

We find that if the MoEFCC's mandate are not implemented in the power generation sector, then water withdrawals will significantly rise from 34 billion cubic metres (bcm) in 2015 to 145 bcm in 2050. This increase reflects the increase in power production for meeting the electricity demands of an increasing population and GDP. Water consumption also increases at a similar rate. However, if the MoEFCC's mandate for the power sector are adopted and strictly implemented, then it will lead to a significant decline of 68 per cent in water withdrawals in 2050 as compared to 2015 levels, as there will be no new plants based on the once through technology (OTC), and all the existing OTC based power plants will have to convert to the cooling tower technology (CT). Even the CT based power plants will need to adhere to stringent limits.

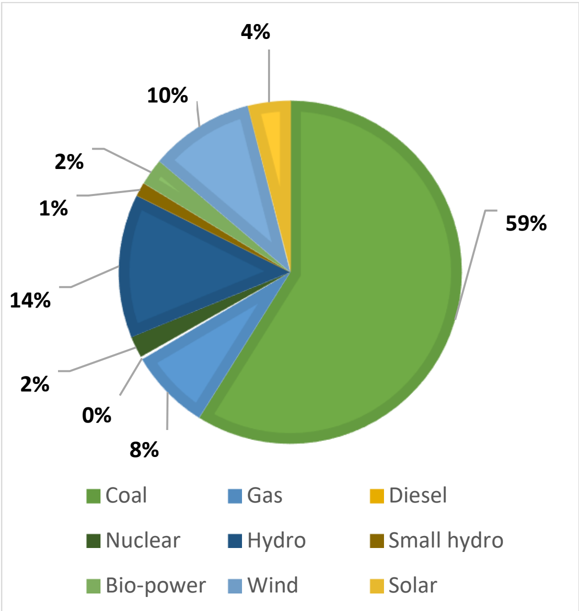
Furthermore, achieving 175 GW RE target by 2022 would reduce the water withdrawal and consumption in future, as solar and wind energy have low water footprint. Ambitious low carbon scenario of 60 per cent and 80 per cent non-fossil based capacity achievement by 2030 and 2050, respectively also helps in reducing the water use significantly due to low carbon interventions. Macro level declines in withdrawals however should not mask the increasing stress at the local level. Especially for solar energy, generation potential is highest in dry regions like Rajasthan, where water problem is most acute. Future research on the electricity-water nexus issue should delve deeper into local level stresses due to a higher share of renewable.

We highlight that if draft power sector rules are successfully implemented, water withdrawal from India's power sector will be much lower compared to business as usual scenario. Irrespective of this impact, water demand for thermal cooling will keep on increasing as the size of India's power generation sector grows. This is bound to put increasing pressure on India's water resources, especially in arid and semi-arid regions. We highlight that India might need to think about the importance of dry cooling technology for addressing the trade-offs of the electricity generation – water nexus. The extra investment required for dry cooling might be worth if the increasing pressure on water availability in arid regions for India can be exacerbated. This possibility will increasingly present itself to policy makers and stakeholders in the future.

1. Introduction

Power generation is critical for meeting the rising energy service demands in developing countries. Electricity is an important resource for improving the living standards of people through providing comfort as well as for supporting better livelihood opportunities. Global power generation in the future is expected to be dominated by thermal electricity production from non-renewable resources in absence of any dedicated policies for moving away from fossils, with coal remaining the largest source.

Figure 1: Total installed electricity generation capacity (330.15 GW) in India as on 31.07.2017



Source: Power Sector Executive Summary, April 2017. CEA, Ministry of Power, Govt. of India

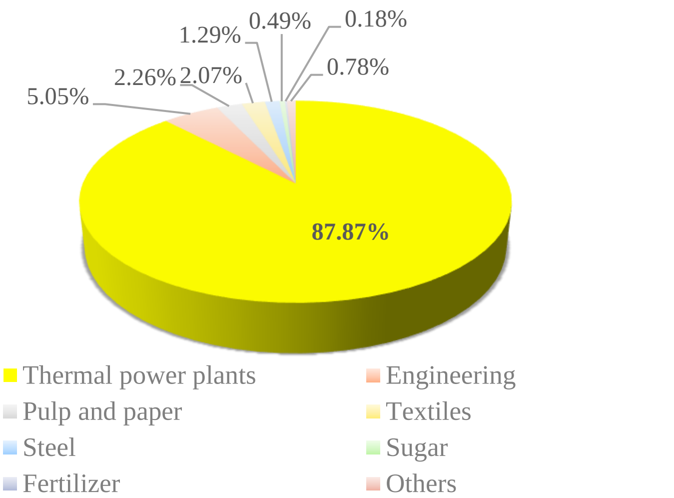
Coal is a key resource in ensuring India's energy security because it is the most abundant non-renewable energy source in India. India has the world's fifth largest proved recoverable reserves of coal (60.6 billion tonnes) (World Energy Council, 2013). 59 per cent of the current installed capacity in India is coal based (CEA, 2017). As per some earlier estimates, the country is on a track to have the fastest growing coal fleet from 2020 onwards with coal-sourced electricity demand projected to more than double by 2040 (e.g. Barnes, 2014). The energy content of locally produced Indian coal is poor, ranging from 2500 kilocalories per kilogram to 5000 kilocalories per kilogram whereas the Australian coal has an average energy content of more than 5500 kilocalories per kilogram (Penney & Cronshaw, 2015).

In addition to poor quality coal, 81 per cent the total installed capacity of thermal power plants is based on subcritical technology (CEA, 2017), though this is set to change as all the new coal power plants in India are expected to be supercritical. Therefore, a huge amount of water is required in coal processing & handling, cooling purposes, and ash handling in thermal power plants, making them water guzzlers.

Majority of thermal power plants (TPPs), including coal, gas as well as nuclear power plants, consume freshwater from dam reservoirs, rivers and canals. Some of the plants that are located near coastal regions depend on sea water. The consumptive water requirement for old thermal power plants with cooling tower is as high as around 8-9 m^3/h per MW without ash water recirculation and 5 m^3/h per MW with ash water recirculation. Recently, TPPs have been designed with consumptive water requirement in the range 3.5 - 4 m3/h per MW.

Water would definitely become a limiting factor in the growth of TPPs given the fact that many regions of the country are struggling to support essential services such as drinking water availability and irrigation. The total available water resources in India is around 4000 BCM of which only 1123 BCM i.e. 28 per cent is utilizable (Central Water Commission, 2011). Now if there is a temporal and spatial variation in monsoon, which is already being experienced, the utilizable water resources would further decline. If we see sector-wise consumption of water, irrigation consumes more than 80 per cent, with few states already extracting more ground water than the amount that is naturally replenished leading to severe fall in water levels (Central Ground Water Board, 2014). The demand from residential and industrial sector is ever increasing (industrial sector water consumption is majorly dominated by TPP, see **Figure 2**); the per capita water availability has decreased rapidly from 5200 m^3 in 1951 to 1588 m^3 in 2010 (Central Water Commission, 2011). The power sector, which accounts for the vast bulk of all water use by India's energy sector at present, remains the major source of incremental water use: it accounts for 98 per cent of additional withdrawals and 95 per cent of additional consumption during the Outlook period (International Energy Agency, 2012).

Figure 2: Industrial water consumption in India



Source: Centre for Science and Environment (2012)

Power generation sector which comes down in the order of priority of water allocation as defined by National Water Policy, 2012 will have to suffer if the water situation further deteriorates. As reported, nearly 7 billion units (kWh) of coal power, with an estimated potential revenue of 24 billion rupees were lost in the first five months of 2016 due to lack of water for cooling (Fernandes & Krishna, 2016).

This necessitates immediate action for conserving water by maximizing the water use efficiency of power plants and limiting the construction and use of the least efficient coal-fired power plants and widely adopting dry cooling or highly efficient closed-loop cooling. The latest notification issued by the Ministry of Environment, Forest and Climate Change (MoEFCC) in December 2015 mandates the existing thermal power plants to limit their specific water consumption to 3.5 m^3/h per MW by December 2017. While the plants commissioned after January 2017 should have maximum water consumption of 2.5 m^3/h per MW. These water use benchmarks shall be instrumental in achieving high WUE in thermal power generation.

