Appendix 1: Water and energy intensities literature review

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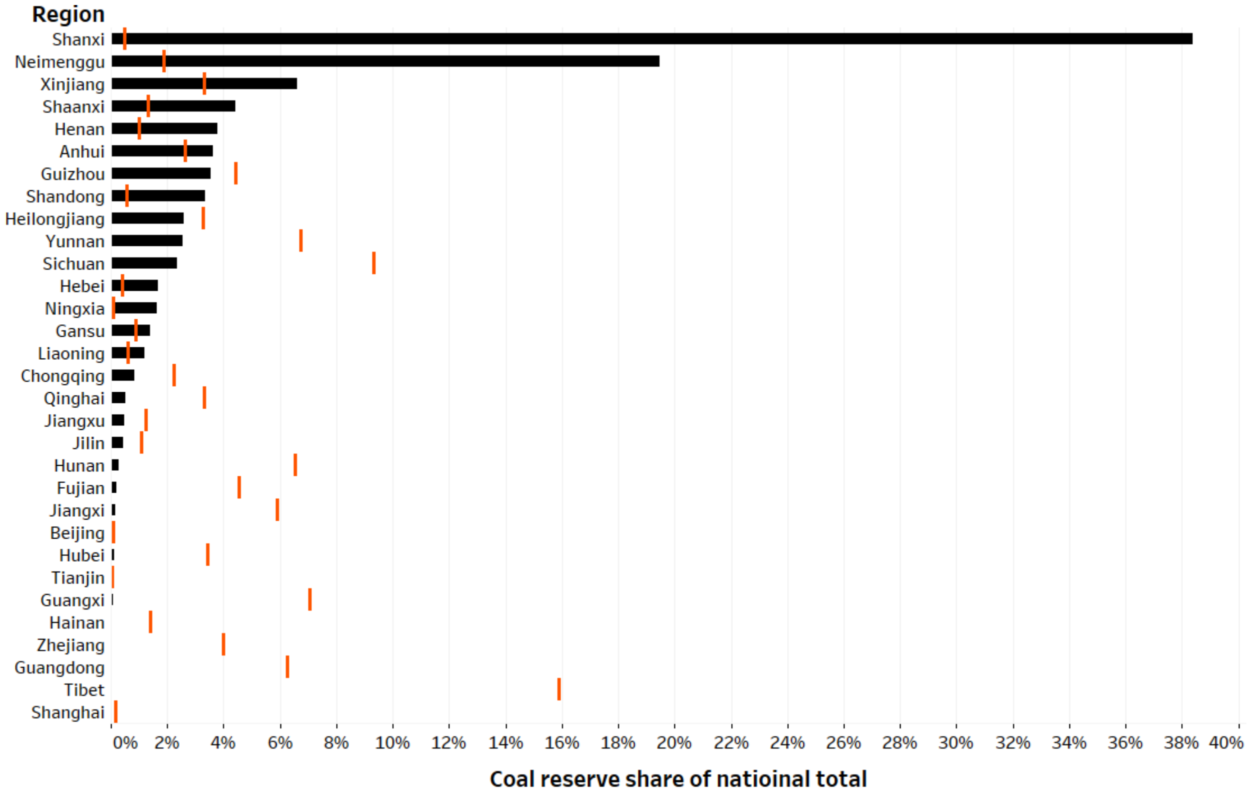
Water Use in Energy Systems

Primary energy production

Coal mining and washing

For decades, the coal mining industry has remained an active research area. China has seen 30 years of growth in coal production and consumption (Tang & Peng, 2017). Only recently has the country seen a decrease in coal supply and consumption. In 2014, China's coal use dropped to 4116 Mt, a decrease of 3% from 2013. Between 2014 and 2015 coal use dropped another 3.5% to 3970 Mt (National Bureau of Statistics of China, 2016). Despite this decreasing trend, in 2015 coal still accounted for 63.7% of China's total primary energy consumption (National Bureau of Statistics of China, 2016). Coal is expected to continue to be a major source of energy until at least 2050 (Chinese Academy of Engineering, 2011; Xiaohan Zhang, Winchester, & Zhang, 2017).

