Impact of Power Sector Growth on Water Resources

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CENTER FOR STUDY OF SCIENCE, TECHNOLOGY & POLICY

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Executive Summary

India's power generation has been increasing at an impressive rate over the last few decades. This is likely to continue in the coming years. India's climate policy and low-carbon policy ambition are also a driver for power supply planning in the country. However, water consumption and dependence of the power sector on water resources is a cause for growing concern. Several water-intensive cooling technologies are still in-use and fossil fuel-based power has a higher direct water footprint than renewable power. Studies in the past suggested that the power sector accounts for a majority of industrial water consumption. In this context, this study by CSTEP assesses the impact of power sector growth on water resources during the modelling horizon 2010–50.

This modelling exercise analysed the power sector's water footprint using an energy-system model. Peer-reviewed literature was used to estimate the water intensities and cooling technology shares in different power plants. Policy targets and regulatory changes informed varying penetration of cooling technologies and consideration for use in the Indian context. We developed a reference scenario to account for the effects of the proposed power sector targets and water regulations on the future water demand.

This study found that water withdrawals by the power sector would grow at around 3.8%—by nearly five times of 2010 levels—to about 276 billion cubic meters (BCM) by 2050. Currently, water standards have been specified only for coal thermal power plants (TPPs). Without any additional water standards or regulations, water consumption will increase to nearly seven times of 2010 levels, which is around 14 BCM by 2050. Coal power plants will account for the largest share of water withdrawals and consumption despite having switched over to recirculating (water-efficient) cooling tower technologies. This is because despite over achieving high renewable energy installed capacity, coal-based generation is projected to dominate the power sector unless future policies target deep decarbonisation strategies in power generation.

Table of Contents

List of Figures

List of Tables

1. Introduction

India is one of the most water-stressed nations in the world. Fifty-four percent of India's total area faces high or extremely high water stress and the country is close to being categorised as a "water scarce" country (Shiao et al., 2015). According to a World Resources Institute study, India's baseline water stress scored 3.6 out of 5.0 in 2010, which indicates a high ratio of total annual water withdrawals to total annual available renewable supply (Gassert et al., 2013). India relies heavily on groundwater and 54% of India's groundwater wells face falling water tables.

Continued economic development will lead to increasing demands for water—for agriculture, electricity, industry and households—putting pressure on local and national planners to develop long-term and forward-looking solutions. Climate change could substantially alter the timing, quantity and location of runoff[1], including changes to monsoon patterns; climate change mitigation will alter the demands for water through, for example, changes in the electricity mix, reducing energy demand through energy efficiency, or the production of bioenergy.

India is the fifth largest electricity producer in the world, but nearly 288 million Indians still have no access to the electricity grid (IEA, 2011; WWAP, 2014). The Indian government aims to substantially increase energy access for millions of Indians and improve the quality of electricity supply for those already with access. The Indian government has started the Power for All campaign to achieve electrification of all villages in India, by the end of 2019. Projections from the International Energy Agency (IEA) indicate that India could add about 600 million new electricity consumers by 2040 and that electricity demand might grow by 5% per year (OECD/IEA, 2015).

Expanding electricity production could exacerbate India's potential water scarcity. Given the limits to water availability, satisfying agricultural and other needs could result in the curtailment of electric power plants and associated blackouts or brownouts. Conversely, increasing water demands for electricity could have repercussions for agriculture and households. Further, like several water-scarce countries, where conventional water resources are inadequate to meet demands, several regions in India are increasingly relying on pumped groundwater for municipal and agricultural needs (Amarsinghe, Shah, Turral, & Anand, 2007). A failure to plan adequately for the long term could lock-in approaches to water management, agriculture and electricity that could prove limiting for decades to come.

India declared a voluntary goal of reducing the emissions intensity of its GDP by 30–35%, over 2005 levels, by 2030 (GOI, 2015b). The power sector contributes 51% of CO_2 emissions and about 38% of greenhouse gas (GHG) equivalent in India as of 2010. Policies to "decarbonise" electricity generation could help constrain future water demands, but the effect will depend on the approach to decarbonisation (GOI, 2015a). On April 22, 2016, India, along with 174 member countries of the United Nations, signed the Paris Agreement to reduce GHG emissions across the globe. India ratified the Paris Agreement on October 2, 2016 and the agreement entered into force on November 4, 2016. Reducing specific CO_2

[1] Runoff is water from rain, snow melting and other sources that flows over the land surface and a major component of the water cycle.

emissions, from electricity generation, is critical for achieving a reduction in emissions intensity. As part of that agreement, all countries will need to make major changes in the way they produce electricity, moving from freely emitting coal and gas generation to increased use of some combination of renewable power (such as wind, solar and hydroelectric power), nuclear power and coal or natural gas with Ultra Super Critical technology or Carbon Dioxide Capture and Storage (CCS). These different options will have very different implications for water demands by the electricity sector. Solar Photo Voltaic (PV) and wind for example, require no water for cooling albeit some water for cleaning, whereas nuclear power and coal or gas (with CCS) are still TPPs with the need for cooling water. Evaporative losses from reservoirs for hydroelectric power can be substantial.

At the same time, the challenge of growing water demand, for electricity production, is increasingly being realised by policy makers in India, as reflected in the Government of India (GoI) rules to minimise water consumption in in-land power plants. This study explored the implications of growing electricity demand, efforts to reduce CO_2 emissions from the electricity sector and power plant cooling technology regulations on water resources.

1.1 Objectives

The objectives of this study were as follows:

- Provide a synthesis of available literature and data on the current and projected status of the power sector by 2050
- Present an overview of changes in policies and technology trends, in water use, in India's power sector
- Identify reasonable water coefficients after reviewing literature and datasets developed in other countries
- Develop and model a reasonable power sector reference scenario to account for announced policies
- Estimate the reliance of the power sector on fresh water and sea water using the Integrated MARKAL-EFOM system (TIMES) model (a system optimisation model) by 2047
- Explore the role of cooling technologies and renewable energy technologies on limiting the impact on water resources.

2. Literature Review

2.1 Power Sector Outlook

India is increasing electricity production at a very impressive rate with coal playing the most important role. India increased its electricity production from 120 Terra Watt-hours (TWh) in 1980 to 293 TWh in 1990 and 932 TWh in 2010. Coal has been playing an increasingly important role in electricity generation: coal power plants produced 51% electricity in 1980, but their share increased to 65% of electricity generation in 2010 and to 75% in 2014 (IEA, 2015). India's Central Electricity Authority (CEA) assessed that the long-term electrical energy requirement could increase to 3,710 TWh by the end of the 15th five year plan (2031-32) (CEA, 2013).

