# Water-Energy Nexus in China

## A study on a national scale

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# Executive Summary

## Mind the Nexus

Almost all forms of energy development require water—to clean coal, cool thermal power plants, move hydropower turbines, frack gas, and grow biofuel crops. China's water availability is far below global average, yet the country continues to expand energy development rapidly from new coal mines and power plants the arid north, shale gas operations in the dry west to the world's most extensive hydropower boom in the southwest and more nuclear power inland. This intensifying energy development adds more pressure to China's water ecosystem that must also provide water to growing urban centers, agriculture, and industry. Chinese policymakers need more systemic understanding and reliable data on the interlinked water-energy trends at both the micro and macro levels so they can better protect the country's constrained water and manage the ambitious energy agenda.

In response to these challenges, Lawrence Berkeley National Lab (LBNL) and China Institute of Water Resources and Hydropower Research (IWHR) recently completed one of the most comprehensive national-level water-energy nexus model. This modeling work was not an academic exercise, rather an attempt to help Chinese policymakers understand more precisely how energy development at the national and regional level is using the country's limited water resources, and examining how much electricity the country is using to move, pump, clean, heat, and desalinate water.

This modeling work is part of the bilateral Clean Energy Research Center on Water-Energy Technologies (CERC-WET), co-led by UC Berkeley and China's Research Institute of Petroleum Exploration & Development (RIPED).

## Data and governance Gaps

Managing water and energy together represents a major governance challenge in many countries. China's fragmented authoritarianism presents particular difficulties for water and energy policy coordination. Besides the inconsistent and often competing policy priorities among sectors, at the most basic level both bureaucratic spheres lack the data and insights into the big impacts water-energy confrontations are causing. The current dominant design for water-energy information gathering and regulation in China has focused on the facility-level. For example, how much water used to clean coal at one mine or cool one coal-fired power plant provides insights into how local water resources are impacted. Correspondingly, the CERC-WET project provides a system-level mapping of water and energy development and how they interact at the macro level. The model highlights the water energy integrated model methodology, the state-of-the-art data review, and governance and policy frameworks, enabling us to create regional water-energy research in the future, which will help China's central and local governments more accurately invest in technologies and create policies to mitigate water-energy challenges.

## China's Thirsty Energy and Increasingly Energy Intense Water Sector

So how thirsty is China's energy sector? Most thermal energy plants need to use significant quantities of water for cooling. Case in point, in 2014, Chinese energy production and energy conversion sector

withdrew three times more water for cooling/processing (79km$^3$) than they actually consumed (17.7 km$^3$), which is about 56% of the industrial total water consumption in 2014. If the current trend continues, the water consumption for energy could peak between 2033-2034, an increase of 30% from the current level, while the water withdrawal for energy peak at 127.5 km$^3$ in 2036. By comparison, the water withdrawal for agriculture is 387 km$^3$ in 2014. Although the Ministry of Water Resources regulates how much water energy projects can consume, there are not yet specific regulations to limit the impact of water withdrawal, which can be severe. Moreover, available water limit standards focus on coal mining and washing, thermal coal power, and coking, but they do not address the macro-level impacts the energy development on water resources.

The CERC-WET modeling also dug into data around the energy footprint of water in China. Historically between 2005 and 2014, China's water supplied for agriculture, industry, residential and ecological use has increased 8%, but the corresponding energy demand to move, pump, clean and heat water has grown 25% due mainly to increases in groundwater pumping and inter-basin water transfer. The modelling results showed the energy use in the water sector will likely increase dramatically from its current level of 210.7 TWh (about 2% of China's electricity consumption). As urbanization continues, by 2050 the nation's water demand will require 23% more energy, and the wastewater treatment sector will need 29% more energy than today. Despite this trend, water's energy use does not garner much attention from government agencies, NGOs or researchers except for indicating the economic concerns at the project or city level.

### Low carbon doesn't always save water

Increasing the renewable and alternative energy supply can not only mitigate climate change, but also save water resources depending on the type of renewable energy that is developed. The CERC-WET team ran a clean/alternative energy scenario[3] that indicated a shift to 68% renewable energy sources by 2050 would lead the energy sector to consume 33% less water, and withdraw 61% less from rivers and groundwater. However, while shifting towards using inland nuclear power plants offers climate benefits, it could potentially increase water consumption by 44% (1.9 km$^3$) by 2050. As an already controversial alternative energy to coal, this significant water footprint poses further challenges for inland nuclear development. Current proposals often seek to use reclaimed water as an alternative source to freshwater, but this is an area where more research is needed to evaluate the sustainability of these projects. Overall, this proves further disincentives to increasing primary coal production and coal thermal power generation in China, pointing towards renewable energy that also integrates a water perspective into its planning.

### Keeping a local perspective

CERC WET showed the water-energy-nexus picture at the aggregated national level, but it is important to note that water-energy conflicts can be exacerbated at the regional level. Arid western provinces are fossil fuel rich, meaning that they are both abundant and lacking in the necessary resources for energy

[3] The clean/alternative energy scenario assumes the renewable energy share to be increased to 36% in 2030 and 68% in 2050, while share gas production is projected to grow from 1.2 Mtoe/year in 2014 to 180 Mtoe/year by 2050. The coal conversion processes are assumed to be the same as the reference scenario.

production—in order to utilize their fossil fuel resources, they have to further over tap their already diminishing water resources. Even eastern regions are facing challenges in supplying sufficient water and clean energy to their growing urban populations—the Beijing-Tianjin-Hebei region provides such an example. In addition to these technical challenges, local communities often perceive these issues differently than policy makers, further complicating the research design to address nexus problems.

Each region faces its own unique set of problems such that a "one size fits all" solution will not work in addressing the diversity of water-energy nexus issues at the local level. It would be useful to develop a research approach to take specific local issues into account and ask research/policy questions in an inclusive and adaptive process. For instance, Endo etc (2015) laid out some groundwork as an effort to applying different research approaches and methodologies in response to the varying local policy and technical contexts.

### The challenge of policy coherence

In addition to the modeling work mentioned above, this report also laid out the groundwork for understanding necessary characteristics of governance structure for this nexus, as there is currently very little social science research on water-energy nexus issues. We unveiled the governance differences revolve around issues such as policy priorities, scale, regulatory and market structure, and actors involved. In order to address the policy coherence/coordination issues, for the short term it is imperative to develop a common dialogue and vision between two sectors that have very different policy goals. Future research needs to continue to work to develop knowledge on bridging the institutional, organizational and behavioral gaps between these two sectors.

Finally, nexus issues require interdisciplinary efforts—before formulating research questions, it is necessary to engage with a diverse set of actors, including scientists from varying disciplines, policy makers, and community members. Through an inclusive and adaptive process, nexus research can hopefully avoid "a hammer looking for a nail" situation.

# Introduction

Given the confluence of increasing energy demands, declining sufficiency and quality of water, and climate change impacts, addressing both energy and water issues together has become a looming global and regional need (DOE, 2014). Work in the water-energy nexus (WEN) concerns the use of energy to obtain water and water to obtain energy, focusing on the areas where these two resources are intertwined. More specifically, water is used in various ways in energy production and power generation. Energy is required to extract and deliver water and to treat wastewater to appropriate standards.

In 2015, about 73% of China's power was fueled by coal (China National Renewable Energy Center, 2016). The country's water availability is far below global average, and the geographic distribution of water resources is highly problematic. Despite these constraints, China continues to rapidly expand its energy production capabilities by establishing new coal mines in the arid north of China, shale gas operations in the arid west, major hydropower facilities in the south, and more nuclear power inland. These plans further exacerbate the pressing environmental and climate change challenges that China faces.

At the 2009 World Water Week in Stockholm, 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 (International Energy Agency, 2016). 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(IRENA, 2015). In the United States, the Department of Energy has laid a comprehensive foundation for studies of the water-energy nexus throughout the nation (DOE, 2014). The National Renewable Energy Laboratory's review of operational water use for generating electricity also is widely cited (Macknick, Newmark, Heath, & Hallett, 2012).

In China, the constraints on water resources and the abundance of coal have resulted in many studies of topics related to water and coal mining and water and coal thermal power (Pan, Liu, Ma, & Li, 2012; S. Wang, Cao, & Chen, 2017; Xiang & Jia, 2016). Quantifying the energy use related to water has been much less studied, however: only a few previous studies have attempted to analyze the increasing energy consumption by the water sector in China (Li, Liu, Zheng, Han, & Hoff, 2016). Although policies and standards for limiting the amount of water used by the coal industry exist, those policies generally address water use issues at individual facilities. China still lacks a broad, comprehensive understanding of the water-energy nexus. In addition, recent research has not focused on the decision-making landscape surrounding the WEN. Policy suggestions often simply call for more policy coordination among water-energy departments.

This study will fill in the research gap by providing a comprehensive, quantitative analysis of issues surrounding the WEN in China, both now and in the future. We also will describe the decision-making landscape for both sectors in order to provide a basis for future study of the priorities, logic, and

implementation process in water and energy governance. We hope this report can serve as the foundation for future, more in-depth studies of WEN issues in China.

The first section of this report reviews the governance perspective and modeling approach regarding the WEN. The second section outlines the decision-making landscape for regulating water and energy systems in China. The third section presents the modeling approaches and assumptions used in this study. Scenarios of the environmental and emission implications of future energy and water plans will be analyzed, followed by conclusions and policy implications based on key findings. The last section briefly summarizes the limitations of current WEN studies and potential areas for future research.

# Literature Review

## Governance of the water-energy nexus

The concept and application of a nexus are not new. The study of the relationships and interdependencies among organizations can be traced back to the 1950s. The examination of polycentric governance dates back to the 1960s (Visseren-Hamakers, 2015). In the early 1990s, a new paradigm led to development of the Integrated Water Resource Management (IWRM) concept, which is needed to better account for the multidimensional nature of water management (Benson, Gain, & Rouillard, 2015). Although its application is still open to debate, the nexus approach is seen as promoting coherence by seeking to coordinate sectors without preferring one over the other. It can be seen as part of the umbrella term in Integrative Environmental Governance (Visseren-Hamakers, 2015). In contrast to the silo or holistic approach (see figure 1), the nexus approach is seen as having the ability to systematically move among disciplines while accounting for the interconnections among them (Oliver & Hussey, 2016).

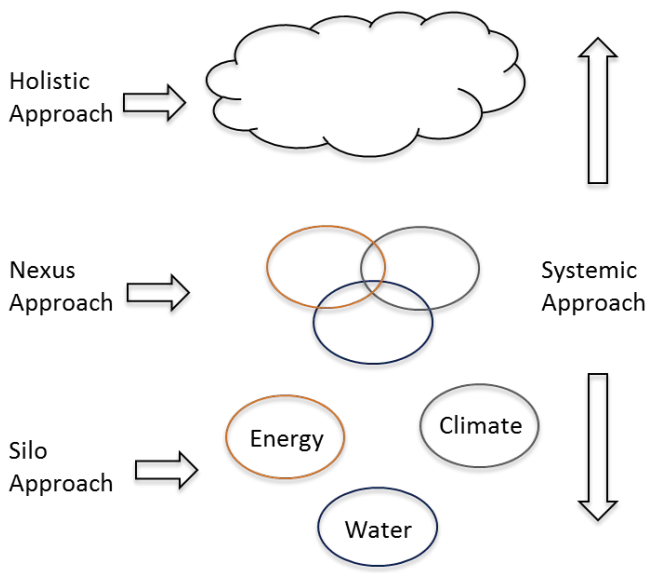


Figure 1. Three Approaches

Current studies of the WEN usually focus on modeling and quantitative analysis of resource trade-offs and efficiency. There are few studies that call for policy coherence for governing the water energy nexus because it is assumed that there is minimal coordination among the regulatory settings for these sectors.

The obvious lack of policy coherence is one reason researchers and policy makers have become increasingly interested in water energy nexus work in the past decade. Weitz etc (Weitz, Strambo, Kemp-benedict, & Nilsson, 2017) identified three primary focuses of WEN governance studies to date: (1) the risk and security of resources—policy disconnection is seen as a failure to account for resource conflicts and scarcity; (2) economic rationality—nexus is seen as a way to improve the cost-effectiveness of policies and efficient use of resources; and (3) policy integration is seen as a political process rather than a technical or administrative matter—requiring negotiation among various actors who have distinct perceptions, interests, and practices.

In this study, the concerns for resource security and economic rationality provide the foundation for the modeling approach. The results of the nexus modeling described in the next section form the basis for discussing the issues facing energy and water development in China. How those issues can be resolved is a separate discussion that requires detailed analysis of the institutions, the actors, and the connections among them. We also acknowledge that policy recommendations must account for the interests of various participants, as well as the political process in the decision-making landscape. The results described in this report should be seen as technical references, not recommendations for regulatory reform. Ultimately, this study aims to identify current and future challenges and opportunities for resource planning and policy coherence focused on WEN.

## 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.

This section briefly reviews the integrated models used to study both water and energy combined. In Table 1, 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 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 (Dai et al., 2017). Table 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. In addition to quantifying WEN issues, recent nexus models have started to incorporate decision-making components into the analysis. For instance, the Platform for Regional Integrated Modeling and Analysis (PRIMA) developed at Pacific Northwest National Laboratory (PNNL) is able to simulate interactions among natural and manmade systems at scales relevant to regional decision making (Dai et al., 2017). The Institutional Analysis and Development (IAD) framework, combined with value chain analysis developed by (Villamayor-Tomas, Grundmann, Epstein, Evans, & Kimmich, 2015) focuses on the role of governance in resolving nexus issues. These tools enable study of the nexus networks of action situations (NAS) wherein actors' decisions depend not only on the institutional structure governing the given situation but also on the decisions made in related situations. As far as utilization goes, the most commonly used model is the Water and Energy Simulation Toolset (WEST) developed by Horvath's research team 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 (Horvath, 2005).

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 tradeoffs between water and energy systems. Users can evaluate outcomes against their policy questions and priorities.

Table 1 Summary of water-energy integrated methods[4]

| System boundary | Tool | Developer, year | Model type |
|---|---|---|---|
| **Water +** | Water, Energy, and Biogeochemical model (WEBMOD) | (Webb, 1992) | Simulation |
| **Energy +** | Market Allocation/The Integrated MARAL EFOM System (MARKAL/TIMES) | (Loulou, 2005) | Optimization |
| **Integrated** | Water-Energy Sustainability Tool (WEST) | (Horvath, 2005) | Simulation |
| **Integrated** | Energy-water planning model | (Tidwell, 2009) | Simulation |

[4] These methods include model, tool, platform, or analytical framework.

| System boundary | Tool | Developer, year | Model type |
|---|---|---|---|
| Integrated | Water-Energy-Climate Calculator (WECalc) | (Pacific Institute, 2010) | n/a |
| Integrated | Wastewater-Energy Sustainability Tool (WWEST) | (Stokes, 2010) | Simulation |
| Integrated | Water Analysis Tool for Energy Resources (WATER) | Argonne National Laboratory (2011) | Simulation |
| Integrated | Water-Energy Simulator (WESim) | (Cooley, 2012) | Simulation |
| Water + energy | Water Evaluation and Planning System - Long-range Energy Alternative Planning (WEAP-LEAP) | (SEI, 2012) | Simulation |
| Integrated | Water and Energy Simulation Toolset (WEST) | (Jeffers, 2013) | Simulation |
| n/a | MuSIASEM-The Flow-Fund Model | (FAO, 2013) | n/a |
| Integrated | Climate-Land-Energy-Water (CLEW) | (Alfstad, 2013) | Simulation |
| Integrated | Foreseer | University of Cambridge (2013) | Simulation |
| Integrated | World Business Council for Sustainable Development (WBCSD) | (Patel, 2014) | n/a |
| Integrated | Regional Energy & Water Supply Scenarios Model (REWSS) | Dale and Bilec (2014) | Simulation |
| Integrated | Platform for Regional Integrated Modelling and Analysis (PRIMA) | Pacific Northwest National Laboratory (2014) | Simulation |
| Integrated | Water-energy-food (WEF) nexus | (Daher, 2015) | Simulation |
| Integrated | The Global Change Assessment Model in USA (GCAM-USA) | Pacific Northwest National Laboratory (2015) | Simulation |

| System boundary | Tool | Developer, year | Model type |
|---|---|---|---|
| **Integrated** | Climate-Land-Energy-Water-Development nexus (CLEWD) | (Dodds, 2016) | Simulation |
| **Integrated** | System-Wide Economic-Water-Energy Model (SEWEM) | (Bekchanov, 2016) | Simulation |
| **Integrated** | Food, energy, water systems (FEW) | (Miralles_Wilhelm, 2016) | Simulation |
| **Integrated** | Water, Energy, and Food security nexus Optimization (WEFO) | (Zhang, 2016) | Optimization |
| **Integrated** | Water-energy-carbon (WEC) nexus | (Shrestha, 2017) | Simulation |
| **Energy +** | South African TIMES Water model (SATIM-W) | (World Bank, 2017) | Partial-equilibrium linear-optimization |
| **Integrated** | SPAtial and Temporal NEXus-Water Energy Model (SPATNEX-WE) | Khan (2017) | Optimization |

** The third column (Developer, year) does not necessarily correspond with the reference. It identifies the developer and the year the method was developed.

