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SDG implications of water-energy system transitions in India, for NDC, 2 °C, and well below 2 °C scenarios

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LETTER

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E-mail: sarithasv@iima.ac.in and vishwanathan.saritha@nies.go.jp**Keywords:** SDG-NDC linkages, water-energy nexus, India, well below 2 °C, integrated approachSupplementary material for this article is available [online](#)**Abstract**

India needs to address the immediate concerns of water supply and demand, due to its increasing population, rapid urbanization, and growing industrialization. Additionally, the changing climate will influence water resources, which will subsequently impact the overall sectoral end-use demand patterns. In this study, we have integrated a water module with the existing bottom-up, techno-economic Asia-Pacific Integrated Model/End-use energy system model for India to estimate the future water demand in major end-use sectors under business-as-usual (BAU), nationally determined contribution (NDC), and low-carbon futures (2 °C and 'well below 2 °C') up to 2050. We also simulate the effects of water constraints on major sectors under different climate-change regimes. Our results show that water-intensive end-use sectors, specifically agriculture and power, will face major impacts under water-constrained scenarios. Over the period between 2020 and 2050, policy measures taken under the NDC scenario can cumulatively save up to 14⁶ billion cubic metres (bcm) of water, while low-carbon scenarios can save 20–21 bcm of water between 2020 and 2050, compared with BAU. In a water-constrained future, NDC and low-carbon futures can save 28–30 bcm of water. There is a need to increase the current water supply by 200–400 bcm. The marginal cost of installing dry cooling systems in the power sector is considerably higher than the cost and benefits of installing micro-irrigation systems with solar PV. Integrated policy coherence is required to achieve sustainable development goals, e.g., NDC and Paris Agreement goals, in both water and energy sectors. Concurrently, regulatory and economic instruments will play an essential role in improving resource-use efficiency at a systemic level, to reduce the overall water demand.

1. Introduction

The adoption of sustainable development goals (SDGs) and the Paris Climate Change Agreement in 2015 focused on mitigation and coping strategies to tackle water security and the impacts of climate change on water as a resource and its various other capacities (COP21 2015, UNSDG 2015).

⁶ 3.7% of the 2000 annual water demand or 2.5% of the 2015 annual water demand.

India's nationally determined contribution (NDC) emphasizes mitigation through emission intensity reduction and renewable energy; however, the focus on water is from the perspective of adaptation (NDC 2015). At a national level, the central government has removed sectoral prioritization for the allocation of water to domestic and economic uses in the most recent draft water policy (GoI, 2012). In addition, the National Water Mission (NWM) under the National Action Plan for Climate Change (NAPCC) has highlighted the need for water-use efficiency

(WUE) in major water-intensive sectors, especially agriculture (NAPCC 2008), a parameter also indicated under SDG6 (UNSDG 2015, GoI 2018). In March 2017, the thirteenth report of the standing committee on water resources, on the subject of 'Indigenous and modern forms of water-conservation techniques and practices' has again highlighted WUE in water-scarce states, in addition to conservation through budgeting and increasing the water supply through various mechanisms of harvesting (GoI 2017a).

India's water demand⁷ is rapidly outpacing its supply⁸. India's utilizable⁹ water supply has remained fairly constant, ranging between 1100 and 1197 billion cubic metres (bcm) (FAO 2012, India-WRIS 2012, FAO 2017). In contrast, studies have projected that the total water demand will rise from 550–710 bcm in 2010 to around 900–1400 bcm in 2050 (India-WRIS 2012, Amarsinghe *et al* 2014). Agriculture accounts for more than 85%, while power, industry, and the domestic (building) sectors share the remaining demand. Groundwater extraction is the main method of irrigation, as opposed to canal-based surface water irrigation. Groundwater contributes to about 62% of irrigation needs and 85% of rural and 45% of urban water supply (Amarasinghe 2014, CGWB 2014).

The physical water scarcity in nine river basins, where four-fifths of the national water usage takes place in India, will lead to an increasing gap between water supply and demand by 2050 (Amarasinghe *et al* 2014, Mishra *et al* 2019). Furthermore, climate change, in addition to extreme events, will impact water as a resource, thereby affecting water storage, supply, and its end-uses. This will not only lead to increased competition for water between different sectors but also severely impact both food and economic security in various regions across the country. Competition for off-flow use in major sectors will also affect the in-flow uses of water, such as the production of electricity (specifically hydropower), fisheries, and inland waterways. Moreover, changes in the climate, an increased frequency of extreme

droughts, environmental degradation, and pollution will exacerbate the stress on water use. Monitoring the water situation in India is relevant, due to its impact on the transition towards a low-carbon economy. This will have significant implications for future food security, industrial, and urban water use, as well as impacts on local and regional environments.

Mishra *et al* (2018) and Zhang *et al* (2017) have categorized about ten years¹⁰ between 2000 and 2020 as drought years¹¹, based on various criteria. Consequently, several districts in various states of India have observed competition between water users in the agricultural, power, and industrial sectors, indicating its vulnerability when compared to international standards. India's water (storage and supply) infrastructure severely lags behind its current water demand requirements. Furthermore, the water storage availability of 91 major reservoirs ranges between 29% and 45% of their total capacity during the summer months, which is further reduced during drought years (Mishra *et al* 2018, CWC 2020). Studies in the physical sciences have demonstrated the presence of water stress at spatial (regional, national, sub-national) levels; however, they have not observed the impacts of water constraints¹² at a systemic level on different sectoral (and sub-sectoral) water demands, i.e. they have not simultaneously considered WUE and water productivity from an end-user's perspective at a systemic level for India.

India is rapidly moving towards becoming a middle-income economy, with a population projected to overtake China's by 2025, and a level of urbanization that will exceed 50% by 2050 (UN 2019). As a developing country, India is committed to achieving its SDG and NDC goals by 2030. Studies such as that of McCollum *et al* (2018) have emphasized the impact of energy policies on other SDGs at the global level, while Dzebo *et al* (2019) conducted a textual analysis of countries' NDCs and concluded that six SDGs¹³ have strong links to NDC activities. Parkinson *et al* (2019) used the Model for Energy Supply Strategy Alternatives and their General Environmental Impact - GLOBIOsphere Model (MESSAGEix-GLOBIOM) integrated assessment model (IAM) to specifically focus on SDG6¹⁴ at a global scale; Krey *et al* (2021) conducted a multi-model (global and national) assessment to simultaneously analyze the co-benefits and trade-offs arising

⁷ In this study, 'water demand' is specified as the total amount of 'water withdrawal' from various resources for each sector. It can include water from primary renewable and secondary freshwater resources, as well as water from the over-abstraction of renewable groundwater or withdrawal from fossil groundwater, direct use of agricultural drainage water, direct use of (treated) wastewater, and desalinated water. It does not include in-stream uses, which are characterized by a very low net consumption rate, such as recreation, navigation, hydropower, inland capture fisheries and so on.

⁸ In this study, 'water supply' suggests the total amount of 'utilizable water' from various resources.

⁹ 'Utilizable water supply' is subset of 'total available water'. 'Internal Renewable Water Resources Potential' (IRWRP) considers the long-term average annual flow of rivers and the recharging of aquifers by endogenous precipitation. India's IRWRP has been estimated to be 1869 bcm annually, out of which, 1100–1197 bcm is considered to be 'utilizable water supply' (FAO 2015).

¹⁰ 2000, 2003, 2004, 2006, 2007, 2010, 2012, 2015, 2016, and 2018.

¹¹ Zhang *et al* (2017) classified drought years into four types, based on the drivers, which include meteorological, hydrological, soil moisture, and vegetation.

¹² Natural systems [Applying an upper water supply limit of 1123 bcm per year].

¹³ These include SDG 7 (Affordable and Clean Energy), SDG 15 (Life on Land), SDG 2 (Zero Hunger), SDG 11 (Sustainable cities and communities), SDG 6 (Clean Water and Sanitation), SDG 17 (Partnerships for goals).

¹⁴ SDG 6: clean water and sanitation.

from implementing integrated policies to achieve NDCs and the subsequent impact of doing so on achieving multiple SDGs¹⁵. The modelling of water demand at a sectoral level under climate change mitigation actions has specifically been focused on a single sector of India, such as power (Macknick *et al* 2012, Clemmer *et al* 2013, Srinivasan *et al* 2018) or agriculture (Chaturvedi *et al* 2015). Studies have not yet captured both the SDG and NDC¹⁶ linkages of water–energy interactions across all sectors at a national level.

Integrated resource assessment modelling requires that the impacts of all resource-sector policies, including water, energy, and land, should be captured. In the past, policymakers and researchers used an integrated water resource management approach to collect data for water availability and usability at the basin level. This approach has certain limitations. First, it does not capture water demand at a sectoral and technological level from the end users' perspectives (socio-technical). Second, it cannot account for improvements in the productivity of water at the technological and economic levels (techno-economic). Third, the basin-level approach does not consider the water–energy interactions at the local, provincial, and national-level jurisdictions (Liu *et al* 2017, Endo *et al* 2020). In reality, in a developing country, water supply and demand heavily impact other resources such as energy and vice versa. Understanding this interaction is essential to evaluate the co-benefits and trade-offs, especially when transitioning towards a low-carbon economy. Since 2011, the study of the water–energy–food–climate-change nexus has been gaining traction in academic circles (Liu *et al* 2017). Mitigation studies observe policies relevant to energy systems only. Switching to low-carbon and carbon-neutral sources of energy does not necessarily lead to efficient water use. In fact, it can exacerbate the existing conditions caused by the increase in water stress.