It is likely that India's electricity demands will continue to grow over the coming decades as the economy grows and more Indians gain access to electricity. As per the National Electricity Plan (Draft Report) 2016, no additional coal-based capacity is required during the years 2017–22, with committed capacity of Hydro (15330 MW), Gas (4340 MW) and Nuclear (2,800 MW). Various Renewable Energy Sources (RES) capacity addition scenarios are also evaluated (sceanrios where installed capacity of RES reaches 1,75,000 MW, 1,50,000 MW and 1,25,000MW by year 2022). However, a coal-based capacity addition of 50,025 MW is already under construction and is likely to be commissioned during 2017–22. Further CSTEP's earlier work has also found that by 2030, India's Nationally Determined Contribution (NDC) target of installing 40% fossil free power generation capacity target is realisable considering technical resource potential and costs (Byravan, et al., 2017).

2.2 Water Footprint (Definitions and Considerations)

Water footprint is an indicator of fresh water use that looks at both direct water use of a consumer or producer, but also at the indirect water use. It can be regarded as a comprehensive indicator of fresh water resources appropriation, next to the traditional and restricted measure of water withdrawal. The idea of evaluating water use along supply chains to assess the actual impact on fresh water systems gained interest after the introduction of the 'water footprint' concept by Hoekstra in 2002. Water footprint 'assessment' refers to the full range of activities to: (i) quantify and locate the water footprint of a process, product, producer or consumer or to quantify in space and time the water footprint in a specified geographic area; (ii) assess the environmental, social and economic sustainability of this water footprint; and (iii) formulate a response strategy. Broadly speaking, the goal of assessing water footprints is to analyse how human activities or specific products relate to issues of water scarcity and pollution, and to see how activities and products can become more sustainable from a water perspective (Hoekstra, Chapagain, Aldaya, & Mekonnen, 2011).

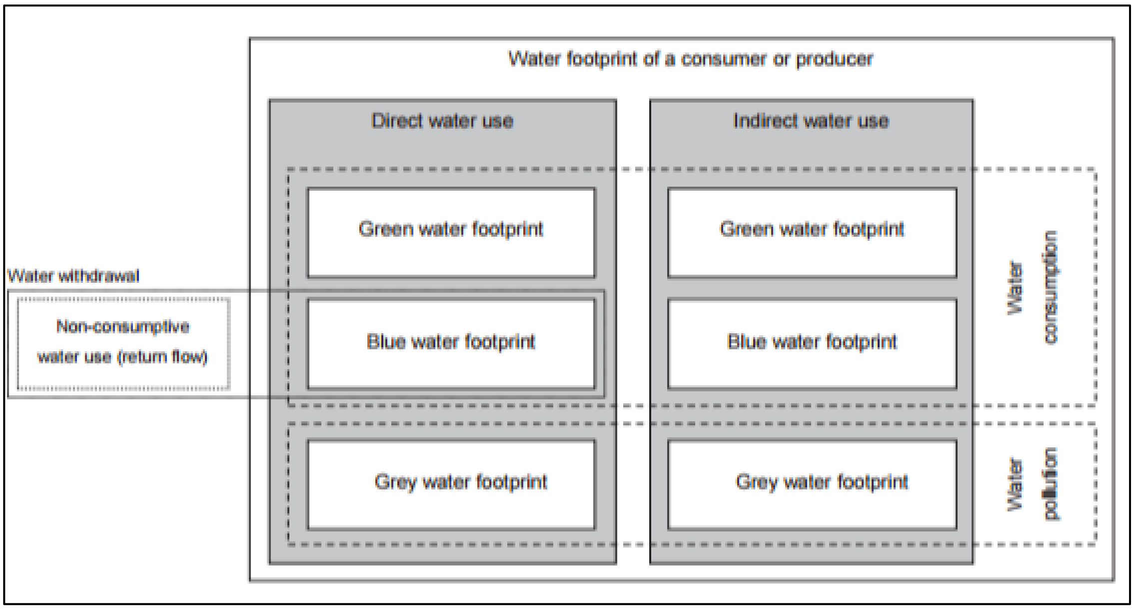

Figure 1: Components of water footprint

As is seen in Figure 1, the non-consumptive part of water withdrawals (the return flow) is not part of the water footprint. It also shows that, contrary to the traditional measure of 'water withdrawal', water footprint includes water from rainwater harvesting (green) and water required to assimilate pollution loads to natural background concentrations and ambient water standards (grey). It also accounts for the indirect water use component (embodied in supply chain). These standards are hence based on a lifecycle assessment.

This globally-accepted standard definition of water footprint aims to help assess the magnitude of potential environmental impacts related to water with consistency. It seeks to enable identification of ways to reduce those impacts and provide reliable information for reporting water footprint results that can be tracked over time. India has expressed reservations in the adoption of the ISO 14046 (international guidelines for Water Footprint standards) on grounds that it lacks scientific basis and hence unsuitable for policy adoption (MoWR, 2016). India is evolving its own water footprint standard for water audits and assessments. However, other than the definitional aspects that it includes lifecycle considerations, the standards itself have not been specified (MoWR, 2016).

Hence, for the purpose of this analysis, indicators assessed include:

1. Water withdrawal
2. Direct water consumption

This study analyses water withdrawals (the traditional indicator) and water consumption by India's electricity generating power plants. Following the definitions given in literature, "water withdrawal" is "water removed from the ground or diverted from a surface-water source" and "water consumption" is "the portion of withdrawn water not returned to the immediate water environment." 'Consumption' refers to loss of water from the available ground-surface water body in a catchment area. Losses occur when water evaporates, returns to another catchment area or the sea or is incorporated into a product.

2.3 Reliance on Fresh Water Resources

There is no comprehensive database to gauge the reliance of the power sector on fresh water resources. CSTEP estimated that in 2012, majority of the plants (about 84% of coal TPPs by count) in India used fresh water resources. For this analysis, we cross-referenced plant-level data from the CEA database for existing plants with data collected on water sources (Refer Appendix 1).

