Applied Energy 238 (2019) 78–91

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Intertwined impacts of water, energy development, and carbon emissions in China

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HIGHLIGHTS

- Integrated water-energy nexus modeling through energy technology characterization.
- Water use for energy varies by technology but energy used by water sector will grow.
- Low-carbon energy resources usually save substantial water, except inland nuclear.
- Water-energy nexus issues are greatly exacerbated at the regional and local levels.
- Systematic data review and policy implications can inform planning in other regions.

ARTICLE INFO

Keywords:
Water
Energy
Nexus
China
Model
Policy

ABSTRACT

China is rapidly expanding its alternative and non-conventional energy production capabilities. Although renewable electricity remains the focus, considerable investment has supported construction of coal liquefaction and coal gasification facilities in the desert steppes of north-central China, new coal mines in arid Inner Mongolia, and tight oil and gas extraction in the Ordos to supplement limited domestic supplies of oil and gas. At the same time, China is also facing severe drought and water scarcity in these same regions and in response has expanded various water supply technologies such as desalination and wastewater treatment. Recent government goals and measures for reducing energy and water consumption and increasing efficiency introduced in national policies, however, are poorly or not coordinated, resulting in contradictory objectives for which physical interlinkages are not well understood. This research intends to provide insights for future energy-water nexus management decisions in China, through systematic, comprehensive modeling of the water-energy nexus in China based on comprehensive, bottom-up technology characterizations. Existing studies fail to adequately characterize the details on specific technologies, nor do they comprehensively cover all energy sectors, including energy conversion for non-energy products. We developed integrated assessment (IA) capabilities to allow stakeholders to observe the tradeoffs between various technology options and policy decisions and to test hypotheses/premises in a scenario-driven environment. The results of our analysis underscore the growing interconnection between water and energy in China, the mixed trade-offs from developing low-carbon technologies such as renewable energy and inland nuclear, and the importance of water-energy nexus issues at the regional and local scales. This study lays the groundwork for an integrated resource policy planning process in China and provides an assessment methodology and research directions for future studies of the water-energy nexus. Finally, this study contributes to the water-energy nexus literature by providing systematic data and policy implications for China, where data are typically less accessible, as well as providing references for other regions in the world that are facing similar water and energy use and planning challenges.

1. Introduction

The confluence of expanding energy demand, declining water availability and quality, and increasing climate change impacts makes addressing energy and water issues together a critical global and regional need [1]. Water-energy nexus (WEN) studies focus on the use of energy to obtain water and water to obtain energy. Energy is required to extract and deliver water and to treat wastewater, and water is used

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https://doi.org/10.1016/j.apenergy.2018.12.085
Received 24 August 2018; Received in revised form 5 December 2018; Accepted 30 December 2018

in numerous ways in energy production and power generation.

At Bonn 2011 Nexus Conference, researchers with the German government expressed support for examining the interconnections among water, food production, and energy use, as well as the impacts of increasing urbanization. Since that time, this area of study has become increasingly popular in both grey literature and academia. For example, the International Energy Agency (IEA) has published several reports addressing the methodology for working on WEN topics and the status of research into the topic [2]. The World Bank has a program called "Thirsty Energy," which focuses on the water demands of power generation. The International Renewable Energy Agency (IRENA) has studied the role of renewable energy in addressing trade-offs between water, energy, and the production of food [3]. In the United States, the Department of Energy has laid a comprehensive foundation for studies of the water-energy nexus throughout the nation [1]. The National Renewable Energy Laboratory's review of operational water use for generating electricity also is widely cited [4].

China's power is fueled predominantly by coal; in 2015, coal represented about 73% of China's fuel sources for electricity production [5]. The constraints on water resources and the abundance of coal in the country have led to many studies of water and coal mining or coal thermal power [6–8]. However, policies and standards to limit the amount of water used by China's coal industry typically only address water use at individual facilities. China's policymakers do not have a comprehensive understanding of WEN, and the potential linkages among water and energy resources are often not considered in resource planning.

Most previous studies on WEN nexus usually look at the interconnection issue from one perspective, i.e., water resource impacts of energy project developments [9,10], or energy use impacts of water supply and treatment [11,12]. Many studies also tend to focus on specific production processes, such as electricity production [13], water treatment [14], desalination [15], or shale gas [16], etc. Bi-directional and systemic nexus impact studies have seldom been conducted before.

The article presents a systematic review of WEN data from China. These data and associated insights are of critical importance for policy makers because of the unprecedented scale of resource demand in China and disparity between planned development and the availability and distribution of resources to support that development. China's water availability is far below the global average, the geographic distribution of the country's water resources is highly problematic, and the country's energy production is expanding rapidly. China's plans to establish new coal mines in the arid north, shale gas operations in the arid west, major hydropower facilities in the south, and more nuclear power inland will exacerbate the country's pressing environmental and climate change challenges.

This paper addresses the technical data gaps in WEN data, as well as the gaps in modeling specific technologies such as coal power plants of different scales and boiler pressures and employing different cooling technologies. Other processes such as coal-to-liquids (CTL), coal-to-gas (CTG), and coal-to-chemicals (CTC) are also explicitly included and characterized for water impact, both directly and indirectly, including the impact of additional coal demand. Unconventional oil and gas are analyzed separately from conventional sources, and biofuel technologies include both starch-based and cellulose-based approaches. Various water supply technologies such as water treatment (of varying degrees) of and desalination technologies are covered, including emerging technologies in this area. Our research is intended to help Chinese policymakers understand precisely how national and regional energy development uses the country's limited water resources; and how much electricity the country is using to move, pump, clean, heat, and desalinate water. Our results have implications for decisions about which energy resources to pursue as well as approaches to conserving water and energy and reducing greenhouse gas emissions. The focus on the national and regional levels are important in this study, as it provides the data and policies at the scale which are useful for the decision makers to make long-term resource plans and targets, under the current centralized administrative structure in China. In addition, this study will also provide references to other regions in the world that are facing similar water and energy resources use and planning challenges.

We also aim to provide a basis for future study of barriers to effectively addressing the WEN; these include governance structures and cross-sectoral coordination challenges.

We modeled WEN in China from 2010 through 2050 using the China 2050 Demand, Resource and Energy Analysis Model (DREAM), developed by the China Energy Group at Lawrence Berkeley National Laboratory (LBNL) to simulate detailed energy end uses in all Chinese economic sectors, as well as water use in the energy sector and energy use in the water sector. The modeling methodology is first contextualized with a literature review of existing integrated modeling approaches in Section 2 and then described in detail in Section 3. Section 4 reviews water intensities for energy technologies and energy intensities for water technologies. Section 5 describes the scenarios used in our analysis, and Section 6 provides key modeling results. We summarize our results and review policy implications in Section 7.

2. Integrated model of the water-energy nexus

In their early applications, models were developed as an indispensable tool for testing new hypotheses and obtaining a better understanding of processes and interactions in a given field. Recent model development shows large gaps between various disciplines. An integrated model is designed to bridge those gaps and estimate how an action in one discipline affects other parts of the system. Some models integrate two or more disciplines, such as water, energy, climate, carbon, socio-economic conditions, technology, and policy.

The review on integrated models used to study water and energy nexus is summarized in the supplementary material Table S-1, in which models are characterized as: (1) establishing system boundaries or (2) simulating or optimizing systems. System boundary models help group related elements. For example, Market Allocation/The Integrated MARKAL EFOM System (MARKAL/TIMES) originally was an energy model, but it was expanded when a water component was added. In Table S-1, MARKAL/TIMES is annotated with a plus sign to indicate it covers more than one discipline. A simulation model shows what would happen given a certain set of conditions, while an optimization model finds the best solution for a set of conditions. A more exhaustive review of current nexus tools and models can be found in a recent paper published by [17]. Table S-1 gives a brief sequential list of the tools we examined.

The earliest WEN model identified through our literature review is the Water, Energy, and Biogeochemical (WEBMOD) model developed in 1992 by the United States Geological Survey. Like the MARKAL/TIMES model, the WEBMOD model was developed as a single-focus model to which the other discipline was appended. Increasingly, integrated water and energy models have been developed that can simulate or optimize not only natural water cycles, but also energy supply and demand. Among all tools, the combined Water Evaluation and Planning System–Long-range Energy Alternative Planning (WEAP-LEAP) model, developed by the Stockholm Environmental Institute, is one of the most commonly used integrated models for evaluating energy and water policy scenarios at various scales. The combined models exchange parameters and results, such as the amount of hydropower generated or cooling water required, and together can portray conditions in both water and energy systems. The Climate, Land-use, Energy and Water strategies (CLEWs) tools, developed by the KTH Royal Institute of Technology, expand on the WEAP and LEAP models. As far as utilization goes, the most commonly used model is the Water and Energy Simulation Toolset (WEST) developed at the University of California Berkeley. Because it can estimate life-cycle impacts, WEST has been used extensively to evaluate and quantify the economic, energy, and environmental impacts of alternative water delivery systems for California [18].

Based on previous work by the China Energy Group at Lawrence Berkeley National Laboratory, we selected the flexible LEAP tool for performing a national-scale study of China that might provide the foundation for performing regional LEAP-WEAP case modeling. Examining water and energy systems together, planners can explore how individual water or energy management choices affect the trade-offs between water and energy systems. Users can evaluate outcomes against their policy questions and priorities.

3. Modeling methodology and scope

In this section, we describe the study scope and the modeling methodology used to map water and energy consumption in China.