If we analyse the water requirements in a TPP, various requirements are for coal handling, ash handling, production of steam, condensing the steam, maintenance of green belt, fire-fighting, and domestic purposes. Most importantly, major requirement for water is for cooling purposes and amounts to 80-90 per cent of the total water requirement, more so in the case of coal TPPs. Thus, improvement in water use efficiency of a power plant would largely depend on improvement in the cooling technology. There are three types of cooling systems:

1) **Once through cooling system (OTC):** Water is withdrawn from the source and run once through the power plant to cool down the steam. The water is then discharged back to the source a few degrees warmer. It is economical and has low water consumption but withdrawal is very high. It may also cause thermal pollution in the water body where the water is discharged.

2) **Closed cycle cooling system/cooling tower (CT):** In closed cycle cooling system, the water is not returned to the source. The hot water coming from condenser goes to cooling tower (which can be dry cooling tower or wet cooling tower) and is cooled and stored in reservoir. From the reservoir, water is again pumped to the condenser where it condenses the steam coming from turbine.

3) **Dry cooling system:** It could be direct where the steam is condensed in air cooled condenser or indirect where a cooling water is utilised to condense turbine steam in a conventional surface condenser or a contact condenser. The cooling water, which has been heated by the condensing steam, is then recirculated to an air-cooled heat exchanger before being returned to the condenser.

The choice of cooling technology has a significant impact on the power generation and the CAPEX requirement. The lesser the water withdrawal, the higher is the cost of the technology, as well as the efficiency penalty on power production. Dry cooling technology reduces the power production by 7-8 per cent, which is significant reduction. Therefore, it is essential to understand not only the implication of water efficient cooling technologies on water use reduction but also the implications of such decisions on the power production efficiency.

The Sustainable Growth Working Group (SGWG), is an India-US partnership spearheaded by the NITI Aayog in India. Energy-water-food nexus is a key theme for research under the SGWG. Four Indian modelling teams and one US modelling team have come together to explore a set of common scenarios for a better understanding of India’s electricity water nexus. CEEW, as one of the Indian modelling teams, will also be exploring scenarios for a deeper understanding of India’s electricity water nexus.

Following are the key objectives of the study:

(i) To understand water consumption and withdrawals from India’s power generation sector under the reference scenario.
(ii) To understand the implications of water efficient technologies for water consumption and withdrawals for thermal cooling.
(iii) To understand the implications of water efficient technologies for power production.
(iv) To recommend policy interventions based on the insights from the research.

The following section presents a comparison of various thermal cooling technologies in the power sector. This is followed by the section on methodology and scenarios, and then results. We then present the supply side situation in India, and finally present key conclusions of our study.

2. A Comparison of Cooling Technologies

As of 2010, 15 per cent of the world's water withdrawals were estimated to be for energy production, of which 11 per cent was consumptive in nature (IEA, 2012). Water withdrawal for thermo-electric power generation is the highest among all industries. Most of this water is used for cooling processes. These power plants boil water to generate steam which is then used to run the turbines used for generating electricity. As discussed earlier, there are three most basic types of cooling systems – once-through, wet recirculating and dry cooling. Choice of cooling systems has implications on resource intensiveness as well as has certain implications on the environment (NRDC, 2014). Given that water stress is a growing concern in many parts of the world, the choice of cooling technology, siting of thermal power plants and plant operation are major choices which policies have to take note of. In most countries, once-through and wet recirculating cooling systems continue to be a major share of cooling systems in thermal power plants, as it is evident in table 2. At this point, it is important to note that each technology has its own advantages and disadvantages in terms of water requirements (withdrawal and consumption), water quality, plant efficiency and cost.

The following table compares these trade-offs for the three cooling systems in terms of resource intensity, environmental effects, financial costs and revenue.

Table 1: Comparison of once-through, wet recirculating and dry cooling systems

	Once-through cooling	Wet-recirculating cooling	Dry cooling	Reference
Water consumption	Minor	1.82- 2.73 m^3/h/MWe	0 to <5 per cent of wet tower	(Electric Power Research Institute, 2002)
	1.48-1.94 m^3/h/MWe (sub-critical); 1.25-1.71 million m3/year (super-critical) t	1.94 m^3/h/MWe (sub-critical); 1.7 million m^3/year (super-critical)	0.22 m3/h/MWe (sub-critical); 0.22 m3/h/MWe (super-critical)	(Smart & Aspinall, 2009)
		3.08 million m^3	11.88 million m^3	(Guan & Gurgenci, 2009)
	0.37-1.19 m^3/MWh of electricity produced	1.81-4.16 m^3/MWh of electricity produced	0 m^3/MWh of electricity produced	(NRDC, 2014)

	Once-through cooling	Wet-recirculating cooling	Dry cooling	Reference
Tower blowdown	NA	337 m^3/h	0	(Zhai & Rubin, 2010)
Tower drift loss	NA	0.6 m^3/h	0	(Zhai & Rubin, 2010)
Total cooling system makeup water	NA	2.46 m^3/h	0	(Zhai & Rubin, 2010)
Tower evaporation loss	NA	1012 m^3/h	0	(Zhai & Rubin, 2010)
Water withdrawal	Around 113 m3/h/MWe	2.27-3.41 m3/h/MWe	None	(Electric Power Research Institute, 2002)
	75-189 m^3/MWh of electricity produced	1.89-4.16 m^3/MWh of electricity produced	0 m^3/MWh of electricity produced	(NRDC, 2014)
Capital cost	<<Base (only for cooling system)	Base (only for cooling system)	1.5x to 3x of Base (only for cooling system)	(Electric Power Research Institute, 2002)
		90.4 $/kW for cooling tower system; 1788 $/kW for plant (US specific number)	224.4 $/kW for cooling tower system; 1940 $/kW for plant (US specific number)	(Zhai & Rubin, 2010)
		734.2 $/kW for plant	807.6 $ – 837.0 $/kW	(Central Electricity Authority, 2012)
Plant revenue requirement (Cost of electricity)		69.1 $/MWh	73.1 $/MWh	(Zhai & Rubin, 2010)

	Once-through cooling	Wet-recirculating cooling	Dry cooling	Reference
		BASE	7-8 per cent increase from BASE	(Central Electricity Authority, 2012)
O&M cost	< BASE. Pump maintenance, condenser cooling	Highly site specific; fan/pump, power; water treatment; tower fill/condensate cleaning	Finned surface cleaning; gearbox maintenance; fan power	(Electric Power Research Institute, 2002)
Performance penalty		BASE	Highly site specific - 5 per cent to 20 per cent capacity shortfall on hot and windy days	(Electric Power Research Institute, 2002)
		While converting a 400MW OTC to Cooling tower system, 0.8 to 1.5 per cent less electricity is produced; during peak demand, 2.4-4 per cent less electricity is produced	While converting a 400MW Cooling tower system to dry cooling, 4.2 to 8.8 per cent less electricity is produced; during peak demand, 8.9 to 16 per cent less electricity is produced	(National Energy Technology Laboratory, 2011)
		BASE	7 per cent less output compared to BASE	(Central Electricity Authority, 2012)
Auxiliary Power Consumption (as a percentage of		6.5 per cent (induced draft cooling tower);	6.8 per cent (direct air cooling condensers); 6.2	(Central Electricity Authority, 2012)

	Once-through cooling	Wet-recirculating cooling	Dry cooling	Reference
gross unit output)		6 per cent (natural draft cooling tower)	per cent (indirect air cooling condensers)	
Discharge	Around 113 m3/h/MWe; thermal plume and residual chlorine issues	0.45-1.14 m3/h/MWe	None	(Electric Power Research Institute, 2002)
Drift	NA	Negligible; <0.001 per cent of circulating water flow	None	(Electric Power Research Institute, 2002)
Plume	NA	Visible plume on cold, humid days	None	(Electric Power Research Institute, 2002)
CO_2 -e intensity as generated	884 tonne/GWh (sub-critical); 750 tonne/GWh (super-critical)	884 tonne/GWh (sub-critical); 758 tonne/GWh (super-critical)	936 tonne/GWh (sub-critical); 796 tonne/GWh (super-critical)	(Smart & Aspinall, 2009)
		BASE	7 per cent more than BASE	(Central Electricity Authority, 2012)
Sent-out efficiency heat rate (HHV)	36 per cent; 10 GJ/MWh (sub-critical); 42 per cent; 8.6 GJ/MWh (sub-critical)	36 per cent; 10 GJ/MWh (sub-critical); 42 per cent; 8.6 GJ/MWh (sub-critical)	34 per cent; 10.6 GJ/MWh (sub-critical); 40 per cent; 9.0 GJ/MWh (sub-critical)	(Smart & Aspinall, 2009)
		36.1 per cent	34.6 per cent	(Zhai & Rubin, 2010)
		38 per cent	35.5 per cent	(Central Electricity Authority, 2012)