2.4 Quantified Estimates of Water Use in Power Sector

There are select estimates for electricity water use in India. The IEA estimated India's water withdrawal for energy production in 2010 at 40 BCM and consumption at 4 BCM, with the vast majority in each category going to electricity generation (IEA, 2012). Mitra, Bhattacharya and Zhou calculated India's water demand for electricity generation in 2010 as 49 BCM, which was based on water use intensity, surveyed at different types of TPPs in India (Mitra, Bhattacharya, & Zhou, 2014). Other reports estimate that all industry accounts for 9% of water consumption in India and TPPs account for about 88% of the total industrial water demand in the country (TERI, 2012) (CSE, 2004).

However, uncertainty regarding the actual water use in India is considerable since the estimates of water use are not based on measurements of actual use at site but on assumptions for each sector (Planning Commission, 2012).

2.5 Impact of Water Scarcity on Power Generation

According to a World Resources Institute study, more than 70% of India's coal power plants are located in water stressed or water scarce areas (WRI, 2014). Inadequate cooling water supply for power plants already creates problems in India's power sector. For example, the Sepat power plant in Chhattisgarh, one of the ten biggest in India, was shut down in March 2008 due to a lack of cooling water. All six units of the Parli thermal power plant, with an installed capacity of 1,130 MW, were shut down in February 2013 because of a severe water shortage in the Maharashtra region (NDTV, 2013). As electricity generation increases, power plants will demand more water for cooling, exacerbating potential conflicts between the use of water for electricity, agriculture, industry and households.

2.6 Technologies and Policies for Water Use in the Power Sector

India still operates older generation TPPs with open-loop, or once-through (OTC), cooling technologies. These cooling systems have an average water withdrawal intensity of about 80–160 m^3/MWh. This is around 40 to 80 times higher than the modern close-loop, or recirculating system (UN-WWAP, 2014). To limit the water use for electricity generation, India banned the construction of TPPs, with OTC using fresh water, in 1999 (OECD/IEA, 2015).

Further, the Ministry of Environment, Forest and Climate Change recently approved the standard on water consumption limits for coal-fired TPPs (Central Pollution Control Board, 2015). The Standards for Water Consumption vide Notification No. S.O. 3305(E) (dated December 7, 2015) require all plants with OTC systems to install cooling towers and achieve a maximum water consumption of 3.5 m^3/MWh by the end of 2017. The standard also expects new plants (to be installed after January 1, 2017) to limit water consumption to 2.5

m^3/MWh and achieve zero liquid discharge. However, no such norms exist for non-coal TPPs and other generating technologies like CSP.

Most of the water withdrawn by the TPPs is used for cooling and ash handling purposes. With dry ash recovery systems and ambitions for zero liquid discharge, TPPs may be able to reduce the grey water discharged. TPPs boil water to produce steam to spin turbines that produce electricity. In cooling systems, large volumes of water are withdrawn from nearby rivers, lakes and oceans to condense and recirculate the steam generated to produce electricity. The three types of cooling systems used in the thermal power plant industry—OTC, closed-loop and dry cooling system—differ dramatically in terms of their water usage or withdrawal. The OTC system consumes the maximum volume of water and significantly impacts the environment (Macknick, Newmark, Heath, & Hallett, 2012).

Ground level data in India is not available on the benefits and trade-offs for using wet cooling towers versus dry cooling towers in power generating plants. Hence, a spreadsheet based MATLAB model was used (Refer Appendix 2). The estimated consumption coefficients and trade-offs with power plant performance have been summarised in Table 1.

Table 1: Impact of cooling technology choice on auxiliary consumption and water consumption

Parameters	**Natural Draft Wet Cooling Tower**	**Induced Draft Wet Cooling Tower**	**Dry Cooling Tower**
Auxiliary Consumption (%)	0.35%	0.90%	1.5%
Water Consumption (m^3/MWh)	3.24	3.24	0

3. Methodology

For this study, we used a combination of iterative review of literature and modelling to arrive at plausible power sector pathways and to quantify impacts on water withdrawals and consumption. The key components of what this entailed is as follows:

1. A review of literature on power sector technologies, their use in India and linkages with water resources
2. A review of literature to identify and model the scope for alternative cooling technologies
3. Finally, model a reference scenario for the power sector on CSTEP's India Multi Region TIMES model (IMRT).

The review of key literature has been presented in previous sections and Appendix I.

We used CSTEP's India Multi Region TIMES (IMRT) model to arrive at power generation profiles for TPPs in India during 2010–50. The TIMES (The Integrated MARKAL EFOM System) model is a cost optimisation modelling platform developed to compute dynamic partial equilibrium on energy and environment systems. Structurally, it consists of primary energy supply curves, energy transformation sector (e.g.: refineries) and power generation (supply technologies and load curves) to ensure sustained provision of electricity to end-users. The IMRT has state-level representation of power supply technologies and unit-wise representation of TPPs. Further, its power sector module is defined at the state and power plant level, hence it was run in isolation with an exogenous electricity demand (based on increase in average per capita electricity consumption)[2]. The consolidated power plant database, including existing units (as on 2015) and planned units (expansion and new proposed units), were defined by technology type—subcritical, supercritical and ultra-super critical—with overall plant efficiency for new units at 36%, 38% and 41%, respectively. A summary of the database used is provided in the Appendix 1.

For new coal TPPs to be built after the CEA plan horizon of 2027, units were assumed to have a plant load factor of 80%. Costs of solar PV technologies reflect current reverse bidding tariffs of INR4/kWh. All other model inputs on technology costs are consistent with previous national modelling exercises provided in supplementary material of referred journal article (Byravan, et al., 2017).

For the purpose of this study, historic baseline of 2010 was chosen for comparison with other government estimates. In IMRT, power sector data has been benchmarked till 2015 and then projections for 2050 were simulated.

3.1 Water Consumption and Water Withdrawal Coefficients

We modelled both water withdrawal and consumption intensities for the reference scenario. Coefficients were taken from recent analysis by Council for Energy Environment and Water (CEEW) where over 40 plants were surveyed across different fuel supply mix in 2017. Another study by TERI had also identified some coefficients for various power technologies. However, since the distinction of consumption and withdrawal was not done and since the

[2] Population projections from World Population Prospects: The 2015 Revision (medium variant) by the United Nations Population Division were considered for estimating demand trajectories.

sample size was limited, the CEEW factors were seen to be more representative of Indian conditions. For technologies not surveyed, values are adjusted according to reviewed literature. Table 2 below shows water withdrawals and consumption intensities for cooling technologies.