China 2050 DREAM was developed in 2015 by the China Energy Group at LBNL and is based on an energy and economic accounting framework for China that was created using the LEAP software platform developed by Stockholm Environmental Institute. The model has been used in many studies [19–21] to evaluate the potential impact of energy-related policies on both the demand and supply sectors.

Building on DREAM's foundation for detailed energy-system modeling, we incorporated consideration of the water sector (including water supply and wastewater). Adding water as an end-use sector enabled the model to account for energy used by water systems, which was not explicitly captured before. Also, adding water intensity coefficients to the energy supply sectors enabled us to examine water use by energy systems.

Our modeling focuses on three components of WEN: (1) energy for water, including final and primary energy consumption for all phases of water supply and water use; (2) water for energy, including water consumption and water withdrawal for primary energy production and for power and heat generation; (3) energy and water inputs for other purposes, including energy converted to non-energy products such as CTC. This study does not consider end-use demands because their energy use is included in the building and industrial end-use sector. End-user consumption such as for water heating is usually the dominant energy use in the water sector. Fig. 1 shows the model's overall accounting scope and structure.

4. Water-energy technical system review

4.1. Water use in energy systems

As shown in Fig. 2, energy systems withdraw water and use it for primary energy production, processing, and power and heat generation. Because China's energy system is dominated by coal, much of the energy sector's water use is associated with the use of coal to produce energy. For example, water used for cooling in thermal power generation represents the largest consumption of water in the energy sector. Water is also needed for mining natural gas, shale gas, coal, oil, and uranium. Oil, natural gas, and uranium require refining before they can be used as fuels, and the refining process also consumes water; for example, depending on its quality, coal may need to be "washed." Water might also be consumed to irrigate biomass fuel crops. Hydropower consumes water through evaporation.

Our review addresses data gaps at the aggregated, national level. Determining water consumption and withdrawal intensities for energy production and processing at this aggregated level is challenging because water is used in many, varying ways in energy production and because intensities depend heavily on the size and location of a project and the specific technologies adopted at individual facilities.

For information about our research to obtain data values and for

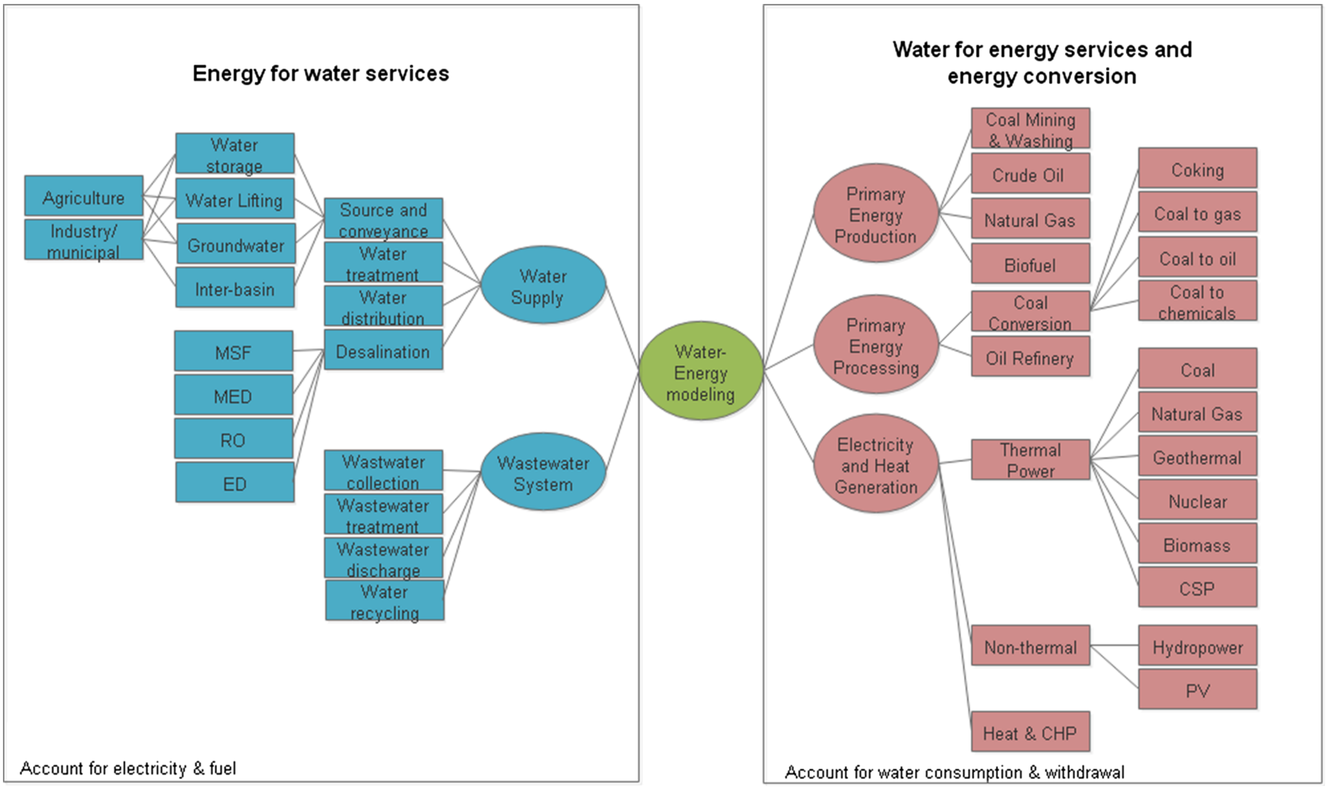

Fig. 1. Water for energy model structure. Note: MSF - multi-stage flash distillation, MED - multiple-effect distillation, RO - reverse osmosis, ED - electrodialysis, CHP -combined heat and power, CSP - concentrating solar power, PV -photovoltaic.

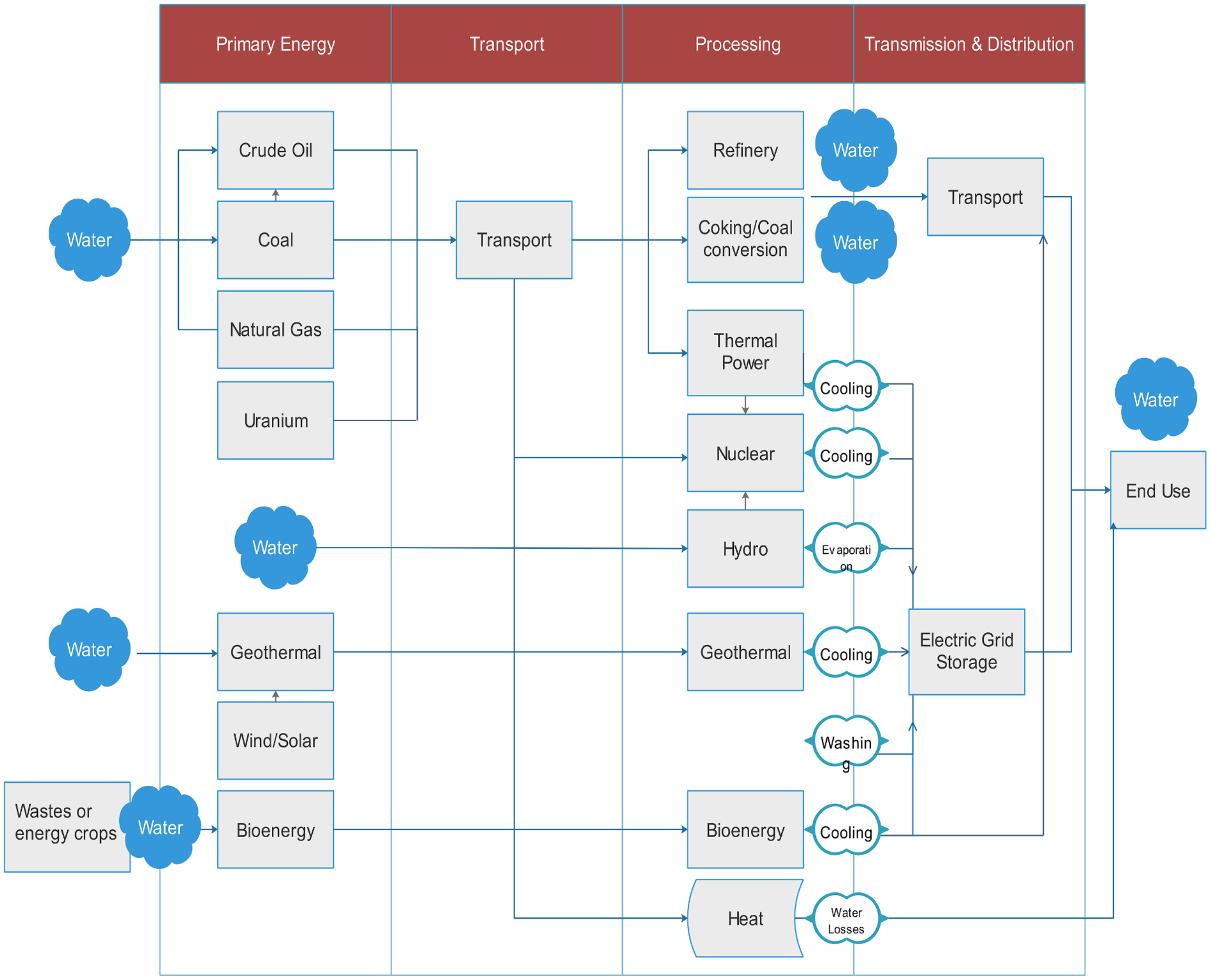

Fig. 2. Water use in energy systems.

explanations about specific intensities assigned to different types of energy production, please see the supplementary material to this article.