	Once-through cooling	Wet-recirculating cooling	Dry cooling	Reference
Coal consumption		310 g /(kW*h) (sub-critical); 298 g /(kW*h) (super-critical)	332 g /(kW*h) (sub-critical); 317-320 g /(kW*h) (super-critical)	(Guan & Gurgenci, 2009)
		BASE	7 per cent more than BASE	(Central Electricity Authority, 2012)
Ecological effect: Fishes killed (relative amounts)	100	5	0	(NRDC, 2014)

Evidently, choice of advanced cooling systems, like dry cooling could greatly reduce the water footprint in these industries, but not without other trade-offs like higher capital costs and lower plant efficiency (IEA, 2012; Zhang, Anadon, Mo, Zhao, & Liu, 2014). Dry cooling technology does not rely on the physics of evaporation, instead it employs either direct or indirect air-cooled steam condensers. In a direct air-cooled steam condenser, the turbine exhaust steam flows through air condenser tubes that are cooled directly by conductive heat transfer using a high flow rate of ambient air that is blown by fans across the outside surface of the tubes. Therefore, cooling water is not used in the direct air-cooled system. In an indirect air-cooled steam condenser system, a conventional water-cooled surface condenser is used to condense the steam, but an air-cooled closed heat exchanger is used to conductively transfer the heat from the water to the ambient air. As a result, there is no evaporative loss of cooling water with an indirect-air dry recirculating cooling system and both water withdrawal and consumption are minimal (Feeley, et al., 2008). To summarise, there is a trade-off between water saved, and the cost of saving water because of increased capital cost as well as energy penalty. The cost of water saving technologies can also be argued as the shadow price of water.

It is important to understand that dry-cooling technology is still at an infant stage, in terms of its technology dissemination. Thermal power plants have been known to use dry-cooling system only in situation of acute shortage of water. There are considerable number of installations around the world including in large installation. The table below outlines the status of dry cooling in four countries.

Table 2: Status of dry-cooling in various countries

Country	Electricity production from coal sources (per cent of total)	Use of dry-cooling technology	Driver for using/ Reason for not using dry cooling
South Africa (The World Bank, 2015; Chen, 2016; IEA, 2016)	93.7	Eskom, the state-owned electricity generating utility, has implemented a dry cooling policy since the 1980s. 6 out of 15 coal fired thermal power plants use this technology. Direct dry cooling is used at Matimba Power Station in the Limpopo Province. Limpopo Province is one of South Africa's richest agricultural areas but also particularly dry and unable to meet its water needs from its local supplies. Matimba Power Station is the largest direct-dry cooled station in the world, with an installed capacity of greater than 4 000MW with water consumption of around 0.1 litre per kWh of electricity distributed. Total capacity of coal fired plants run by Eskom = 37,745 MW. As of 2004, South African coal-fired generating capacity using dry cooling was about 10,500 MW, which reportedly saves about 90 million m3/of water per year (about 65 mgd) over what should have been consumed had these plants used wet cooling systems (Pather 2004). Entire fleet of Coal fired thermal power plants = 40,036 MW.	Major driver was medium to long-term water resource security.

Country	Electricity production from coal sources (per cent of total)	Use of dry-cooling technology	Driver for using/ Reason for not using dry cooling
China (Zhang, Anadon, Mo, Zhao, & Liu, 2014; Guan & Gurgenci, 2009; IEA, 2015)	75.4	Dry = 14 per cent of total thermal power capacity installed. IEA puts the number at 12 per cent. By 2020, the share of air-cooled drying systems is expected to rise to 22 per cent.	One driver for the surge in applications of dry cooling systems is the government regulation that requires all new coalfired power plants built in Northern China region to use dry cooling systems. Northern China has plenty of coal but no water for wet cooling in its coal-fired power plants.
US (Union of Concerned Scientists, 2012)	39.9	Once through = 52.4 per cent Recirculating = 40.2 per cent Cooling ponds = 9.9 per cent Dry = 0.4 per cent	
Australia (National Energy Technology Laboratory, 2011)	64.7	In Australia, dry cooling is used in two Queensland power stations (Millmerran and Kogan Creek).	Coal is projected to continue to supply more than half the total electrical generating capacity through 2035; many areas are subject to prolonged drought; groundwater use is restricted.

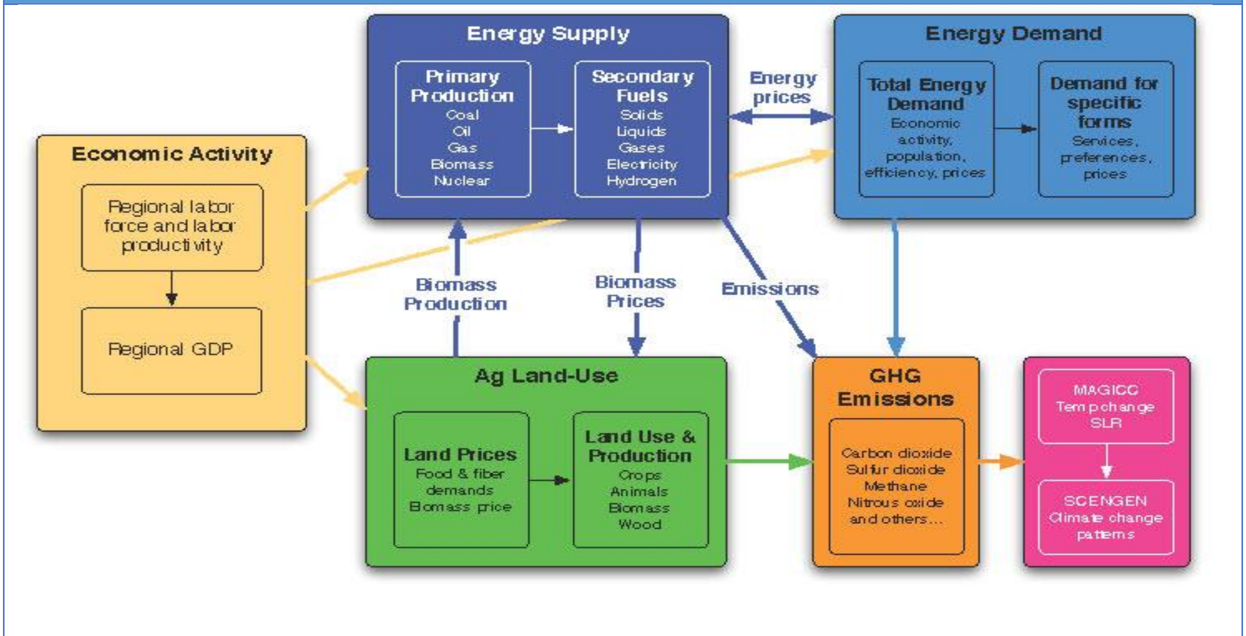
It is interesting to note that within China, 12-14 per cent of total installed power capacity is based on dry cooling technology, mainly spread in the northern region of China which is water scarce region. China has a huge power generation capacity and the share of dry cooling is bound to increase in the future. Generally speaking, dry cooling technology has been adopted across the world in very specific situations where water is extremely scarce. This forces us think that it might be possible that in extreme water scarce regions in India, there could be value in using the dry cooling technology as well.

In India, the idea of dry-cooling installations, especially in areas with acute water stress is recognised and their feasibility explored (CEA, 2012; CEA, 2014). Some small size combined cycle plants, captive power plants and industrial units have been provided with air cooled condensers. Across the country, about 1 GW of thermal installed capacity has air based thermal cooling such as Ind-Barath Power India Ltd, Odisha (2x350 MW); Ind-Barath Power India Ltd, Tamil Nadu (3X63 MW); Ind-Barath Power India Ltd Phase 1, Tamil Nadu (2X150 MW); KSK Energy, Rajasthan (135 MW); Sarda Energy, Siltara plant (81.5 MW) use air-cooled condensers in their plants (NTPC, 2015) Captive power plants in Birla White, Jaypee group, JK Laxmi, Shree Cements, Ultratech Cements industries use air-cooled condensers too (NTPC, 2015).