Table 2: Water withdrawal and consumption coefficients

Fuel Source for Power Generation	Cooling Technology	Withdrawal Coefficient (m^3/MWh)	Consumption Coefficient (m^3/MWh)
Coal[3]	OTC	216	1.6
	Recirculating	3.79	2.6
	Dry Cooling	0	0
Fossil non-coal	OTC	4.55	0.91
	Recirculating	152.36	3.13
	Dry cooling	0	0
Nuclear	OTC	242.71	1.5
	Recirculating	6.42	3.8
	Dry cooling	0	0
Biomass	Recirculating*	4.35	3.65
Solar		2.673	2.673
Hydro			68.13

*References: (Chaturvedi, Nagar Koti, Sugam, Neog, & Hejazi, 2018) & (Macknick et al 2012)

Cooling technology shares are based on review of Indian assessments and similar modelling assessments (Bhushan et al., 2015) (Davies et al., 2013) (Kyle et al., 2013). In this study, we assumed that after 2030, the share of recirculating technologies will increase from around 50% during 2015–20 to around 70% for coal in 2021–50. In fossil non-coal and nuclear power plants, the recirculating cooling technology ratio share changed from around 50% to 90% in the same time periods. These shares reflect India's ongoing policy ambition to move towards recirculating technologies.

[3] Water consumption coefficients for coal were increased by 30% to account for ash handling (Bhushan et al., 2015) and (FICCI-HSBC, 2013).

4. Results and Discussion

4.1 Growth of Power Sector

CSTEP estimated that driven by economic growth and urbanisation, India's per capita electricity demand is likely to grow from around 1100 kWh/capita (present day) to about 2400 kWh/capita in 2030 and 3500 kWh/capita in 2050. Based on this exogenous input regarding electricity demand and the UN's median population projections, power sector demand is projected to grow at 5.2% during 2015 to 2050. Since the model has also accounted for transmission losses[4], the electrical energy requirement seen by the power generating module in 2015 was around 1170 billion units (BU), which matches CEA's estimates.

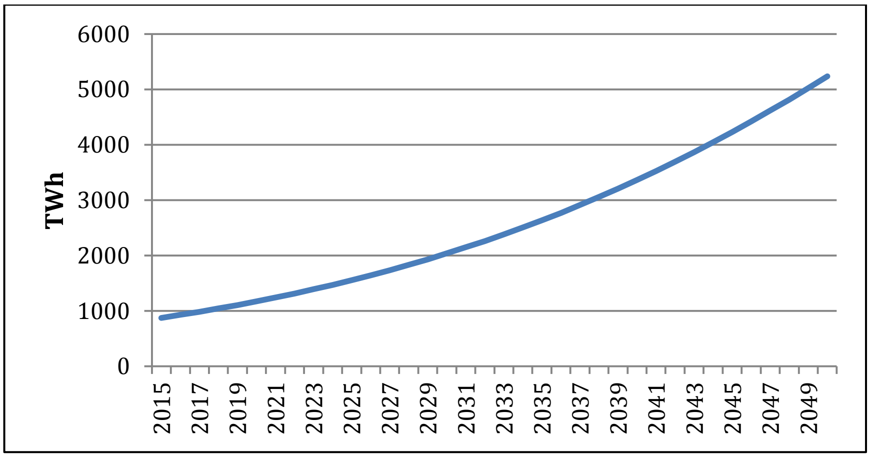

Figure 2: Projected end-use demand CSTEP-IMRT model during 2015-50

India has a stated ambition to achieve 100 GW of solar energy and 60 GW of wind energy by 2022. Further, in its NDC, India aims to make at least 40% of its installed power generation capacity fossil-free. The reference scenario developed in the IMRT model accounts for this ambition. In this reference scenario, around 50% of the total installed capacity is met from fossil-free sources (RES, nuclear and hydro). Further, this is achieved without any additional modelled policy constraint. This is possibly due to lowered costs of solar technologies, modelled based on recent market behaviour, driven by government subsidies to the sector. Further, new coal technologies are also modelled as being marginally costlier[5] owing to the recent emission norms.

[4] T&D loss reduction targets as specified by the Ministry of Power in 36 states and union territories were modelled up till 2027. By 2050 most states limit T&D losses to 10%.
[5] Investment costs for new coal technologies increases by 20% after 2020.

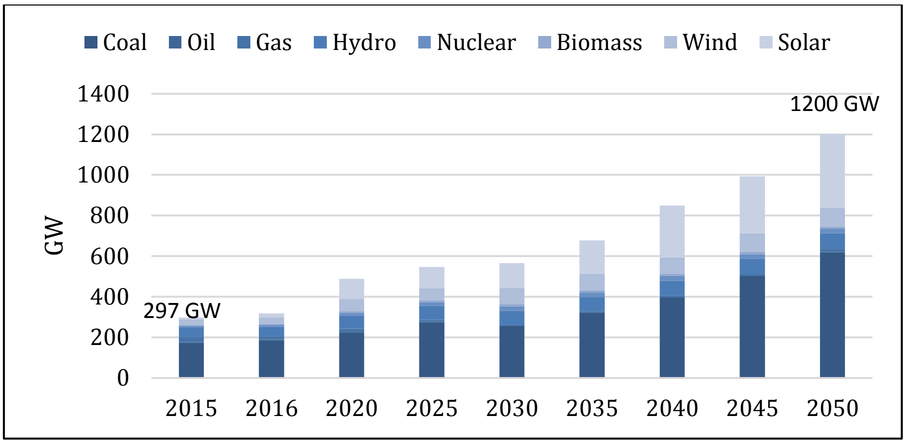

Figure 3: Projected installed capacity 2015-50

Table 3: Growth rates for installed capacity (by fuel category)

	2015–30	2030–50
Coal	3%	5%
Oil	-24%	17%
Nat Gas	-8%	4%
Hydro	3%	1%
Nuclear	7%	0%
Biomass	5%	0%
Wind	8%	1%
Solar	18%	6%

Within the reference scenario itself, solar grows at 18% till 2030 and thereafter is seen to grow at a slower pace. However, in power generation terms, the results present interesting insights. Total generation is projected to grow to about 5700 BU. Despite the high rate of growth of solar power and realising announced low carbon policy ambitions, during 2015–50, coal-based power generation continues to dominate the power generation mix. Although the share of RES (biomass, wind, solar) in the total installed capacity is over 40% by 2030, its share in generation is not as significant. RES accounted for about 8% of the total generation in 2010. Despite aggressive growth in solar installed capacity, RES will contribute only up to 15% of the total generation in 2050.