# Decision-Making Landscape for Energy and Water

This section introduces the regulatory structures for both the water and energy sectors in order to identify the challenges to developing policy coherence and to establish the basis for future in-depth research on WEN governance. This section identifies some differences in water energy governance in China, both vertically between central and local regulatory systems, and horizontally between the water and energy sectors.

## Energy regulatory system

Many ministries and government agencies have responsibilities related to energy development and conservation. The National Development and Reform Commission (NDRC) is responsible primarily for overall national policy making. The National Energy Administration (NEA), managed by the NDRC, is responsible for developing national regulations, policies, and plans regarding energy and energy development, energy conservation and resource utilization, and power sector operations (National Energy Administration, 2017). The Ministry of Industry and Information Technology (MIIT) and Ministry of Housing and Urban-Rural Development (MoHURD) are responsible for energy conservation in the

industry and buildings sectors, respectively. There are overlaps of responsibilities among these ministries and agencies, however. This "fragmented authoritarianism" in the implementation of China's energy policy is widely recognized and produces inter-ministerial competition and disjointed policymaking (F. Zhang & Huang, 2017). A similar bureaucratic structure applies to implementing energy policy in China, as shown in Figure 2.

Several departments currently address both water and energy issues. The Environmental Protection and Resources Conservation Department of NDRC is responsible for issues related to both energy and water conservation and resource utilization (National Development and Reform Commission, 2017b). In addition, MIIT has an Energy Conservation and Comprehensive Use Department, which is in charge of developing and implementing policies in energy/water conservation and resource utilization in the industry and information technology sectors. The Building Energy Efficiency and Technology Department of MoHURD is responsible for developing and implementing energy efficiency policies for buildings, developing plans and building standards that address both water and energy requirements.

At the local level, local governments above the county level are responsible for energy management. As with the national ministries, the local Development and Reform Commissions, local Economic and Information Commissions, and local building departments are in charge of overall energy management, energy project approval, and energy issues related to industry and the building sector, respectively.

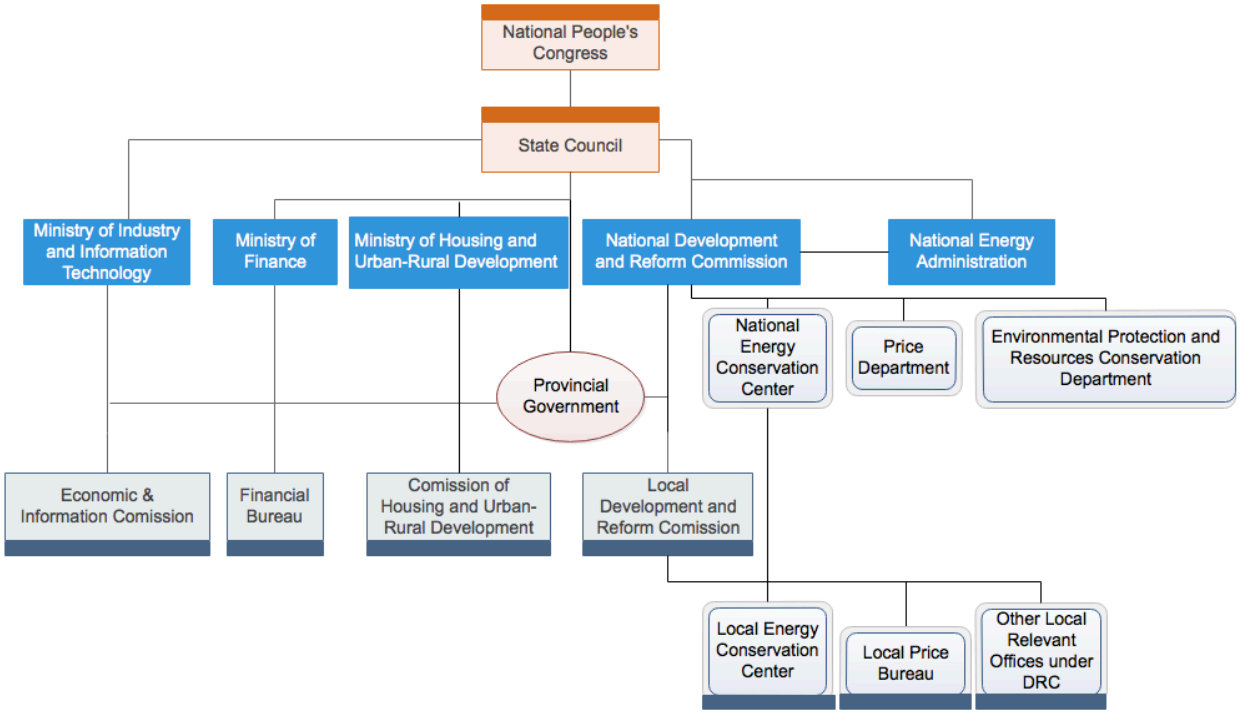


Figure 2. Energy Regulatory Structure

## Water regulatory system

The Ministry of Water Resource (MWR) is the primary body in charge of developing and executing water policies at the national level, including resource exploitation and utilization, water conservation, and water protection. The National Water Saving Office (or Water Resources Department) is the primary operating body for the MWR (Ministry of Water Resources of the People's Republic of China, 2017). The Ministry of Agriculture (MOA) is responsible for developing and implementing water use policies that apply after water is delivered to the field, such as through water-saving irrigation practices (Lohmar, Wang, Rozelle, Huang, & Dawe, 2003).

As mentioned previously, a few departments are responsible for both water and energy issues (e.g., NDRC, MIIT, and MoHURD). While NDRC oversees general water issues, the Department of Urban Construction at MoHURD is responsible for urban water supply, water conservation, and wastewater treatment (Ministry of Housing and Urban–Rural Development, 2017)

The Department of Water Environment Management at the Ministry of Environmental Protection (MEP) is responsible for water quality management and environmental protection. MEP and MWR operate their own separate water monitoring systems. The State Oceanic Administration under the Ministry of Land and Resources is responsible for protecting the oceanic environment, utilizing oceanic resources (e.g., desalination), and developing oceanic renewable energy (e.g., offshore wind) (State Oceanic Administrion, 2017). The Ministry of Finance and Ministry of Health are also involved in domestic water management (A. Gu, Teng, & Lv, 2016).

One distinctive administrative aspect of the water sector is the basin commissions, which cross jurisdictional boundaries. A basin commission usually serves as the designated agent of MWR. For much of their existence, the commissions have been hydro-technical agencies devoted to water conservation and to disaster prevention and mitigation. These responsibilities limit the commissions to a professional authority rather than an integrated platform (Huang & Xu, 2017).

The regulatory structure at the local level is similar to the national organization. As part of the top-down governance system, Provincial Water Resources Bureaus are responsible for water management and implementation to comply with the national regulations. Figure 3 shows the regulatory structure of the water system in China.

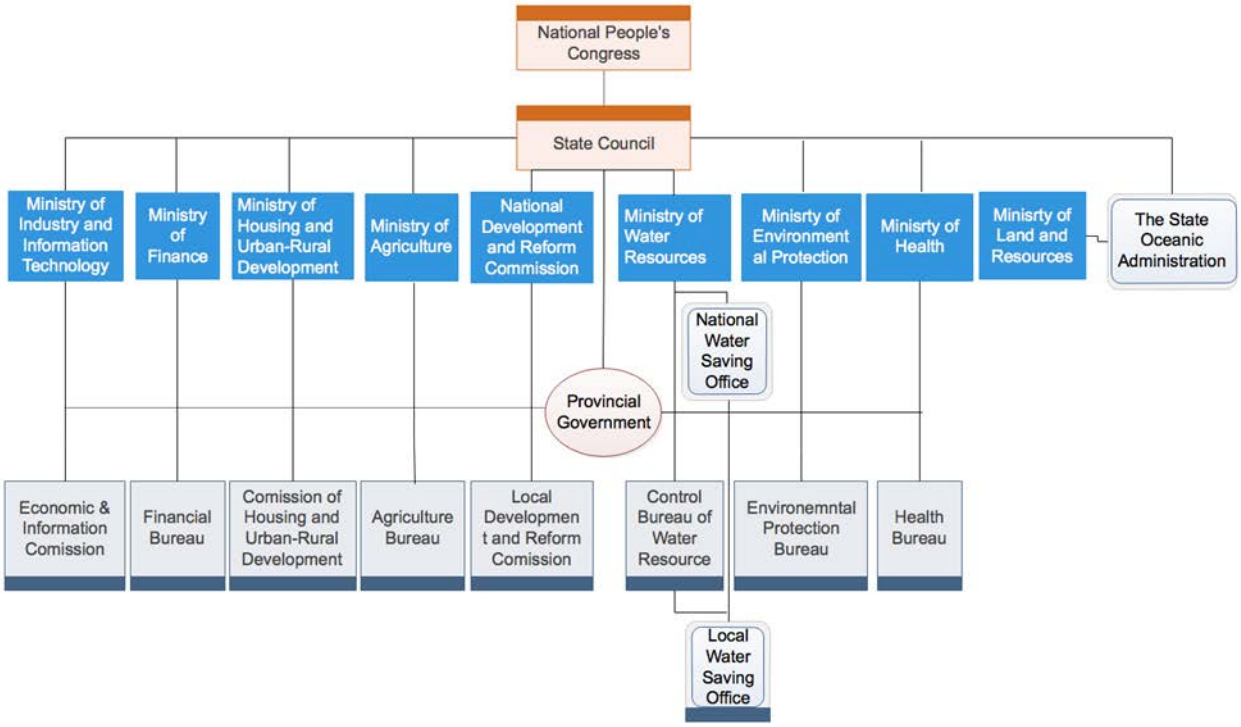


Figure 3. Water Regulatory Structure

## Key energy and water policies and goals

For the past decade, China has taken significant steps to reduce the energy and water intensity of its economy. Listed below are highlights of selected national policies in energy and water conservation.

- **China's Climate Change Goals (2015):** China announced its international climate pledge (Intended National Determined Contribution, or INDC) in June 2015. China's national goal is to have peak $CO_2$ emissions in about 2030, making efforts to reach that peak sooner, to increase non-fossil energy to 20% of its energy mix by that same year, and to reduce the carbon intensity of its economy ($CO_2$ emissions per unit of GDP) by 60% to 65% from 2005 to 2030 (Su, 2015).
- **Energy Conservation Law (2007):** China's Energy Conservation Law was enacted in 1990 and amended in 2007. The law covers energy conservation in the industrial, buildings, and transportation sectors, The law established a responsibility and evaluation system for energy conservation by integrating the requirement to achieve energy conservation targets into the performance evaluations of local governments and their officials (The Central People's Government of the People's Republic of China, 2007)
- **Renewable Energy Law (2005) and Five-Year Plans (FYPs) for Renewable Energy:** China's 2005 Renewable Energy Law set the foundation for promoting renewable energy, and China's Five-Year Plans expanded on those efforts. China exceeded its 12th five-year plan (FYP) target of 11.4% non-fossil energy for total primary energy consumption, reaching 12% of non-fossil energy in 2015. The 13$^{th}$ FYP for Renewable Energy sets goals of 100 GW of new hydropower capacity and 40 GW of installed hydro capacity. By

2020, hydropower curtailment should be mostly achieved (National Development and Reform Commission, 2016b).

- **13th Five-Year Plan for Energy Development (2014):** China's 13th FYP for Energy Development for the first time set a cap on coal consumption. The goal is to limit total coal consumption to 4100 Mtce by 2020 (National Development and Reform Commission, 2016a).
- **Water Law (2002):** China's Water Law was enacted in 1988 and amended in 2002, 2009, and 2016. The law covers water exploitation, utilization, conservation, and protection. The law calls for the relevant provincial and local departments to develop industry-specific "norms of water intake," which should be reported to the Ministry of Water Resources. Water Intake Norm, used by the Chinese government to save water, is set based on improvements in water management capabilities and advances in water-saving technologies (Shang, Wang, et al., 2016).
- **Water Intake Norms/Standards:** By 2017, there were 29 water intake standards established for the industrial sector, 25 of which are effective with the rest scheduled for implementation. The 29 standards cover many energy-related sectors: thermal power generation, petroleum refining, ammonia synthesis, coal washing, ethylene production, starch sugar production and so on (CSRES, 2017).
- **Water Resources "Three Red Lines" (2011):** China announced "Three Red Lines" for the "most stringent water resources management" to control total water use, water efficiency, and water pollutants discharged into rivers and lakes. Indicators from the National Water Resources Comprehensive Plan (2010-2030) are used to measure the three lines: By 2030, total water use should be limited to 700 billion $m^3$; water use efficiency should reach or approach the highest levels found around the world; water consumption per 10,000 yuan of industrial value added should be lower than 40 $m^3$; water use efficiency for agricultural irrigation should exceed 0.6; and the rate of compliance to water quality standards should exceed 95% (The State Council, 2012).
- **The 13th Five-Year Plans for Water-Saving Society Construction:** Five-Year Plans (FYPs) for Water-Saving Society Construction set targets for water conservation. The 13th FYP for Water-Saving Society Construction was announced by NDRC, MWR, and MoHURD in January 2017. The 13th FYP sets goals for capping total water consumption and increasing water efficiency in terms of water consumption per unit of GDP, water consumption per unit of industrial value added, and agricultural irrigation. The 13th FYP also sets specific goals for various sectors (the agricultural sector, the industrial sector, and urban systems) (National Development and Reform Commission, 2017a).
- **11th (2006-2010), 12th (2011 – 2015) and 13th (2016 – 2020) Five-Year Plans:** To address the surge in domestic construction and industrial production and the associated dramatic increases in energy use and carbon emissions in the early 2000s, China set a national target for reducing energy intensity (energy use per unit of GDP) by 20% during the period of the 11th Five Year Plan (Xinhua Net, 2006). The 12th Five Year Plan added a goal to reduce the carbon intensity ($CO_2$ emissions per unit of GDP) of the economy by 17%, along with lowering the national energy intensity target by 16%. The 12th FYP identified a goal for the proportion of non-fossil energy to primary energy use (Xinhua Net, 2011). The 13th Five Year Plan has a goal of reducing national energy intensity by 15%, a goal of having 15% non-fossil fuels, and a goal of 5000 Mtce for total energy consumption (Xinhua Net, 2016). Table 2 presents

a summary of key energy and water targets in the 11th, 12th, and 13th FYPs. Together, the three FYPs provide an overall picture of the country's efforts and ambitions in gradually reducing fossil fuel consumption and production, increasing the efficient use of water resources, and improving environmental quality. The FYPs provide near-term guidelines for social and economic development. The FYPs also form the basis for China's complicated "cadre evaluation," which evaluates local party and government cadres based on performance criteria determined by their immediate higher-up level of government.

Table 2. Energy and Water Targets in the 11th, 12th, and 13th FYPs

| Indicators | 11th FYP Targets | Realized by the end of 11th FYP | 12th FYP Targets | Realized by the end of 12th FYP | 13th FYP Targets |
|---|---|---|---|---|---|
| Reduction in energy consumption per unit of GDP (%) | ~20% | 19.1% | 16% | 18.2% | 15% |
| Reduction in $CO_2$ emissions per unit of GDP (%) | NA | | 17% | 20% | 18% |
| Proportion of non-fossil energy use to primary energy use (%) | NA | 8.3% | 11.4% | 12% | 15% |
| Reduction of water consumption per unit of industrial added value (%) | 30% | 36.7% | 30% | 35% | 20% |
| Reduction of water consumption per unit of GDP (%) | NA | | 30% | 31% | 23% |
| Effective use efficiency of water for agricultural irrigation | 0.5 | 0.5 | 0.53 | 0.532 | 0.55 |
| Reduction in COD (%) | 10% | 12.45% | 8% | 12.9% | 10% |
| Reduction in $SO_2$ emissions (%) | 10% | 14.29% | 8% | 18.0% | 15% |
| Reduction in ammonia nitrogen emissions (%) | NA | | 10% | 13.0% | 10% |
| Reduction in $NO_x$ emissions (%) | NA | | 10% | 18.6% | 15% |
| Surface water quality – percentage of water reaching or exceeding Type III standards (%) | NA | | NA | 66% | >70% |

| Indicators | 11th FYP Targets | Realized by the end of 11th FYP | 12th FYP Targets | Realized by the end of 12th FYP | 13th FYP Targets |
|---|---|---|---|---|---|
| Surface water quality – percentage of water testing lower than Type V (%) | NA | | NA | 9.5% | <5% |

## Summary

To ensure synergy of energy and water resources policies, it is important to have coordination and shared views among the various departments and ministries involved (A. Gu et al., 2016). As mentioned, the primary policy bodies that must work together include NDRC, NEA, MoHURD, MoA, MWR, and the cross-jurisdictional basin commissions agencies.