3. Methodology

The Global Change Assessment Model, IIM Ahmedabad version (GCAM-IIM) has been used for our analysis. GCAM is a global energy-agriculture-emissions model that has been widely used in climate policy analysis. Within GCAM-IIM, the world is disaggregated into 32 regions, with India as a separate region. GCAM has a detailed power sector with representation of fossil and non-fossil power generation technologies. GCAM is a state-of-the-art model and has been consistently used for IPCC related exercises, and has widely published and cited literature. GCAM output gives information on electricity production by technology, energy demand of building, transportation and industrial sectors, and GHG emissions from energy as well as land use sector. Being an integrated assessment model, GCAM also has a reduced form climate model that informs increase in global atmospheric GHG concentrations as well as temperature increase. GCAM runs till 2100 in five-year time steps, and can model energy policies as well as climate policies like carbon markets and carbon taxes. GCAM is also being developed to incorporate a water supply module to understand water constraints on the energy and land use systems and this capability will be very useful for this project. Additional information on GCAM can be found in Edmonds and Reilly (1983), Clarke and Edmonds (1993), Clarke *et al.* (2008), Kyle and Kim (2011), Shukla and Chaturvedi (2012), Chaturvedi and Shukla (2013), and Chaturvedi et al. (2014a, 2014b) (Chaturvedi & Shukla, Role of energy efficiency in climate change mitigation policy for India: Assessment of co-benefits and opportunities within an integrated assessment modeling framework., 2013; Chaturvedi, Clarke, Edmonds, Calvin, & Kyle, 2014; Clarke, et al., 2008; Edmonds & Reilly, 1983; Chaturvedi, Eom, Clarke, & Shukla, 2014; Kyle & Kim, 2011; Shukla & Chaturvedi, 2012; Clarke & Edmonds, 1993).

Figure 3: Global Change Assessment Model (GCAM)



Source: Joint Global Change Research Institute/ Pacific Northwest National Laboratory, USA

GCAM has been extensively used for IPCC exercises as well as global and regional energy and climate policy analysis. Detailed global energy data based on IEA statistics is already within the data structure of the model. Data on socio economic assumptions as well as water coefficients is based on desk top research. No primary data collection has been undertaken for this study. The study area is India from a macro perspective. Scenario analysis has been undertaken for analysing the research questions.

For our scenario with water policy failure, we use India specific water coefficients collected from water tariff petitions for coal and gas-based generation and from Environment Impact Assessment reports for nuclear based generation. For all other scenarios, we use the coefficients as specified as limit on water consumption in the 2015 draft power sector rules.

Table 3: Water withdrawal and consumption coefficients used in the study

Technology	Cooling technology	Water withdrawal (m^3/MWH)	Water consumption (m^3/MWH)
Coal (Conv. Pul.)	OTC	216	1.6
	CT	3.8	2.6
Refined liquids	CT	4.6	3.13
Gas	CT	1.62	1.1
Biomass	CT	4.35	2.75
Nuclear	OTC	242.7	1.5
	CT	6.42	3.8
CSP		2.67	2.67
PV		0.1	0.1
Geothermal		6.8	6.8

Source: Based on Chaturvedi et. al. (2017)

We undertake scenario analysis for answering our research questions. We model the following scenarios:

(i) Reference scenario for electricity and economic growth rate with water conservation policy failure (MedGR_RefElec_NoWP)

(ii) Reference scenario for electricity and economic growth rate with successful water conservation policy (MedGR_RefElec_WP)

(iii) Reference scenario for economic growth rate with domestic policy target of 175 GW renewable based capacity by 2022 (MedGR_NDC175_WP), and NDC based target of

40 per cent non-fossil based capacity by 2030 (MedGR_NDCNF_WP) with successful water conservation policy

(iv) Low carbon scenario with 60 per cent and 80 per cent non-fossil based capacity by 2030 and 2050, respectively with successful water conservation policy (MedGR_LC_WP);

(v) Sensitivity over economic growth rate with reference electricity growth and successful water conservation policy – High GDP growth rate of 7.4 per cent average between 2015 and 2050 (HighGR_RefElec_WP); Low GDP growth rate of 5.8 per cent average between 2015 and 2050 (LowGR_RefElec_WP).

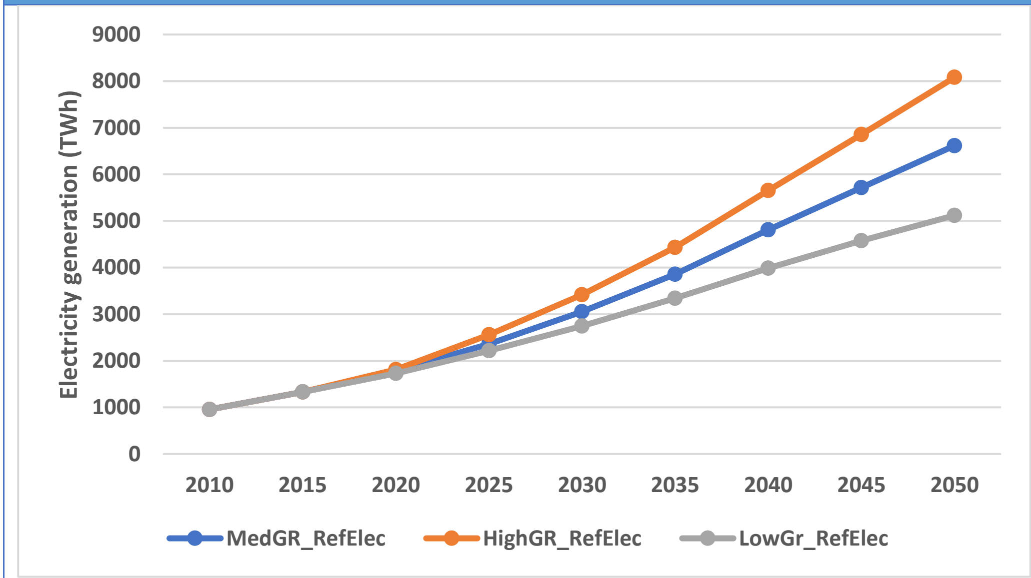
The scenario set covers sensitivity of future water demand to growth rates, success of water policy as well as its failure, and implications of India's renewable ambitions and emission mitigation policy.

4. Results

4.1 Growth of electricity generation sector

India's electricity generation will increase significantly from now onwards till the mid of this century, which will imply a much higher standard of living. India's electricity generation doubles between 2015 and 2030, and again increases by 2.17 times between 2030 and 2050. This means that per capita electricity consumption will be 3988 kWh in 2050. Though this is a significant increase compared to electricity consumption level of below 1100 kWh as of now, still this is much lower than the levels enjoyed by developed countries at 7000-8000 kWh/capita. Increase in electricity consumption owes to the fact that urbanization rate would increase from 35 per cent in 2015 to 51 per cent in 2050. Rapid urbanization and modernization lead to a widespread requirement of better electricity access, hence under high economic growth scenario of average 7.4 per cent between 2015 and 2050, the per capita electricity consumption would rise to 2260 kWh and 4870 kWh in 2030 and 2050, respectively. A wealthier and urbanised society means higher ownership of air-conditioners and other electricity consuming appliances in the residential sector, as well as higher industrial growth resulting in increased electricity consumption in this sector. Growth in economy would significantly impact the electricity generation as well consumption, in a manner that electricity generation would increase to more than two and a half times in 2030 as compared to 2015 level in high GDP growth rate, whereas electricity generation sector would merely see a rise of two folds from 2015 to 2030 and then 1.9 times growth from 2030 to 2050 in a low economic growth rate situation.