China's coal reserves are concentrated in the north part of the country, where there are significant constraints on water resources. Four provinces, Shanxi, Inner Mongolia, Xinjiang, and Shaanxi, hold the bulk of coal resources, accounting for about 69% of nationwide available reserves in 2013 (Shanghai Coal Exchange Center, 2017). In contrast, water resources in the four provinces represent only 7% of the national total in 2014 (Ministry of Water Resources of the People's Republic of China, 2014). See Figure A1-1 below.



Note: the red line indicates the water resource share of national total

Figure A1-1. Coal reserves and water resources as percent of the national total

Coal mining produces a series of environmental impacts, including water use, declines in groundwater level, wastewater, soil salinization, land desertification, and water inrush accidents. There are two types of coal mining: surface mining and underground mining. In China 95% of coal mines are underground mines, which use more water than does surface mining. Underground mining uses water for, among other activities, equipment cooling, dust control, fire protection, tunnel washing, and revegetation (Chadwick, Highton, & Lindman, 2013). Studies have found that coal mines of different sizes in different regions of China use an average of0.06 to 3.4 m^3 of water to mine one ton of coal (Pan, Liu, Ma, & Li, 2012) Qin, Curmi, Kopec, Allwood, & Richards, 2015). Smaller mines tend to consume more water per ton of mined coal than do larger mines. In addition to water use, coal mining mined in China produces approximately 1.6 to 10 m^3 of wastewater for each ton of coal. The wastewater can be recovered for low-quality reuse. It is estimated that 22% of the water use in China's coal mines is recycled and reused; the rest is incorporated in the product, evaporated, or returned to a river system (Qin, Curmi, Kopec, Allwood, & Richards, 2015).

After it is mined, raw coal must be washed to remove noxious minerals and achieve the desired quality. There are both wet and dry methods for preparing coal. In China, 94% of mined coal is prepared using wet methods. On average, 2.5 m^3 of water is withdrawn to prepare one ton of raw coal (Pan et al., 2012). Little of the withdrawn water (0.2 m^3/ton) is consumed in preparing the coal (Pan et al., 2012); the rest is recycled in a closed-water loop. In 2015, about 66% of China's raw coal was washed. This quantity is expected to increase to 75% by 2020 (National Development and Reform Commission of China, 2016b).

Crude oil extraction

In 2015 China extracted about 215 Mt of crude oil, accounting for 39% of the total national supply (National Bureau of Statistics of China, 2016). China's oil industry has relied increasingly on imports. In 2014, it surpassed the United States as the world's largest net importer of total petroleum (crude oil and petroleum products) (US Energy Information Administration, 2017). The amount of water consumed in oil production varies substantially by geography, geology, recovery technique, and reservoir depletion. In extracting oil, water is produced primarily during enhanced oil recovery (EOR): a reservoir is flooded with water or steam to displace or increase the flow of oil to the surface. Oil extraction also generates large volumes of produced water, on average close to 7 times the volume of oil produced (Mielke, Diaz Anadon, & Narayanamurti, 2010). The produced water can be treated and re-injected to support additional EOR activities. With proper treatment, the produced water also can be reused for irrigation or environmental purposes. Depending on recovery technologies and geographic conditions, water consumption intensity for extracting crude oil ranges from 0.036 to 0.14 m^3/GJ (Spang, Moomaw, Gallagher, Kirshen, & Marks, 2014). In most countries, fossil fuel extraction and processing usually represent the dominant water consumers in fuel production and refining (including coal, crude oil, unconventional oil, oil refining, natural gas, and shale gas) (Spang et al., 2014). In China, however, the coal industry dominates.

Conventional gas extraction and shale gas

Natural gas usually is extracted from deep vertical wells, which require relatively small quantities of water as part of the drilling mud and for drill bit lubrication and cooling (Mielke et al., 2010). The intensity of water consumption in conventional extraction of natural gas ranges from 0.001 to 0.027 m^3/GJ (Spang et al., 2014). Although a small amount of water is used, a large amount of water surfaces along with the extracted natural gas. Proper handling and management of produced water can significantly affect the profitability of oil or gas production (Colorado School of Mines, 2017).