The regulatory framework for the nexus between water and energy is embedded in the same fragmented authoritarianism system as are the separate agencies. Thus the departments that oversee the combination of energy and water comprise centralized institutional hierarchies (vertically) and polycentric networks of formal organizations at jurisdictional or sub-basin scales (horizontally), as discussed earlier. Offices and agencies of two different bureaucracies that hold the same horizontal rank in a bureaucracy cannot issue binding orders to each other.

Vertically, the governance mode in China is distinctly hierarchical, although some market elements have been introduced. In this fragmented vertical and horizontal structure of governance, mandatory standards and hard targets have been the most useful measures (Kostka & Hobbs, 2012). The targets are interconnected to a cadre evaluation system for government workers, in which performance evaluations and political promotions are based primarily on short-term economic growth. Although environmental criteria, in particular air quality parameters, have been introduced to the cadre evaluation system, short-term targets that conflict with long-term sustainability goals often dominate the decision-making process.

Horizontally, energy and water policies generally are developed separately. One exception at the facility level: the conflicting interests regarding energy and water in the coal industry, which are addressed by industrial standards. For example, since 2012 many standards for water intake have been updated or established for specific industrial sectors, including many key energy-consuming sectors such as thermal power (GB/T 18916.1-2012), petroleum refining (GB/T 18916.3-2012), coking (Ministry of Industry and Information Technology, 2014), coal to ammonia (GB/T 18916.8-2006). In 2017 the National Institute of Standardization proposed adding water use standards for converting coal to chemicals products. The standards are intended to assign water limits to individual projects, rather than addressing integrated resource management at the macro level.

More recently, there also has been a greater recognition of the need to address both energy and water issues at the national policymaking level, placing greater emphasis on developing synergic management of energy and water resources (Zhou, Li, Wang, & Bi, 2016). For example, in 2013 China added the “water-for-coal” plan to the “3 Red Lines” water policies, requiring that future large-scale coal projects in water

scarce regions be developed in partnership with local water authorities (Qin, Curmi, Kopec, Allwood, & Richards, 2015). Also, the number of water-related targets increased in the 12th and 13th FYPs, including increasing the water efficiency of the industrial sector. Finally, the cap on total coal consumption stipulated in the 13th FYP for Energy Development is a key way to address combined energy and water issues through energy sector management alone (Shang, Hei, et al., 2016).

Overall, several policies support limiting the water resources used by the energy sector, especially in coal-related businesses such as coal mining and thermal coal power plants. By comparison, policies that limit energy use by the water sector are largely nonexistent. It is reasonable to state that, at the national level, water resources constrain energy development more than the other way around.

Although we found that energy and water administration and policies are not coordinated, we did not examine the government objectives behind the lack of coordination. Based on the analysis of cross-sectoral governance in California (Oliver & Hussey, 2016), Table 3 is an attempt to outline the major governance differences between the water and energy sectors in China, in order to illustrate the challenges for policy coherence. These challenges include, for example, the lack of common goals/policy language; the fact that the water sector is mostly disaggregated into numerous regional public/foreign water companies, whereas energy production and services usually are operated by large state enterprises. Because water is scarce in China, water demand generally depends on supply, whereas energy is sold as a commodity and thus depends partly on both domestic and global energy policies and market conditions. The differences between water and energy use as regards (1) scale (local vs. national); (2) regulatory and market structure (public good vs. commodity, demand vs. supply); (3) type of actor (disaggregated local/foreign companies vs. state enterprises) complicate the attempt to develop coordinated policies, even though the 12th and 13th five-year plans present both water and energy saving targets.

More research is required to determine whether it will be possible to develop coordinated engineering policies. Although coordination might be desirable, there frequently are good political and policy reasons for policymakers to equivocate (Jordan & Halpin, 2006). After all, legitimacy, rather than rationality or efficiency, is central to the survival of any organization.

Finally, it is worth noting that the administrative structure described above is undergoing major reform—the organizational relationships and responsibilities related to WEN issues represents only the governance structure when this research was conducted in 2017.

Table 3. Major governance difference in water and energy sector in China

| Sector | Water sector | Energy sector |
|---|---|---|
| Regulatory oversight | Water is governed primarily by the MWR, together with a complex web of ministries and national, sub-national, and cross-jurisdictional agencies. | Energy is governed primarily by NDRC, along with NEA and other national and sub-national agencies. |

| | | |
|---|---|---|
| | | |
| Market players | Local governments and public/private/foreign groups involved in water supply and distribution and wastewater treatment. Market is disaggregated: the top 10 water service companies share 16.47% of the market in 2016 (E20, 2017). | Two state grid companies, seven major power generators, three major state oil and gas companies, major coal mining companies, new emerging clean energy producers. Most energy-related companies are owned by large state enterprises. |
| Market structure | Defined as a state-owned resource, although trading of water rights has been practiced. | Defined as a commodity sold by regulated state-owned companies. |
| Price setting | The state price bureau sets guidelines for provincial bureaus to use in setting prices that take local supply and demand into account | NDRC sets price guidelines for energy sold to customers. Primary energy prices usually depend on market rates |
| Financing | Subsidized by state and local government funding, especially for rural agricultural users. | Funded through a combination of state subsidies, state-determined and market rates, and market investments, depending on the type of energy and the step in value chain. |

# Modeling Methodology

## Modeling scope

As noted above, this report addresses the bidirectional quantitative relationship between the energy and water sectors in China. Figure 4 shows the overall accounting scope of the model. Some previous analyses failed to specify the study boundaries, making it difficult for policymakers to identify reasonable research targets. We find it useful to think about three components for modeling the water-energy nexus: (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 and end-use demands such as residential appliances. This study does not consider end-use demands because their energy use is included in the building and industrial end-use sector. The energy use by end users usually is the dominant energy use in the water sector.

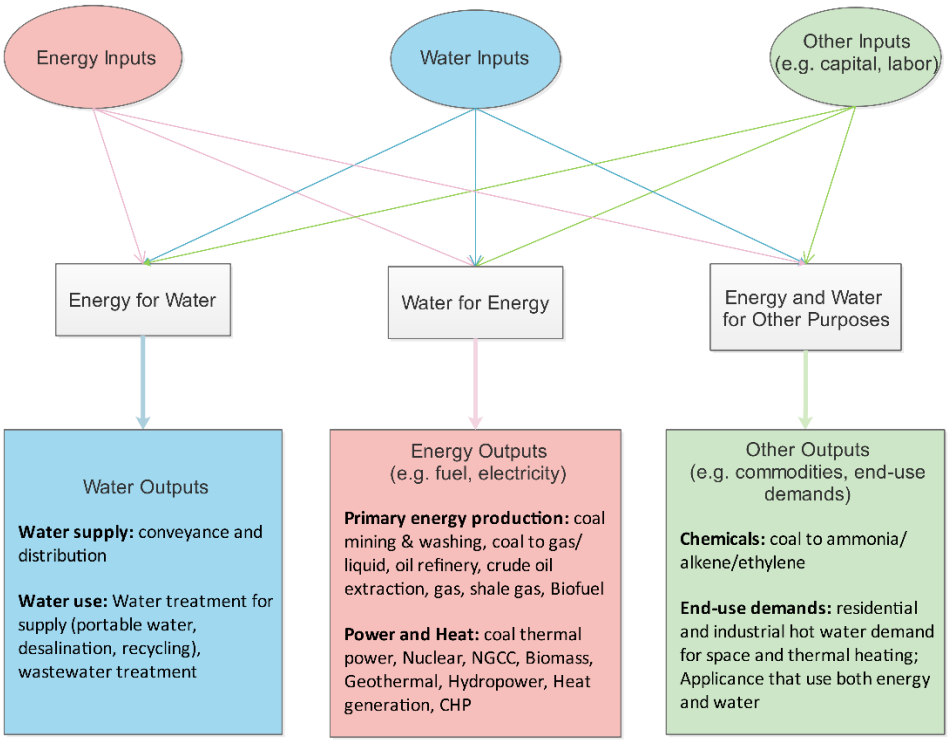


Figure 4. Water-energy nexus accounting scope. Revised from (Kyle et al., 2016).

## China 2050 DREAM Model

To model the water-energy nexus in China from 2010 through 2050, we used the China 2050 Demand, Resource and Energy Analysis Model (DREAM) developed by the China Energy Group to model detailed energy end-uses by all economic sectors as well as water use in the energy sector and energy use in the water sector. The China 2050 DREAM model is based on an accounting framework of China's energy and economic structure developed using the LEAP software platform developed by Stockholm Environmental Institute. LEAP is a medium- to long-term integrated modeling tool that can track energy consumption, production, and resource extraction in all sectors of an economy, as well as conducting analyses of long-range scenarios. A more detailed introduction to LEAP can be found here[5]. Although LEAP was designed for energy planning and accounting, its flexible structure and customizability allows water to be added as a "fuel" type and to be tracked at an aggregate level. This capability is discussed further in the next section.

[5] https://www.energycommunity.org/default.asp

The China 2050 DREAM includes a demand module composed of five demand subsectors (residential buildings, commercial buildings, industry, transport, and agriculture) and a transformation module consisting of energy production, transmission, and distribution subsectors. Using LEAP's generation dispatch algorithms for the power sector, the model captures diffusion of end-use technologies and macroeconomic and sector-specific drivers of energy demand as well as the energy required to extract fossil fuels and produce energy. The model enables detailed consideration of technological developments—industrial production, equipment efficiency, residential appliance usage, vehicle ownership, power sector efficiency, lighting and heating usage—in evaluating China's energy and emission reduction path below the level of its macro-relationship to economic development. The China 2050 DREAM has been used in various studies to evaluate potential national energy and $CO_2$ emissions scenarios for China through 2050 and to evaluate the potential impact of energy-related policies for both the demand and supply sectors.

## *Macroeconomic drivers*

The model's key drivers of energy use include activity drivers (total population growth, urbanization, building and vehicle stock, and commodity production); economic drivers (total GDP, value-added GDP, and income); trends in energy intensity (energy intensity of energy-using equipment and appliances); and trends in carbon intensity. These factors are driven in turn by changes in consumer preferences, settlement and infrastructure patterns, technical change, and overall economic conditions. Key macroeconomic parameters such as economic growth, population, and urbanization are aligned with international sources (e.g., the United Nations World Population Prospects) and Chinese sources (e.g., China Energy Research Institute reports). These macroeconomic drivers in turn have important links to the energy demand subsectors shown in Figure 5.

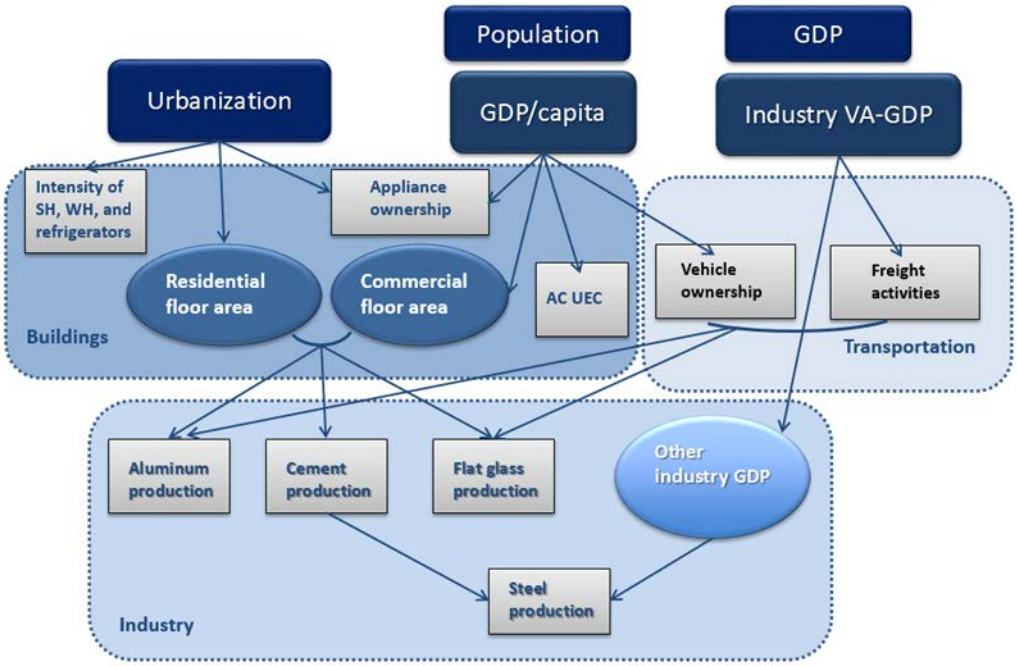

Figure 5. Links between Macroeconomic Drivers and Energy End Uses

## *Demand module*

The demand module includes the five primary economic sectors of residential buildings, commercial buildings, industry, transportation, and agriculture. Because of the marginal and decreasing role of economic activity from agriculture, the agricultural sector is described in less detail than are the others. Within the energy demand module, the model is able to address sectoral patterns of energy consumption in terms of end use, technology, and fuel shares, including trends in saturation and use of energy-using equipment, efficiency improvements, and complex linkages between economic growth, urban development, and energy demand.

### *Residential buildings*

Residential energy demand, which supports numerous household services, is shaped by various factors, including location, climate, and building vintage. For China's residential building sector, urbanization and growth in household income drive energy consumption. First, urban households generally consume more commercial energy than do rural households. In addition, rising household incomes are reflected in larger housing units (and thus increased heating, cooling, and lighting loads) and in expanded ownership of appliances and other equipment. The China Energy End-Use Model divides households into urban and rural categories across three climate zones; within those categories, end uses are designated space heating, air conditioning, appliances, cooking and water heating, lighting, and a residual "Others" category.

### *Commercial buildings*

Energy consumption by commercial buildings is driven by two key factors: building area (floor space) and end-use intensities such as heating, cooling, and lighting (MJ per $m^2$). The model determines commercial floor space based on the total number of service sector employees and the amount of built space per employee. Commercial building construction in China is expected to be driven by the expansion of the services sector, as happened with today's developed economies. Because commercial building energy consumption varies by building type and function, the commercial building sector is broken down into the major building types of retail, office, school, hospital, hotel, and other buildings. The key end uses for each commercial subsector include space heating, space conditioning or cooling, water heating, lighting, and equipment.

### *Industry*

The industry sector is divided into 12 energy-intensive industrial, including cement, iron and steel, aluminum, ammonia, ethylene, paper, glass, copper, alumina, caustic soda, soda ash, and calcium carbide. Production and associated energy-related demand in these energy-intensive industrial subsectors are determined by physical drivers for demand, such as population, building and infrastructure, as products, as shown in Figure X1. In addition to the 12 energy-intensive subsectors, there are 18 value-added industrial subsectors that include manufacturing, chemicals, light industry, and all other small industrial subsectors. As a conglomerate of various industries, production activity in these

value-added subsectors are characterized by value-added GDP, the annual growth of which is expected to slow over time.

### *Transportation*

Activity in the transportation sector is driven by demand for freight and passenger transport. Freight transport is calculated as a function of economic activity measured by value-added GDP; passenger transport is calculated based on average kilometers traveled by each vehicle mode (e.g., bus, train, car) used to move people. For passenger transport, increasing vehicle-kilometers traveled in different modes are driven by population growth and rising income levels that increase the demand for personal vehicles. Transport energy consumption differs by the mode of transport, type of technology, and type of mobility services provided.

## *Supply and transformation module*

The transformation sector consists of a number of modules that represent energy conversion sectors such as district heating supply, cogeneration, electricity generation, transmission and distribution, oil refining, and coking. For each module, the individual processing technologies that convert energy from one form to another or transmit or distribute energy are identified, such as groups of power plants and technology data such as capacities, efficiencies, and capacity factors.

### *Energy Extraction and Processing Subsectors*

The transformation module accounts for the energy required to extract primary fossil fuels such as coal, natural gas, and oil and to operate processing and conversion plants that derive products such as electricity, coke, and petroleum products. The energy extraction and processing subsectors in the model include coal mining, oil extraction, natural gas extraction, coking, oil refining, coal liquefaction, coal gasification, coal gas production, ethanol production, biodiesel production, biogas production, and shale gas extraction.

The energy required to extract, process, and convert primary fuels is accounted for by considering technological improvements, resource quality, and resource limitations. Although technological improvements can increase the efficiency of resource extraction, resource quality declines over time. Resource quality is decreased by factors such as deeper coal mines, lower coal quality, and secondary recovery in the oil and gas sectors, which increase the total energy investment required. Similarly, although the efficiency of technologies used in the energy processing sectors may improve, more stringent standards for product quality (such as lower sulfur content in oil products) require more intensive processing overall, increasing total energy consumption. Using this model, energy extraction was examined based on assumptions for the Energy Return on Energy Investment (EROEI) ratio, or the quotient of usable acquired energy from coal, oil, and natural gas, over energy expended for coal mining and oil and natural gas extraction.[6]

### *Coal Liquefaction*

[6] Energy return on energy investment ($\frac{Energy\ output}{Energy\ input}$) typically is calculated by including the indirect as well as direct energy inputs (e.g., embodied energy of machinery). This study considers only direct energy inputs.