Figs. 3 and 4 broadly compares the water use intensity for primary energy production and electricity and heat generation in China (Fig. 3) with the global intensities (Fig. 4) determined by the International Energy Agency [2]. When comparing the two charts, note that the types and percentages of cooling technologies for thermal coal, combined heat and power (CHP), natural gas combined cycle, CSP, nuclear, and geothermal energy have been accounted for in our analysis of current practices in China. The water intensity for biofuel has been taken into account in valuing that fuel source.

4.2. Energy use in water systems

Water resources in China are scarce and unevenly distributed. Between 2003 and 2013, the average annual renewable water resource per capita was 2,015 m^3, just above the United Nations water stress level of 1700 m^3 [22].

Water systems usually comprise six components: water withdrawal, water supply (including raw water treatment), water transfer, water end use, wastewater processing, and water recycling. Water can be supplied from various sources: rivers, lakes, reservoirs, groundwater, seawater, rainwater, or reclaimed water. According to China's annual water resource report [23], agriculture end uses consume the most

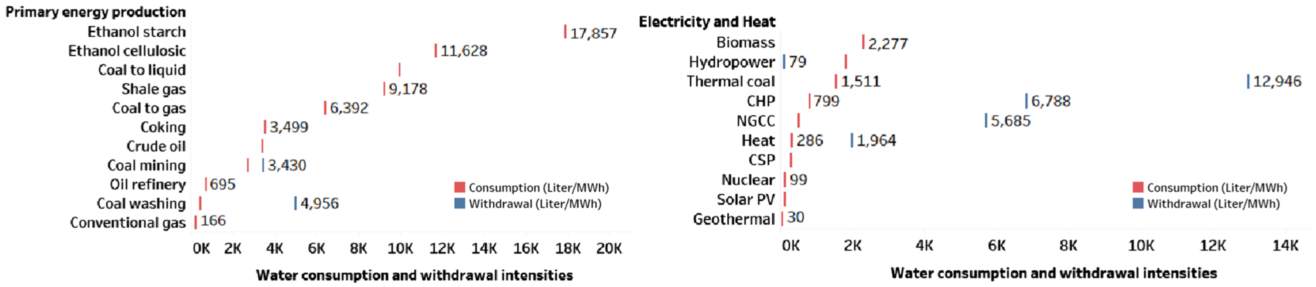

Fig. 3. Freshwater use intensities of primary energy production (left) and electricity and heat generation (right) in China, 2014 (Note that the water consumption and withdrawal intensities for the following energy technologies and processes are assumed to be the same: Ethanol starch, Ethanol Cellulosic, Coal to liquid, Shale gas, Coal to gas, Coking, Crude oil, Oil refinery, Conventional gas, Biomass, CSP, Nuclear, Solar PV, Geothermal). Source: Published scientific papers and reports and policy documents. Specific references and values can be found in the Supplementary Materials Table S-2

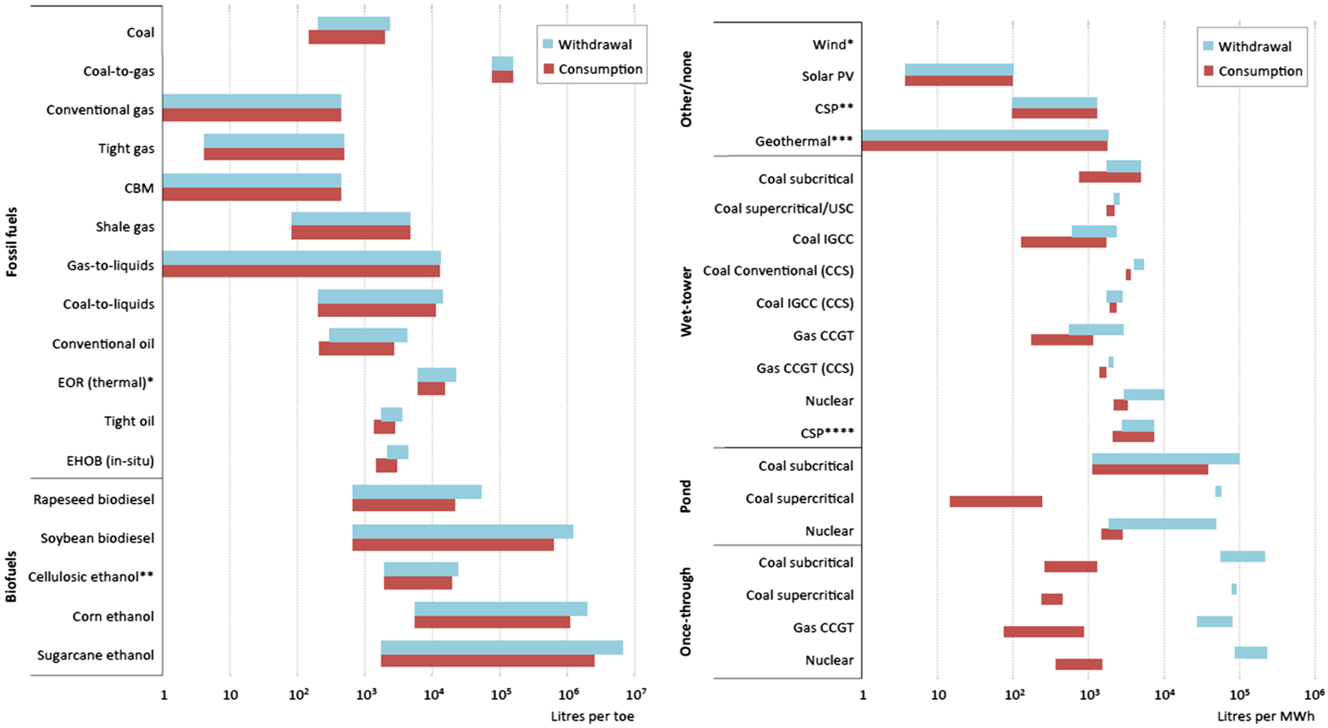

Fig. 4. International water use intensity values for primary energy production (left) and electricity and heat generation (right). Source: [2]

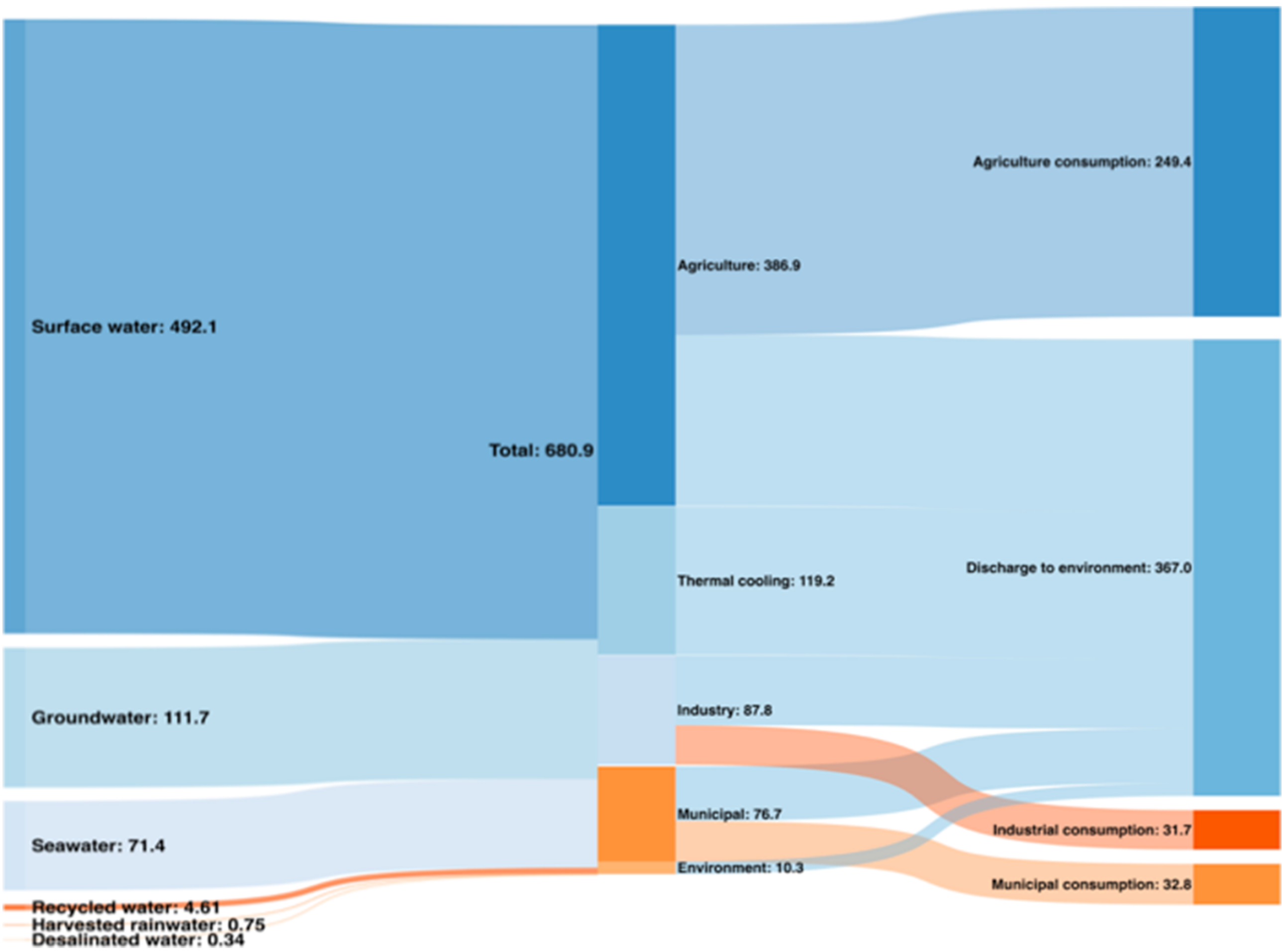

Fig. 5. Sankey diagram of China's water supply and consumption, 2014. Unit: cubic kilometers (km^3).