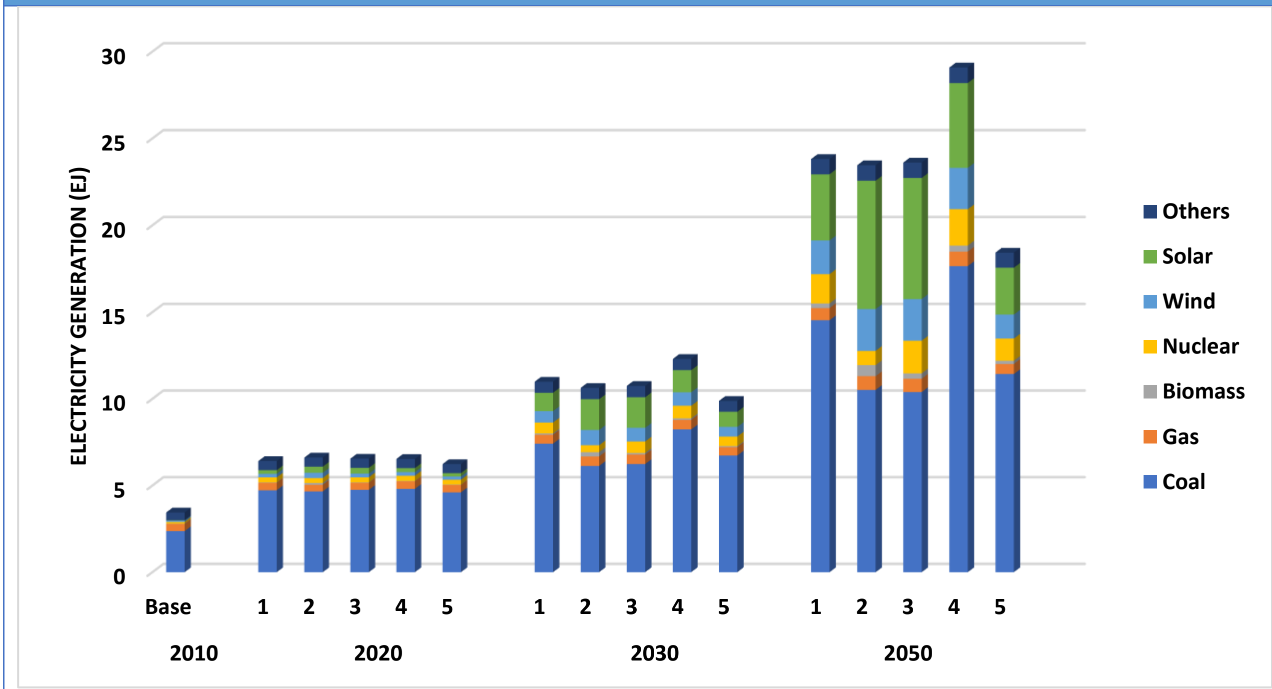
Figure 4: Impact of GDP sensitivity over electricity generation (utility and captive)



Source: CEEW analysis (2018)

India's domestic policy target is to achieve 100 GW of solar energy and 60 GW of wind energy by 2022. The international commitment under the Paris Agreement is 40 per cent share of non-fossil capacity by 2030. We find that in our reference scenario itself (MedGr_RefSc), the share of non-fossil capacity crosses 40 per cent by 2030. Hence, we don't need to model the NDC scenario separately. However, we don't see the domestic policy targets for 2022 being achieved without any dedicated policy push, so we model and present the result of this scenario.

Figure 5: Electricity generation mix across scenarios



Scenario description:

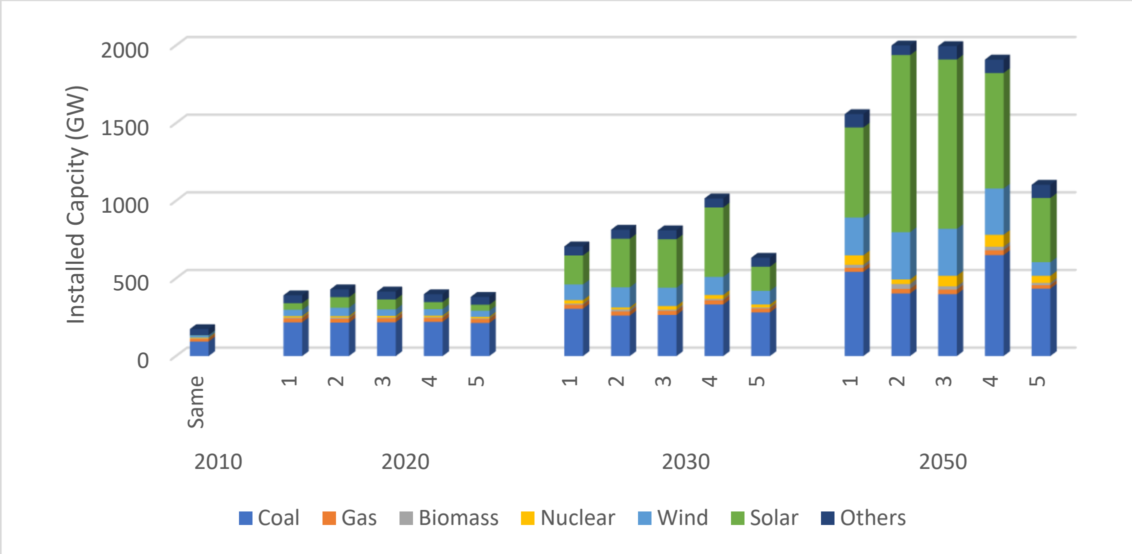
1. **Medium GDP growth rate with reference electricity growth (MedGR_RefElec)**
2. **Medium GDP growth rate with INDC target and 175 GW doemstic policy target (MedGR_INDC_175)**
3. **Medium GDP growth rate with low carbon (MedGR_LC)**
4. **High GDP growth rate with reference electricity growth (HighGR_RefElec)**
5. **Low GDP growth rate with reference electricity growth (LowGR_RefElec)**

Source: **CEEW analysis**

With regard to the Paris agreement, India has submitted its NDC and electricity sector has a major role in that. For electricity sector, one of the NDC targets is to achieve 40 per cent non-fossil-based capacity share in 2030. The domestic policy aims to achieve a 175 GW renewable energy-based capacity by 2022, which includes 100 GW of solar, 60 GW of wind, 10 GW of biomass and 5 GW of small hydro. Our analysis takes into account achieving such target in order to know its implication on water use in future. With the reference scenario, solar sector would see 66 GW of grid connected PV capacity and

50 GW of wind capacity by 2022. Whereas, by giving a push to renewable through government subsidies mainly, we see accelerated adoption of renewable energy in the long run.

Figure 6: Installed power capacity across scenarios



Scenario description:

1. **Medium GDP growth rate with reference electricity growth (MedGR_RefElec)**
2. **Medium GDP growth rate with INDC target and 175 GW doemstic policy target (MedGR_INDC_175)**
3. **Medium GDP growth rate with low carbon (MedGR_LC)**
4. **High GDP growth rate with reference electricity growth (HighGR_RefElec)**
5. **Low GDP growth rate with reference electricity growth (LowGR_RefElec)**

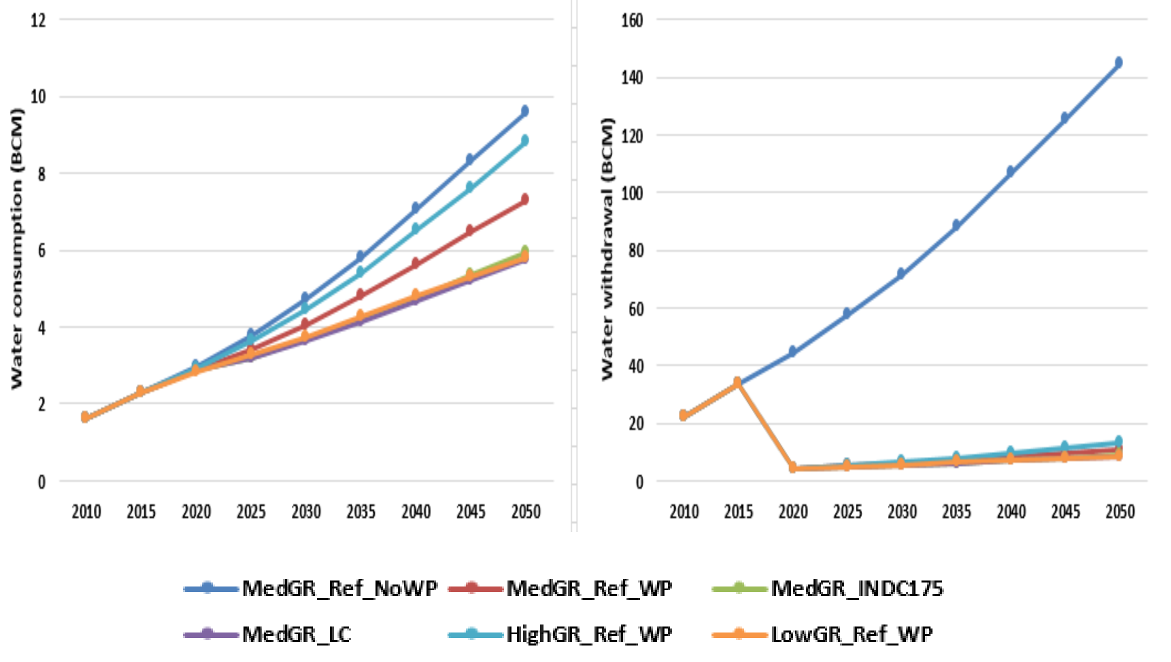
***Source:* CEEW analysis (2018)**

The low carbon scenario (MedGR_LC) envisages a world where there is deep decarbonisation and all countries move toward the 2 Degree Celsius target. As compared to NDC scenario of 40 per cent non-fossil target, MedGR_LC is a kind of scenario where we will achieve a greater level of decarbonisation with 519 GW and 1569 GW of non-fossil based capacity in 2030 and 2050, respectively. This implies that there will be a shift away from fossil energy dominated electricity system in India. There are some interesting things that are happening under this scenario. First, the electricity system moves away from being fossil intensive to being renewable energy intensive. The share of coal based electricity declines from over 61 per cent in 2015 to 19 per cent in 2050. Second, non-fossil sources such as nuclear, solar, wind, hydro and biomass; would cater the power demand of the country. As the economy starts putting a price on carbon, the relative price of electricity production using coal increases, making zero carbon sources (renewable and nuclear energy) more competitive, leading to an increased share in the generation mix. Our scenario achieves a 60 per cent non-fossil energy share in 2030 and 80 per cent share in 2050 in electricity generation capacity.