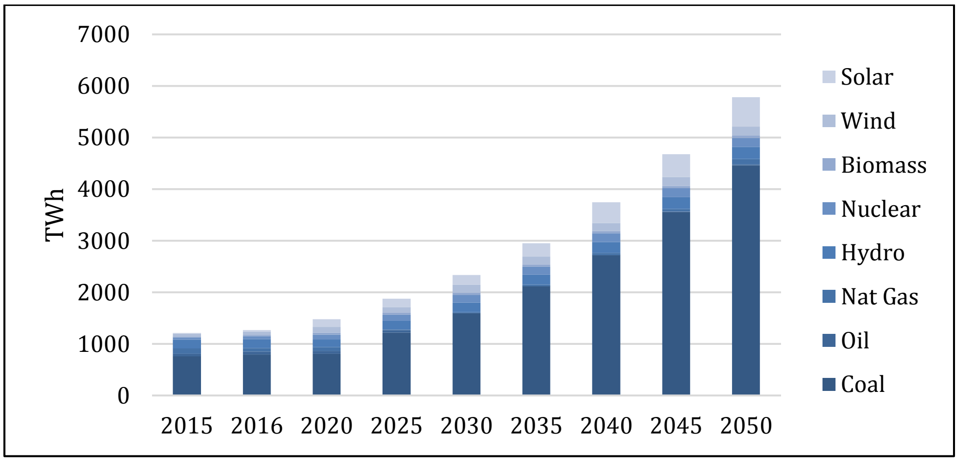

Figure 4: Fuel-wise generation 2015–50

4.2 Impact on Water Resources

In this reference scenario, in 2010, we estimated that total water consumption from the power sector was about 2 BCM. Over 95% of both withdrawals and consumption is estimated to be from fresh water sources. Coal power plants withdraw the largest share of water while hydro-power plants are the largest water consumers (water withdrawals for hydro are not included). Without any additional water regulation, average water withdrawals and consumption are projected to grow five-fold, to 276 BCM and 14 BCM by 2050, respectively (refer Figure 5 and Figure 6).

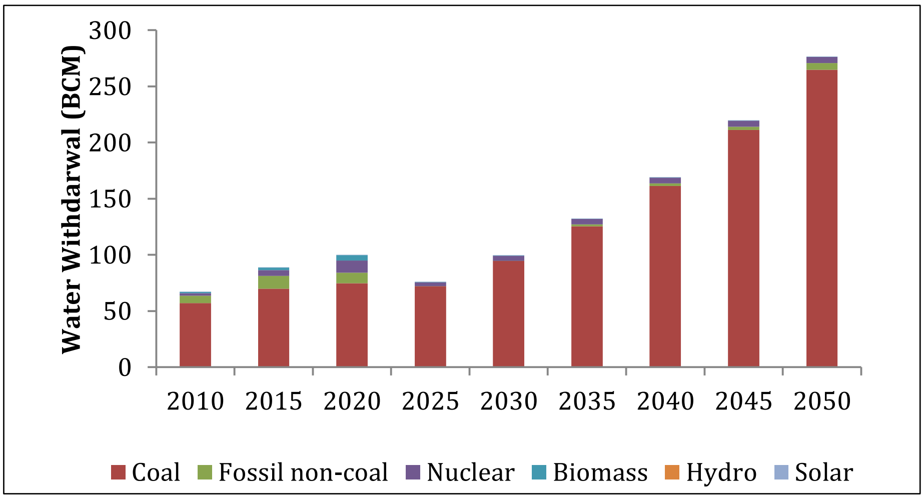

Figure 5: Projected water withdrawal from the power sector

We have factored-in India's announced policies for emission intensity reductions in the power sector along with water use standards in this reference scenario. The modelling results show that the most significant contributors to this water withdrawal trajectory is the changing share of cooling technologies. Phasing out OTC technologies and the change in cooling technology shares, especially in TPPs—i.e., switching from OTC to recirculating technologies—can explain the trajectory of water withdrawals. The share of OTCs modelled for nuclear during 2010–20 was 47%, which was changed to 10%[6] in 2020–50. Around 90% of plants have been modelled to rely on fresh water recirculating technologies to reflect changes in law and plans for future nuclear plants. Hence, the share of nuclear water withdrawals reduces, from 12% in 2020 to 5% in 2025. Similarly, withdrawals from coal power plants also decline in 2025. Hydro involves a larger water consumption footprint owing to evaporative losses. Hence, it is not accounted for in water withdrawals.

During the modelled time horizon, in conjunction with the share in supply mix, shares of coal water withdrawals increase. Meanwhile owing to its minimal water withdrawal and consumption footprint, RES's shares are negligible. Water withdrawals will grow around 4.5 times during 2015 to 2050 despite a focus on recirculating technologies in the future. Further, shifting to lower water intensity technologies like dry cooling and increasing RES shares can potentially curb water draws further.

[6] Assumed so as to accommodate nuclear plants with sea water as source.

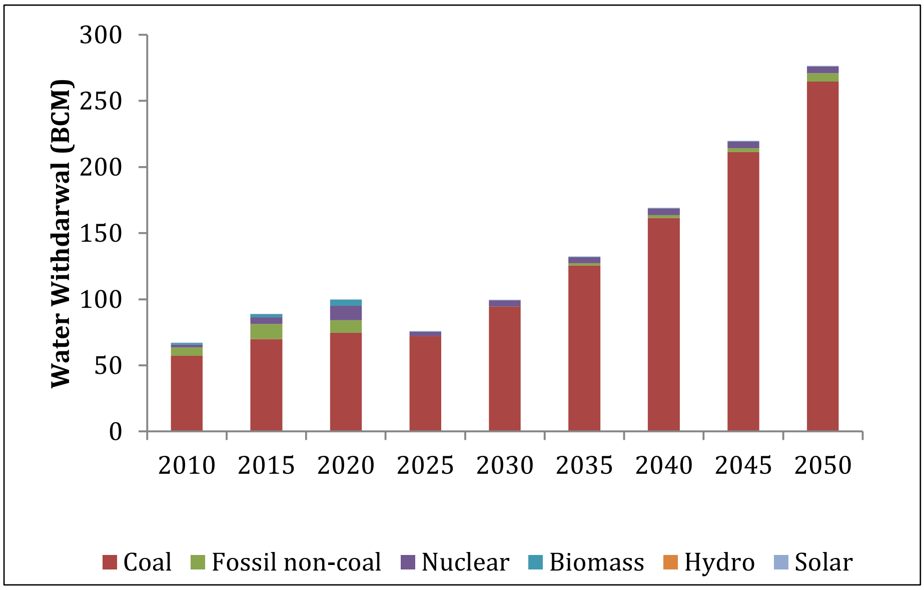

Figure 6: Projected water consumption from the power sector

Meanwhile, with an increased emphasis on recirculating technologies, the water consumption footprint of the power sector increased by six times from around 2 BCM in 2010 to 14 BCM in 2050. While the electricity mix is an important driver for this trajectory, the ability of coal TPPs to comply with regulatory mandates and lowering water consumption by switching cooling technologies has also been modelled.