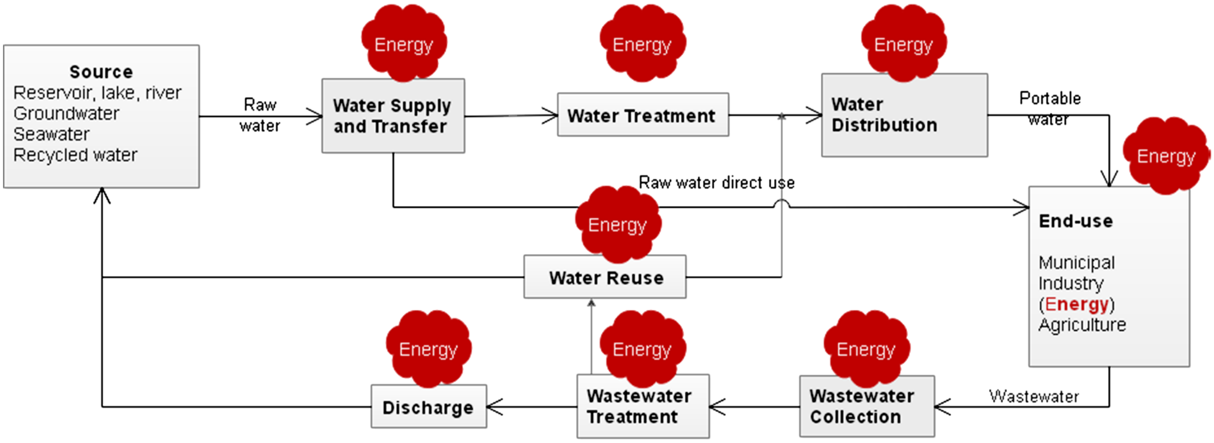

Fig. 6. Energy use in water systems. Revised based on [24,25].

water (77.4% of total consumption). Municipal and industrial water uses account for about 10.2% and 9.8% of consumption, respectively. Fig. 5 shows the water resource Sankey diagram for China.

Energy is needed to pump water from sources such as groundwater wells and reservoirs to water utilities for treatment and to distribute treated water to end users. Energy is also needed to collect, treat, and discharge wastewater. Increasingly, energy is needed to treat water to various standards so that it can be recycled and redistributed to end users. The energy needed for each of these processes is affected by distance, elevation, treatment standard, and climate and other factors (Fig. 6).

Among water services in China, seawater desalination, water reclamation, and inter-basin water transfer are the most energy intensive (see Table S-2 in the supplementary material). Because desalination technologies such as multiple-effect distillation (MED) and multi-stage flash distillation (MSF) require thermal energy, many MED plants are built near thermal power or steel plants to take advantage of waste heat. Water reclamation is also energy intensive; significant energy can be consumed to distribute reclaimed water to end users. The energy consumed by inter-basin water-transfer projects depends strongly on the distance and difference in elevation between the source and end users. In this study we aggregate the energy intensities of inter-basin water-transfer projects at the national level for analytical purposes although the energy intensity of water services can differ significantly among regions and localities.

The energy consumed by water services in China (Fig. 7) differs in some ways from typical international levels (Fig. 8). Treating raw water appears to consume more energy in China than elsewhere. This might be explained by different accounting boundaries applied in studies. For instance, electricity usage data in China are obtained at the utility meter and therefore include some of the energy consumed to obtain, pump, and discharge water. The different scopes of various studies and the variety of technologies and standards adopted for handling wastewater make it challenging to compare the energy intensities of wastewater systems. In general, the energy intensity of wastewater treatment is much lower in China than in other countries, primarily because China employs very little tertiary treatment (only approximately 8% as of 2011) [26]. The energy used for wastewater collection and discharge in China might also be underestimated because our current study applied average international values. The average energy intensity for inter-basin water transfer in China (an aggregated value of 0.815 kW-h [kWh]/m^3) represents only the water that is pumped by the eastern

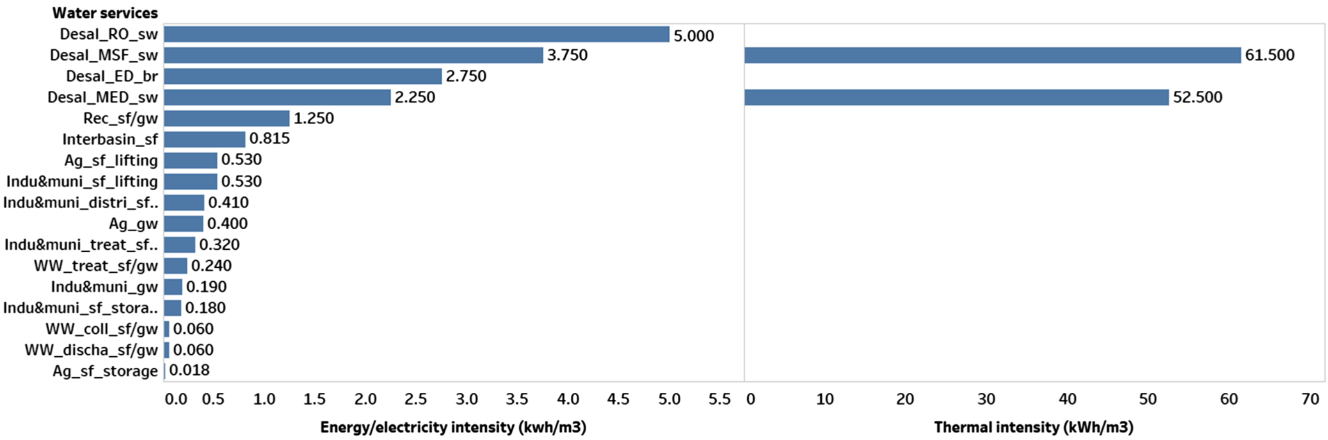

Fig. 7. Energy intensities of water services in China, 2014 (Desal_RO_sw - reverse osmosis desalination, Desal_MSF_sw - multi-stage flash distillation desalination of seawater, Rec_sf/gw - Wastewater recycling (includes both surface water and groundwater); Interbasin_sf – inter-basin surface water transfer, Ag_sf_lifting - surface water lifting for agricultural use, Indu&muni_sf_lifting – surface water lifting for industrial and municipal uses, Indu&muni_distri_sf - surface water distribution for industrial and municipal uses, Ag_gw - groundwater pumping for agriculture, Indu&muni_treat_sf - surface water treatment for industrial and municipal uses, WW_treat_sf/gw - wastewater treatment, Indu&muni_gw - groundwater pumping for industrial and municipal uses, Indu&muni_sf_stora - surface water storage for industrial and municipal uses, WW_coll_sf/gw - wastewater collection (includes both surface water and groundwater); WW_discha_sf/gw - wastewater discharge (includes both surface water and groundwater); Ag_sf_storage - surface water storage for agriculturedesalination of seawater, Desal_ED_br - electrodialysis desalination of brackish water, Desal_MED_sw – Seawater multiple-effect distillation). Source: Original research by authors, published scientific papers and reports as cited in Supplementary Materials Table S-3.

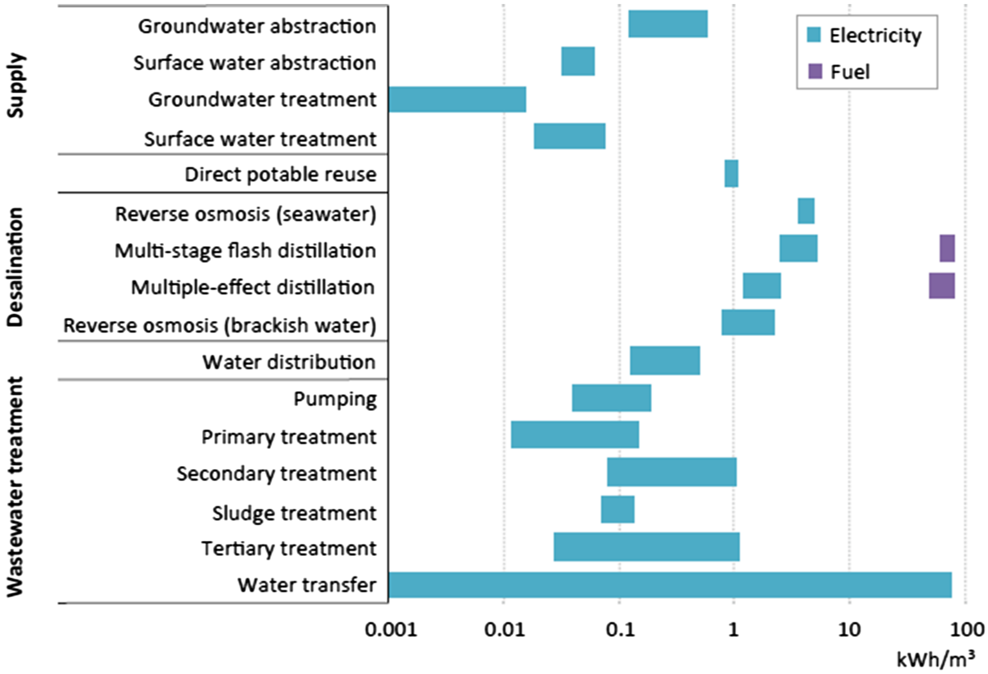

Fig. 8. International energy intensity values for various water-sector processes. Note: The water transfer category includes wastewater collection, treatment, and discharge or re-use. Source: [2].

route because the central routes primarily use gravity. For comparison, the energy consumed by the California State Water Project ranges from a low of 676 kWh/acre-foot (0.55 kWh/m^3) to a high of 3236 kWh/acre-foot (2.62 kWh/m^3), depending on where the water is delivered [27].