4.2 India's thermal water consumption and withdrawal in the long term

The increasing electricity generation will also mean increased pressure on India's water resources. The Ministry of Environment, Forest and Climate Change (MoEFCC) has come up with the rules for the power sector, which mandates that all power plants have to switch their once-through cooling system into recirculating cooling technology, which is an efficient cooling technology and limit the water consumption from India's power plants. Reference scenario without water policy analyses the question that what will be India's water consumption and withdrawals if the power sector rules are not strictly followed by the power plants. In this case, we assume that the share of inland thermal power plants based on once through cooling (OTC) will be the same (16 per cent) as it exists in 2016-17. Such non-compliance would result into four and a half times more water withdrawal from freshwater based systems in 2050 as compared to 2015 levels, this means that there will be immense pressure on India's water resources, especially in areas that are already reeling under water supply. When water conservation policy implementation fails, withdrawals are huge because of 16 per cent of TPPs are based on once through cooling. It is interesting to note that even if the share of OTC technology is small, it is still dominating the overall water withdrawals from inland TPPs. Whereas, compliance will lead to rapid fall in water withdrawal from 34 billion cubic metre (bcm) in 2015 to 4.2 bcm in 2020, and then it will rise to 10.7 bcm till the mid of this century.

Figure 7: Long- term water use for electricity generation



Source: **CEEW analysis (2018)**

There is some interesting dynamics that need to be highlighted- when older plants move from OTC to CT technology, there is an increase in water consumption. The consumption coefficient of CT technology is higher as compared to the OTC technology. But all the new power plants, have to adhere to the new rules, and the consumption limit proposed by these rules are more stringent compared to what the power plants are consuming right now. Hence, the consumption of all new power plants that have to adhere to the rules will be lower compared to the reference scenario when existing coefficients are in place. The total consumption under the water efficient technology scenario increases from 2.3 bcm in 2015 to 7.3 bcm in 2050. The ratio of water consumed to water withdrawn in 2050 is 68 per cent.

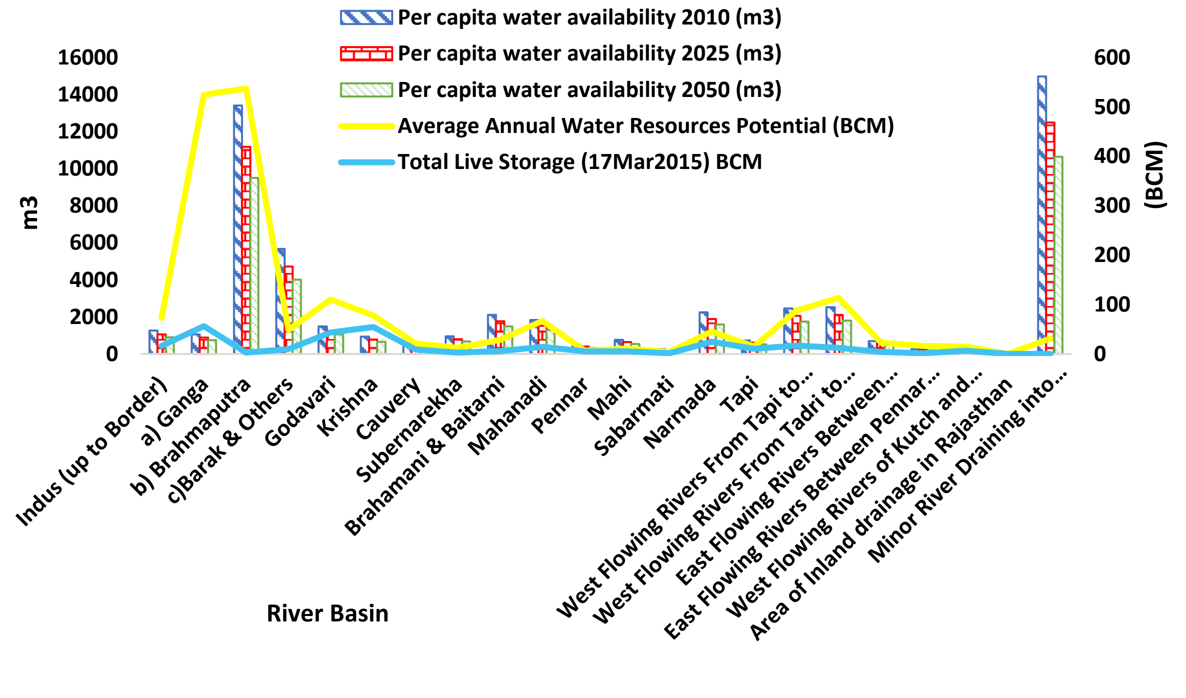
Relative to the MedGr_Ref_WP scenario, water consumption in the MedGr_LC scenario declines by 12 per cent in 2030 and 26 per cent in 2050. This is a very interesting finding as it shows that water consumption will be declining with increasing share of low carbon technologies in the generation mix. Same is the case for water withdrawals. There are two reasons behind this decline; first, there is a higher share of wind and solar energy. Both these sources need very low water as these are not thermal cooling technologies. Second, the share of nuclear energy also increases, and water consumption per unit for thermal cooling of nuclear energy is greater than that of coal or gas based power plants. But the decline in coal consumption is too large to be compensated by nuclear energy. Overall, water savings appears to be an important co-benefit of moving India's electricity generation towards a low carbon world. This macro level number might mask the increasing stress at the local level. Water is a local issue, and even if at the macro level water demand might decline, it might still increase in water stressed pockets and policy needs to anticipate and respond to the local level water challenges.

With high economic growth rate of 7.4 per cent average CAGR between 2015 and 2050, increased power consumption will raise the water consumption to the highest level amongst all scenario. This will further put stress over already scarce water resources in the country. Under the reference scenario, consumption is estimated to be 4 bcm and 7.3 bcm in 2030 and 2050, respectively but with high economic growth this would further rise by 10 per cent and 21 per cent in 2030 and 2050, respectively. A recent study presents water coefficients that are on an average higher than the coefficients used by us for wet closed loop systems. Our average coefficients for wet closed loop cooling system are based on a larger dataset as compared to TERI (2017), and hence we have used these. Same is the story with withdrawals where the rise is 10 per cent in 2030 as compared to reference scenario. If the economic growth rate of the country slows down with 5.8 per cent as an average CAGR between 2015 and 2050, then this would have major impact on electricity generation and associated water use. Water consumption for relatively low growth in future would lead to two-and-a-half-fold rise as compared to 2015 levels, whereas a higher growth situation would lead to approximately four folds rise.

5. The Water Supply Scenario

India receives an average annual rainfall of around 1170 mm but there is huge regional and temporal variation in the distribution of rainfall (PIB, 2013). The country receives more than 80 per cent of the rainfall within June to September. The unequal spatial distribution could be easily observed by the fact that Brahmaputra and Barak basin, with only 7.3 per cent of the geographical area and 4.2 per cent of the country's population, have 31 per cent of the annual water resources (CPCB, 2014). Further the utilizable water resources are only 28 per cent (1123 BCM) of the total available water resources in India (4000 BCM). Figure 7 below highlights the total and per capita water availability basin wise in the country. Water storage structures forms an important component of water management system for any nation. They provide buffering against drought and floods, in addition to other benefits such as fisheries, hydro-electricity etc. The live storage capacity of dams in India is around 253 BCM (with additional 50 BCM of reservoir work under construction), which is only 13 per cent of the average annual flow as could be seen in figure 6 below (CWC, 2015). Thus per capita water storage in India is quite low (209 m^3), as compared to countries such as Australia (3223 m^3) and USA (2192 m^3) (PIB, 2012).