In this paper, we present the first detailed country-level analysis of integrated water–energy systems that captures SDG-NDC linkages from the sectoral end users' perspectives. We analyze water demand at the sectoral and sub-sectoral levels under existing policies, NDC, and low-carbon pathways. Additionally, we study the impacts of water-constrained, energy-constrained, and carbon-constrained futures on water demand and power generation. Our results demonstrate the need for integrated assessment models and policy coherence to study the impact of low-carbon transitions on

resources such as water. Subsequent sections provide details of the methodology and the results of the model, followed by key insights into future water demands and the need for efficient resource-use policy measures in the major water-intensive sectors of India.

2. Methodology

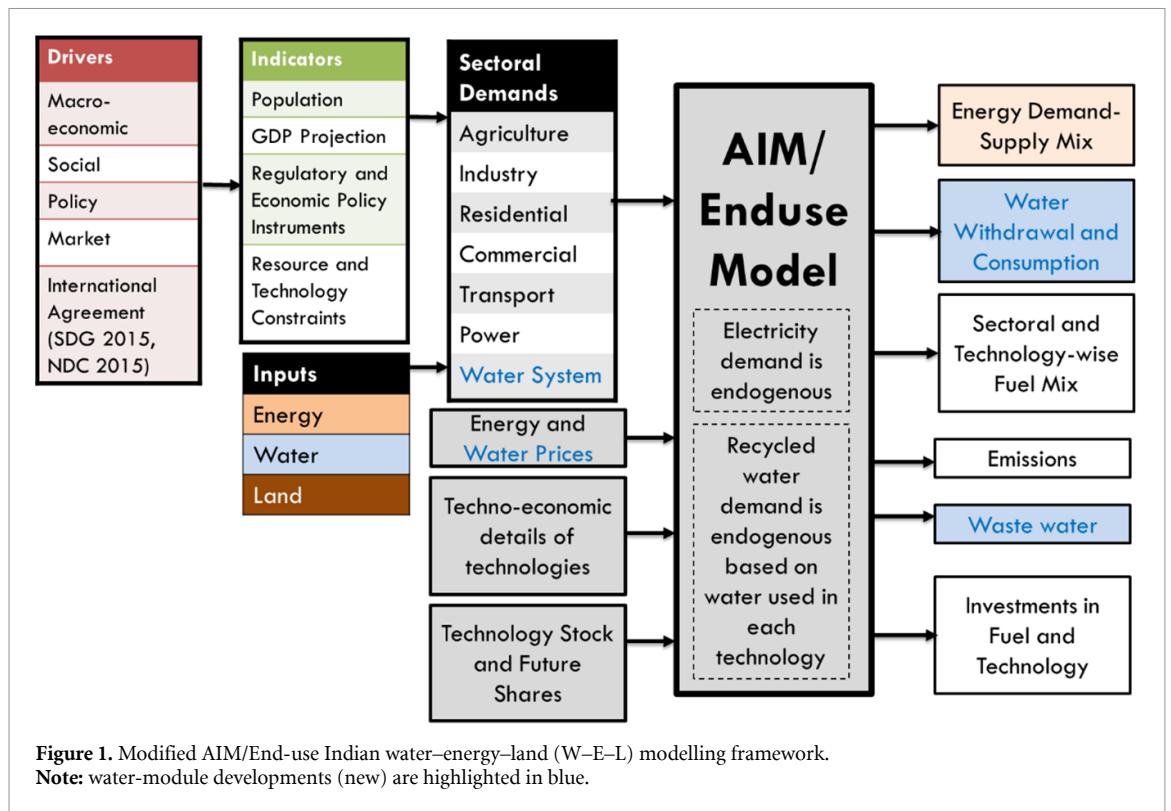
Integrated water–energy systems have been captured through top-down IAMs, such as Global Change Analysis Model-Indian Institute of Management (GCAM-IIM) and Integrated Research and Action for Development-Integrated Assessment Model (IRADe-IAM), in addition to bottom-up models, such as The Integrated MARKAL-EFOM System (TIMES/MARKAL-Water), Long-range Energy Alternatives Planning System-Water Evaluation And Planning (LEAP-WEAP) and the Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE-Water) models. While most IAMs have used sectoral water-use coefficients¹⁷ to capture water demand in the agricultural and power sectors, the industrial and building sectors have not been accounted for. Furthermore, these models run simulations for a fixed time period (the shortest being five years) (Bazaz 2011, Rodriguez *et al* 2013, Mitra *et al* 2014, Chaturvedi 2015, IEA 2017, Srinivasan *et al* 2018). Studies since the 1990s have estimated water demand at basin level for 193 countries. They have considered region-wise structural changes at a macroeconomic level through economic growth, demography, lifestyles and demand patterns, and technological advances in improving water-use efficiencies, in addition to variations in climatic factors and their impact on water use (Gleick 2000, Alcamo *et al* 2003, Shiklomanov and Balonishnikova 2003, FAO 2012, Amarasinghe *et al* 2014). In order to capture techno-economic details with sectoral and sub-sectoral granularity at a national level, the Asia–Pacific Integrated Model (AIM)/End use, a bottom-up optimization model, was selected for India (Kapshe *et al* 2003, Kainuma *et al* 2003, Vishwanathan *et al* 2017)¹⁸. This model is unique, as it can describe the sectoral competition for water and energy from the end-users' perspectives through a technology–resource mix. Additionally, we have also simulated water stress by applying water supply

¹⁵ These include SDG 2 (zero hunger), SDG 3 (good health and well-being), SDG 6 (clean water and sanitation), SDG 7 (affordable and clean energy), SDG 8 (decent work and economic growth), SDG 12 (responsible consumption and production), SDG 14 (life below water), SDG 15 (life on land).

¹⁶ Development policies, SDG 2015, NDC (2015).

¹⁷ The sectoral water-use coefficient does not capture the sectoral and sub-sectoral granularity of technologies and resources (energy and water).

¹⁸ The AIM/End-use model has been widely used to capture energy, environmental, and material systems at the national (especially in Asian countries) and global levels since its inception in the early 1990s. The novelty of this study is the inclusion of a water module for the first time at a national level with technological granularity. It captures water and energy-intensive sectors from a systems perspective. This work and module is yet to be included in the AIM/End-use global model.



constraints to the water–energy systems to observe their impact on water demand across sectors. Unlike the aforementioned studies, this study captures water, energy, and land systems in one model. The following section describes the AIM/End-use Indian model, supported by appendices A–C (available online at stacks.iop.org/ERL/16/085011/mmedia), which provides the framework, policy, and model assumptions for the study in detail.

2.1. Model description

The AIM/End-use Indian model integrates the water module at the resource and technological level into the existing energy and environment systems (Vishwanathan *et al* 2017, 2018a, Vishwanathan and Garg 2020) to capture the impacts of existing and future policies for water, energy, and land systems on the major water- and energy-intensive sectors. The model uses recursive dynamics and runs in annual time steps. It optimizes costs (technology, energy, and water) and resources (water, energy) by selecting a set of best available technologies based on given physical resources and technological and environmental parameters. A detailed characterization of the inputs reflects an optimistic engineering view of technological progress. Economic parameters, such as taxes, subsidies, resource (energy, water, and land) technologies, policies, and social costs are also classified. The final service demand is exogenous, and is driven not only by the gross domestic product (GDP) but also by end-use consumption and policies across various sub-sectors. The model is also being soft-linked to climatic–hydrological models (Vishwanathan *et al*

2018b). Figure 1 illustrates the addition of water and land as inputs into the major sectors of the existing AIM/End-use Indian energy model¹⁹. Figure 2 details the variables, parameters, database, and information flow in the current integrated assessment model.

2.2. Scenario architecture

Table 1 presents the salient features of the AIM/End-use Indian (water–energy–land) model. Appendix B presents the SDG–NDC interlinks captured in the model. Appendix C (tables C1–C5) provides policy targets and assumptions pertaining to the water sector. Four scenarios have been explored, combining sectoral policies, mitigation actions, and SDG and NDC targets set for India, in both water as well as energy. Table 2 presents scenario descriptions for the business-as-usual (BAU), NDC, and alternate low-carbon futures. Table C6 (appendix C) lists the policy drivers and model assumptions for each scenario.

3. Results

3.1. Impacts of energy and carbon constraints on water demand

3.1.1. Overall

Figure 3 presents the segregation of water demand among major water-intensive end-use sectors, based on energy and carbon constraints. The water demand exceeds the country's water supply limit of 1100–1197 bcm yr⁻¹ in and after 2020 for all

¹⁹ Appendix A, figure 1 provides the research framework for the current study.