5. Scenario analysis

To evaluate the potential effects on China's national WEN of coordinating water and energy policies, we take into account key existing energy and water plans and policies. Based on this information, we develop policy scenarios for water and for energy resource planning. Key plans and policies include the nation's medium and long-term renewable energy plans, the "Three Red Lines" policy that limits total water consumption, water efficiency and water quality requirements that must be met by 2030, and energy and water efficiency targets specified in the latest Five-Year Plans (FYPs). We compared these policy scenarios to a reference scenario of no policy change. Fig. 9 shows the hierarchical structure and key assumptions of the eight energy-policy scenarios and seven water-policy scenarios that we studied.

5.1. Energy-policy scenarios

The first set of eight scenarios evaluates the implications of energy policy pathways for the water sector's contribution to climate change. We examine impacts on water resources and carbon dioxide (CO_2) emissions.

Energy Policy Scenario 1, the reference energy-policy scenario, projects a continuation of conditions from the base year 2014 and assumes that all energy policies in place today will continue to affect the energy demand, supply, and transformation sectors. The reference scenario also assumes that alternative energy production (e.g., coal conversion and shale gas production) is frozen at today's levels, based on the latest reported production levels.

Energy Policy Scenario 2 increases renewable and alternative energy supplies, including increased coal conversion and shale gas production. This scenario assumes that by 2050 China adopts the maximum feasible share of today's commercially available, cost-effective energy-efficiency technologies while maximizing the adoption of cleaner fossil fuels (e.g., natural gas) in place of dirtier fossil fuels such as coal and coke. More details about the sector-specific assumptions for adoption of cost-effective technologies and fuel switching can be found in *Reinventing Fire: China Executive Summary* [28,29].

For coal conversion processes, we obtained projections through 2020 for production of coal to liquid and coal to gas from the 13th FYP for the coal chemical industry [30]. Projections through 2050 were based on the reference scenario in a report by the Natural Resources Defense Council (NRDC) [31]. We projected increasing shale gas production in China through 2050 based on the multi-cycle Weng model that we developed [32]. Based on the Weng model, exogenous capacity of shale gas production is projected to grow from 1.21 million tonnes of oil equivalent (Mtoe)/year in 2014 to 180.4 Mtoe/year by 2050.

Energy Policy Scenario 3 starts with the conditions defined in Energy Policy Scenario 2 and incorporates limited future coal conversion resulting from the 2020 coal consumption cap announced in the 13th FYP. The lower production levels projected for 2050 are based largely on the Coal Cap Scenario in the NRDC report [31].

Energy Policy Scenario 4 also starts with Energy Policy Scenario 2′s renewable and alternative energy supply assumptions and incorporates improved water efficiency for all coal conversion processes. Under Scenario 4′s assumptions about enhanced water efficiency, water consumption intensities for coal conversion processes decrease from 2014 through 2030, at which time the intensities have achieved the advanced levels in the proposed new standards and remain constant thereafter.

Energy Policy Scenario 5 builds on Scenario 2 by including the potential impact on China's water resources of expanded inland nuclear power generation. New nuclear capacity is characterized as inland or coastal based on proposed plant locations. We project that, in 2050, 62% of the total installed nuclear capacity will be from inland nuclear plants that consume significant fresh water and greatly increase freshwater withdrawal intensities. The water consumption and withdrawal intensities for nuclear power generation are extrapolated from 2015 to 2050 to reflect an increasing shift toward inland nuclear.

Energy Policy Scenario 6 builds on Scenario 2 by considering the potential impact of improved water efficiency in shale gas extraction and production from 2014 through 2030. All shale gas production is

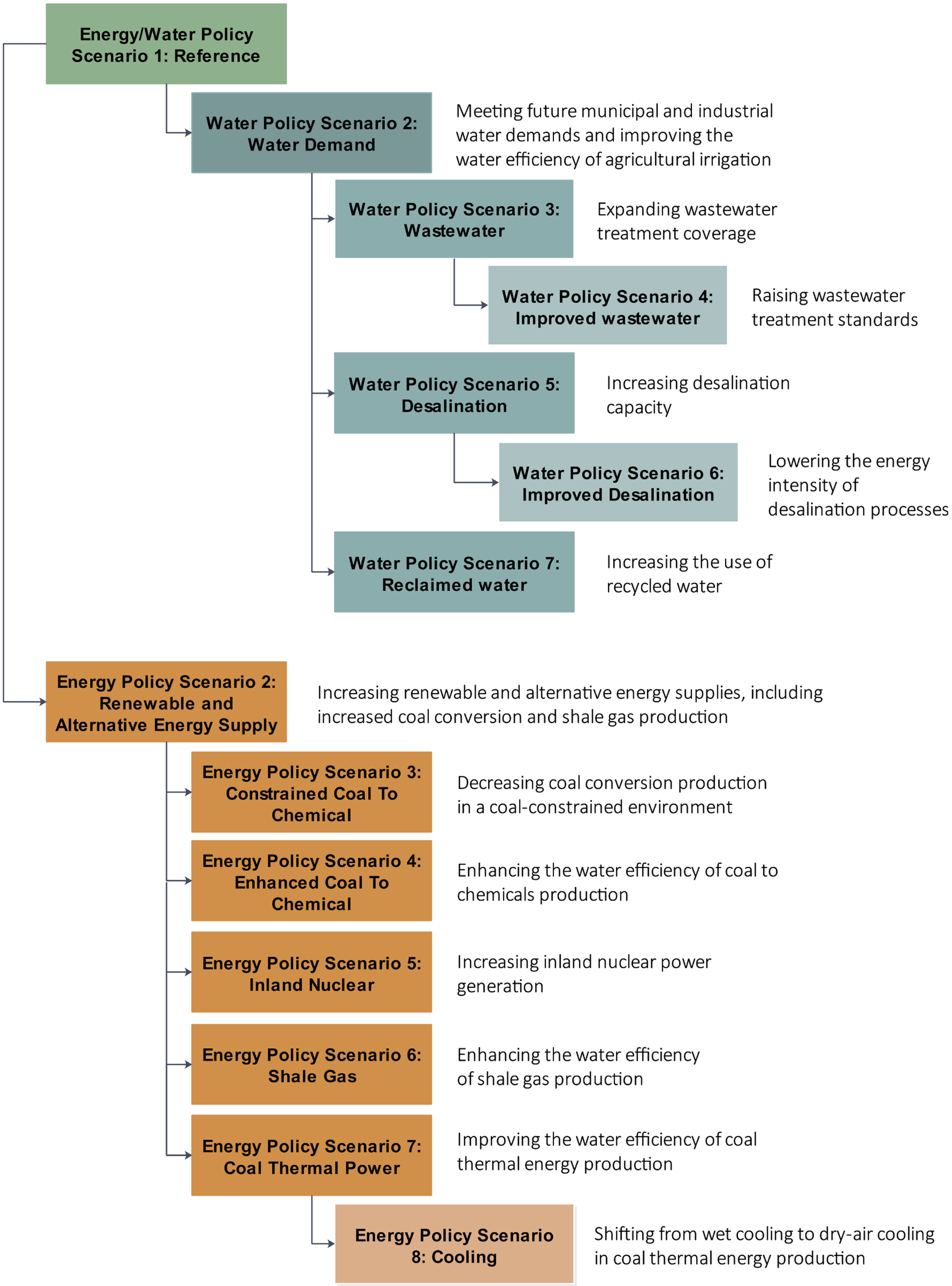

Fig. 9. The hierarchical structure and key assumptions of our water- and energy-policy scenarios.

assumed to incorporate advanced water efficiency measures and to minimize water withdrawal intensities by 2030 instead of the intensities being frozen at current levels.

Energy Policy Scenario 7 builds on Scenario 2 by evaluating the impact of improving the water efficiency of coal thermal power generation. We adopted the average water use intensity for the base year based on the average level requirements presented in water use standards for fossil-fuel-fired power production (GB/T 18916.1-2012) [33]. We assume that, by 2030, the water consumption and withdrawal intensities will achieve the advanced levels specified in the standard. The type of cooling technology share is assumed to be constant.