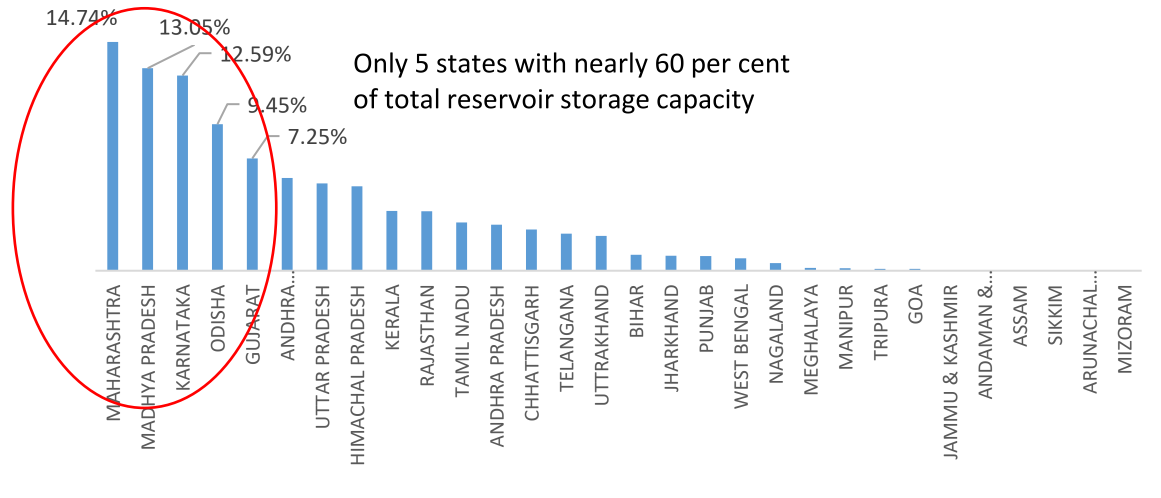
Figure 8: Basin wise water availability details



Source: Central Water Commission, GoI, 2015

Groundwater which is currently the lifeline of India, as it supports more than 60 per cent irrigation and 85 per cent drinking water requirements in rural areas, is depleting at an unprecedented rate (World Bank, 2010). Out of the annual renewable GW resources of 433 BCM current estimated draft in India is around 250 BCM (63 per cent). In north western states of Punjab, Haryana, Delhi, Western Uttar Pradesh replenishable GW resources is high but due to over extraction the groundwater draft has crossed the annual GW recharge. Overall, India in real sense is mining groundwater and is way ahead, in terms of total groundwater withdrawal, of various countries (Fig 8). The storage capacity is not only low but unequally distributed across the country. As could be seen in the figure 8 below, only 5 states namely Maharashtra, Madhya Pradesh, Karnataka, Odisha and Gujarat have more than 60 per cent of the country's reservoir storage capacity (Fig 8).

Figure 9: State wise distribution of India's Live Storage Capacity of Reservoirs (2015)



Source: Adapted from CWC data of 2015

Interestingly, in terms of the importance of basins, the Ganga basin is by far the basin arguably of the highest importance as 43 per cent of India's population is dependent on this basin directly or indirectly (CWC, 2015). This is also one of geographical regions in India with the highest population density and hence immense pressure on the water resources for competing demands. The per capita water availability is hence very low in this basin. The basin next to Ganga basin is the Krishna basin, which has 7 per cent of the total population dependent on it. In terms of the importance for regional dynamics, all the river basins are equally important for their respective regions. At the national level, however, it is the Ganga basin that appears to be the most importance in terms of the national economy and livelihood of Indians dependent on it.

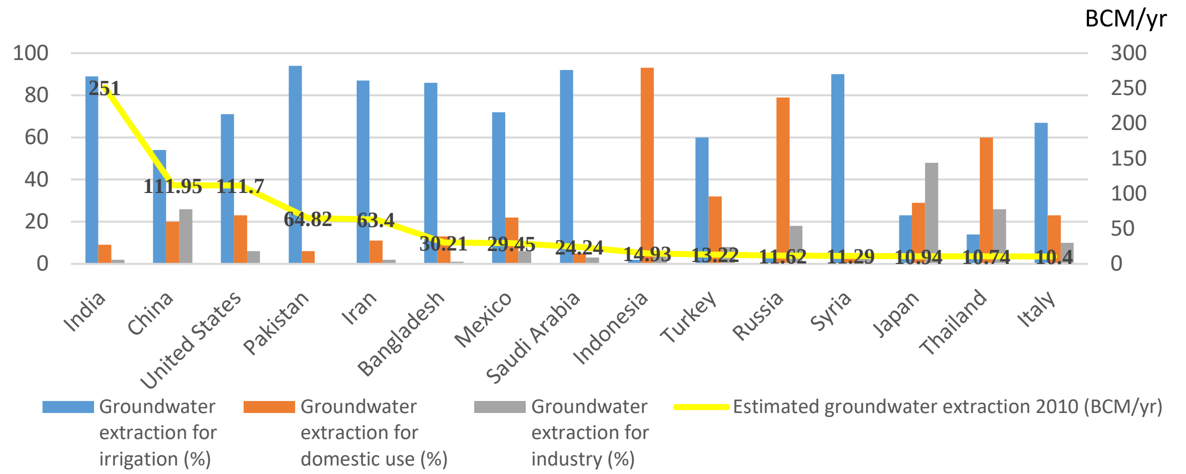
Decreasing rainfall, increasing rainfall variability, low storage capacity, inefficient utilisation, high level of GW extraction and pollution ultimately makes India more vulnerable to climate extremes. A data released by Central Water Commission in April, 2016 shows that this year most of the reservoir have lower levels that the last 10 years' average.

Researchers at Stanford University analysed 60 years (1951-2011) of Indian Monsoonal trends (Singh, Tsiang, Rajaratnam, & Diffenbaugh, 2014). They found, through a comprehensive statistical analysis of precipitation, that: (i) peak-season precipitation has decreased over the core monsoon region and daily-scale precipitation variability has increased; (ii) frequency of dry spells and the intensity of wet spells has increased; (iii) 1981-2011 had more than twice as many years with 3 or more dry spells as compared to 1951-1980, and the dry spell frequency shows an increase by 27 per cent.

While climate change impacts such as variations in rainfall pattern is a serious issue, the increasing pollution levels of water bodies has further decreased the usability of available water resources.

Vanishing wetlands and small ponds and tanks are definitely adding to the overall water supply problems in India.

Figure 10: Top 15 nations with the largest estimated annual groundwater extractions (2010)



Source: Adapted from National Ground Water Association data (2016)

In 2010, India remained one of the countries of the top 15 nations with the largest estimated annual groundwater extractions. The largest groundwater extraction accounted for irrigation, then for domestic use and remainder supplied to industrial sector. Whereas in countries like Indonesia, Russia and Thailand, the first priority of groundwater extraction is domestic use. Thus, to augment the supply wastewater reuse and recycling, reducing pollution, and rain water harvesting should be encouraged across the country without further delay.

6. Conclusion and Way Forward

Water is a critical resource for India and year on year the pressure on water resources is only increasing. Though agriculture is the largest consumer for water resources in India, power plants are increasingly demanding more and more water. With India's power sector set to expand by many-folds in the future, it is critical to understand the scale of water demands from this sector, and the strategies for minimising the same. We expect this electricity-water nexus issue to become increasingly important in the future, and understanding this issue in a deeper way has been the motivation of our study.

For answering this broader question, we undertake scenario analysis to find out the extent of potential increase in India's power sector related water demand for up to 2050. We do this for scenarios when the draft power sector rules on water consumption of power plants are successfully implemented, or when the implementation is not successful. Along with these, we also find water demand for meeting the 2022 target of renewable energy penetration in the grid, and a scenario with deeper emission mitigation target.

Importance of draft rules for limiting water demand from Indian power plants

Our analysis highlights that in absence of the draft power sector rules for limiting power generation associated water withdrawals, India's water demand from this sector is bound to grow many folds, pushing many areas into increasing water scarcity. The draft rules by the Government of India are a welcome move and should be implemented as envisaged.

Implication of India's domestic renewable energy policies, nationally determined contributions (NDC), and a low-carbon pathway

The low carbon scenario tested in this report is commensurate to the 2-degree scenario, which means that deep decarbonisation will have to start 2020 onwards. We find that a move towards low carbon scenario will lead to significant decline in water withdrawal and consumption at the macro level relative to the reference scenario. This is because both solar and wind have very low water demand for cooling, and also because the total electricity generation declines with electricity being costlier. The (I)NDCs, as submitted by India (as well as other countries), however will not lead to a 2-degree scenario as many studies have highlighted. Significant additional decarbonisation needs to be undertaken for moving from the INDCs towards the 2-degree pathway. Though many elements of a 2-degree scenario, like higher share of nuclear energy and solar energy, will be reflected in the INDC scenario as well. India's domestic renewable energy target of 175 GW by 2022 also has a significant focus on solar and wind energy, and if these replace coal, then there will be significant benefit in terms of water consumption.