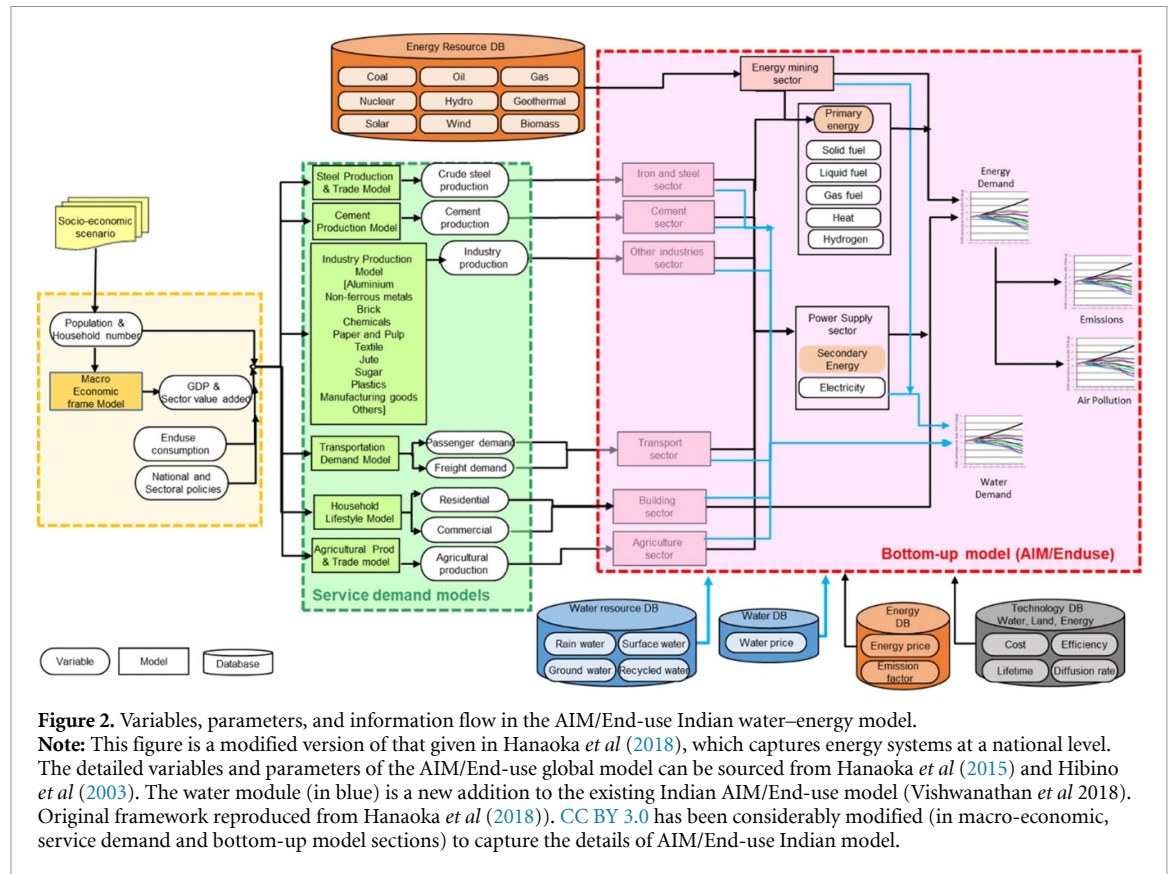


Table 1. Salient features of the AIM/End-use Indian water–energy–land model.

| Feature | Description |
|-----------------|---|
| Time frame | 2000–2050 (50 years) |
| End-use sectors | Four major demand sectors: Agriculture: more than 15 crops, including rice, wheat, other cereals, pulses, sugarcane, fruits and vegetables Power: coal (sub-critical, super-critical, IGCC), gas (OGCT, CCGT), oil (diesel), nuclear, hydro (large and small), bioenergy, solar (photovoltaics (PV), concentrated solar power (CSP)), wind, waste-to-energy, and negative-emission technologies Industry: more than 15 water-intensive industries (paper and pulp, textiles, cement, steel, fertilizer, leather, distillery), Negative emission technologies Building: includes both residential (drinking, cooking, water heating, bathing, flushing) and commercial sectors (hotels, educational buildings, and so on) |
| Resources | Fresh water (rain water, ground water, surface water from rivers, canals) and recycled water Energy (fossil fuels, renewables) Land |
| Technologies | Over 470 devices in end-use demand sector |
| Services | Over 75 services have been captured |

scenarios. The demand exceeds the supply limit²⁰ by 27% in 2030 and by 69% in 2050 under BAU, by 15% in 2030 and by 34% in 2050 under NDC, by 10% in 2030 and by 18%–25% in 2050 under low-carbon futures.

The agricultural water share decreases from 81% of the total demand in 2000 to 69% in the BAU scenario, to 66% in the NDC scenario, and to 57% in the low-carbon futures in 2050. The power sector water share increases from 6% in 2000 to 11% in the BAU scenario, to 10% in the NDC scenario, and to 15%–17% in the low-carbon futures in 2050.

The industrial sector water share increases from 5% in 2000 to 7% in the BAU scenario, to 9% in the NDC scenario, and to 10%–11% in the low-carbon futures in 2050. The building (residential and commercial) sector water share increases from 8% in 2000 to 13% in the BAU scenario, to 16% in the NDC scenario, and to 15%–17% in the low-carbon futures in 2050.

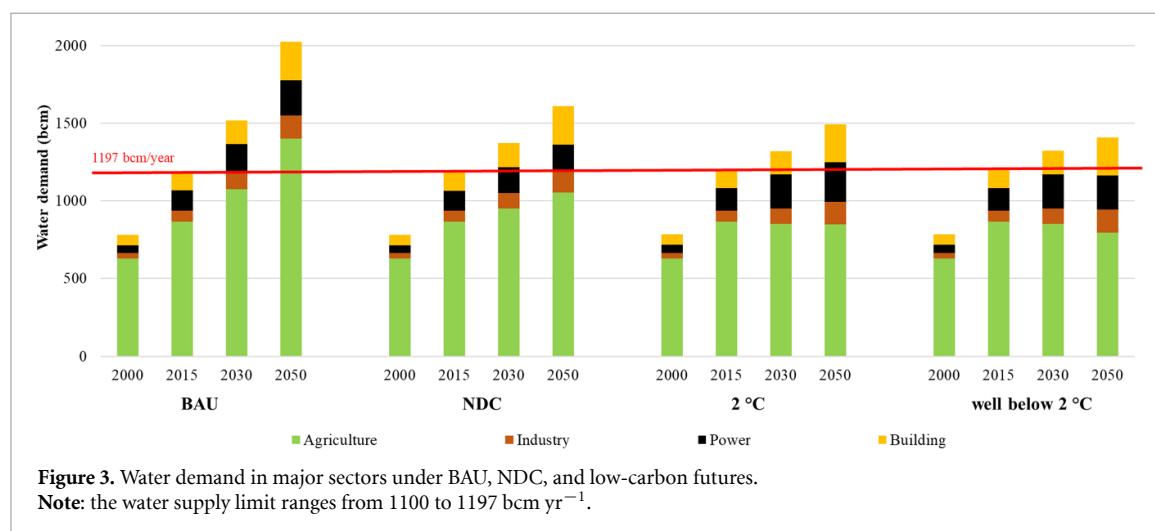
3.1.2. Agriculture

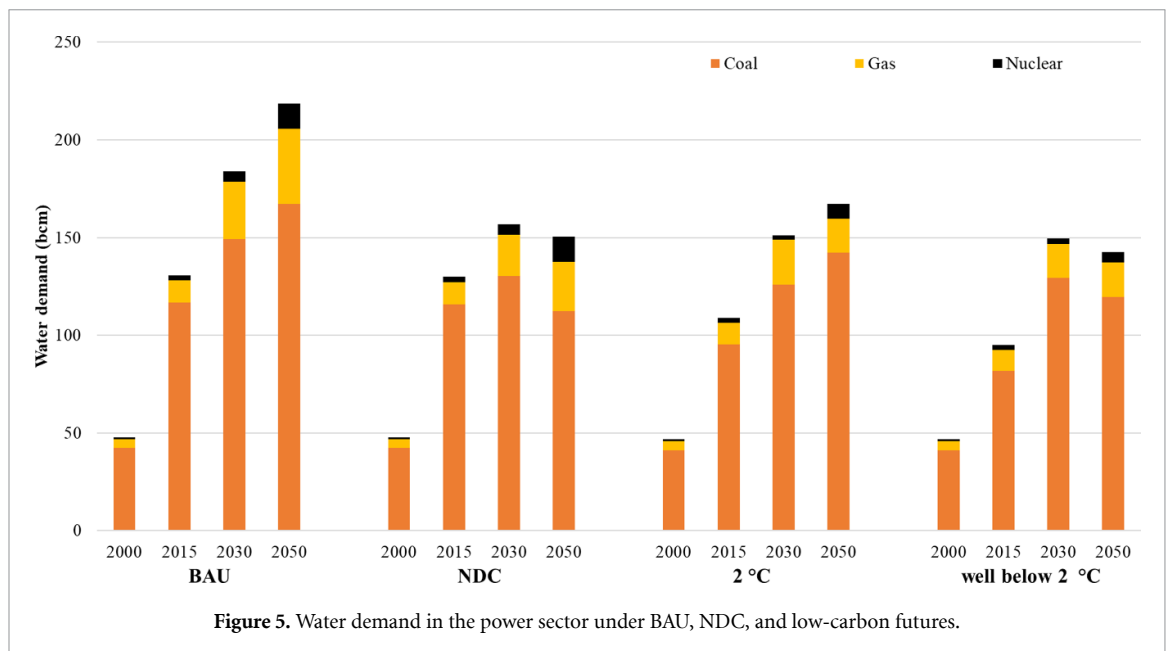
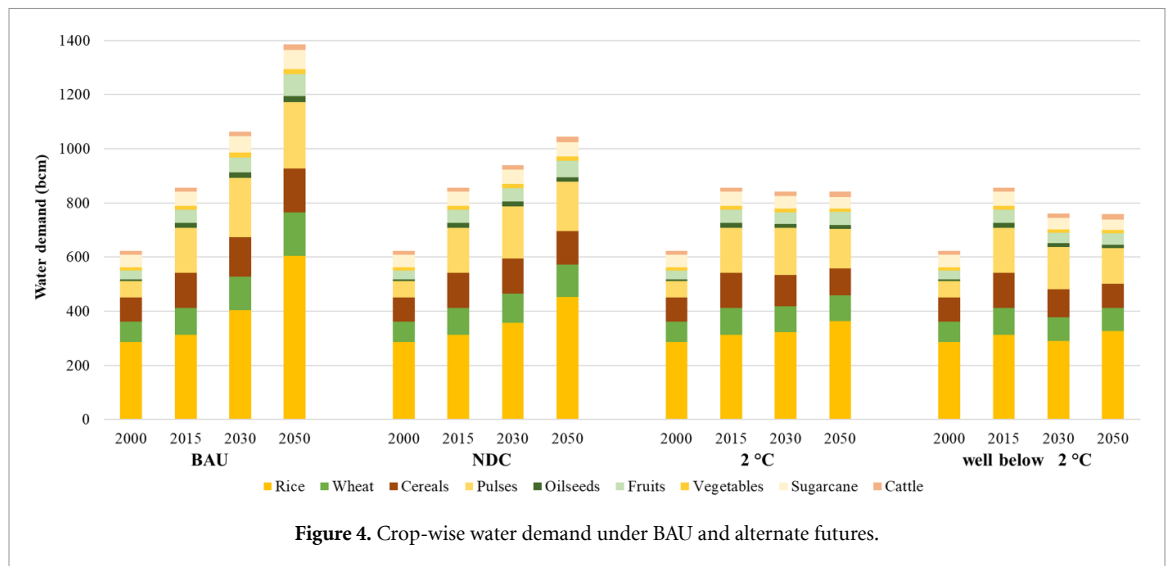
In this study, we have described WUE as the relationship between water demand and sectoral output (crops, industrial outputs, power generation and capacity). This indicator has been used at national

²⁰ The upper water-supply limit presented in the literature.