These results are consistent with recent assessments of water implications due to power generation in India, the US, China and the UK (Byers et al., 2014; Konadu et al., 2015; Liao et al., 2016; Macknick et al., 2012; Wan et al., 2016). Macknick et al. (2012) also highlight that the retirement of OTC systems over time can significantly reduce water withdrawals. On the other hand, consumptive uses are seen to increase (post 2030) in several low-carbon scenarios where gas-based plants and nuclear plants generate more power and increases overall consumption owing to the adoption of recirculating water cooling technologies. Similar to this study, Wan et al. (2016) and Konadu et al. (2015) highlight the complementarity of low-carbon options as a strong driver of reducing water consumption and thereby water stress. Wan et al. (2016) also highlighted the increase in indirect water use in some power generation technologies and cautions that low-carbon transformation may be constrained in India due to water scarcity for upstream manufacturing. The analysis in this study has identified that direct water use can significantly be limited with a combination of water-use efficiency (due to the shift to recirculating technologies) and a higher share of renewables supply, as determined under national policy mandates.

5. Conclusion

Considering that the country's electricity demands will only continue to grow in the coming years, with India's climate mitigation commitments, decarbonising the electricity sector has become an important concern. The rapid increase in electricity generation will also require far more water for cooling electricity power plants. An increase in water consumption, for electricity generation, will likely affect water availability for other sectors of the economy. In turn water stresses can also disrupt power generation. This has wide ranging policy implications since India is already a water-stressed country.

This report explored water withdrawals and water consumption due to electricity generation in India, during 2010–50. We developed a reference scenario to account for the effects of the proposed power sector targets and water regulations on the future water demand. This research evaluated how recent goals, set towards reducing emissions intensity, meeting NDC targets on fossil-free generation capacity (by 2030) and announced water saving standards in coal TPPs can affect the future water footprint of the sector.

Elsewhere, similar scenario based analysis has shown that implementing recirculating cooling technologies significantly reduces water withdrawals by the power sector (Srinivasan, et al., 2017). By implementing water saving technologies, India can offset some of the increase in water withdrawals and consumption resulting from the growth of the power sector. Further, in this reference scenario no additional RE targets beyond 2030 were modelled. Focusing on RES like wind and solar power reduces water consumption. Hence, policies to facilitate the decarbonisation of the electricity sector, by increasing the share of renewable energy technologies further, can serve to improve the overall water savings. However, the implications on electricity generation due to localised scarcity can vary depending on the geographical region. Thus, a Geographical Information Systems (GIS) based mapping of plants and scarcity projections in river basins may be required to identify where hybrid and dry cooling technologies can be appropriately installed. Such a GIS based assessment could also help identify areas that could see intensified water stress and predict areas where water stress could be developing. Such a system would be useful to suggest specific policies that could be designed for specific regions in order to proactively address and perhaps mitigate the water stress and improve water availability.

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Appendix 1: CSTEP's Power Plant Database in India

Coal-based TPPs

Unit level capacity and vintage from the CEA database is provided in Table 4. Based on new environmental standard classification, the existing and proposed power plant units were classified into the three categories, namely plants commissioned: (1) before 2003, (2) 2003-2016, and (3) 2017-2030. This was further, sub-classified based on unit capacity (<500 MW and ≥500 MW).

Table 4: Summary of power plant database

Commissioning year	Category	No of Units	Total Capacity as on 2015 (GW)	Ownership					
				Centre		State		Pvt.	
				No of Units	Capa-city (GW)	No of Units	Capa-city (GW)	No of Units	Capa-city (GW)
Before 2003	Plant Capacity <500 MW	286	42	59	11	201	29	26	3
	Plant Capacity ≥500 MW	24	12	18	9	5	2.5	1	0.5
Between 2003-2016	Plant Capacity <500 MW	163	35	18	5	52	13	99	20
	Plant Capacity ≥500 MW	136	80	48	22	31	16	66	41
On or after 2017	Plant Capacity <500 MW	37	9	1	0.20	4	1	26	6.623
	Plant Capacity ≥500 MW	115	81	17	12	25	17	64	39

From table above, it can be inferred that majority of the TPP units before 2003 were less than 500 MW. It is also seen that increasingly larger capacity units have been installed since 2003. Around 72% of the total existing installed capacities are between 2003 and 2016. In the proposed plants category (to be commissioned after 2016), nearly 80% of all units in the pipeline are 600 or 660 MW unit capacity (CEA, 2013) (CEA, 2016) (Center for Media and Democracy, 2017). Also, majority of the high capacity (≥500 MW) plants are in private ownership.

Plant efficiency

Efficiency is the ratio of the energy generated to the total heat units of fuel consumed. Station heat rate (kCal/kWh) is the energy expended to obtain a unit of useful work (Nowling, 2015). The efficiency is the inverse of heat rate. Efficiency of a thermal power plant can be calculated in two methods referred in Equation *1* and Equation *2*.

Equation 1: Efficiency from station heat rate

Efficiency (%) = (1/Station heat rate)*conversion factor[7]

[7] Conversion factor (1 kCal=0.116 kWh)

Equation 2: Efficiency calculations from emission factors

Efficiency = (Fuel emission factor/Total specific emission factor)*conversion factor[8]

CSTEP calculated the efficiencies of all the existing TPPs. It was seen that the average efficiencies of the coal TPPs calculated by from the CEA data was 32.47% (from Method 1) and 33.33% (from Method 2) (Central Electricity Authority, 2013). Around 5% of the installed capacity or 56 units had efficiency lesser than 30%.

Resource Linkages

Water source for existing and proposed TPPs (fresh or sea)

Plant level data from the CEA database for existing plants was cross-referenced with data collected on water sources. These included 48% authenticated sources of data points (data obtained from the Global Energy Observatory, 2015), 36% non-authenticated sources (newspaper articles, industry visit reports and research reports online) and 16% data points based on assumption of 3 km proximity to sea water. Water source for the existing power plants is shown in Table 5, accounting to 160 plants.