Pilot projects of direct and indirect coal liquefaction processes have been established in Inner Mongolia. Shenhua Group's direct coal liquefaction plant, which began operating in December 2009, converts coal into gasoline, diesel, and other oil products. Direct coal liquefaction involves adding hydrogen to the organic structure of coal that has been rendered into distillable liquids by high temperature and pressure. The coal-derived liquids are further hydrocracked to produce synthetic crude oil and are refined and hydrotreated to produce transport fuels. Annually, 3.45 million tons (Mt) of raw coal is used to produce 1.1 Mt of fuel and oil products, including 715,000 tons of diesel, 250,000 tons of naphtha, and 102,000 tons of LPG (Wu, Yin, Yuan, Zhou, & Zhuang, 2010). Another group, the Yitai group, also initiated an indirect coal liquefaction pilot plant in March 2009. The annual production capacity of that plant is 160,000 tons with diesel and naphtha as the primary outputs. Under indirect liquefaction, the coal structure is broken down completely by gasification with steam. Then the composition of the gasification products is adjusted to produce synthesis gas, which is reacted over a catalyst at relatively low pressures and temperatures. Following these two pilot projects, larger coal liquefaction projects have been undertaken, including the Shenhua Group's project in Ningxia, which has an annual production capacity of 4 Mt. Another Yitai Group project underway in Inner Mongolia has an expected capacity of 2.15 Mt (Xinhua Net, 2017). The China 2050 DREAM models coal liquefaction as using water and electricity to transform coal primarily into diesel, naphtha, and LPG.

### *Coal Gasification*

China began exploring the transformation of coal to synthetic natural gas in the late 2000s, starting with four pilot projects in Inner Mongolia, Liaoning, and Xinjiang provinces and plans for expanding capacities. The demonstration projects used a domestic two-step conversion process based on high-pressure pulverization of coal gas. The central government also has encouraged joint-venture projects using foreign technology such as the one-step coal-to-gas technology used in the United States. The China 2050 DREAM models coal gasification as an energy transformation process that uses electricity and water to convert coal into synthetic natural gas.

### *Power Generation*

The power generation sector can be modeled using various technologies, including coal, natural gas, biomass, nuclear, wind, hydro, on-grid solar, and distributed solar photovoltaics. Coal generation is further divided into six categories based on size and efficiency, ranging from units that generate less than 100 MW at average efficiency of 27% to ultra-supercritical generation units that generate more than 1000 MW at average efficiency of 44%. For each type of plant, the model includes parameters on total installed capacity, availability, and dispatch order. Following parameters specified for the power sector module, the model calculates the amount and type of capacity required to be dispatched to meet the electricity demand of the associated economic sectors. Specifically, the China 2050 DREAM uses an environmental dispatch order for generation, which favors non-fossil generation and reflects dispatch priority policies that currently are supported in China. In the model, nuclear, wind, hydropower, and other non-fossil generation technologies are dispatched first, with coal generation dispatched last to meet all remaining electricity demand. The model also follows merit-order dispatch for coal generation, whereby the largest and most efficient units are dispatched first to provide the efficiency gains from the shift to newer, larger generation units and the mandated retirement of small, outdated generation units.

China's announced targets for expansion of renewable generation and nuclear capacity are used as the basis for establishing the installed generation capacity.

### *Energy Transformation Subsectors*

In addition to the power generation sector, there are several energy processing, transformation, and distribution subsectors within the transformation module. The transmission and distribution (T&D) subsector accounts for losses through electricity T&D as well as T&D losses through crude oil and natural gas pipelines. The heat supply subsector represents the heat generated using coal and natural gas from centralized district heating plants in China's northern climate zones, as well as commercial heat supply for industrial uses. The cogeneration subsector models gas cogeneration units that generate electricity and produce heat as a co-product.

## Modeling water-energy nexus with China 2050 DREAM

Building on the foundation for detailed modeling of energy systems using China 2050 DREAM, we incorporated consideration of the water sector (including water supply and wastewater). Adding the water sector as an end-use sector enabled the model to account for energy used by water systems, which was not explicitly captured before. Further, adding water intensity coefficients to the energy supply sectors enabled us to examine water use by energy systems.

### *Modeling water use by energy systems*

To account for the total water consumption and water withdrawal attributable to China's energy sector, we added water consumption and water withdrawal intensities for each energy extraction and transformation process. As we did for tracking the energy used to extract, process, and convert energy, we added water consumption and water withdrawal as new auxiliary "fuels" in each energy transformation subsector. Figure 6 shows the model structure as it incorporates water consumption and withdrawal intensities for coal gasification (coal-to-gas or CTG) and natural gas extraction. Using this structure, the model is able to track the total water consumption and water withdrawal as an auxiliary fuel related to the total amount of energy produced in each transformation subsector, which in turn is determined by the total energy demand for different fuel types and by resource constraints.

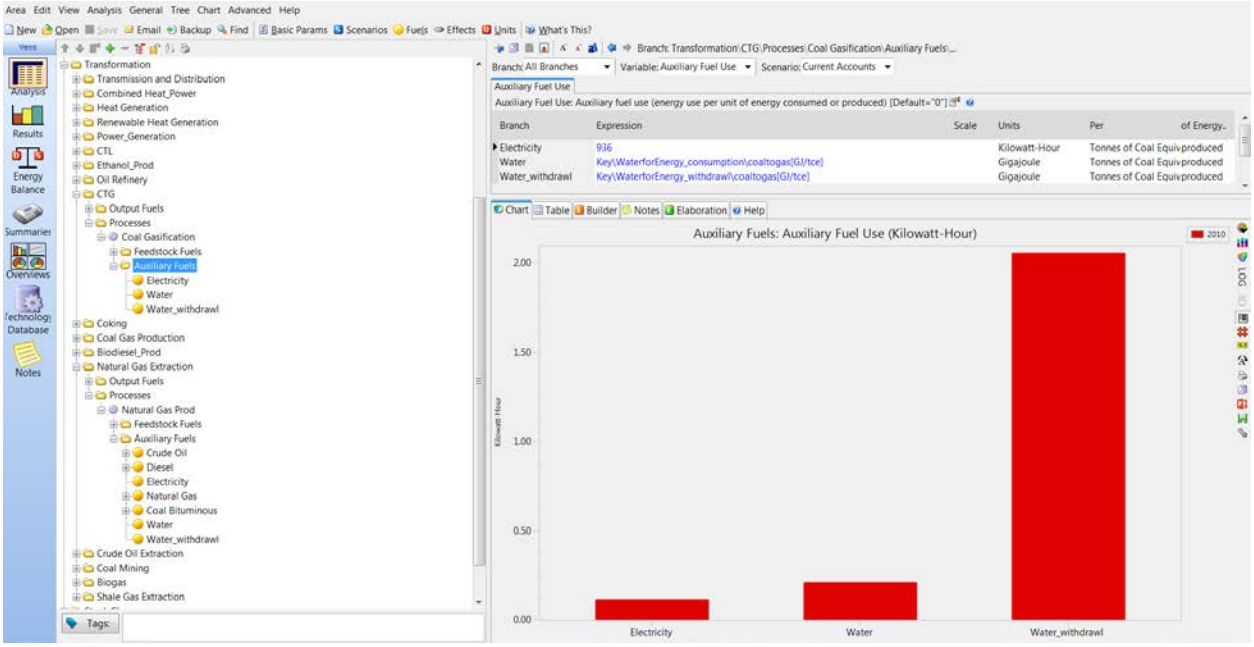


Figure 6. An example of LEAP model structure

For coal-to-chemical transformations, including coal to ammonia, coal to olefins, and coal to ethylene glycol, the water consumption and withdrawal intensities were added to the industrial sector as part of the chemicals subsectors for ammonia and ethylene. Specifically, water was added as an auxiliary fuel to the established process for transforming coal to ammonia. Both coal and electricity as well as water consumption and withdrawal intensities were added to the ethylene subsector to account for the innovative processes for transforming coal to methanol to olefins and coal to ethylene glycol. Figure 2 shows details of the structure of the "water for energy" model/module.

## *Modeling energy use by water systems*

In order to model the energy used by water systems, a new demand sector (the water sector) was added to account for energy-consuming processes in both water supply and wastewater systems. The water supply subsector includes source and conveyance, water treatment, water distribution, and desalination. Each process is differentiated based on groundwater versus surface water and further divided into primary water end uses, including agriculture, industry, municipal for source and conveyance, and industry and municipal for water treatment and water distribution. For desalination, the four primary processes are multi-stage flash, multiple effect distillation, reverse osmosis, and electrodialysis. Figure 7 shows the model structure for the water supply subsector.

The subsector for wastewater systems is divided into the three major stages of wastewater collection, treatment, and discharge. Electricity is the primary fuel used in each process, and both industrial and municipal sectors are considered for each stage. Figure 7 shows the model structure for the wastewater system subsector.

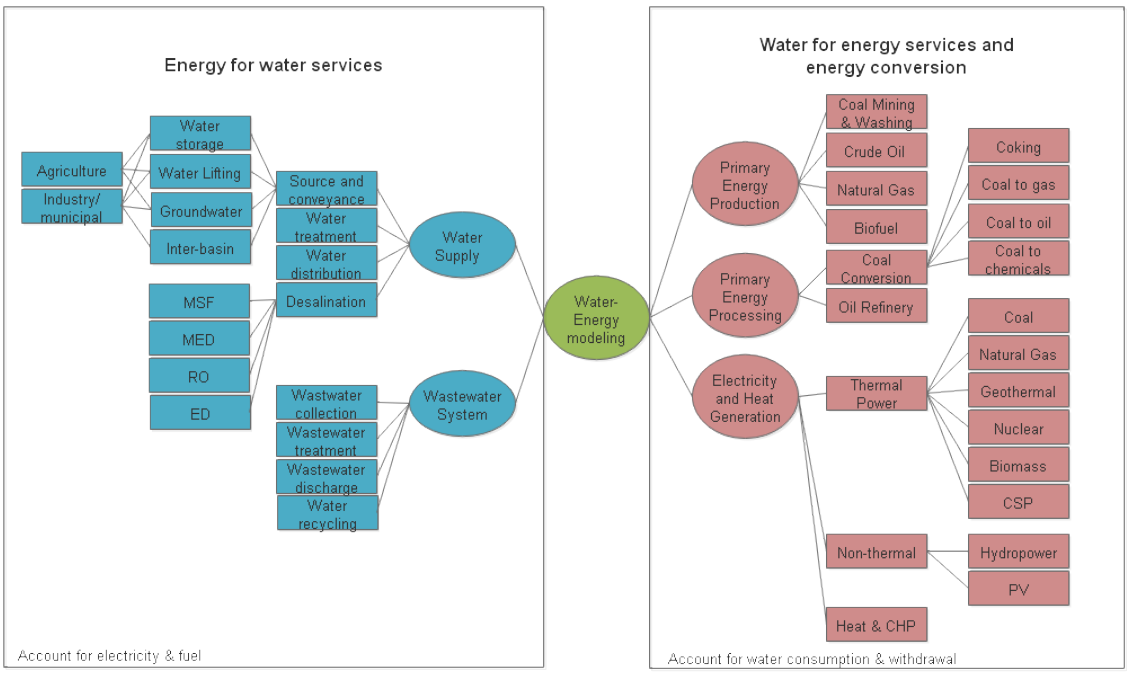


Figure 7. Water for Energy Model structure

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).

# Water Use in Energy Systems

## China's technical energy system

China's energy system has been and remains dominated by coal, as shown in Figure 8. The figure presents the historical primary energy supply by fuel and primary electricity's share of energy supply. Coal maintained a 72% share of total primary energy supply in 2015 (National Bureau of Statistics of China, 2016). Electricity's share of primary energy has increased dramatically during the past 35 years, accounting for about 14.5% of total primary energy supply in 2015 (National Bureau of Statistics of China, 2016).

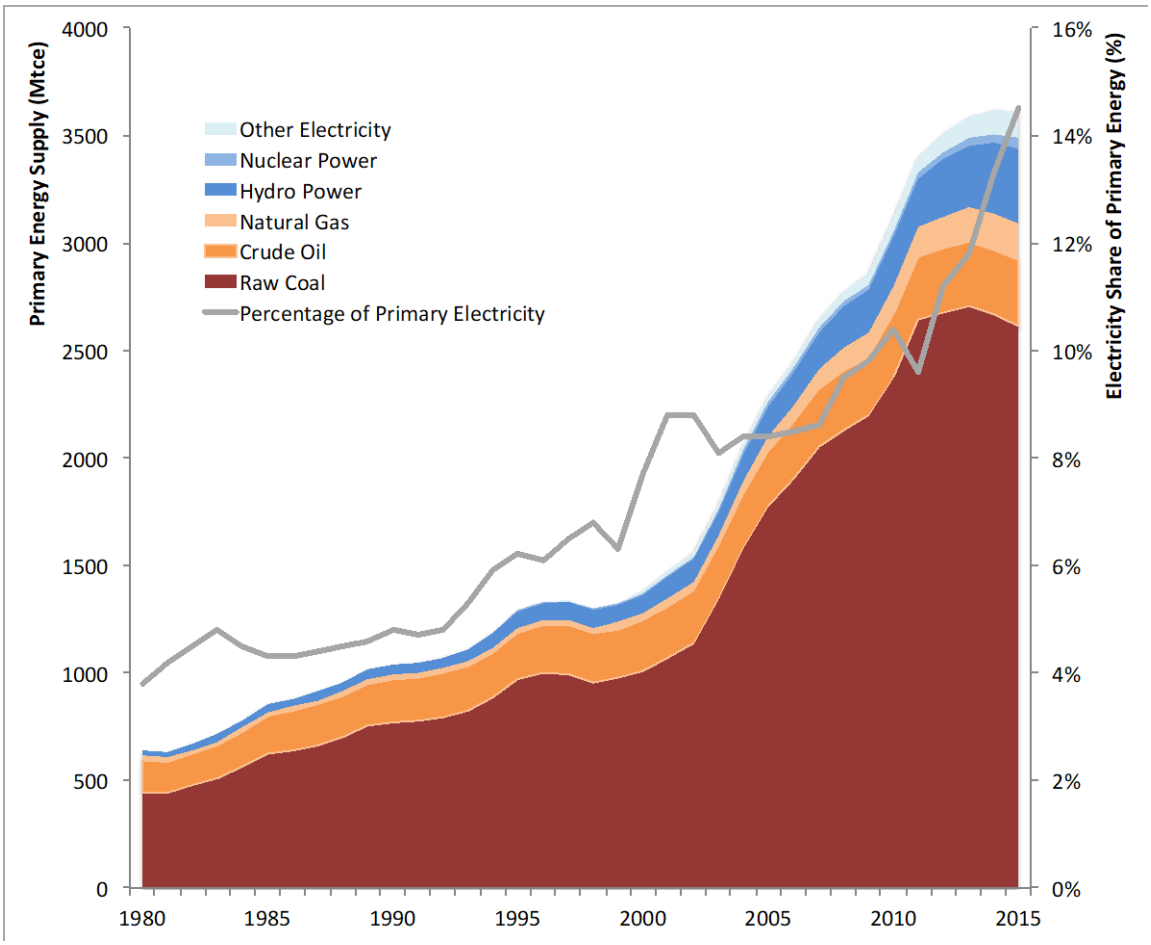


Figure 8. Historical trends in China's primary energy supply structure. Source: (National Bureau of Statistics of China, 2016). Note: The calculation of electrical supply utilized the coal-equivalent method.

Energy systems use water for water withdrawal 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.