Table 2. Scenario description of current and alternate futures.

| Scenario name | Scenario description |
|--|--|
| Business-as-usual scenario | The business-as-usual (BAU) scenario assumes the continuation of existing water and energy policies under current socio-economic dynamics. These include policies put in place before the development of the climate action plan and the NDC document. The water policies did not provide quantitative targets; however, they focus on efficient use of water through conservation. Similarly, the energy policies stress energy efficiency through the Energy Conservation Act of 2001 and the Integrated Energy Policy of 2006. |
| Nationally Determined Contribution (NDC) scenario | This scenario takes into account the ongoing mitigation and adaptation strategies under the climate-change action plan, consisting of policies mentioned in the National Water Mission (NWM) in the National Action Plan on Climate Change (NAPCC 2008) and NDCs adaptation goal, which are supported by programmes such as the Integrated Watershed Management Programmes (IWMP), the scaling up of micro-irrigation (sprinkler, drip) technologies under the National Mission for Sustainable Agriculture (NMSA). The NDC scenario accounts for India’s commitment to UNFCCC in response to decisions taken at COP19 and COP20 for energy and emissions targets. The NWM establishes the target of improving the water use efficiency by 20% in the agricultural sector. In the power sector, a mandatory policy was enforced in 2017 to limit the water use to 4 m ³ MWh ⁻¹ for older thermal power plants and to 2.5 m ³ MWh ⁻¹ for newer power plants. The NDC targets highlight mitigation through reducing the greenhouse gas (GHG) intensity of the gross domestic product (GDP) by 33%–35% compared to the 2005 level, increasing the renewable power generation capacity to 40% of the total mix, and increasing the carbon sink by 2.5–3 billion tonnes (bt) by 2030. |
| Low-carbon futures (the 2 °C scenario and the ‘well below 2 °C’ scenario) | As India is committed to mitigating its emissions to meet the Paris Climate Change Agreement, the study evaluates these futures using 2 °C and ‘well below 2 °C’ scenarios. The 2 °C low-carbon scenario assumes that the carbon budget for India is estimated to be in the range of 115–136 bt CO ₂ from 2011 to 2050 (Tavoni et al 2014, Shukla et al 2015, Vishwanathan et al 2018a). The use of carbon-capture and storage technologies is at the pilot demonstration stage, and the shift to solar PV in the agricultural sector is being encouraged through regulatory and economic instruments. Carbon Capture and Storage (CCS) has been proved to be water intensive (GCI 2015, Rosa et al 2020), while the shift to solar-powered irrigation systems has been shown to use water indiscriminately (FAO 2018). Hence, the water-use efficiency targets are assumed to be 25%, based on the integration of solar PV with micro-irrigation systems (MIS). The ‘well below 2 °C’ low-carbon scenario assumes that the carbon budget for India is estimated to be less than 115 bt—CO ₂ during 2011–2050 (Vishwanathan et al 2018a). The WUE targets are set at 30% to correspond to the maximum feasible actions that can be implemented in most sectors. |
| Water-constrained scenarios (BAU, NDC, 2 °C scenario and ‘well below 2 °C’ scenario) | In addition to carbon- and energy-constrained scenarios, the water-constrained scenarios capture the stress in water supply across all sectors. Applying a water supply limit of 1197 bcm up to 2050, we have simulated the impact of water constraints (water stress) on water demand across sectors. The current model has not included rainwater water harvesting as a means of water supply, due to non-availability of data at a national level. |





(NAPCC, INDC) and international levels (SDG 6, Target 6.4) to guarantee sustainable withdrawals and freshwater supply. It should be noted that the model includes rain water, surface water (canal, river), and groundwater. In the agricultural sector, rice accounts for more than 35% of the total water demand, followed by pulses, wheat, and other cereals in all scenarios (figure 4).

In the agricultural sector, between 2015 and 2050, crop productivity is assumed to increase from 2.2 t ha^{-1} to 3.7 t ha^{-1} for rice, from 2.6 t ha^{-1} to 6.6 t ha^{-1} for corn, from 0.05 t ha^{-1} to 0.44 t ha^{-1} for pulses, and from 70 t ha^{-1} to 75 t ha^{-1} for sugarcane for the NDC and low-carbon futures (GoI 2017b). Hence, the improvement in agricultural WUE is due to a combination of higher yields and a shift to water-efficient irrigation techniques. The model simulation shows a WUE improvement from 16% to 55% for rice, from 14% to 53% for wheat and from 13% to 53% for sugarcane in 2050 for the NDC

and low-carbon scenarios, compared to the year 2000 (table D1).

The power mix shifts from diesel to energy-efficient electric and solar pumps due to the application of stringent government policies in the alternate futures. The decrease in water demand (40%–45% of 2050 BAU) in the low-carbon futures is driven by: a) a shift to efficient micro-irrigation technologies and b) the application of improved WUE measures to crops, such as rice, sugarcane, fruits, and vegetables. However, it can be seen that the current WUE is not sufficient, especially in case of extreme events, such as droughts²¹.

3.1.3. Power

Figures 5 and 6 show the water demand for the power sector and the power generation mix in

²¹ Presented and discussed under water-constrained scenarios (section 3.2 of this paper).

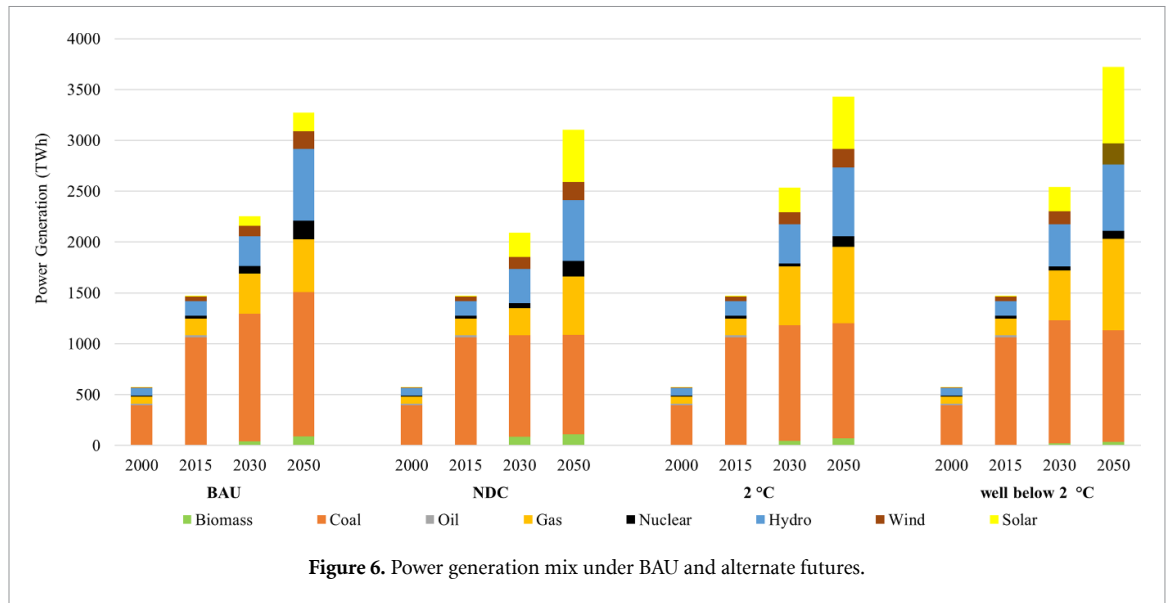


Figure 6. Power generation mix under BAU and alternate futures.