Table 5: Water source for existing and proposed

Water source	No. of plants	No. of units	Capacity (MW) as on Mar 31, 2012
Fresh water	143	552	1,23,872.0
Sea water	14	49	16,280.0
Fresh water and Sea water	2	6	3,200.0
Sewage water	1	1	270.0
Total	160	608	1,43,622.0

CSTEP estimated that in 2010, the majority of the plants (about 84% of coal based TPPs) used fresh water resources.

Non-coal Power Plants

The CEA database was used to baseline generation, installed capacity and efficiency for nuclear, gas and diesel power plants (Table 6). The installed capacity of renewables was benchmarked against data provided by the CEA (2016) for which the model identified representative plants.

Table 6: Non-coal power generation installed capacity used in IMRT

Ownership	Gas	Diesel	Nuclear	Hydro	Renewable	Total (GW)
Central	7	0	7	12	0	26
State	7	0	0	30	2	39
Private	11	0	0	3	55	70
All India	25	1	7	45	57	135

Appendix 2

[8] Conversion factor (1 MWh=3600J)

Cooling Technologies

Cooling systems play an important role in coal power plants, to reject unutilised heat of around 25–40%. The two major types of cooling systems widely used in Indian TPPs are OTC and Wet Cooling Towers (Natural Drafts or Induced Drafts) (Figure 7 and Figure 8). Recently, Dry Cooling Towers are also becoming popular among Indian TPPs due to water scarcity concerns (Figure 9). As part of this study, we modelled factors affecting water consumption and auxiliary power consumption in wet cooling towers and dry cooling towers. OTCs are not included as they need to be phased out with cooling towers, by 2019, as per policy.

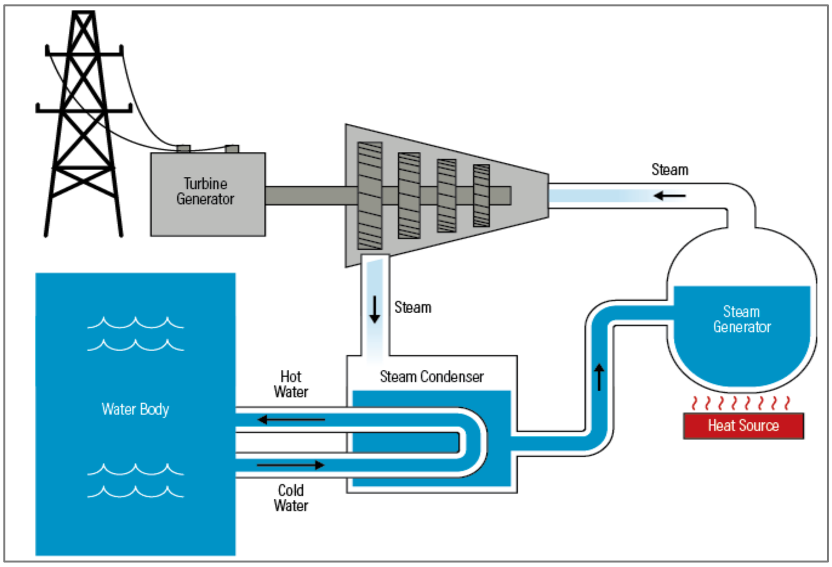

Figure 7: OTC Systems (Williams & Simmons, 2013)

Wet Cooling Tower (WCT)

A WCT works on the principle of evaporative cooling. Hot water from the condenser is distributed from the top of the tower, via spray nozzles, and gets into contact with atmospheric air. During this contact, small volumes of water evaporate into air, lowering the temperature of the remaining water. The water is circulated until its temperature is lowered to the desired value. Atmospheric air is circulated into the tower either by natural drafts or fans. Depending on the type of drafts used in the WCTs, it can be classified as Natural Drafts or Mechanical Drafts. Based on the cooling requirements, water loading and atmospheric conditions, suitable type of cooling towers can be chosen. The schematic diagrams of widely used WCTs are shown in Figure 8.

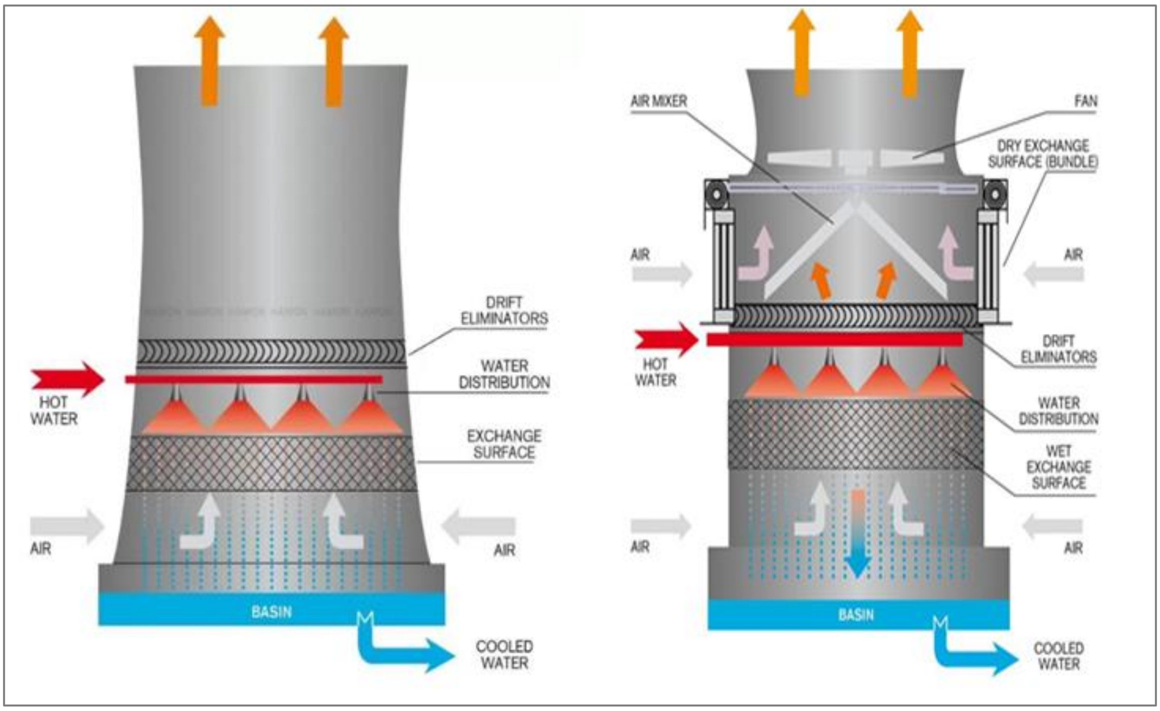

Figure 8 (a): Natural draft cooling tower (b): Induced draft cooling tower

In natural draft towers, cooling occurs based on evaporative cooling, stimulated by natural convection. Since cooling is based on natural convection, the tower height of around 100 to 200 m is required to attain preferred cooling requirements; very high compared to mechanical draft WCTs (~10–50 m). Due to this, the capital cost of natural draft towers are 60% more than mechanical draft towers (Gupta, 2012). However, power consumption for fan operation and frequent maintenance are not required for natural draft WCTs.