Energy Scenario 8 builds on Scenario 7, adding assumptions that enable us to evaluate the potential energy and water impacts of an increasing shift toward dry cooling in coal thermal power generation. Shifting from wet to dry cooling in new coal thermal power plants would reduce water withdrawal and consumption but with the trade-off of lower thermal efficiency. Based on previous studies, we assume that thermal efficiency decreases by an average of 2% [34] in a shift from wet to dry cooling technology. For scenario 8, we assume that the share of coal thermal capacity that uses dry cooling will increase by 2% by 2030, taking into consideration the limited growth of new power plants in China in response to the focus on power sector de-carbonization.

5.2. *Water-policy scenarios*

The water-policy scenarios are designed to evaluate the impacts of water policies on energy consumption. ***Water Policy Scenario 1*** is the baseline or reference scenario, in which water demand and wastewater intensities are frozen at 2014 levels.

Water Policy Scenario 2 enables us to examine the water demand related to improved agricultural practices and increasing urbanization as reflected in the growth of municipal and industrial water use. Water Policy Scenario 2 assumes improved efficiency in storing and lifting surface water and pumping groundwater for irrigation. We use the term “irrigation efficiency” to describe the losses that occur throughout all phases of the water transport and distribution system for agricultural irrigation [35]. We base Water Policy Scenario 2 on China’s 13th FYP for a water-efficient society, which calls for raising the national water efficiency of irrigation to 0.55 by 2020 and to 0.6 by 2030 [36]. We assume that water-use efficiency will continue to improve, reaching 0.65 by 2050.

To develop assumptions regarding future water demand for municipal and industrial uses, we relied on external projections [37,38]. As China continues to urbanize and develop, water demand from these sectors is expected to grow although the water intensity per industrial gross domestic product (GDP) will decline. According to the national integrated plan for water resources [38], water withdrawal per industrial GDP is expected to decline to 40 $m^3/10^4$ yuan by 2030, and total industrial water withdrawal allocation is expected to be 171.8 billion m^3. For the municipal and agriculture sectors, the withdrawal allocations are 102.1 billion m^3 and 407.8 billion m^3, respectively. We assume that the energy needed for inter-basin water transfer remains the same as in the base year, 2014.

Water Policy Scenario 3 builds on the Scenario 2, adding the assumption that the share of wastewater receiving treatment increases from 69% in 2014 to 95% in 2030 and 100% by 2050 [39]. The energy intensity of wastewater treatment is assumed to be frozen at the 2014 level. Because the energy needed to reclaim water is incorporated in the Water Policy Scenario 7 below, the volume of recycled water is deducted from the volume of wastewater to avoid double counting.

For the sub-scenario that involves improved wastewater treatment standards (***Water Policy Scenario 4***), we assume that, in 2014, 90% of treated wastewater undergoes secondary treatment, and 10% undergoes tertiary treatment [40]. By 2050, 60% of treated wastewater is assumed to undergo secondary treatment and sludge treatment (which requires an additional 0.1 kwh/m^3) [2]. In addition, 40% of treated wastewater is assumed to undergo tertiary or other advanced treatment [40]. The energy intensity is assumed to be that of the typical U.S. municipal treatment level 0.43 kwh/m^3 [41].

Water Policy Scenario 5 expands the demand in Water Policy Scenario 2. By 2020, China's desalination capacity is assumed to reach the 13th FYP target [42]. The International Water Association predicts that global desalination capacity will double by 2030; therefore, we assume that China's 2030 desalination capacity will be double the 2020 level, and that the capacity in 2050 will be triple that of 2020. The trend in deploying desalination technologies is very uncertain; we assume that the new desalination capacity adopts reverse osmosis (RO) and MED systems at their current market shares of 35% and 65%, respectively.

For the sub-scenario in which the energy intensity of seawater desalination declines (***Water Policy Scenario 6***), we assume that the decrease will follow the trend developed from our literature review. For instance, the energy intensity of seawater desalination using RO will decline from 5kwh/m^3 in 2014 [43] to 3 kwh/m^3 in 2020 and to about 2.1–2.4 kwh/m^3 by 2035 [44]. For MED, we assume that the energy intensity (including both electrical and thermal energy) declines from 55kwh/m^3 in 2014 [15] to 15 kwh/m^3 by 2030 [43].

Finally, ***Water Policy Scenario 7*** builds on the water demand in Water Policy Scenario 2 so that the volume of recycled water depends on an increasing rate of recycling even though the volume of treated wastewater remains the same. For the year 2020, we use the 13th FYP target for recycled water [39]. We assume that the rate of recycling (the ratio of recycled water to the volume of treated wastewater) increases from the current 10% to 20% in 2030 and to 30% in 2050.

6. Results

We incorporated the assumptions and methods described above into China 2050 DREAM to obtain national results for the base year (2014) and for each scenario in terms of energy consumption, CO_2 emissions, and water use impacts on both the energy and water sectors. On the regional level, we calculated similar results for each province for only the base year of 2014 based on province-specific inputs and/or intensities developed through our research collaboration and literature review. The sum of the provincial results were also compared and calibrated to the national total for 2014 from our national model results to maintain consistency.

6.1. *Base year*

6.1.1. *National results*

Table 1 shows the water and CO_2 emissions from the energy production and conversion sectors under the base-year scenarios we evaluated using China 2050 DREAM. It also includes the reported agricultural, industrial, and national levels for comparison. In this study, the entire energy production and conversion sector accounts for about

Table 1
National energy, CO_2, and water impacts results and comparison (2014).

	Energy Production and Conversion	Water	Agriculture	Industry	Residential	National total
CO_2 emissions missions (MMton)	5704.2 (direct emissions)	134.5 (direct and indirect emissions)				10,050.6 (direct and indirect emissions)
Water consumption (km^3)	17.65		249.4[a]	31.7[a]	32.8[a]	322.2[a]
Water withdrawal (km^3)	79.4		386.9[a]	87.8[a]	76.7[a]	680.9[a]
Final energy consumption (TWh)		210.7		15,573 (industrial hot water 604.1[b])	2590 (residential hot water 350.6[b])	25,540
Primary Energy Consumption (TWh)		520.1		22,107	3927	37,170

[a] [23].
[b] [45].

56% of China's total industrial water consumption. Compared to the total for industry, our estimate of water withdrawal for the energy production and conversion sector seems to be on the high end. This might be the result of an accounting boundary difference for water withdrawal; in Chinese statistics, the term “water use” is often applied interchangeably for both “water consumption” and “water withdrawal.” The power sector represents a major opportunity to reduce water and climate impacts, e.g., it is responsible for 40% of total water consumption, 56% of total water withdrawal, and 59% of total CO_2 emissions in China. Among all sectors, agriculture is still the dominant water consumer (77%); The energy production and conversion sectors together account for about 5% of total national water consumption.

In 2014, the water sector represented only about 0.8% of China's overall energy consumption and about 1.4% of total national primary energy consumption. Similarly, the CO_2 emissions from energy use related to the water sector represented about 1.3% of the national total. Although these percentages are small, water-sector energy use is trending higher. [45] showed that China’s water supply increased by 8% from 2005 to 2014, but the associated energy use increased by 25% as a result of increased groundwater pumping and inter-basin water transfers. When the water end-use sector is excluded, obtaining and conveying water consumes the most energy and emits the largest amount of CO_2. Wastewater treatment and water distribution to end users use the next-largest amounts of energy. The final energy consumption by the water end-use sector alone accounts for about 3.7% of national final energy consumption in 2014.

More details on the national results can be found in Figs. S-1 to S-6 in the supplementary material.

6.1.2. Regional results

The national results indicate that coal-sector activities have the greatest impacts on the water sector. At the same time, 80% of the nation’s coal reserves are located in 14 coal areas where the water resources in the associated river basins (including the Yellow, Hai, Huai, and Liao Rivers) only provide about 13% of total national water supply. The water use in some of these 14 regions (e.g., western Inner Mongolia, Eastern Ningxia, Eastern Shanxi, Xinjiang, and Lianghuai) approaches or exceeds the 2020 Red Line Limit. For more details, see [45] and [46]. Limited water resources are affecting energy plans for the regions, as are air quality requirements, the need to mitigate climate impacts, and safety-related concerns. We will study the conflicts between energy and water resources at the regional level in a related research project that we plan to undertake next year. In the supplemental material (Figs. S-7 to S-8), we show water resource impacts from energy production and conversion, by province, to lay the groundwork for our future regional study.

In many provinces, inter-basin water transfer projects and groundwater pumping are the dominant energy consumers in the water sector, for example, Shandong, Jiangsu, and Anhui provinces, which all receive water supplies via the south-north inter-basin project. Where surface water is limited, groundwater pumping is common. For example, significant energy is consumed for groundwater pumping in Hebei, Xinjiang, Heilongjiang, and Neimenggu (“Inner Mongolia”) provinces. Fig. S-9 in the supplemental material provides a basis for studying the energy implications of choices that could be made regarding water services at the regional level.

In general, despite the significant energy consumed by both inter-basin water transfers and groundwater pumping, the energy consumed by the water sector (excluding water consumed by end users) is negligible at both the national and regional levels. At the provincial level, the amount of energy consumed by the water sector ranges from 0.5% to 4% of electricity use. The amount of energy consumed at the city or utility level could be much greater, especially as rapid urbanization continues.

6.2. Scenario results

This section reports our modeling results for the energy and water sectors. We report CO_2 emissions (Fig. 10), water consumption (Fig. 11), and water withdrawal (Fig. 12) for the eight energy scenarios described earlier, plus an additional combined energy scenario. Similarly, we report the final energy consumption, primary energy consumption, and CO_2 emissions for seven water scenarios and an additional combined water scenario.