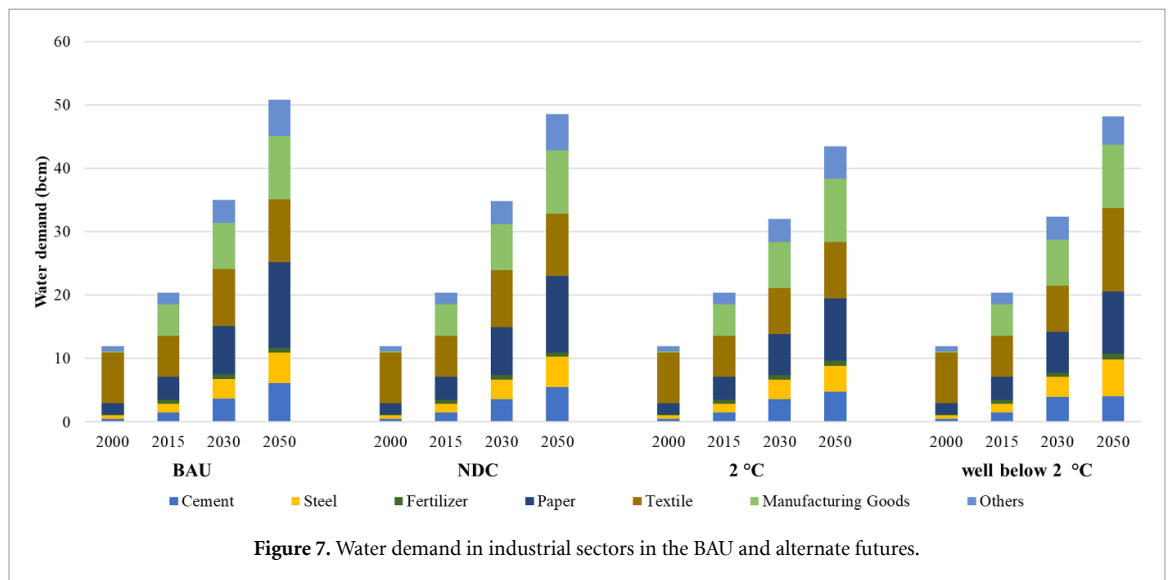


Figure 7. Water demand in industrial sectors in the BAU and alternate futures.

the BAU, NDC, and low-carbon futures, respectively. The differences between the scenarios are largely a consequence of shifts in the mix of technology generations, the selection of cooling technologies used, and the penetration rate of power production. These are endogenously determined by the model, based on sectoral electricity end-use demand, technology, and resource (energy, water) parameters.

There is a rise in overall water demand in BAU until 2050; however, a decrease in demand is observed under the NDC after 2030 due to: a) a shift to natural gas and renewables, and b) a switch from once-through cooling to efficient closed-loop and dry-cooling systems. The observed rises in water demand in the 2 °C and ‘well below 2 °C’ scenarios for 2030 correspond to an increase in CCS and Bioenergy with Carbon Capture and Storage (BECCS) in the power technology mix. The share of CCS retrofitted coal-power capacity ranges from 37% to 55%, while for

dry-cooling systems, it is 9%–10% in the low-carbon futures.

3.1.4. Industry

In the industrial sector, major water-intensive industries include textiles, paper and pulp, steel, and cement (figure 7). There is an increase in demand in the 2 °C scenario due to CCS in the steel and cement industries. However, an overall improvement is observed because of WUE (autonomous efficiency parameter), in particular, in the textile, paper, cement and steel industries, which ranges from 4% to 60%, depending on the industry and the type of technology used.

3.2. Impacts of water constraint on water demand and energy demand

3.2.1. Water demand

The application of a water-supply limit (1197 bcm) as a constraint on these water-energy systems was

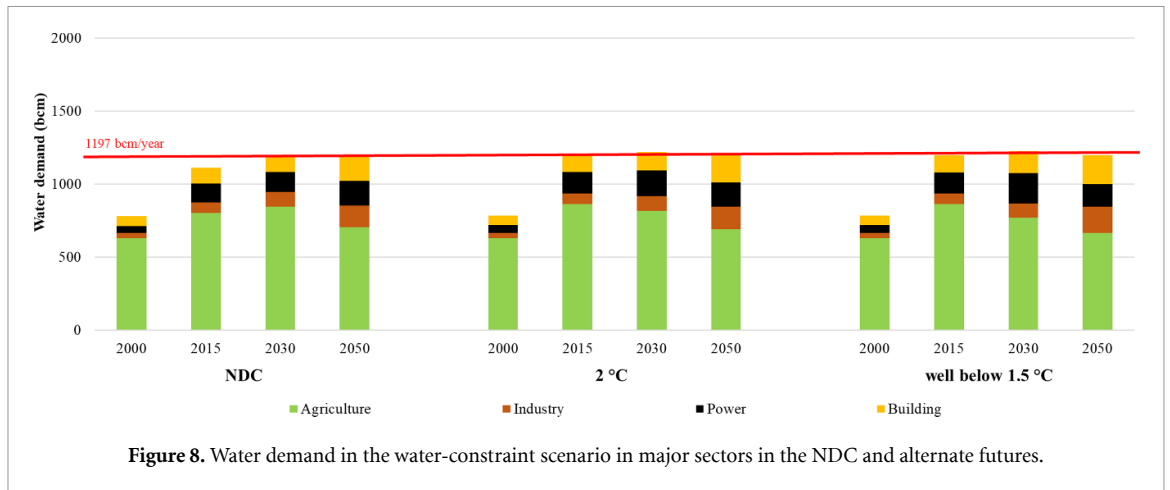


Figure 8. Water demand in the water-constrained scenario in major sectors in the NDC and alternate futures.

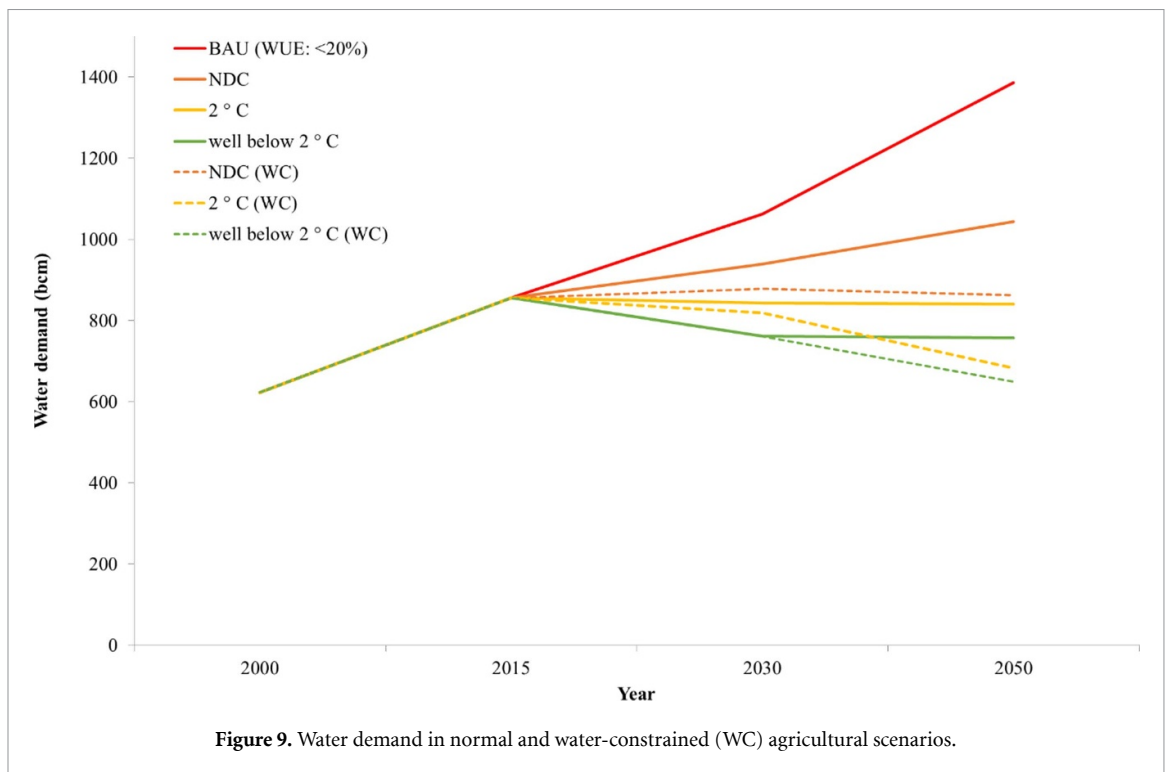


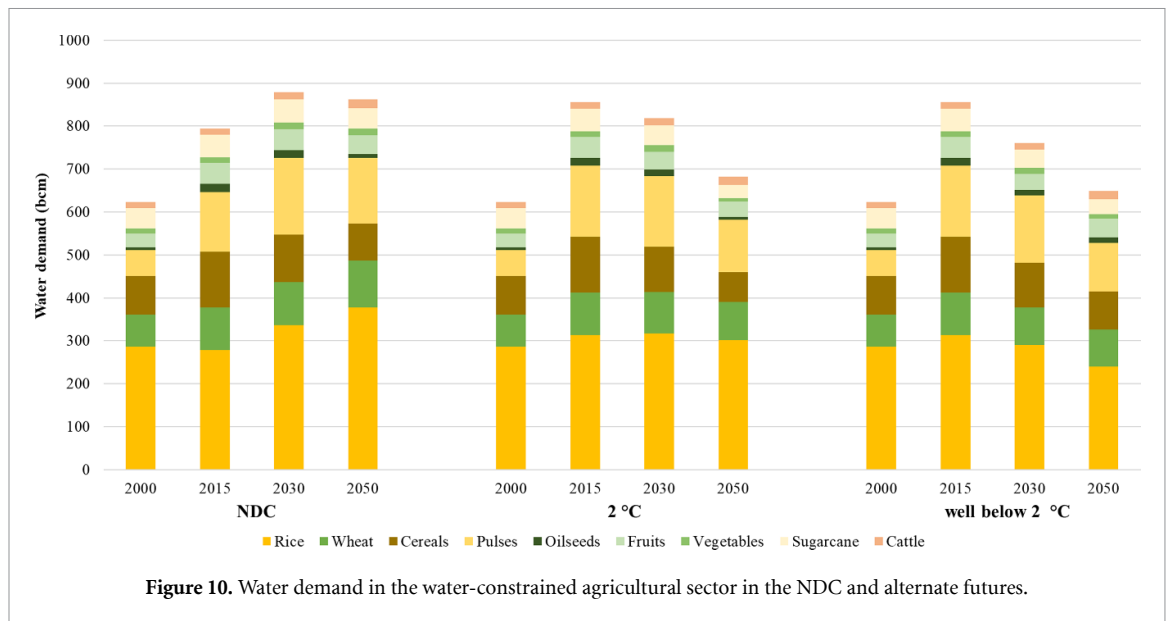
Figure 9. Water demand in normal and water-constrained (WC) agricultural scenarios.

simulated to capture the water stress at a national level and to estimate its subsequent impact on final water demand in the major water-intensive sectors (figure 8). Agriculture (figure 9) is observed to experience the greatest impact, followed by the power sector, compared to ‘without constraint’ water-demand scenarios.