Mechanical draft WCTs use fans for enhancing air circulation. The main advantages of this type of tower are low capital cost and capability to regulate air flow depending on ambient air condition. Mechanical draft towers are of two types, induced drafts (ID) and forced drafts (FD). In induced draft, the fan is located at the top of the tower and air is sucked in from the bottom of the tower. In forced draft, the fan is located at the bottom of the tower, which pushes air into the tower. In recent times, induced draft fans have been used more widely as compared to forced draft, even though FD consumes lesser power (FD fans deals with cooler air). The air exit velocity from the top of the tower is very less and can result in recirculation of air. This lowers the tower efficiency of FD-based towers.

Dry Cooling Towers (DCT)

A dry cooling tower operates similar to an automobile radiator. There is no direct contact with air and thus there is no loss of water from DCTs. Hence there is an increasing interest in dry cooling towers in areas where water scarcity prevents plants from using a traditional water cooled condenser in a steam power plant.

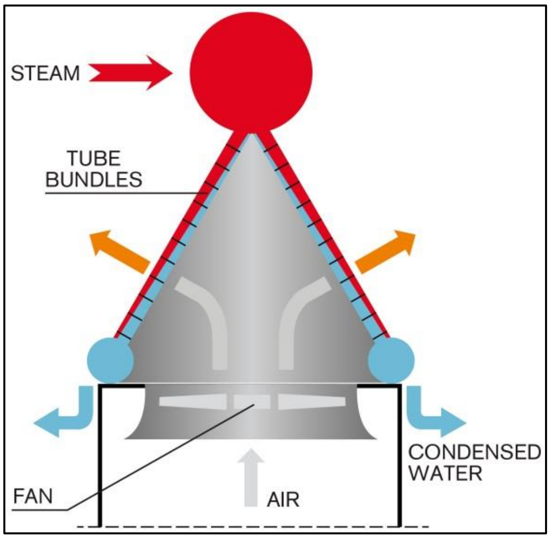

Figure 9: Dry Cooling Tower (Bushart, 2014)

Dry cooling systems use substantial amounts of electricity, thereby, effectively lowering the power output of the plant. Dry cooling systems usually require higher capital investment than other cooling systems. The volume of air required for DCTs are higher than WCTs as the heat transfer co-efficient for air is less than the water used in wet cooling towers. Therefore the auxiliary consumption by the fan will be higher than that of WCTs. Unlike wet cooling systems, the tower performance depends on dry bulb temperature rather than wet bulb temperature. Depending on the heat transfer area and air flow velocity, the air flow rate required to condense steam is calculated. The required fan power is estimated from air flow rates and air side pressure drops, which depend on the heat load in the DCT.

Hybrid cooling

These systems combine dry cooling and wet cooling to reduce water use, relative to wet systems, while improving hot-weather performance, relative to dry systems. Hybrids can be designed to operate as dry cooling systems during the cooler seasons, supplemented with wet cooling during the hot seasons—when the dry systems lose their efficiency.

Water Consumption

Though cooling towers can reduce wastage of water considerably, as compared to OTC, due to evaporation, drift and blow down loss, makeup water is needed to maintain the required water quantity in CTs. Drift loss is mainly due to entrainment of water along with the air and vapour. It is typically less than 0.2% of the circulation water flow (Perry & Green, 2008). The drift eliminators can reduce the entrainment to 0.01% of the circulation flow. In our current analysis, drift eliminators are not considered as it is an advanced technology.

The blowdown operation in CTs includes the discarding of some amount of the circulating water to reduce the solid concentration. It is calculated based on the number of Cycles of Concentration (CoC) possible with limited scale formation, which mainly depends on the quality of water. CoC typically ranges from 3 to 7. The main equations used for calculating makeup water consumption in cooling towers are given below (Perry & Green, 2008) (Marisamy, 2015).

For a 330 MW base model plant (655.9 tph steam at turbine outlet), the water consumption by cooling tower ranges between 926 m^3/hr and 1492 m^3/hr based CoC (CoC 6-2). Further higher the Cycle of Concentration (CoC), lower the water consumption. Increasing CoC from 2 to 4 can reduce water consumption by 30%. But for an average performing tower that operates above 4 CoC, increasing CoC does not decrease the amount of makeup water required as the curve starts levelling off after 4 cycles. For same part loads, as the steam flow rate at the turbine outlet increases, consumption of water also increases.

Auxiliary Power Consumption

Auxiliary power consumption depends mainly on the type of drafts. For a natural draft tower, the power is consumed only to pump water to the desired height, whereas for mechanical draft towers, power is consumed to operate fans along with the pumping operation. The auxiliary consumption by the pumps depends mainly on the required head (in feet) and water flow rate. Key factors that determine the fan power consumption are desired cold water temperature, ambient air condition such as wet bulb temperature and relative humidity.

The percentage share of auxiliary consumption by a wet cooling tower to total generation ranges between 0.5 to 1% depending on the draft used. Illustratively, for a 330 MW base plant that was modelled, the percentage of auxiliary consumption by WCT is 0.9% (2659 kW power output). The auxiliary consumption increases with increase in steam flow rate for the same part load conditions. Meanwhile for a similar power system configuration, the auxiliary consumption by a dry cooling tower is estimated to be 1.54% of the total electricity generation. However, the specific water consumption in dry cooling is zero (Refer to Table 1).

Seasonality Constraints

By lowering the temperature of the cooling water from the cooling systems, the effectiveness of the condenser would increase, which in turn allows for more efficient electricity generation. When water is too warm for power plant cooling, it decreases a power plant's efficiency, making it less competitive. Power plants suffer from water temperature problems during hot summer months, when the temperature of intake water is elevated at the same time that plants are running at full capacity to meet peak loads.

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