Because China lacks large gas reserves, it has sought to increase its gas production from unconventional sources, notably shale. In the United States, two technologies have been adopted to increase shale gas production: horizontal drilling and hydraulic fracturing (M. Guo et al., 2016). Hydraulic fracturing involves drilling into the ground and injecting a mixture of thousands of tons of water, sand, and chemicals at a high pressure in order to fracture the shale rocks and release gas. (Chou, 2013). The specific water requirements for each shale well depends on the characteristics of the underlying formation (depth, porosity, organic content, etc.) and the design of the fracturing method (e.g., properties of fracturing fluid, length of horizontal part of shale well, and number of stages of fracture). Shale wells that have greater depth, higher porosity, longer horizontal sections, and/or more stages of fracture generally require more freshwater (F. Gao, 2012). In addition to water supply, water pollution is a major topic in shale gas research. Water pollution can include both permitted and unintentional discharges of drilling-related contaminants into surface waters and groundwater, as well as cases of methane migration into water supplies (Brantley et al., 2014; Renjin & Zhenjie, 2015).

A study conducted in the United States estimated that shale gas consumes more water during its life cycle (0.013 to 0.037 m^3/GJ) than does natural gas extracted conventionally (0.093 to 0.096 m^3/GJ) (Corrie E Clark, Horner, & Harto, 2013). The water consumption for shale gas ranges from 0.003 to 0.221 (m^3/ GJ) (Chou, 2013; World Energy Council, 2010). The water consumption related to shale gas, however, also depends whether it is used as a transportation fuel or as a fuel for generating electricity. Shale gas uses much less water than do other transportation fuels, for example. Until 2014, there was only one large-scale Chinese shale gas field operating. This field, called Fuling, is located at part of the Lower Silurian Longmaxi Shale deposit in the Sichuan Basin. If other factors are held constant, each additional lateral meter for a shale gas well in Fuling requires roughly 50% more water than required in typical U.S. formations (also called plays) (M. Guo et al., 2016). The difference in fracking water intensity between the two countries reflects a combination of geological, technological, and economic factors. This study selected the maximum calculated water consumption intensity (0.221 m^3/GJ) for Chinese shale gas plays in the base year (2014). In both the United States and China, work is underway to minimize water use in shale gas production, as well as to find fluids or gases (such as propane or CO_2) to replace water in hydraulic fracturing (Marsters, 2012).

As stated in the 13th FYP for shale gas development, China aims to produce 30 billion m^3 and 80 to 100 billion m^3 of shale gas by 2020 and 2030, respectively (National Energy Administration, 2016b). Some studies have shown that to date water supply has not become a major constraint on shale gas production in China (Chou, 2013; F. Gao, 2012; Sandalow, Wu, Yang, Hove, & Lin, 2014). In the medium or long term, however, shale gas production may face increasing challenges because of its rapid expansion and concerns regarding environmental impacts.

Biofuel

The bioenergy subsector is where water, energy, food, and land systems have the most intense interactions. This study considers both ethanol and biodiesel production. In 2015, China produced about

2.1 Mt of ethanol and 0.8 Mt of biodiesel (National Energy Administration, 2016a). This amount is less than the goals of 4 Mt of ethanol and 1 Mt of biodiesel established in the 12th Five-year plan (National Energy Administration, 2012). China's mandated target by 2020 is for 10 Mt of non-grain-based fuel ethanol and 2 Mt of biodiesel (National Energy Administration, 2016a). To date, significant challenges remain for collecting and transporting feedstock from the small-scale farms in China, which has not achieved the commercially viable production of cellulosic ethanol (Anderson-Sprecher, Ji, & Cottrell, 2015).

The competition with food demand and the increase of grain prices results in regarding non-edible crops such as cassava (starch-based) and sweet sorghum (sugar-based) as the primary feedstock for producing ethanol (Hao, Jiang, Wang, Fu, & Huang, 2017). For producing ethanol, corn and cassava, represent about 70% and 25% of the feedstock, respectively (Anderson-Sprecher et al., 2015). Nearly all biodiesel is made from waste cooking oil. Partly because of the restrictions on using recycled cooking oil for human consumption, biodiesel production almost doubled between 2010 and 2015. Challenges to increasing biodiesel production based on waste oil include the limitations on sales channels imposed by the two state-owned oil companies. Most biodiesel used for road transportation currently is sold at private gas stations in small cities or in the countryside (Anderson-Sprecher et al., 2015).