The agricultural water share decreases from 80% of the total demand in 2000 to 59% in the NDC scenario, and to 56%–58% in the low-carbon futures. Rice and sugarcane will be the most-impacted crops in the water-constrained futures (figure 10). Rice, wheat, and sugarcane became more water efficient (table D2) as the model switched to solar PV combined with micro-irrigation systems and the technical autonomous efficiencies were improved over the same time frame to reduce water demand.

3.2.2. Impact on power generation

The power sector’s water share increases from 6% in 2000 to 13%–15% in the NDC and alternate futures in 2050. However, the overall water demand (figures 11 and 12) decreases by 20% in the NDC water-constrained (WC) scenario, and by around 50% in the low-carbon futures, compared to the non-water-constrained scenarios (figure 5). The water-constrained scenario impacts electricity demand in the agricultural, power and industrial sectors. During high and extreme water stress conditions, electricity generation shifts from coal to natural gas, hydro, and nuclear (figure 13). In the WC futures, the share of CCS technologies decreases to 8%–14% of the generation capacity, while that of the dry-cooling systems increases to 42%–49% in 2050. Additionally, the use of recycled water



increases by 15%–70% in the NDC and low-carbon futures.

4. Discussion

4.1. Key insights

4.1.1. The need to increase the water supply (in the non-water-constrained scenarios)

All the (non-water-constrained) scenarios depict a rise in water demand that exceeds the water-supply limit. This indicates the need to increase India's water supply by at least 200–400 bcm (figure 4) in the NDC and alternate futures through measures such as installing additional storage, recycling, desalination, and water harvesting. Long-term strategies need to be planned, developed, and implemented at national, state, and local levels in order to avoid water-stress conditions. This depends not only on the development and implementation capabilities of the state and local governments, but also consideration of the increase in haphazard land-use change due to increasing urbanization.

4.1.2. Stranded coal assets (in the water-constrained scenarios)

With more than ten partial and full drought years between 2000 and 2020, the increasing competition for water in the major water-intensive sectors has become apparent. Figure 14 presents the stranded coal capacity, in particular, coal-fired plants retrofitted with CCS and BECCS in the water-constrained scenarios in 2030 and 2050. This mirrors reality, in which acute water shortages have led to coal power-plant shutdowns (ranging from a week to six months) in many parts of India. The frequency of such occurrences will increase, especially during

extreme events, such as droughts. Stranded power-plant shutdowns have resulted in revenue losses²² for coal-based power plants. In the WC scenarios, the estimated revenue losses for these assets may amount to about 9–29 million USD per day in 2030 and 15–127 million USD per day in 2050.

4.1.3. Impacts on system costs and future investments

The agricultural sector conserves more than 80% of the cumulative water saved, while the power sector saves 7%–9% in the water-constrained scenarios. This mainly takes place through (a) incremental improvements in water-use efficiency measures and (b) transitions towards low-water, low-carbon, and/or waterless technologies. Shifting 20–25 million hectares of cultivable land to MIS will require an investment of about 700–1500 USD ha⁻¹ depending on geography, climate, soil conditions, technologies (sprinkler or drip), and crops (food grains, other crops)²³. While installing retrofitted CCS leads to a cost increase of 25%–36%, the addition of dry cooling technologies will require an investment of about 123 million USD (~11 GW) in the NDC scenario and around 300–600 million USD (~29–50 GW) in the low-carbon futures. The marginal cost of installing dry cooling technologies²⁴ in power plants to save water (m⁻³) is higher than the cost of installing MIS with solar PV in the agricultural sector.

²² Shutdown of 1 GW of coal power plant leads to a financial loss of USD 0.6–1.5 million per day (Vishwanathan *et al* 2018b).

²³ Water saved using a drip irrigation system on one hectare can be used to irrigate two more hectares of land.

²⁴ The capital cost of a dry cooling system is twice that of a closed looped system, while the operational costs are two-thirds of those of the closed-loop system.

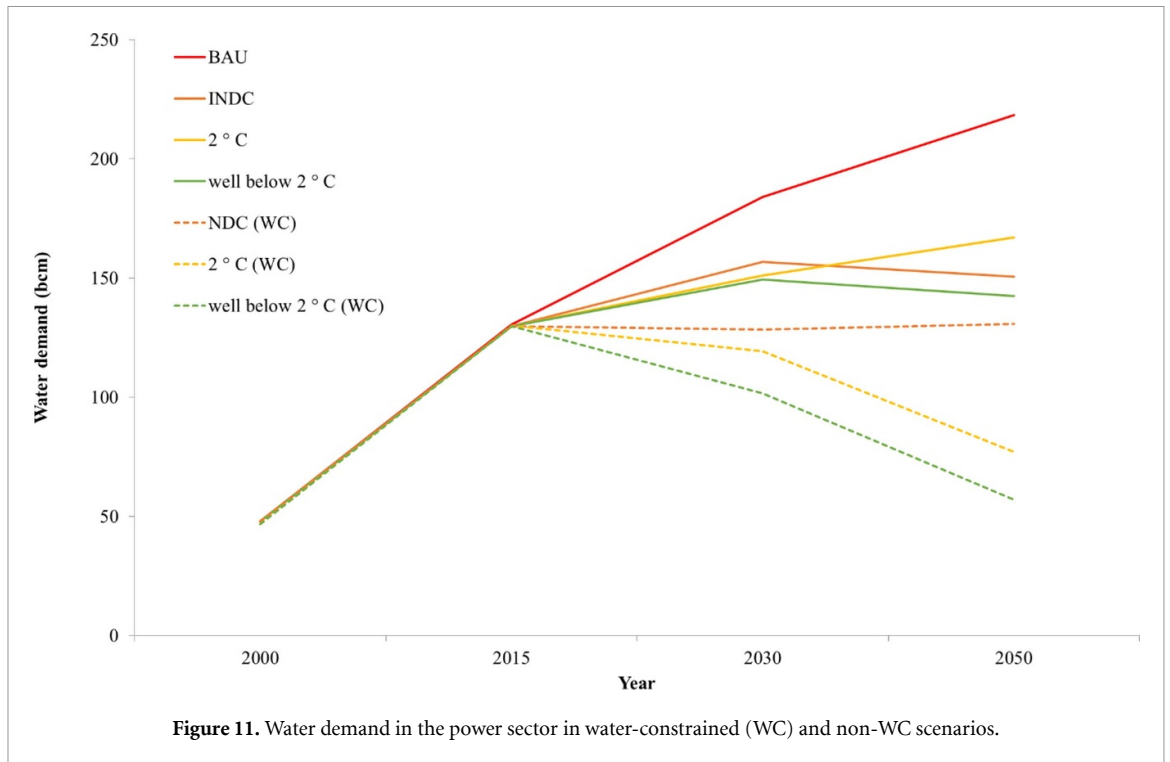


Figure 11. Water demand in the power sector in water-constrained (WC) and non-WC scenarios.

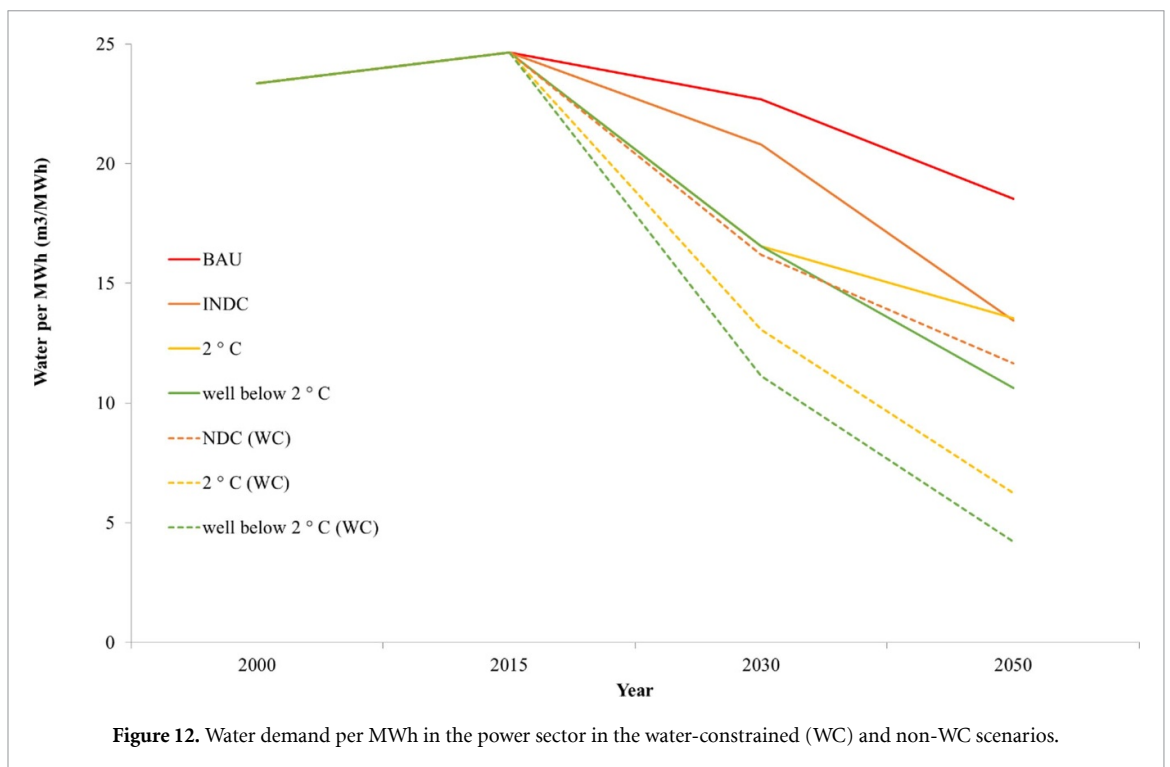


Figure 12. Water demand per MWh in the power sector in the water-constrained (WC) and non-WC scenarios.