6.2.1. Energy sector

In the energy sector, Energy Policy Scenario 3, which constrains the amount of coal used in converting coal to chemicals, offers the greatest potential for reducing both CO_2 emissions (by 0.2–25%) and water consumption (by 0.1–11%). These results highlight the significant emissions-reduction and water-conservation benefits of curbing development of the coal conversion sector. Energy Policy Scenario 4 (enhanced coal to chemical), which includes enhanced water efficiency for coal conversion, also offers substantial potential for increasing water efficiency in the coal-to-chemical sub-sector, thereby reducing the need to choose between water resources and climate mitigation.

The results of modeling Energy Policy Scenario 5 (the “inland nuclear” scenario) show that although increasing nuclear power generation offers climate benefits, it could increase water consumption by 15% by 2050 when compared to Energy Policy Scenario 2. The results for Energy Policy Scenario 8 (the “cooling” scenario) indicate that shifting to dry cooling could significantly reduce water use intensity (a 0.3–3.3% reduction in withdrawal and a 0.2–2.3% reduction in consumption); however, this approach could increase CO_2 emissions by 0.01–0.06% because dry cooling is less efficient than wet cooling. The results for these two scenarios illustrate the importance of addressing water and climate issues together.

However, the results for Energy Policy Scenario 2, “Increased Renewable and Alternative Energy Supplies,” demonstrate that changes in one sector alone sometimes generate benefits for other sectors. The results for this scenario show that shifting to more renewable and alternative energy (as detailed previously) could reduce water consumption by 33% and could lower water withdrawal by 61% in comparison to the reference scenario.

As with CO_2 emissions, coal-related sectors dominate water use. These include the power sector, coal mining and washing, CHP, and coking. This situation differs from that in many other developed countries where crude oil production dominates water use for the energy sector. Using more renewable and alternative energy supplies results in an increased share of water consumption from other coal-related activities. Modeling results indicate that by 2050 CHP dominates water withdrawals, perhaps in part because the model assumes that CHP will remain coal-based, and cooling technologies will maintain their current market shares.

We report more details of the scenario results in the supplemental material (Figs. S-10 to S-17).

6.2.2. Water sector

The modeling results for all scenarios (Fig. 13) illustrate the water sector's increasing energy use in China. If current policies are implemented, including meeting targets for desalination (with improved energy intensity), water reclamation, and increased wastewater treatment coverage and tertiary treatment, the water sector’s final energy consumption could increase by about 54% by 2050. Although this value may not represent a significant percentage of total national final energy consumption, the water sector's increasing energy consumption could be important at local and facility levels. Water sector final energy consumption has already become an important topic for policymakers in some jurisdictions.

Climate impacts from the water sector will be determined by the power content, rather than amount, of the sector’s energy consumption.

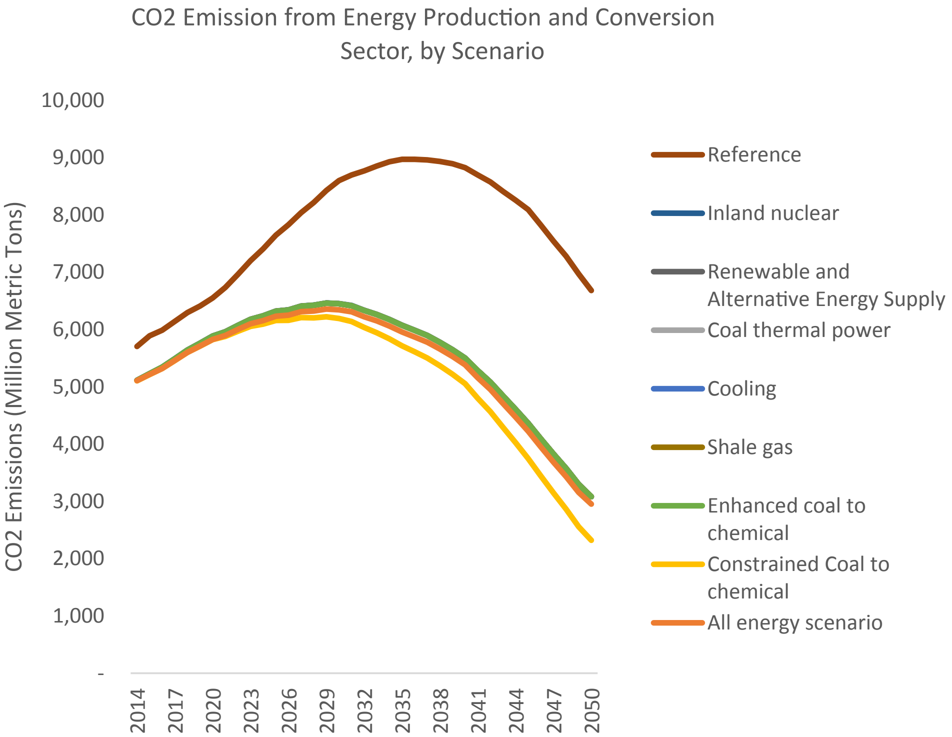

Fig. 10. CO_2 emissions from the energy production and conversion sectors, by scenario.

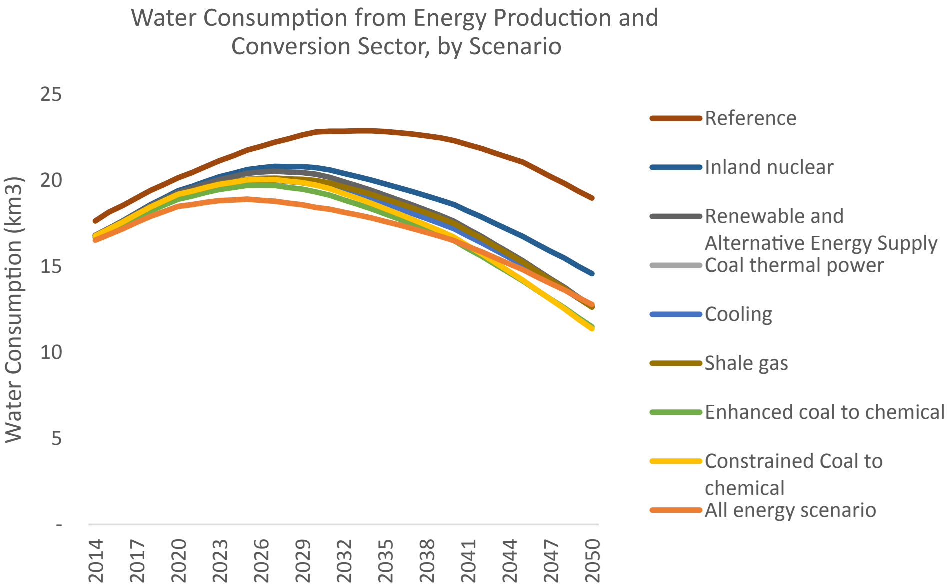

Fig. 11. Water consumption by the energy production and conversion sectors, by scenario.

Fig. 14 shows the water sector's CO_2 emissions trend, which is dictated by the decreasing coal content in China's power mix from 2030 to 2035 onward. In areas where renewable energy is curtailed, bringing it back on line or expanding it could help reduce water-sector CO_2 emissions impacts; In some cases, water sector can provide solutions to maintain grid stability, for example, increasing pumping amount during times when there is a surplus supply of solar energy.

Although the energy used to obtain water and convey it from the source will remain the largest percentage of total energy used by the water sector, the amount of energy used by wastewater systems is expected to increase from 11% (2014) to 29% (2050), assuming that the energy intensity for desalination improves substantially. This trend reflects China's rapid urbanization and rising living standards. As urbanization continues, the nation's water demand will require 23% more energy by 2050, and the wastewater treatment sector will need 29% more energy than today. More details on the water policy scenario results can be found in Figs. S-18 to S-19 in the supplementary material.

7. Conclusions and policy implications

The results from our comprehensive study of the relationship between water and energy use in China shed light on current and potential future effects of China's water and energy policies. In particular, this study confirms that water supply will constrain energy development both nationally and regionally. Our analysis also highlights that even though the water sector's energy use currently accounts for a

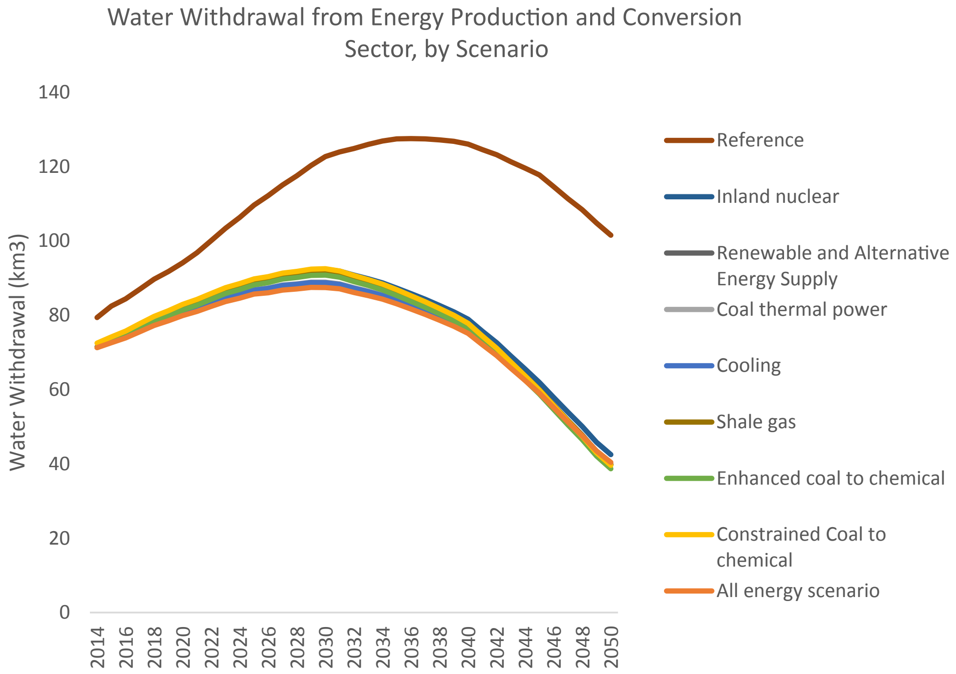

Fig. 12. Water withdrawals by the energy production and conversion sectors, by scenario.