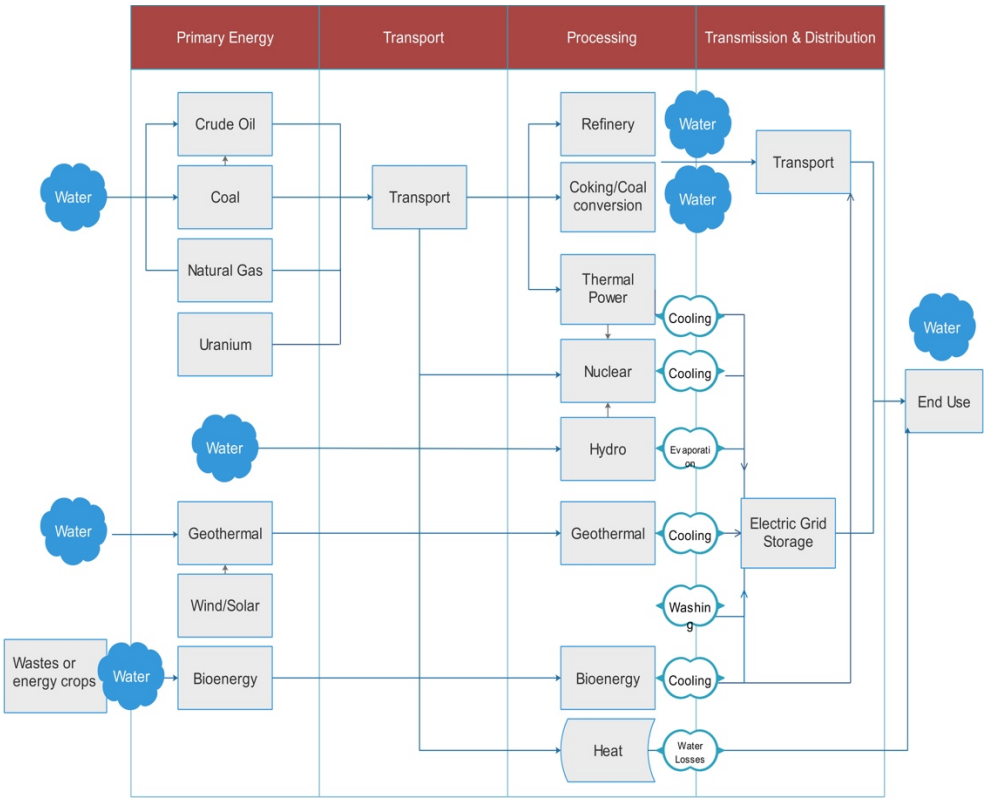


Figure 9. Water use in energy systems

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 explanations about specific intensities assigned to different types of energy production, please see the Table A1-4 in the appendix 1 to this report.

Figure 12 broadly compares the water use intensity for primary energy production and electricity and heat generation in China (Figure 10) with the global intensities (Figure 11) determined by the International Energy Agency (2016). 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.

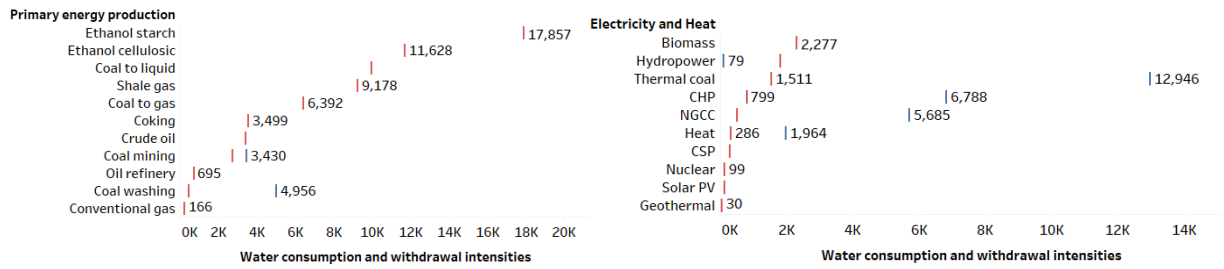


Figure 10. Freshwater use intensities of primary energy production (left) and electricity and heat generation (right) in China, 2014[7]

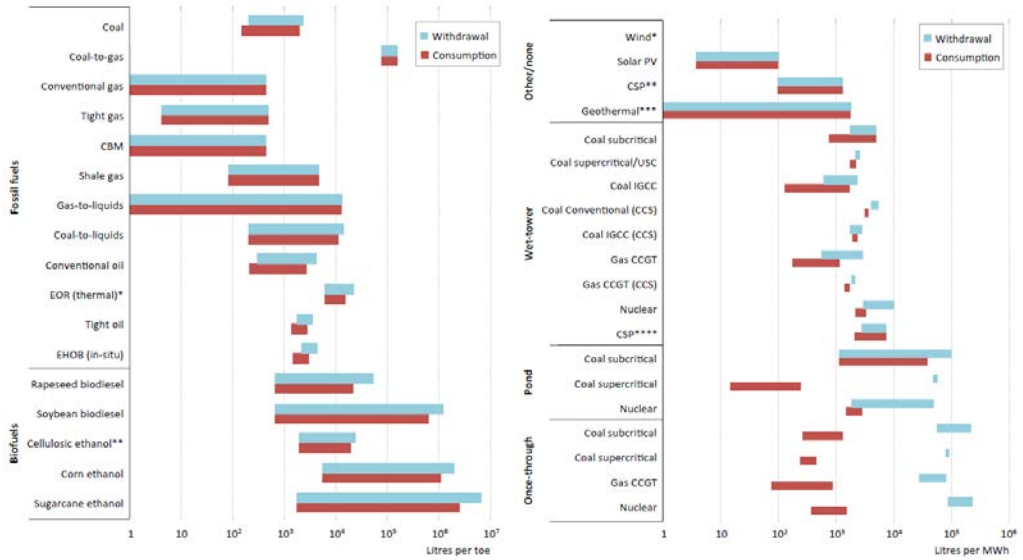


Figure 11. International water use intensity values for primary energy production (left) and electricity and heat generation (right)

Source: International Energy Agency (2016)

[7] 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.

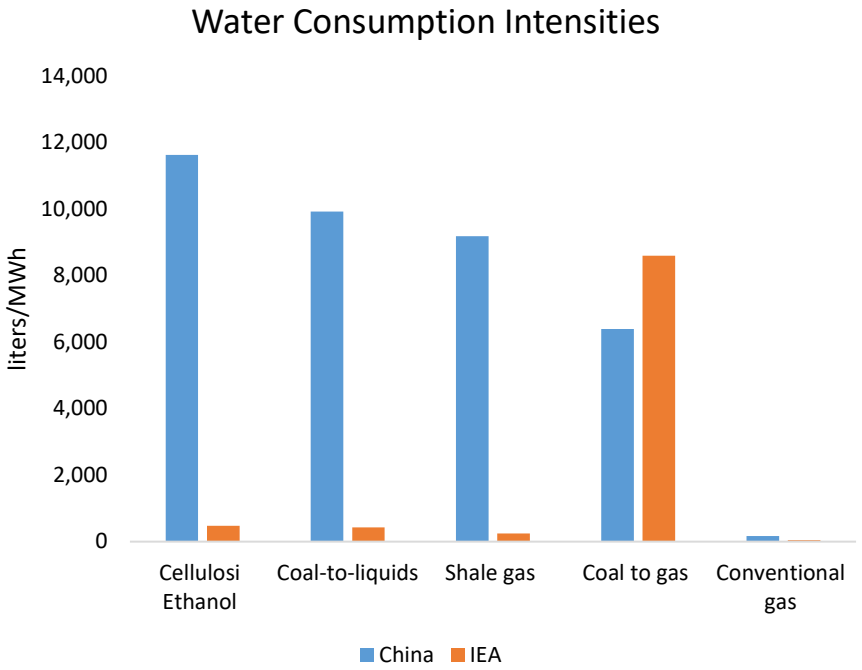


Figure 12. Comparison of Chinese and International Water Consumption Intensities

# Energy Use in Water Systems

## China's technical water systems

Water resources in China are scarce and unevenly distributed. Between 2003 and 2013, the average annual renewable water resource per capita was 2,015m$^3$, just above the United Nations water stress level of 1,700m$^3$ (Tan, Hu, Thieriot, & McGregor, 2015).

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 (Ministry of Water Resources of the People's Republic of China, 2015), agriculture end uses consume the most water (77.4% of total consumption). Municipal and industrial water uses account for about 10.2% and 9.8% of consumption, respectively. Figure 12 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 (Figure 13).

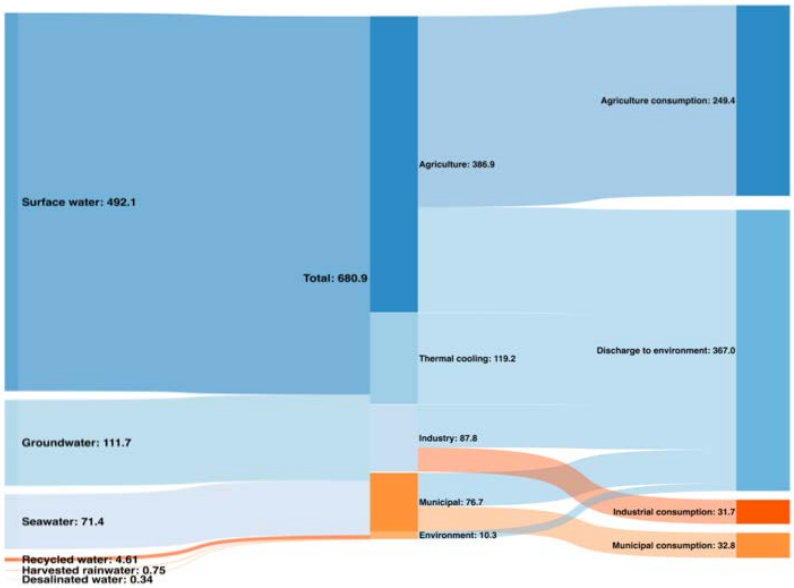


Figure 13. Sankey diagram of China's water supply and consumption, 2014. Unit: cubic kilometers ($km^3$)

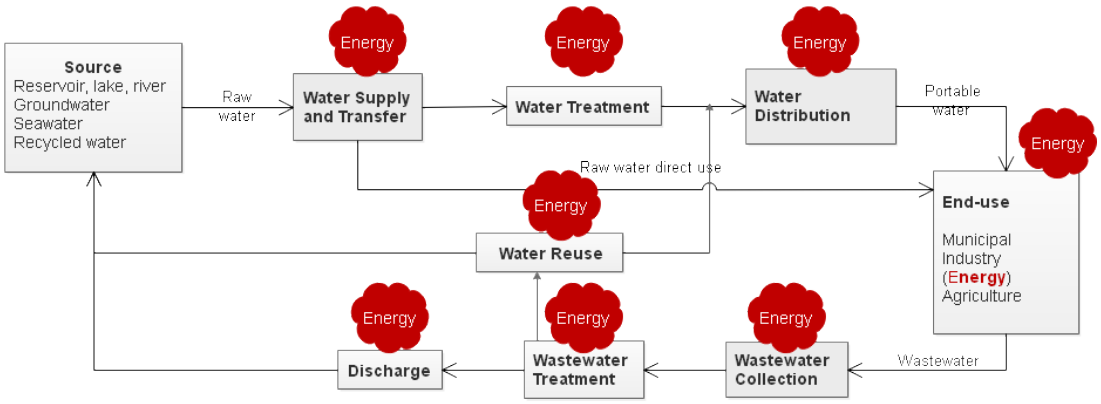


Figure 14. Energy use in water systems

Revised based on Hamiche, Stambouli, & Flazi (2016) and Rothausen & Conway (2011).

Among water services in China, seawater desalination, water reclamation, and inter-basin water transfer are the most energy intensive (see Table A1-8 in Appendix 1). 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 (Figure 14) differs in some ways from typical international levels (Figure 15). 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) (Zeng, Chen, Dong, & Liu, 2017). 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 kilowatt-hours [kWh]/ $m^3$) represents only the water that is pumped by the eastern 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 3,236 kWh/acre-foot (2.62 kWh/$m^3$), depending on where the water is delivered (Klein, Krebs, Hall, O'Brien, & Blevins, 2005).

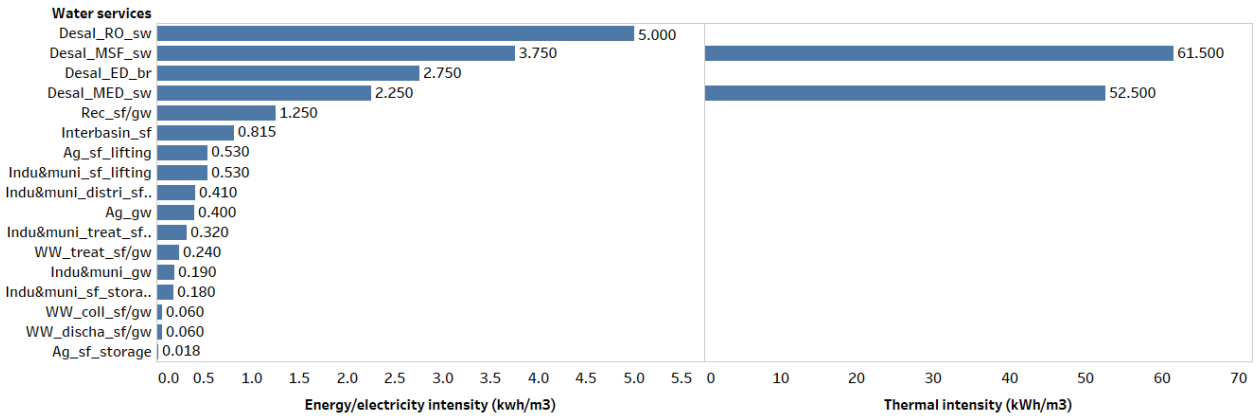


Figure 15. Energy intensities of water services in China, 2014[8]

[8] 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

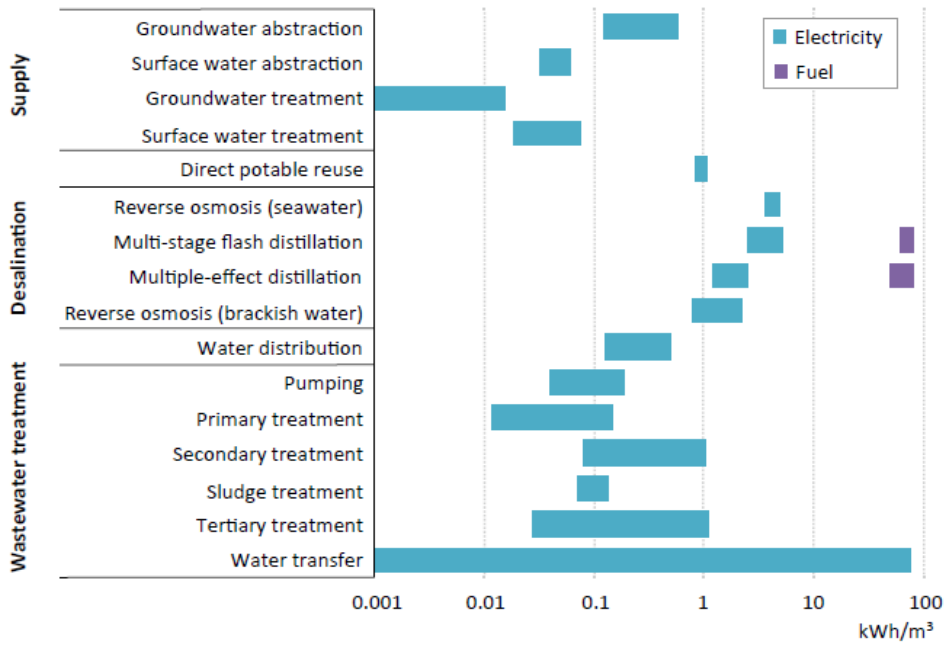


Figure 16. International energy intensity values for various water-sector processes

Note: The water transfer category includes wastewater collection, treatment, and discharge or re-use. Source: International Energy Agency (2016).

## 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 developed 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. Figure 9 shows the hierarchical structure and key assumptions of the eight energy-policy scenarios and seven water-policy scenarios that we studied.