Implications of water-cooling technologies

For a country, scarce with water resources, saving each drop of water matters. Within India, agriculture is the biggest consumer of water and could be expected to remain so in the foreseeable future. However, the marginal pressure that India's power plants are expected to generate within local areas could be enough to warrant the focus on water efficient technologies for thermal power plants. The draft power sector rules will lead to a significant decline in the withdrawals of water for cooling thermal power plants, as well as small increase in the water consumption. India will greatly benefit from the move from once through cooling technology towards cooling tower based cooling systems. For extreme water stress scenarios, dry cooling could also become a reality. There is additional expense to move from OTC technology to CT technology, and further to dry cooling technology. This additional expense could be argued as the shadow price of scarce water. There is a trade-off between the cost of water technology and the water that could be saved, and policy makers have to balance these trade-offs.

Implications for future research

The focus of our research has been at the macro level, and we derive some important insights based on our research. Water is however a local issue, and the nexus issue should be further explored at the local level. Solar PV based electricity will reduce water consumption at the macro level as its water coefficient is very low as compared to coal-based electricity. But its highest potential is in arid regions like the desert region of western India where water is the biggest challenge. Managing these local level trade-offs should be the focus of next set of research on the nexus issue. Geo-spatial mapping of power plants will reveal some useful information in this regard and can be employed as a useful methodology.

References

Barnes, I. (2014). *Upgrading the efficiency of the world's coal fleet to reduce CO2 emissions.* London: IEA Clean Coal Centre.

CEA, Ministry of Power, Govt. of India. (2017). *Executive Summary Power Sector.* New Delhi: GoI.

Central Electricity Authority. (2012). *Report on minimisation of water requirement in coal based thermal power stations.* New Delhi: CEA.

Central Electricity Authority. (2014). *Recommnedations on operation norms for themal power stations: Tariff period 2014-19.* New Delhi: CEA.

Central Ground Water Board. (2014). *Dynamic Ground Water Resources of India, 2011.* Faridabad: CGWB, MoWR, GoI.

Central Water Commission. (2011). *Water Resources at a Glance.* New Delhi: CWC. MoWR, GoI.

Chaturvedi, V., & Shukla, P. (2013). Role of energy efficiency in climate change mitigation policy for India: Assessment of co-benefits and opportunities within an integrated assessment modeling framework. *Climatic Change , 123 (3-4),* , 597-609.

Chaturvedi, V., Clarke, L., Edmonds, J., Calvin, K., & Kyle, P. (2014). Electricity generation investment for emission mitigation: How much more do we need? . *Energy Economics , 46*, 267-278.

Chaturvedi, V., Eom, J., Clarke, L., & Shukla, P. R. (2014). Long term building energy demand for India: Disaggregating end use energy services in an integrated assessment modeling framework. *Energy Policy , 64*, 226-242.

Chen, D. H. (2016). *Sustainable Water Management Volume I.* CRC Press.

Choudhury, N. (2011). From Sectoral to Water-Food-Energy Nexus based Planning: An Emerging Country Context. *Young Scientists Reports.* Bonn: "The Water Energy and Food Security Nexus – Solutions for the Green Economy", organized by the Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU) and the Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung (BMZ), .

Clarke, J., & Edmonds, J. (1993). Modeling energy technologies in a competitive market. *Energy Economics 15, 15*, 123-129.

Clarke, L., Kyle, P., Wise, M., Calvin, K., Edmonds, J., Kim, S., . . . Smith, S. (2008). *CO2 Emission Mitigation and Technological Advance: An Updated Analysis of Advance Technology Scenarios. Pacific Northwest National Laboratory Technical Repo.* Richland, WA, USA.: PNNL-18075; U.S. Department of Energy.

CPCB. (2014). *Status of water quality in India.* New Delhi: CPCB, MoEFCC.

CWC. (2015). *Water and related statistics.* New Delhi: MoWR, GoI.

Edmonds, J., & Reilly, J. (1983). A long-term global energy-economic model of carbon dioxide release from fossil fuel use. . *Energy Economics , 5*.

Electric Power Research Institute. (2002). *Comparision of Alternate Cooling Technologies for California Power Plants: Economic, Environmental and Other Tradeoffs.* EPRI.

Feeley, T. J., Skone, T. J., Stiegel, G. J., Mcnemar, A., Nemeth, M., Schimmoller, B., & Manfredo, L. (2008). A critical resource in the thermoelectric power industry. *Energy, 33*, 1-11.

Fernandes, A., & Krishna, J. R. (2016). *Water shortages threaten coal company revenues.* Bengaluru: Greenpeace India Society.

Guan, Z., & Gurgenci, H. (2009). Dry Cooling Technology in Chinese Thermal Power Plants Cooling Technology in Thermal Power Wet / Dry Cooling Towers. Australian Geothermal Energy Conference.

IEA. (2012). Water for energy: Is energy becoming a thristier resource? In IEA, *World Energy Oulook 2012* (pp. 501-530). IEA.

IEA. (2015). China Energy Outlook. In *World Energy outlook.* Retrieved from http://www.worldenergyoutlook.org/media/weowebsite/2015/WEO2015_Ch08_ChinaWater.pdf

IEA. (2016). *South Africa: Coal and Energy Security.* IEA.

International Energy Agency. (2012). *World Energy Outlook.* International Energy Agency.

Kyle, P., & Kim, S. (2011). Long Term Implications Of Alternative Light-duty Vehicle Technologies For Global Greenhouse Gas Emissions And Primary Energy Demands. *Energy Policy , 39*, 3012-3024.

National Energy Technology Laboratory. (2011). *Reducing fresh water consumption at coal-fired plants: Approaches outside United States.* NETL.

NRDC. (2014). *Power plant cooling and associated impacts: The need to modernize US power plants and protect our water resources and aquatic ecosystems.* NRDC.

NTPC. (2015). Air cooled condensers. Retrieved from http://www.slideshare.net/ravi0704/air-cooled-condensers

Penney, K., & Cronshaw, I. (2015). *Coal in India 2015.* Canberra: Department of Industry and Science, Australian Government.

PIB. (2012, May 14). Water Storage Capacity. *Press Informaiton Bureau*.

PIB. (2013, August 19). Rainwater harvesting. *PIB*.

Shukla, P., & Chaturvedi, V. (2012). Low carbon and clean energy scenarios for India: Analysis of targets approach. . *Energy Economics , 34*, S487-S495.

Singh, D., Tsiang, M., Rajaratnam, B., & Diffenbaugh, N. S. (2014). Observed changes in extreme wet and dry spells during the South Asian summer monsoon season. *Nature Climate Change, 4*(6), 456–461.

Smart, A., & Aspinall, A. (2009). *Water and the electricity generation industry Implications of use.*

TERI. (2017). *Study of Assessment of Water Foot Prints of India's Long-Term Energy Scenarios* . TERI [Project Report No. 2015WM07], Prepared for NITI Aayog.

The World Bank. (2015). *Direct dry cooling in the power sector.* The World Bank. Retrieved from https://www.waterscarcitysolutions.org/wp-content/uploads/2015/07/Direct-dry-cooling-in-the-power-sector-Matimba-South-Africa.pdf

Union of Concerned Scientists. (2012). *The UCS EW3 Energy-Water Database*. Retrieved from http://www.ucsusa.org/clean-energy/energy-water-use/ucs-power-plant-database#.WIg1cRt97IU

World Bank. (2010). *Deep Wells and Prudence: Towards Pragmatic Action for Addressing Groundwater Overexploitation in India.* Washington D.C.: World Bank.

World Energy Council. (2013). *World Energy Resources 2013 Survey.* London: WEC.

Zhai, H., & Rubin, E. S. (2010). Performance and cost of wet and dry cooling systems for pulverized coal power plants with and without carbon capture and storage. *Energy Policy, 38*(10), 5653–5660.

Zhang, C., Anadon, L. D., Mo, H., Zhao, Z., & Liu, Z. (2014). Water-Carbon Trade-off in China's Coal Power Industry Water − Carbon Trade-off in China's Coal Power Industry. *Environmental Science and Technology, 48*, 11082-11089.

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