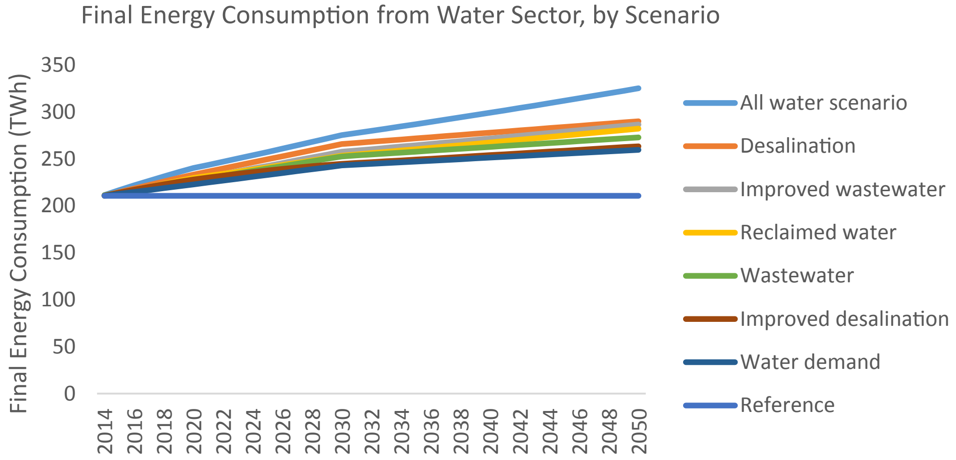

Fig. 13. Final energy consumption from the water sector, by scenario.

negligible percentage of the national total, water-sector energy use is increasing.

We summarize key conclusions from our modeling below along with preliminary conclusions regarding policy approaches. The research framework developed for this study will form the basis for forthcoming regional case studies.

7.1. Significant water is used by China's energy sector, and the water sector's energy consumption is increasing.

Currently, energy production and conversion consume and withdraw 17.7 km^3 and 79.4 km^3, respectively, of water. The water consumption portion of these totals accounted for 56% of total industrial water consumption in 2014. If the current trend continues, water consumption for energy could increase 30% from the 2014 level, peaking between 2033 and 2034. Water withdrawal for energy peaks at 127.5 km^3 in 2036. By comparison, agricultural water withdrawal was 387 km^3 in 2014. Although China's Ministry of Water Resources regulates how much water energy projects (e.g., coal mining and washing, thermal coal power, and coking) can consume, there are not yet specific regulations to limit the sometimes severe impacts of water withdrawal, i.e., water resource needs to be available for withdrawal in the first place even though they are returned back to environment through recirculated cooling system. Water use standards do not address the macro-level impacts of energy development on water resources.

The water sector's energy consumption is expected to increase dramatically. Final energy consumption for the sector is currently estimated to be 210.7 terawatt hours (TWh), representing about 2% of China's final electricity consumption and 0.8% of final national energy consumption. By contrast, the energy consumed by water end uses (hot water uses in industrial and residential sector) represents 9% of total national electricity consumption, i.e., the water industry's share is currently comparatively small. However, from 2005 to 2014, water supply increased by 8% while the energy demand associated with water supply increased 25% because of increasing groundwater pumping and inter-basin water transfers. This trend is even more pronounced in the north where surface water resources are limited.

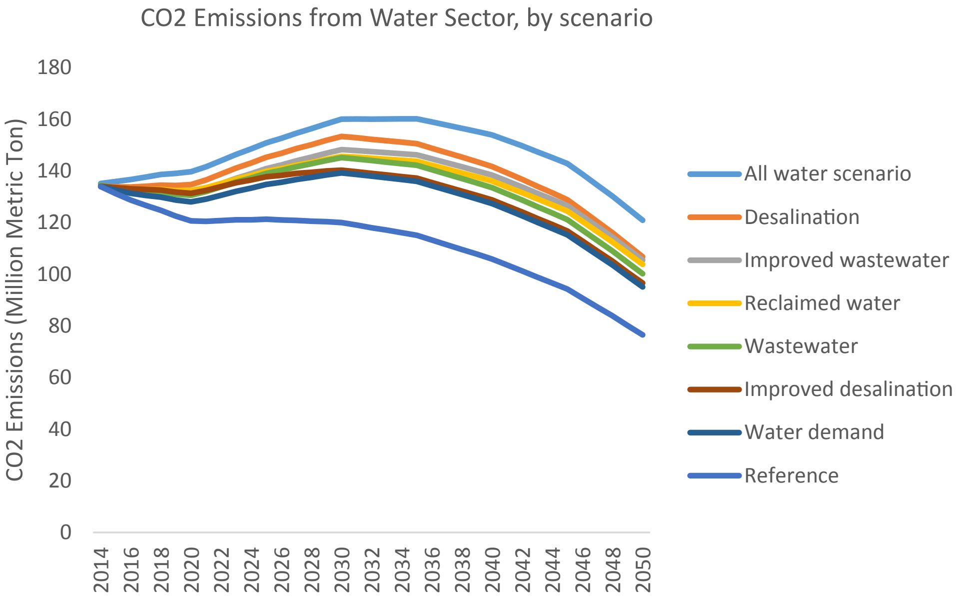

Fig. 14. CO_2 emissions from the water sector, by scenario.

7.2. Low-carbon energy resources usually save substantial water, but not always.

This study confirms that increasing renewable and alternative energy supplies could produce substantial water conservation and climate mitigation benefits in China. The scenario results for Energy Policy Scenario 2, “increased renewable and alternative energy supply,” demonstrate the unintended but positive consequences of energy policies; in this case, shifting to more renewable and alternative energy[1] could consume 33% less water and result in a 61% decrease in water withdrawal. Because our results utilized aggregated accounting, the savings might be greater in some regions than others. This result provides additional impetus for dis-incentivizing primary coal production and coal thermal power generation in China.

There are also, however, less favorable unintended consequences from transitioning to one form of low-carbon energy, nuclear power. This study shows that although building inland nuclear plants has climate benefits, those plants could increase water consumption by 44% ($1.9\,km^3$) by 2050 and would require fresh river water instead of saline seawater. In addition to other controversies that surround the use of nuclear power to replace coal, nuclear plants’ intensive water consumption is another impediment to developing inland nuclear power facilities. Some current proposals use reclaimed water instead of freshwater for nuclear-plant cooling. More research is needed to evaluate the sustainability of those projects.

7.3. The importance and variety of nexus issues is exacerbated at the regional and local levels.

Although this study examines WEN at an aggregated national level, WEN conflicts can also arise at the regional and local levels. One conflict is that the richest fossil fuel resources lie in the arid western provinces where water supplies are scarce. Other regions, such as Beijing-Tianjin-Hebei, might face difficulty in supplying sufficient water and clean energy to a growing urban population. In addition to technical challenges, perceptions of WEN issues by community members, policymakers, and other stakeholders in different regions might differ. A one-solution-fits-all approach will not be able to address the range and diversity of local WEN issues. It would be useful to develop an inclusive, adaptive policy research approach that accounted for specific local issues. Endo et al. [47] laid the groundwork for applying different research approaches/methodologies to different local policy and technical contexts.

7.4. Future research should take into account the different scales of WEN issues.

In evaluating interconnected impacts of water and energy in China, we found that issues differ from the national to the regional and facility/project levels. This study was limited in modeling scope to the national level with selected energy and water development pathways scenarios, with limited analysis of region-specific data for only one year (2014) to draw upon some national versus regional WEN issues. Water resource concerns related to energy development are a national, regional issue, or watershed/catchment basin issue. The energy impacts of water infrastructure are more prominent at the facility/project or local level. Future research to address the interconnected impacts of WEN should consider this difference in the level at which issues are most evident or pressing. Studying the WEN impacts at one scale (in terms of geography as well as time) could overlook important elements of and trade-off opportunities associated with the relationship between these resources. In addition, seasonal/daily differences and local climate factors contribute to variation in impacts.

Acknowledgements

This work was supported by the Energy Systems Analysis and Integration Division of the U.S. Department of Energy’s Office of Policy under Lawrence Berkeley National Laboratory Contract No. DE-AC02-05CH11231. The authors would also like to thank Energy Foundation China for their contributions to this work.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2018.12.085.

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[1] As a reminder, Energy Policy Scenario 2 assumes that the renewable energy share increases to 36% in 2030 and 68% in 2050 while the share of gas production is projected to grow from 1.2 Mtoe/year in 2014 to 180 Mtoe/year by 2050. Coal conversion processes are assumed to be the same as in the reference scenario.

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