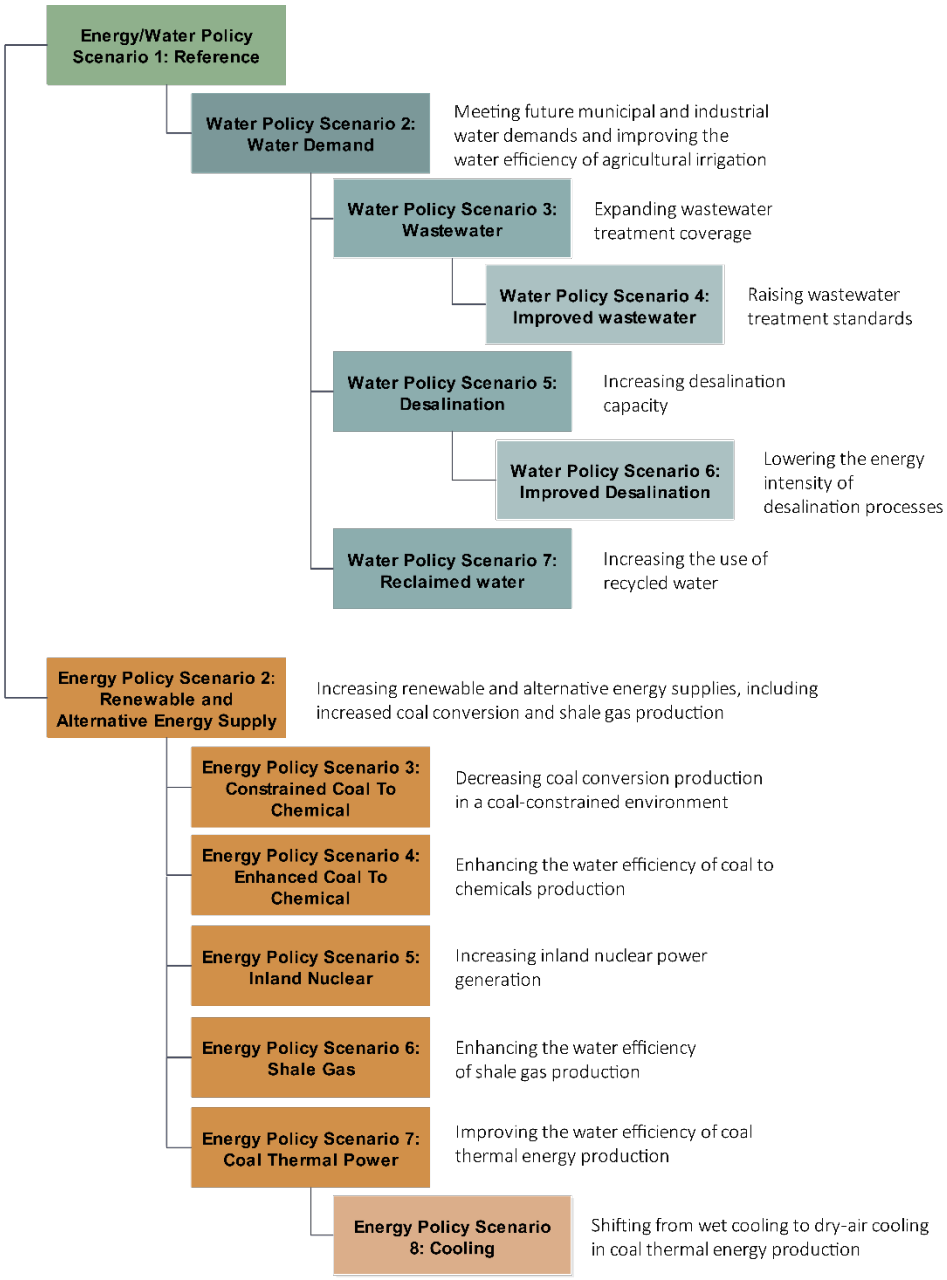


Figure 17. The hierarchical structure and key assumptions of our water- and energy-policy scenarios

## 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.

1. Reference Scenario (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 effects of this scenario include meeting all of China's stated targets for reducing energy use and $CO_2$ emissions, as well as meeting announced targets for increasing the capacities of non-fossil-fuel power sources. The Reference Scenario assumes that no new policies will be adopted, although independent technological improvements are expected to occur through 2050. 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. In addition, national energy data was calibrated to the latest reported year to account for the most recent trends. For example, the installed capacities for the various generation sources in the power sector are calibrated through 2015 using reported installed capacities. We then considered the stated energy targets for 2020 and projections based on specific energy plans and experts' inputs to extrapolate expansion of future installed capacity.

2. Increased Renewable and Alternative Energy (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. Because it is a more realistic scenario than the Reference Scenario, we use this Renewable and Alternative Energy Supply scenario as the baseline for evaluating scenarios of other energy policy pathways. See Table 4. 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 (Energy Research Institute of the National Development and Reform Commission of China and Lawrence Berkeley National Laboratory and Rocky Mountain Institute, 2016) (Price et al., 2017).

Table 4. Total installed energy capacity assumed for Energy Policy Scenario 2

| | Total Installed Capacity (GW) | | | | |
|---|---|---|---|---|---|
| | 2010 | 2020 | 2030 | 2040 | 2050 |
| Distributed solar PV | 0 | 19 | 69 | 223 | 504 |
| Geothermal | 0 | 0 | 0 | 0 | 1 |
| Biomass | 4 | 15 | 19 | 22 | 34 |
| Solar | 0 | 124 | 313 | 801 | 1,416 |
| Wind | 30 | 271 | 482 | 1,002 | 1,217 |
| Nuclear | 11 | 58 | 100 | 155 | 221 |

| | Total Installed Capacity (GW) | | | | |
|---|---|---|---|---|---|
| | 2010 | 2020 | 2030 | 2040 | 2050 |
| Hydro | 216 | 380 | 410 | 444 | 501 |
| Natural gas | 17 | 110 | 161 | 225 | 294 |
| Diesel | 9 | 11 | 11 | 10 | 6 |
| Coal | 559 | 855 | 904 | 833 | 442 |

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 (China Petroleum and Chemical Industry Federation, 2016). Projections through 2050 were based on the reference scenario in a report by the Natural Resources Defense Council (NRDC) (2016). We projected increasing shale gas production in China through 2050 based on the multi-cycle Weng model that we developed (J. Wang, Feng, Zhao, Snowden, & Wang, 2011). 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.

3. Increased Renewable and Alternative Energy Supplies with Constrained Coal (Energy Policy Scenario 3)

*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 13$^{th}$ FYP. The lower production levels projected for 2050 are based largely on the Coal Cap Scenario in the NRDC report (Natural Resources Defense Council, 2016).

4. Increased Renewable and Alternative Energy Supplies with Enhanced Water Efficiency for Coal Conversion Processes (Energy Policy Scenario 4)

*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.

5. Increased Renewable and Alternative Energy Supplies with Inland Nuclear (Energy Policy Scenario 5)

*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.

6. Increased Renewable and Alternative Energy Supplies with Increased Water Efficiency for Shale

Gas (Energy Policy Scenario 6)

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

7. Increased Renewable and Alternative Energy Supplies with Increased Water Efficiency for Coal Thermal Power (Energy Policy Scenario 7)

*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) (General Administration of Quality Supervision Inspection and Quarantine & Standardization Administration of China, 2012), see Table 5. 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.

Table 5. Current and projected levels of water use intensity for thermal power coal plants

| Thermal power capacity | 2014 Cooling technology (consumption, withdrawal) (Unit: $m^3$/MWh) | 2030 Cooling technology (consumption, withdrawal) (Unit: $m^3$/MWh) |
|---|---|---|
| <300 MW thermal power | Once through (0.9, 100)<br>Recirculating (2.7, 2.6)<br>Dry cooling (0.18, 0) | Once through (0.6, 82.9)<br>Recirculating (2.2, 2.1)<br>Dry cooling (0.18, 0) |
| >300 MW &<600 MW thermal power | Once through (0.42, 100)<br>Recirculating (2.39, 2.6)<br>Dry cooling (0.18, 0) | Once through (0.38, 82.9)<br>Recirculating (2.03, 1.96)<br>Dry cooling (0.18, 0) |
| >600 MW thermal power & supercritical | Once through (0.43, 90)<br>Recirculating (2.13, 2.6)<br>Dry cooling (0.18, 0) | Once through (0.33, 92.8)<br>Recirculating (2.03, 1.96)<br>Dry cooling (0.18, 0) |

Note: the water use intensities for 2014 reflect the average levels presented in water use standards for fossil-fuel-fired power production (GB/T 18916.1-2012) (General Administration of Quality Supervision Inspection and Quarantine & Standardization Administration of China, 2012).

8. Increased Renewable and Alternative Energy Supplies with Increased Water Efficiency for Coal Thermal Power and a Shift in Cooling (Energy Policy Scenario 8)

*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% (C. Zhang, Anadon, Mo, Zhao, & Liu, 2014) 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.

## Water Policy Scenarios

The water-policy scenarios are designed to evaluate the impacts of water policies on energy consumption.

1. Reference Scenario (Water Policy Scenario 1)

*Water Policy Scenario 1* is designed to evaluate the impacts of water policies on energy consumption. Under the Reference Scenario, which we use as the baseline, we assume no major changes to the energy demand sectors so we can focus on a range of potential changes in the water demand sector. Under the Reference Scenario, water demand and wastewater intensities are assumed to be frozen at their 2014 levels.

2. Increased water demand from municipal and industrial sectors with improved water efficiency for agricultural irrigation (Water Policy Scenario 2)

*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 (S. Grigg, 2016). 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 (National Development and Reform Commission of China and Ministry of Water Resources of China and Ministry of Housing Urban and Rural Development of China, 2017). We assume that water-use efficiency will continue to improve, reaching 0.65 by 2050. See Figure 7.

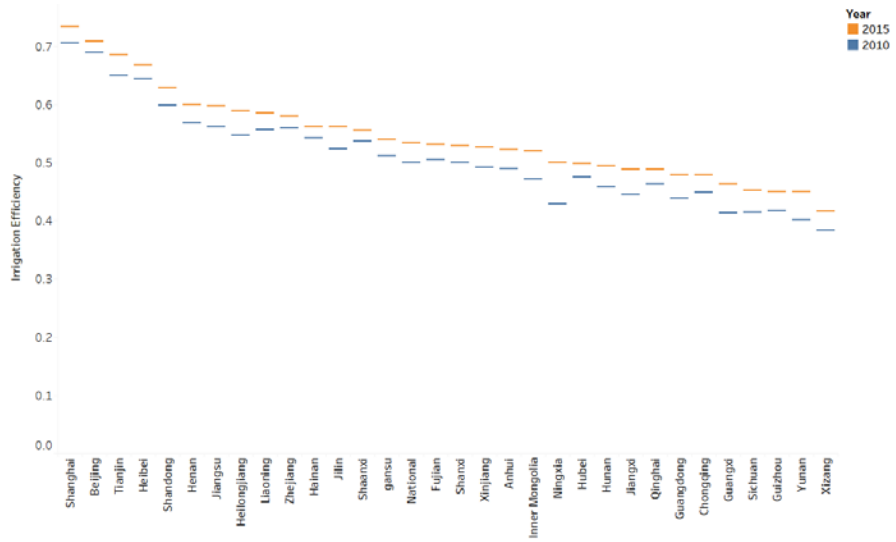


Figure 18. Irrigation efficiency by province in China, 2010 and 2015

To develop assumptions regarding future water demand for municipal and industrial uses, we relied on external projections (Shen et al., 2005) (State Council of China, 2011). 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 (State Council of China, 2011), 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. See Table 6.

Table 6. Current and assumed future water demand by sector

| Unit: billion $m^3$ | 2014 | Share (%) | 2030 (State Council of China, 2011) | Share (%) | 2050 assumption | 2050 | Share (%) |
|---|---|---|---|---|---|---|---|
| Municipal | 76.7 | 12.6 | 102.1 | 14.0 | *Increases 17.5% from 2030 (Shen et al., 2005) | 119.9 | 15.8 |
| Industrial | 135.6 | 22.2 | 171.8 | 23.5 | | 201.8 | 26.6 |
| Agriculture | 386.9 | 63.5 | 407.8 | 55.8 | *Irrigation efficiency improves from 0.6 (2030) to 0.65 | 387.4 | 51.0 |
| Environ-mental (Shen et al., 2005) | 10.3 | 1.7 | 48.5 | 6.6 | | 50.1 | 6.6 |

*****The rate of increase/decrease is assumed to be the same for water supply (whether from storage/lifting or groundwater pumping), wastewater discharge, etc. Planned water transfer projects rely largely on gravity. We assume that the energy needed for inter-basin water transfer remains the same as in the base year of 2014.

3. Expanded wastewater treatment coverage (Water Policy Scenario 3)

*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 (National Development and Reform Commission of China and Ministry of Housing and Urban-Rural Development, 2016). 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.

4. Expanded wastewater treatment coverage and advanced wastewater treatment standards (Water Policy Scenario 4)

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 (Hou, Tian, & Tanikawa, 2015). By 2050, 60% of treated wastewater is assumed to undergo secondary treatment and sludge treatment (which requires an additional 0.1 kwh/$m^3$) (International Energy Agency, 2016). In addition, 40% of treated wastewater is assumed to undergo tertiary or other advanced treatment (Hou et al., 2015). The energy intensity is assumed to be that of the typical U.S. municipal treatment level 0.43 kwh/$m^3$ (Y. Gu et al., 2017).

Table 7. Key targets from the 13th FYP regarding urban wastewater treatment and recycling

| Indicator | | 2015 Baseline (%) | 2020 Target (%) |
|---|---|---|---|
| Wastewater treatment rate (%) | Cities | 91.9 | 95 (cities at the prefecture level or above reach 100) |
| | Counties | 85 | ≥85 (counties in the eastern region aim for 90) |
| | Towns | / | 70 (towns in central-west region aim for 50) |
| Sludge treatment rate (%) | Cities | 53 | 75 (cities at the prefecture level or above to reach 90) |
| | Counties | 24.3 | Aim for 60 |
| | Key towns | / | Increase by 5% |
| Reclaimed water re-use rate (%) | Beijing-Tianjin-Hebei Region | 35 | ≥30* |
| | Beijing | 65.9 | 68 |
| | Tianjin | 28.5 | 30 |
| | Hebei | 27.7 | 30 |
| | Water-scarce cities | 12.1 | ≥20 |

| Indicator | | 2015 Baseline (%) | 2020 Target (%) |
|---|---|---|---|
| | Other cities & counties | 4.4 | Aim for 15 |
| Wastewater transport network ($10^4$ km) | | 29.65* | 42.24 |
| Total wastewater treatment capacity ($10^4$ m3/day) | | 21,744 | 26,766 |
| Total sludge treatment capacity ($10^4$ tons/day) | | 3.74* | 9.75 |
| Total reclaimed water capacity ($10^4$ m3/day) | | 2653* | 4158* |

*Towns excluded. Source: (National Development and Reform Commission of China and Ministry of Housing and Urban-Rural Development, 2016).

5. Expanded desalination (Water Policy Scenario 5)

*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 (National Development and Reform Commission of China and State Oceanic Administration of China, 2017). 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.

6. Expanded desalination with increased water efficiency (Water Policy Scenario 6)

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 (Semiat, 2008) to 3 kwh/$m^3$ in 2020 and to about 2.1-2.4 kwh/$m^3$ by 2035 (International Water Association, 2016). For MED, we assume that the energy intensity (including both electrical and thermal energy) declines from 55kwh/$m^3$ in 2014 (Shahzad, Burhan, Ang, & Ng, 2017) to 15 kwh/$m^3$ by 2030 (Semiat, 2008).

7. Expanded use of reclaimed water (Water Policy Scenario 7)

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 (National Development and Reform Commission of China and Ministry of Housing and Urban-Rural Development, 2016). 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.

# Results

We incorporated the assumptions and methods described above into China 2050 DREAM to develop 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 developed similar results for the base year only.

## Base year

### *National level*

Table 8 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 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. Jiang (2017) 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 Figures A2-1 to A2-6 in Appendix 2.

Table 8. 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* | 31.7* | 32.8* | 322.2* |
| Water Withdrawal ($km^3$) | 79.4 | | 386.9* | 87.8* | 76.7* | 680.9* |
| Final Energy Consumption (TWh) | | 210.7 | | 15,573 (industrial hot water 604.1**) | 2590 (residential hot water 350.6**) | 25,540 |
| Primary Energy Consumption (TWh) | | 520.1 | | 22,107 | 3927 | 37,170 |

*Ministry of Water Resources of the People's Republic of China(2015) **Jiang (2017)

### *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 Table 9. 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 in the near future. In Appendix 2 (Figures A2-7 to A2-8), 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. Figure A2-9 in Appendix 2 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. See Table 10. The amount of energy consumed at the city or utility level could be much greater, especially as rapid urbanization continues.

Table 9. 14 Major coal bases and associated water use and availability in China

| Coal base | Average Precipita-tion (mm/year) | Total water resource ($km^3$) | 2014 water withdra-wal ($km^3$) | Amount of water consumed by coal industry*($km^3$) | 2020 Red Line Limit ($km^3$) | Available water resource ($km^3$) | Share of available water used (%) |
|---|---|---|---|---|---|---|---|
| Shendong (western Inner Mongolia) | 168-286 | 3.743 | 2.886 | 0.38 | 3.018 | 0.132 | 4.38 |
| Eastern Inner Mongolia | 265-422 | 47.382 | 8.16 | 0.334 | 10.947 | 2.786 | 25.46 |
| Eastern Ningxia | 365-442 | 0.185 | 4.241 | 0.114 | 4.351 | 0.11 | 2.52 |
| Northern Shanxi | 196-255 | 4.815 | 2.345 | 0.217 | 3.063 | 0.718 | 23.43 |
| Central Shanxi | 406-498 | 4.664 | 3.631 | 0.115 | 4.85 | 1.219 | 25.13 |
| Eastern Shanxi | 467-574 | 2.899 | 1.288 | 0.19 | 1.387 | 0.099 | 7.14 |
| Northern Shaanxi | 526-630 | 4.035 | 0.986 | 0.145 | 1.615 | 0.629 | 38.94 |
| Huanglong | 394-534 | 3.829 | 1.728 | 0.082 | 2.36 | 0.632 | 26.8 |
| Xinjiang | 468-610 | 44.113 | 35.016 | 0.127 | 31.338 | -3.678 | -11.74 |
| Central Hebei | 47-220 | 10.583 | 8.368 | 0.151 | 9.658 | 1.29 | 13.35 |
| Henan | 391-576 | 12.7 | 11.121 | 0.71 | 13.084 | 1.963 | 15.01 |
| Lianghuai | 546-821 | 1.83 | 2.268 | 0.886 | 2.452 | 0.184 | 7.5 |
| Western Shandong | 851-887 | 13.497 | 7.522 | 0.207 | 9.096 | 1.574 | 17.03 |
| Yungui | 665-802 | 7.7564 | 10.347 | 0.757 | 16.377 | 6.03 | 36.82 |
| Total | 983-1396 | 23.1839 | 99.908 | 4.415 | 11.3595 | 13.687 | 12.05 |

*coal industry covers coal power, coal production &washing, coal to chemicals in this table.