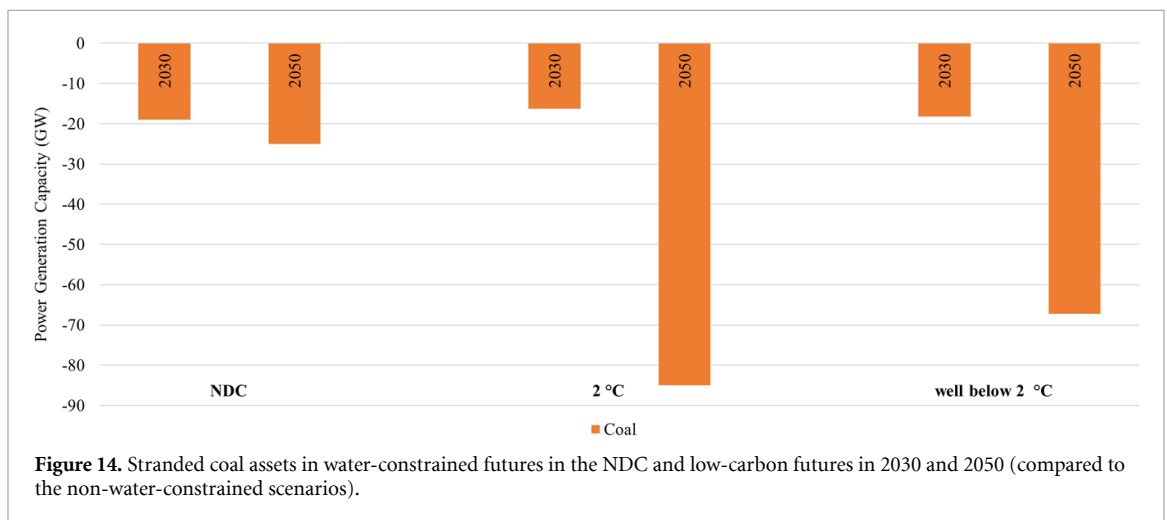
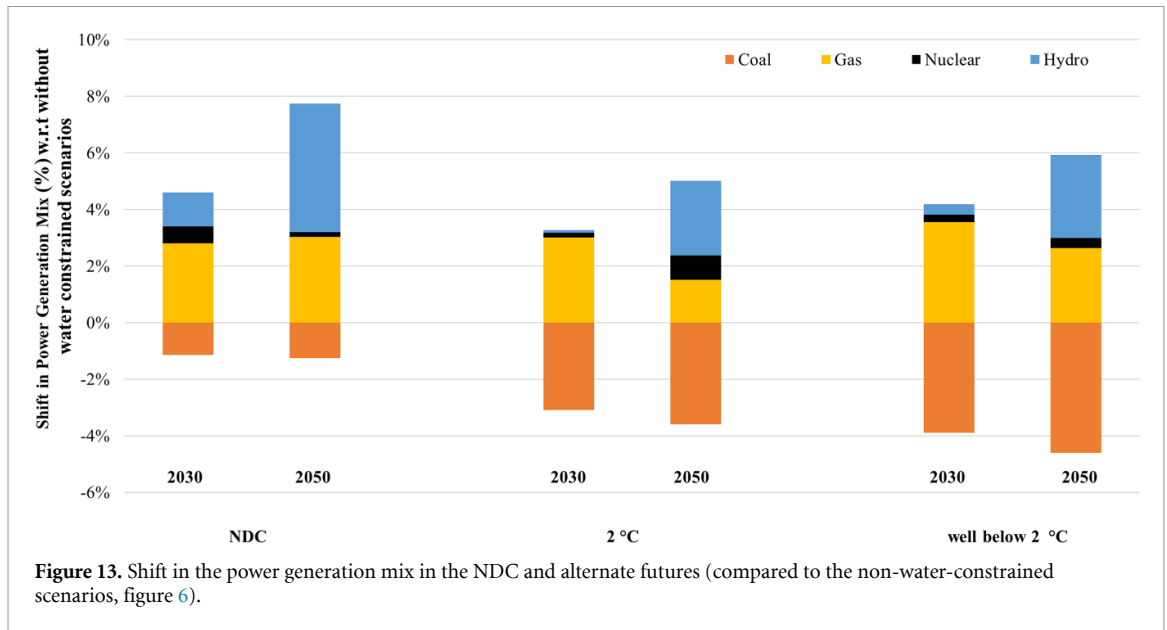
4.2. SDG-NDC linkages

The Indian government stresses the priority of development goals, followed by climate action. This study integrates water, energy, and carbon systems to model SDG-NDC linkages. Implementing NDC policies will result in the achievement of targets under SDG7, SDG11, SDG12, SDG13, and SDG15²⁵. However, this

may put stress on water resources (SDG6) without WUE measures. Achieving SDG targets can help India to meet resource-use efficiency goals, in addition to the NDC and Paris Agreement goals (as these targets are a subset of SDG13). Table 3 presents the impact

²⁵ Details of the SDG-NDC linkages used in this study are presented in appendix B. SDG 7 (affordable and clean energy), SDG 11

(sustainable cities and communities), SDG 12 (responsible consumption and production), SDG 13 (climate action), and SDG 15 (life on land).



of water (SDG 6) on the NDC and low-carbon pathways. This study shows that the NDC and Paris Agreement goals can be achieved, even under WC scenarios. The installation of CCS and BECCS in the low-carbon futures reduces emissions in the non-WC scenarios, while a shift from coal to natural gas, hydro, and nuclear power, in addition to implementing more stringent WUE measures, results in the attainment of the same decarbonization goals.

4.3. The need for integrated policy coherence

An integrated approach is co-beneficial in terms of resource efficiency in both the water and energy sectors. Current national policies, as observed in the BAU and NDC scenarios, mean that the current WUE target is not sufficient to move towards low-carbon pathways. For example, the use of solar pumps does not necessarily decrease the amount of water extracted; however, efficient use of water does conserve the total amount of energy used. This modelling exercise demonstrates that the installation of

solar PVs should be accompanied by micro-irrigation technology measures to achieve maximum resource-use efficiency. Additionally, regressive policies, such as highly subsidized electricity prices, need to be reformed to reduce the over-exploitation of water. Crop diversification needs to be promoted along with water-efficient micro-irrigation technologies, in particular, in water-scarce regions, in addition to the growth of water-scarce (or water-efficient) crops. Similarly, both central and state governments need to mandate the installation of dry-cooling systems instead of new closed-loop systems in water-stressed regions. This option will result in an overall high energy penalty and implementation costs²⁶. The low-carbon scenarios indicate that the installation of CCS and BECCS needs a more detailed local-level analysis, as it will impact future water and biomass demands.

²⁶ Implementation costs: 1.5–3 times the cost of installing the closed loop system (CEA 2012, Chaturvedi *et al* 2018). Energy penalty: 5%–10% increase in auxiliary consumption of power.

Table 3. Impact of SDG 6 (water) on NDC goals and the Paris Agreement.

| | NDC | 2 °C | Well below 2 °C | NDC (water constrained) | 2 °C (water constrained) | Well below 2 °C (water constrained) |
|---|------------------------------|------------------------------|------------------------------|------------------------------|------------------------------|-------------------------------------|
| NDC Goal 3 (Unconditional) Reduce the emissions intensity of its GDP (GHG/GDP) by 33%–35% by 2030 from the 2005 level. | 46.8% in 2030 | 37.3% in 2030 | 39.4% in 2030 | 45.7% in 2030 | 39.8% in 2030 | 42.2% in 2030 |
| NDC Goal 4 (Conditional) Non-fossil fuel share of cumulative power generation capacity to reach 40% by 2030 | 41% in 2030 (50% in 2050) | 45% in 2030 (48% in 2050) | 43% in 2030 (53% in 2050) | 44% in 2030 (54% in 2050) | 46% in 2030 (56% in 2050) | 44% in 2030 (60% in 2050) |
| Impact of the Paris Agreement goals' cumulative carbon budget (btCO ₂) | 143 | 135 | 113 | 126 | 112 | 107 |

In the industrial sector, a combination of slab water prices and a building-water market may encourage stakeholders to move towards recycling and zero-waste pathways. Energy efficiency schemes such as 'perform, achieve, and trade' can be recommended for water-intensive sectors to improve their WUE.

5. Conclusions

This study assesses India's water demand and the impacts of water-constrained and carbon-constrained scenarios on national water–energy–land–environment systems in the NDC and low-carbon futures. Using a bottom-up analysis, we studied the SDG-NDC linkages and their impacts on the water–energy nexus for India at a sectoral level. This study estimates that policy measures taken in the NDC scenario can cumulatively save up to 14²⁷ bcm of water, while low-carbon scenarios can save 20–21 bcm of water between 2020 and 2050, compared to BAU. In a WC future, the NDC and low-carbon futures can save 28–30 bcm of water. In the agricultural sector, efficient water systems can help save water by more than 80% compared to BAU for all scenarios between 2020 and 2050. In the power sector, a shift in the technology mix towards water-efficient coal, natural gas, and comparable water-free renewable technologies can cumulatively save about

7%–9% (28–30 bcm) in the water-constrained scenario. Overall, the marginal cost of installing micro-irrigation systems is lower, with the added benefits of increased crop yield (food security) in addition to water savings (water security) and energy savings (energy security).