Source: (Jiang, 2017) and (Shang et al., 2017).

Table 10. Final energy consumption by the water sector (2014) and percent of total electricity/final energy consumption by province

| Province | Share of final electricity consumed (%) | Share of final energy consumed (%) |
|---|---|---|
| Anhui | 4.9% | 1.0 |
| Beijing | 4.4 | 0.9 |
| Chongqing | 4.0 | 0.6 |
| Fujian | 1.4 | 0.4 |
| Gansu | 4.4 | 1.1 |
| Guangdong | 1.5 | 0.5 |
| Guangxi | 2.5 | 0.5 |
| Guizhou | 3.6 | 0.7 |
| Hainan | 2.9 | 0.5 |
| Hebei | 3.6 | 0.6 |
| Heilongjiang | 9.8 | 1.1 |
| Henan | 2.6 | 0.6 |
| Hubei | 2.0 | 0.3 |
| Hunan | 3.4 | 0.5 |
| Jiangsu | 1.6 | 0.5 |
| Jiangxi | 3.0 | 0.6 |
| Jilin | 4.4 | 0.4 |
| Liaoning | 2.4 | 0.3 |
| Neimenggu | 2.5 | 0.6 |
| Ningxia | 3.5 | 1.1 |
| Qinghai | 2.7 | 1.0 |
| Shaanxi | 2.2 | 0.4 |
| Shandong | 3.2 | 0.6 |
| Shanghai | 1.5 | 0.3 |
| Shanxi | 2.5 | 0.4 |
| Sichuan | 1.7 | 0.3 |
| Tianjin | 7.5 | 1.2 |
| Tibet | | |
| Xinjiang | 5.5 | 1.2 |
| Yunnan | 16.0 | 0.5 |
| Zhejiang | 1.7 | 0.6 |

## Modeling results

This section reports our modeling results for the energy and water sectors. We report $CO_2$ emissions (Figure 18), water consumption (Figure 19), and water withdrawal (Figure 20) 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.

### *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% to 25%) and water consumption (by 0.1% to 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% to 3.3% reduction in withdrawal and a 0.2% to 2.3% reduction in consumption); however, this approach could increase $CO_2$ emissions by 0.01% to 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 Appendix 2 (Figures A2-10 to A2-17).

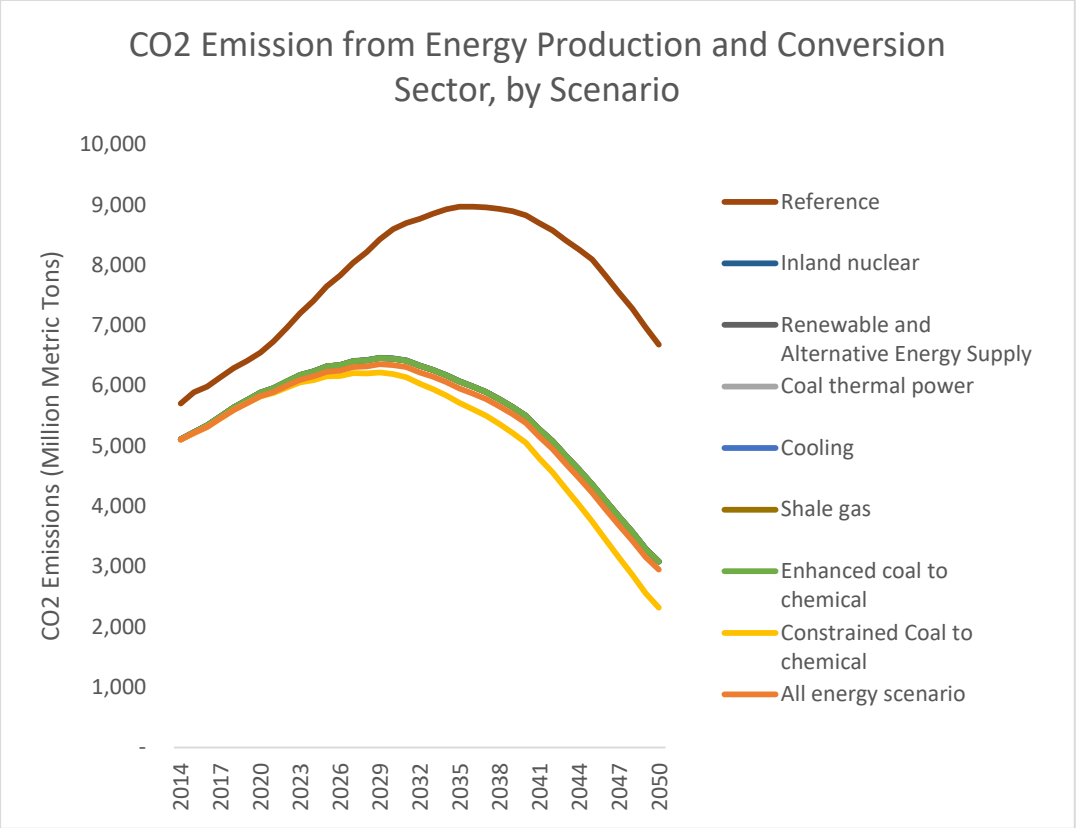


Figure 19. $CO_2$ Emissions from the Energy Production and Conversion Sectors, by Scenario

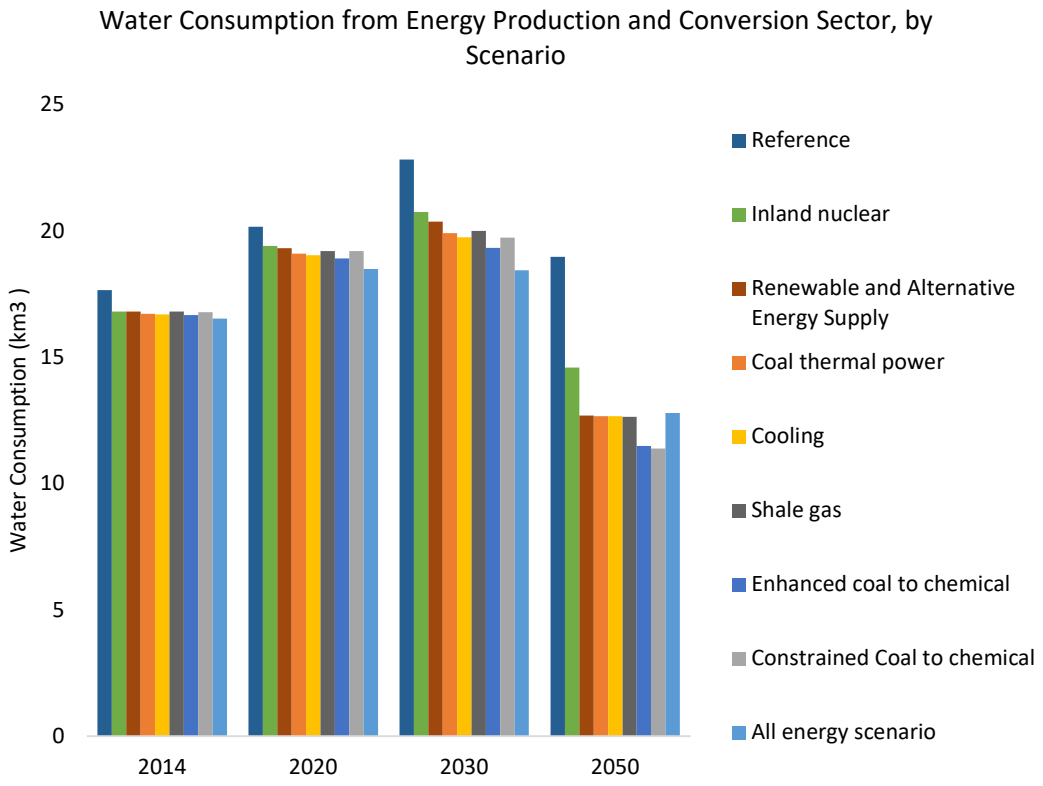


Figure 20. Water Consumption by the Energy Production and Conversion Sectors, by Scenario

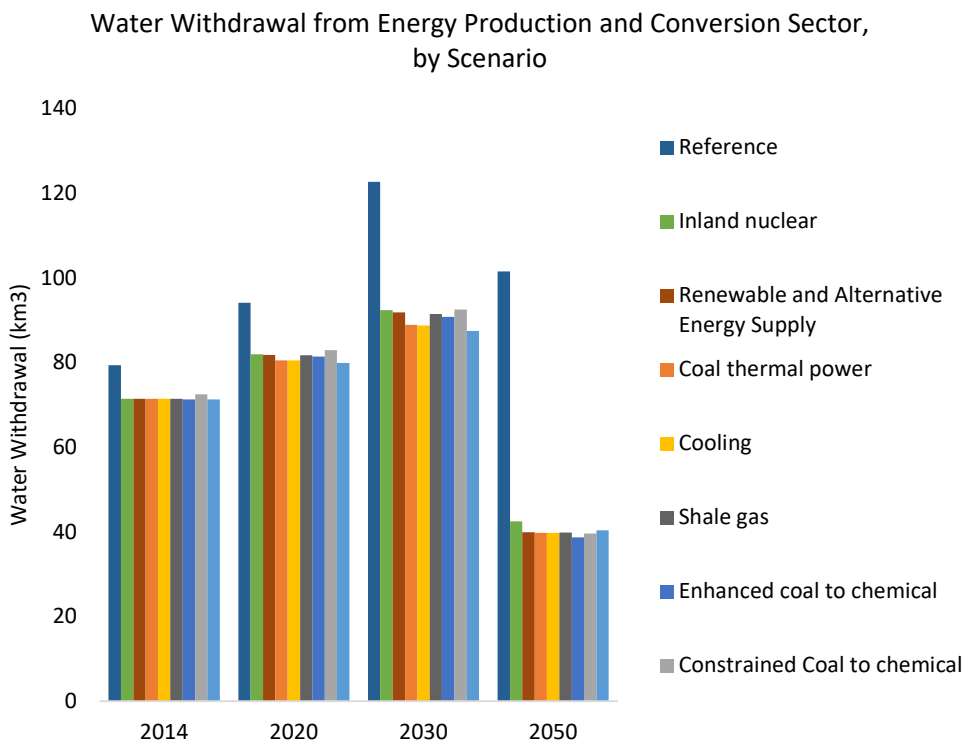


Figure 21. Water Withdrawals by the Energy Production and Conversion Sectors, by Scenario

### *Water sector*

The modeling results for all scenarios (Figure 21) 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. Figure 22 shows the water sector's $CO_2$ emissions trend, which is dictated by the decreasing coal content in China's power mix from 2030-2035 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 Figures A2-18 to A2-19 in Appendix 2.

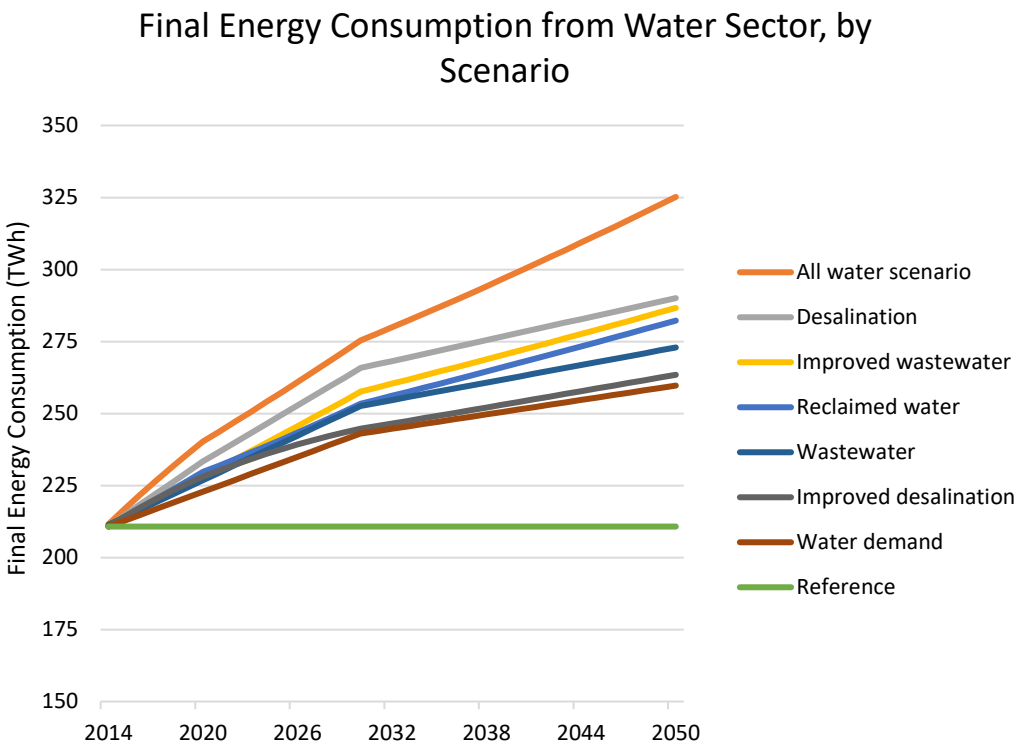


Figure 22. Final Energy Consumption from the Water Sector, by Scenario

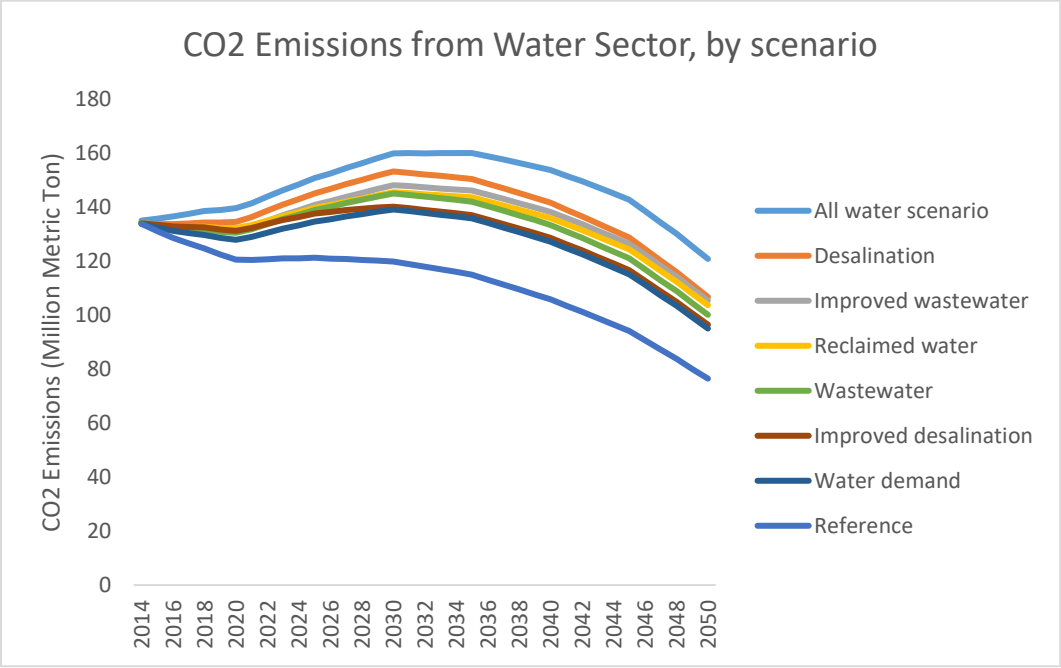


Figure 23. $CO_2$ Emissions from the Water Sector, by Scenario

# Conclusions and Policy Implications

This report has comprehensively and robustly examined the relationship between water and energy consumption in China. The results shed light on the current and potential future effects of China's water and energy policies. In particular, this study confirms the constraints on energy development that water supply presents at both the national and regional level. This analysis also highlights the trend of increasing energy use by the water sector, even though the sector currently represents a negligible percentage of the national total.

In addition, this report describes major differences in governance between the agencies and policymakers that oversee the water and energy sectors, indicating that attaining policy coherence and coordination will be challenging. The research framework developed for this study will serve as the basis for forthcoming regional case studies. Key conclusions from the modeling work and the policy analysis are summarized below.

### *Significant water is used by the energy sector in China, 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.

Despite this trend, both national and provincial governments pay little attention on the energy required for water. On a project level, energy use usually is associated with cost, thus gaining the attention and concern of the water/wastewater project developers and city planners.

### *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[9] 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 15%[10] (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.

### *The importance and variety of nexus issues is exacerbated at the regional and local level.*

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.(2015) laid the groundwork for applying different research approaches/methodologies to different local policy and technical contexts.

### *Future research should take into account the different scale 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. 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

[9] 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.

[10] The percentage increase from Energy Policy Scenario 2 to Energy Policy Scenario 5.

these resources. In addition, seasonal/daily differences and local climate factors contribute to variation in impacts.

### *It is challenging to achieve policy coherence between the water and energy sectors.*

As mentioned earlier, it is relatively easy to identify the incoherence between policies and practices related to the water and energy sectors. The conflicts among government departments often are the natural products of bureaucracy, which is characterized by task specialization and hierarchical authority. Task specialization is demonstrated in the differences in the governance styles for the water and energy sectors, including scale (local vs. national); regulatory and market structure (public good vs. commodity, demand vs. supply); and the parties involved (disaggregated local/foreign company vs. state enterprise). We must ask how feasible and effective is the goal of developing policy coherence in the ongoing management of climate, energy, and water. We must consider how policy coherence are affected by current organizational values, the distribution of political power and resources, and the methods for enacting policy decisions. These are some of the challenging and meaningful issues to be addressed by future research regarding the WEN. For the short term, it is imperative to start developing a common language for achieving cross-sectoral goals while utilizing existing institutional settings and resources.

## References


Benson, D., Gain, A. K., & Rouillard, J. J. (2015). Water Governance in a Comparative Perspective: From IWRM to a'Nexus' Approach? *Water Alternatives*, *8*(1), 756–773.

China National Renewable Energy Center. (2016). *China Energy Statistical Analysis (In Chinese)*. Beijing.

China Petroleum and Chemical Industry Federation. (2016). *Guidance for modern coal chemical industry deveopment during 13th Five-year plan period (In Chinese)*. Beijing.

CSRES. (2017). Norms of Water Intake. Retrieved July 21, 2017, from http://www.csres.com/sort/ics/13.060.25_1.html

Dai, J., Wu, S., Han, G., Weinberg, J., Xie, X., Wu, X., … Yang, Q. (2017). Water-energy nexus: A review of methods and tools for macro-assessment. *Applied Energy*, (November 2016). http://doi.org/10.1016/j.apenergy.2017.08.243

DOE. (2014). *U.S. DEPARTMENT OF Water-Energy Nexus: Challenges and Opportunities*.

E20. (2017). *China water services market report (In Chinese)*. Beijing, China.

Endo, A., Burnett, K., Orencio, P. M., Kumazawa, T., Wada, C. A., Ishii, A., … Taniguchi, M. (2015). Methods of the water-energy-food nexus. *Water*, *7*, 5806–5830. http://doi.org/10.3390/w7105806

Energy Research Institute of the National Development and Reform Commission of China and Lawrence Berkeley National Laboratory and Rocky Mountain Institute. (2016). *Reinventing Fire: China, A Roadmap for China's Revolution in Energy Consumption and Production to 2050*. Retrieved from https://rmi.org/insights/reports/reinventing-fire-china/

General Administration of Quality Supervision Inspection and Quarantine & Standardization Administration of China. GB/T 18916.1-2012 Norm of water intake--Part 1: Fossil fired power production (In Chinese) (2012).

Gu, A., Teng, F., & Lv, Z. (2016). Exploring the nexus between water saving and energy conservation: Insights from industry sector during the 12th Five-Year Plan period in China. *Renewable and*

*Sustainable Energy Reviews*, *59*, 28–38. http://doi.org/10.1016/j.rser.2015.12.285

Gu, Y., Li, Y., Li, X., Luo, P., Wang, H., Wang, X., … Li, F. (2017). Energy Self-sufficient Wastewater Treatment Plants: Feasibilities and Challenges. *Energy Procedia*, *105*, 3741–3751. http://doi.org/10.1016/j.egypro.2017.03.868

Hamiche, A. M., Stambouli, A. B., & Flazi, S. (2016). A review of the water-energy nexus. *Renewable and Sustainable Energy Reviews*, *65*, 319–331.

Horvath, A. (2005). *Life-cycle energy assessment of alternative water supply systems in California*.

Hou, W., Tian, X., & Tanikawa, H. (2015). Greening China's Wastewater Treatment Infrastructure in the Face of Rapid Development: Analysis Based on Material Stock and Flow through 2050. *Journal of Industrial Ecology*, *19*(1), 129–140. http://doi.org/10.1111/jiec.12186

Huang, Q., & Xu, J. (2017). Scales of Power in Water Governance in China: Examples From the Yangtze River Basin. *Society & Natural Resources*, *30*(4), 1–15. http://doi.org/10.1080/08941920.2016.1268657

International Energy Agency. (2016). *Water Energy Nexus*. *World Energy Outlook*.

International Water Association. (2016). Desalination-Past, Present and Future. Retrieved November 15, 2017, from http://www.iwa-network.org/desalination-past-present-future/

IRENA. (2015). Renewable energy in the water, energy and food nexus. *International Renewable Energy Agency*, (January), 1–125. http://doi.org/10.1016/j.renene.2012.10.057

Jiang, S. (2017). *Water energy nexus analysis and simulation (PhD thesis) (In Chinese)*. China Institute of Water Resource & Hydropower Research (IWHR).

Jordan, G., & Halpin, D. (2006). The political costs of policy coherence: Constructing a rural policy for Scotland. *Journal of Public Policy*, *26*(1), 21–41. http://doi.org/10.1017/S0143814X06000456

Klein, G., Krebs, M., Hall, V., O'Brien, T., & Blevins, B. B. (2005). California's Water – Energy Relationship. *Caligornia Energy Commicion*, (November), 1–180. http://doi.org/CEC-700-2005-011-SF

Kostka, G., & Hobbs, W. (2012). Local Energy Efficiency Policy Implementation in China : Bridging the Gap between National Priorities and Local Interests *. *The China Quarterly*, *211*, 765–785. http://doi.org/10.1017/S0305741012000860

Kyle, P., Johnson, N., Davies, E., Bijl, D. L., Mouratiadou, I., Bevione, M., … Hejazi, M. (2016). Setting the system boundaries of "energy for water" for integrated modeling. *Environmental Science and Technology*, *50*(17), 8930–8931. http://doi.org/10.1021/acs.est.6b01066

Li, X., Liu, J., Zheng, C., Han, G., & Hoff, H. (2016). Energy for water utilization in China and policy implications for integrated planning. *International Journal of Water Resources Development*, *32*(3), 477–494. http://doi.org/10.1080/07900627.2015.1133403

Lohmar, B., Wang, J., Rozelle, S., Huang, J., & Dawe, D. (2003). *China's Agricultural Water Policy Reforms: Increasing Investment, Resolving Conflicts, and Revising Incentives*.

Macknick, J., Newmark, R., Heath, G., & Hallett, K. C. (2012). Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature. *Environmental Research Letters*, *7*(4), 45802. http://doi.org/10.1088/1748-9326/7/4/045802

Ministry of Housing and Urban–Rural Development. (2017). Building Energy Efficiency and Technology Department of Ministry of Housing and Urban–Rural Development. Retrieved July 21, 2017, from

http://www.mohurd.gov.cn/csjs/index.html

Ministry of Industry and Information Technology. (2014). Market Access Standard for Coking Industry (In Chinese). Beijing.

Ministry of Water Resources of the People's Republic of China. (2015). *China Water Resource Bulletin 2014 (In Chinese)*. Beijing, China.

Ministry of Water Resources of the People's Republic of China. (2017). Organizational Structure of Ministry of Water Resources. Retrieved July 21, 2018, from http://www.mwr.gov.cn/jg/zzjg/jgsj/

National Bureau of Statistics of China. (2016). *China Energy Statistical Yearbook*.

National Development and Reform Commission. (2016a). 13th Five-Year Plan for Energy Development (In Chinese). Retrieved July 21, 2017, from http://www.ndrc.gov.cn/zcfb/zcfbghwb/201701/W020170117350627940556.pdf

National Development and Reform Commission. (2016b). 13th Five-Year Plan for Renewable Energy Development (In Chinese). Retrieved July 21, 2017, from http://www.ndrc.gov.cn/zcfb/zcfbghwb/201612/t20161216_830269.html

National Development and Reform Commission. (2017a). The 13th FYP for Water-Saving Society Construction. Retrieved July 21, 2017, from http://www.ndrc.gov.cn/zcfb/zcfbghwb/201701/t20170122_835993.html

National Development and Reform Commission. (2017b). The Environmental Protection and Resources Conservation Department of National Development and Reform Commission. Retrieved July 21, 2017, from http://hzs.ndrc.gov.cn/

National Development and Reform Commission of China and Ministry of Housing and Urban-Rural Development. (2016). The 13th Five-year plan on national urban wastewater treatment & recycling infrastructure development (In Chinese). Beijing, China. Retrieved from http://www.ndrc.gov.cn/zcfb/zcfbghwb/201701/t20170122_836133.html

National Development and Reform Commission of China and Ministry of Water Resources of China and Ministry of Housing Urban and Rural Development of China. (2017). The 13th Five-year Plan on Water Efficient Society (In Chinese). Beijing, China. Retrieved from http://www.ndrc.gov.cn/zcfb/zcfbghwb/201701/t20170122_835993.html

National Development and Reform Commission of China and State Oceanic Administration of China. (2017). The 13th Five-year Plan on Seawater Utilization (In Chinese). Beijing, China. Retrieved from http://www.soa.gov.cn/xw/hyyw_90/201701/t20170104_54300.html

National Energy Administration. (2017). National Energy Administration. Retrieved July 21, 2017, from http://www.nea.gov.cn/

Natural Resources Defense Council. (2016). *Coal cap and policy analysis of coal chemical industry (In Chinese)*. Beijing.

Oliver, G., & Hussey, K. (2016). Cross-sectoral governance of the climate , energy and water sectors : A " Rubik " s cube ' analysis of cross-sectoral co-ordination. In I. J. Pittock, K. Hussey, & S. Dovers (Eds.), *Climate, Energy and Water: Managing Trade-offs, Seizing Opportunities* (pp. 172–197). Cambridge: Cambridge University Press. http://doi.org/10.1017/CBO9781139248792.011

Pan, L., Liu, P., Ma, L., & Li, Z. (2012). A supply chain based assessment of water issues in the coal industry in China. *Energy Policy*, *48*, 93–102. http://doi.org/10.1016/j.enpol.2012.03.063

Price, L., Khanna, N., Fridley, D., Hasanbeigi, A., Lu, H., Wei, F., … Yee, C. (2017). Reinventing fire: China – the role of energy efficiency in China's roadmap to 2050. In *European Council for an Energy Efficient Economy Summer Study 2017* (pp. 113–120).

Qin, Y., Curmi, E., Kopec, G. M., Allwood, J. M., & Richards, K. S. (2015). China's energy-water nexus - assessment of the energy sector's compliance with the "3 Red Lines" industrial water policy. *Energy Policy*, *82*(1), 131–143. http://doi.org/10.1016/j.enpol.2015.03.013

Rothausen, S. G. S. A., & Conway, D. (2011). Greenhouse-gas emissions from energy use in the water sector. *Nature Climate Change*, *1*(4), 210–219. http://doi.org/10.1038/nclimate1147

S. Grigg, N. (2016). *Integrated Water Resource management: An Interdisciplinary Approach*. Fort Collins, Colorado, USA: Palgrave Macmillan.

Semiat, R. (2008). Energy Issues in Desalination Processes. *Environmental Science & Technology*, *42*(22), 8193–8201. http://doi.org/10.1021/es801330u

Shahzad, M. W., Burhan, M., Ang, L., & Ng, K. C. (2017). Energy-water-environment nexus underpinning future desalination sustainability. *Desalination*, *413*, 52–64. http://doi.org/10.1016/j.desal.2017.03.009

Shang, Y., Hei, P., Lu, S., Shang, L., Li, X., Wei, Y., … Wang, H. (2016). China's energy-water nexus: Assessing water conservation synergies of the total coal consumption cap strategy until 2050. *Applied Energy*. http://doi.org/10.1016/j.apenergy.2016.11.008

Shang, Y., Lu, S., Li, X., Hei, P., Lei, X., Gong, J., … Wang, H. (2017). Balancing development of major coal bases with available water resources in China through 2020. *Applied Energy*, *194*, 735–750. http://doi.org/10.1016/j.apenergy.2016.07.002

Shang, Y., Wang, J., Liu, J., Jiang, D., Zhai, J., & Jiang, S. (2016). Suitability analysis of China's energy development strategy in the context of water resource management. *Energy*, *96*, 286–293. http://doi.org/10.1016/j.energy.2015.12.079

Shen, F., Geng, L., Cao, X., Wang, J., Zhong, H., & Xu, P. (2005). Perspective on long term water resource demand in China (In Chinese). *Advance in Water Science*, *16*(4), 552–555. http://doi.org/10.14042/j.cnki.32.1309.2013.01.009

State Council of China. (2011). The National Water Resource Integrated Plan (In Chinese). Beijing, China.

State Oceanic Administrion. (2017). State Oceanic Administration. Retrieved July 21, 2017, from http://www.soa.gov.cn/

Su, W. (2015). China's Intended Nationally Determined Contributions. Retrieved July 21, 2017, from http://www4.unfccc.int/submissions/INDC/Published Documents/China/1/China's INDC - on 30 June 2015.pdf

Tan, D., Hu, F., Thieriot, H., & McGregor, D. (2015). *Towards a water and energy secure china: tough choices ahead in power expansion with limited water resources*.

The Central People's Government of the People's Republic of China. (2007). Energy Conservation Law of the People's Republic of China (2007 Revision) (In Chinese). Retrieved July 21, 2017, from http://www.gov.cn/flfg/2007-10/28/content_788493.htm

The State Council. (2012). The Most Stringent Water Resources Management. Retrieved July 21, 2017, from http://www.gov.cn/zwgk/2012-02/16/content_2067664.htm

Villamayor-Tomas, S., Grundmann, P., Epstein, G., Evans, T., & Kimmich, C. (2015). The water-energy-food

security nexus through the lenses of the value chain and the institutional analysis and development frameworks. *Water Alternatives*, *8*(1), 735–755.

Visseren-Hamakers, I. J. (2015). Integrative environmental governance: enhancing governance in the era of synergies. *Current Opinion in Environmental Sustainability*, *14*, 136–143. http://doi.org/10.1016/j.cosust.2015.05.008

Wang, J., Feng, L., Zhao, L., Snowden, S., & Wang, X. (2011). A comparison of two typical multicyclic models used to forecast the world's conventional oil production. *Energy Policy*, *39*(12), 7616–7621. http://doi.org/10.1016/j.enpol.2011.07.043

Wang, S., Cao, T., & Chen, B. (2017). Water-energy Nexus in China's Electric Power System. *Energy Procedia*, *105*, 3972–3977. http://doi.org/10.1016/j.egypro.2017.03.828

Weitz, N., Strambo, C., Kemp-benedict, E., & Nilsson, M. (2017). Closing the governance gaps in the water-energy-food nexus : Insights from integrative governance, *45*(June), 165–173.

Wu, C. Z., Yin, X. L., Yuan, Z. H., Zhou, Z. Q., & Zhuang, X. S. (2010). The development of bioenergy technology in China. *Energy*, *35*(11), 4445–4450. http://doi.org/10.1016/j.energy.2009.04.006

Xiang, X., & Jia, S. (2016). Estimation and trend analysis of water demand of energy industry in China (In Chinese). *Journal of Natural Resources*, *31*(1), 114–123.

Xinhua Net. (2006). 11th Five-Year Plan (In Chinese).

Xinhua Net. (2011). 12th Five-Year Plan (In Chinese). Retrieved July 21, 2017, from http://www.china.com.cn/policy/txt/2011-03/16/content_22156007.htm

Xinhua Net. (2016). 13th Five-Year Plan (In Chinese). Retrieved July 21, 2017, from http://news.xinhuanet.com/politics/2016lh/2016-03/17/c_1118366322.htm

Xinhua Net. (2017). China starts building large private coal to liquid project (In Chinese). Retrieved July 1, 2017, from http://news.xinhuanet.com/english/2017-06/09/c_136350861.htm

Zeng, S., Chen, X., Dong, X., & Liu, Y. (2017). Efficiency assessment of urban wastewater treatment plants in China: Considering greenhouse gas emissions. *Resources, Conservation and Recycling*, *120*, 157–165. http://doi.org/10.1016/j.resconrec.2016.12.005

Zhang, C., Anadon, L. D., Mo, H., Zhao, Z., & Liu, Z. (2014). Water − Carbon Trade-off in China's Coal Power Industry. *Environmental Science & Technology*, *48*(9), 11082–11089. http://doi.org/DOI: 10.1021/es5026454

Zhang, F., & Huang, K. (2017). The role of government in industrial energy conservation in China: Lessons from the iron and steel industry. *Energy for Sustainable Development*, *39*, 101–114. http://doi.org/10.1016/j.esd.2017.05.003

Zhou, Y., Li, H., Wang, K., & Bi, J. (2016). China's energy-water nexus: Spillover effects of energy and water policy. *Global Environmental Change*, *40*, 92–100. http://doi.org/10.1016/j.gloenvcha.2016.07.003