This study emphasizes the need to increase the current water supply and the need to prioritize water use at both national and state levels. This is dependent not only on the quantity of water resources available in any region but also on how each of the sectors extracts water, to what extent, and the way that they supply, use and consume it. Water demand is likely to vary across states because: (a) each state varies in terms of its physiography, climate, and land and water resources, and (b) there are regional differences in availability, accessibility, affordability, capital investment, governance structures, and regulatory environments. These differences lead to regional variations in the availability and accessibility of water as a resource.

India will be able to achieve its SDG and NDC goals by 2030, but these targets are not enough to reach its objective to be a climate leader and contribute to the Paris Climate Change Agreement. India will need to deepen its SDG6 targets in order to match its revised NDCs and Paris Agreement goals and move towards low-carbon pathways.

Data availability statement


The data that support the findings of this study are available upon reasonable request from the authors.

²⁷ 3.7% of the 2000 annual water demand or 2.5% of the 2015 annual water demand.


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References

- Alcamo J, Döll P, Henrichs T, Kaspar F, Lehner B, Rösch T and Siebert S 2003 Global estimates of water withdrawals and availability under current and future 'business-as-usual' conditions *Hydrol. Sci. J.* **48** 339–48
- Amarasinghe U A and Smakhtin V 2014 Global water demand projections: past, present and future. (IWMI Research Report 156) (Colombo, Sri Lanka: International Water Management Institution (IWMI)) p 32
- Amarsinghe U A, Shah T, Turrall H and Anand B K 2014 India's water future to 2025–2050: business as usual scenarios and deviations. (No. Research Report 123) (Colombo, Sri Lanka: International Water Management Institution)
- Bazaz A B 2011 Managing the water-energy-climate change nexus: an integrated policy road map for India Indian Institute of Management—Ahmedabad, Vikram Sarabhai Library
- CEA 2012 Report on minimisation of water requirement in coal based thermal power stations (New Delhi: Central Electricity Authority, Government of India)
- CGWB 2014 *Groundwater Year Book* (Government of India)
- Chaturvedi V, Hejazi M, Edmonds J, Clarke L, Kyle P, Davies E and Wise M 2015 Climate mitigation policy implications for global irrigation water demand *Mitigation Adapt. Strateg. Glob. Change* **20** 389–407
- Chaturvedi V, Sugam R K, Koti P N and Neog N 2018 Energy-water nexus and efficient water-cooling technologies for thermal power plants in india: an analysis within an integrated assessment modelling framework Council on Energy, Environment and Water
- Clemmer S, Rogers J, Sattler S, Macknick J and Mai T 2013 Modeling low-carbon US electricity futures to explore impacts on national and regional water use *Environ. Res. Lett.* **8** 015004
- COP21 2015 Report of the conference of the parties on its twenty-first session
- CWC 2020 Reservoir storage bulletin. Central water commission, department of water resources, river development and Ganga rejuvenation, Ministry of Jal Shakti
- Dzebo A, Janetschek H, Brandt C and Iacobuta G 2019 Connections between the Paris Agreement and the 2030 Agenda: the case for policy coherence (Stockholm Environment Institute)
- Endo A *et al* 2020 Dynamics of water–energy–food nexus methodology, methods, and tools *Curr. Opin. Environ. Sci. Health* **13** 46–60
- FAO 2012 AQUASTAT main database Food and Agriculture Organization, United Nations
- FAO 2015 Country profile—India FAO AQUASTAT Reports. Food and Agriculture Organization, United Nations
- FAO 2017 AQUASTAT main database, food and agriculture organization, United Nations
- FAO 2018 The benefits and risks of solar-powered irrigation—a global overview Food and Agriculture Organization of the United Nations and Deutsche Gesellschaft für Internationale Zusammenarbeit
- GCI 2015 How does carbon capture affect water consumption? Global CCS Institute Insights
- Gleick P H 2000 *The world's water 2000–2001: The biennial report on freshwater resources* (Washington, DC, USA: Island Press)
- GoI 2017a Thirteenth report of the standing committee on water resources on the subject of 'indigenous and modern forms of water conservation-techniques and practices' Government of India
- GoI 2017b Production enhancement through productivity gains. Report of the committee for doubling farmers' income (Volume VIII) Ministry of Agriculture and Farmers' Welfare
- GoI 2018 SDG India index—baseline report National Institution for Transforming India, Government of India
- GoI National Water Policy 2012, Ministry of Water Resources, Government of India 2012 (http://jalshakti-dowr.gov.in/sites/default/files/NWP2012Eng6495132651_1.pdf)
- Hanaoka T and Masui T 2018 Co-benefit reductions of short-lived climate pollutants and air pollutants by 2050 while achieving the 2 degree target in Asia *J. Sustain. Dev. Energy Water Environ. Syst.* **6** 505–20
- Hanaoka T, Masui T, Matsuoka Y, Hibino G, Fujiwara K, Motoki Y and Oshiro K 2015 AIM enduse model manual AIM Interim Report (National Institute for Environmental Studies)
- Hibino G, Pandey R, Matsuko Y and Kainuma M 2003 A guide to AIM/enduse model (National Institute for Environmental Studies)
- IEA 2017 World energy outlook International Energy Agency
- India-WRIS 2012 River Basin Atlas of India
- Kapshe M, Garg A and Shukla P R 2003 Application of AIM/Local model to India using area and large point sources, Climate Policy Assessment
- Krey V *et al* 2021 Implications of the Paris agreement for achieving the Sustainable Development Goals
- Kainuma M, Matsuka Y and Morita T R 2003 Climate Policy Assessment (Japan: Springer)
- Liu J, Yang H, Cudennec C, Gain A K, Hoff H, Lawford R, Qi J, Strasser L, Yillia P T and Zheng C 2017 Challenges in operationalizing the water–energy–food nexus *Hydrol. Sci. J.* **62** 1714–20
- Macknick J, Newmark R, Heath G and Hallett K C 2012 Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature *Environ. Res. Lett.* **7** 045802
- Macknick J, Sattler S, Averyt K, Clemmer S and Rogers J 2012 n.d. The water implications of generating electricity: water use across the United States based on different electricity pathways through 2050 *Environ. Res. Lett.* **7** 045803

- McCullum D L, Echeverri L G, Busch S, Pachauri S, Parkinson S, Rogelj J, Minx J C, Nilsson M, Stevance A and Riahi K 2018 Connecting the sustainable development goals by their energy inter-linkages *Environ. Res. Lett.* **13** 033006
- Mishra V 2018 Long-term (1870–2018) drought reconstruction in context of surface water security in India *J. Hydrol.* **580** 124–228
- Mishra V and Bhatt J R 2019 *Water Resources Under Changing Climate in India: An Overview*, in: *Climate Change and Water Resources in India* (New Delhi: Ministry of Environment and Forest and Climate Change (MOEFCC))
- Mitra B K, Bhattacharya A and Zhou X 2014 A critical review of long term water energy nexus in India
- NAPCC 2008 National action plan on climate change
- NDC 2015 India's intended nationally determined contribution: working towards climate justice
- Parkinson S *et al* 2019 Balancing clean water-climate change mitigation trade-offs *Environ. Res. Lett.* **14** 014009
- Rodriguez, D J, Delgado A, DeLaquil P and Sohns A 2013 Thirsty energy. water partnership program (WPP) World Bank
- Rosa L, Reimer J A, Went M S and D'Odorico P 2020 Hydrological limits to carbon capture and storage *Nat. Sustain.* **3** 658–66
- Shiklomanov I A and Balonishnikova J A 2003 World water use and water availability: trends, scenarios, consequences *Water Resources Systems—Hydrological Risk, Management and Development. Proc. Int. Symp. (Symp. HS02b) Held during IUGG 2003, the XXIII General Assembly of the Int. Union of Geodesy and Geophysics, at Sapporo, Japan, from June 30 to July 11, 2003* ed G Blöschl, S Franks, M Kumagai, K Musiak, D Rosbjerg IAHS Publication no. 281 (Wallingford: IAHS Press) pp 358–264
- Shukla P R, Dhar S, Pathank M and Garg A 2015 Pathways to deep decarbonization in India, SDSN–IDDRI (http://deepdecarbonization.org/wp-content/uploads/2015/09/DDPP_IND.pdf)
- Srinivasan S *et al* 2018 Water for electricity: a multi-model study of future challenges and linkages to climate change mitigation *Appl. Energy* **210**
- Tavoni M, Riahi K, Jewell J, Rao N and McCollum D 2014 Limiting global warming to 2 degrees C. Policy findings from Durban Platform scenario analysis (FEEM, Milan, Italy: LIMITS Publications)
- UN 2019 World population prospects: highlights (ST/ESA/SER.A/423). population division, department of economic and Social Affairs, United Nations
- UNSDG 2015 Transforming our world: the 2030 Agenda for Sustainable Development
- Vishwanathan S S and Garg A 2020 Energy system transformation to meet NDC, 2 °C, and well below 2 °C targets for India *Clim. Change* **162** 1877–91
- Vishwanathan S S, Garg A and Tiwari V 2018b Coal transitions in India. Assessing India's energy transition options IDDRI and Climate Strategies
- Vishwanathan S S, Garg A, Tiwari V, Kankal B, Kapshe M and Nag T 2017 *Enhancing Energy Efficiency in India: Assessment of Sectoral Potentials* (Copenhagen: Copenhagen Centre on Energy Efficiency, UNEP DTU)
- Vishwanathan S S, Garg A, Tiwari V and Shukla P R 2018a India in 2 °C and well below 2 °C worlds: opportunities and challenges *Car. Manage.* **1**
- Zhang X, Obringer R, Wei C, Chen N and Niyogi D 2017 Droughts in India from 1981 to 2013 and implications to wheat production *Nat. Sci. Rep.* **7** 44552