Different types of bioenergy systems will have different consequences for water consumption. The net effects of establishing a bioenergy project depend on the local context, including the previous land use (Dallemand & Gerbens-Leenes, 2013). Recent studies usually have focused on the life-cycle water footprint of bioenergy. The water consumption for producing cassava-based fuel ethanol can range from 7.9 to 12.6 m^3/t of fuel ethanol. The water consumption for producing sweet sorghum-based fuel ethanol ranges from 3.79 to 9.5 m^3/t (Hao et al., 2017)(T. Zhang, Xie, & Huang, 2014). These figures exclude the water consumed for planting and transporting the feedstock, transporting the ethanol fuel, and utilizing the fuel. The water consumption for producing biodiesel from waste cooking oil is minimal and is ignored in this study. However, if other promising alternatives, such as jatropha and microalgae, were to become the primary feedstock for biodiesel, the associated water footprint would increase. For jatropha and microalgae, the water consumption intensity is about 2.04 and 10.06 m^3/t, respectively, during factory processing (T. Zhang et al., 2014). Growing jatropha uses minimal direct irrigation water, whereas microalgae must grow in an aquatic environment, therefore requiring a large amount of water, about 15244 m^3 per ton of biofuel. Throughout its life cycle, bioenergy uses significant amounts of water. For example, bioethanol produced from cassava and sweet sorghum have life-cycle water footprints of 3708 and 17156 m^3 per ton of bioethanol, respectively. Biodiesel sourced from jatropha and microalgae have life-cycle water footprints of 5787 and 31361 m^3 per ton of biodiesel, respectively (T. Zhang et al., 2014). To provide a consistent and comparable accounting approach throughout this study, we focus only on the impacts from the biofuel's production processes.

Primary energy processing

Coal conversion

To curb China’s reliance on coal, its excess coal capacity, the increasing demands for oil and gas, and the resulting environmental and climate issues, the Chinese government has advanced the concept of “clean coal." Clean coal technology usually encompasses high-efficiency power generation from coal-fired plants, industrial coal and energy conservation, clean conversion of coal, and sometimes carbon capture and storage. Modern coal conversion technologies generally include direct and indirect coal liquefaction, coking, transforming coal to gas, coal gasification and its conversion to conventional coal chemicals such as ammonia and to new coal chemicals such as ethylene glycol or olefins such as ethylene and propylene.

In China, coal liquefaction was developed rapidly from the late 1990s to 2006. After 2006, the Chinese central government reversed its policy toward coal liquefaction, slowing down its rapid expansion, partly because of concerns for its impacts on water resources and the environment (Rong & Victor, 2011). As with coal liquefaction, the development of synthetic natural gas (SNG) from coal has been controversial. Coal-to-gas transformation is an important alternative for meeting China's gas demand without importing it from abroad. Before 2013, the national policy toward developing SNG was restrictive. Since 2013 the policy environment has become more encouraging (Kong, Dong, & Liu, 2016). By the end of 2016, there were more than 60 coal-to-chemical projects operating or under construction in China, of which about 36% are located in Xinjiang and 32% in Inner Mongolia (China Society of Environmental Science, 2017). In 2015, China produced about 1.32 Mt of oil from coal, 1.6 billion m^3 of SNG from coal, 2.12 Mt of ethylene glycol from coal, 6.48 Mt of olefin from coal (China Petroleum and Chemical Industry Federation, 2016), and 0.45 billion tons of coke from coal (China Coking Industry Association, 2016). Coal-derived synthetic ammonia accounts for 80% of China's total production (Pan et al., 2012). In 2014 the amount of synthetic ammonia produced was about 57 Mt, down 0.8% from 2013. It is believed that the production of synthetic ammonia peaked in 2013 (Natural Resources Defense Council, 2016).

Current water withdrawal requirements for coal conversion technologies in China usually encompass water supplied for primary production, such as water used for coal processing or cooling water; auxiliary water production such as water needed for power supply or equipment maintenance; and residential water used by employees living near the factories (China national institute of standardization, 2017). According to the 13th Five-year plan (National Energy Administration, 2017a), the threshold for water withdrawals for coal to gas or direct coal liquefaction are 6 m^3/t and 7.5 m^3/t, respectively. According to an industry survey (China national institute of standardization, 2017), the current industrial performance for water use in coal liquefaction typically is about 6.5 m^3/t ; the advanced performance is 6.2 m^3/t. For indirect coal liquefaction, the typical average industrial performance is 10 m^3/t, and the advanced performance is 7 m^3/t. New coal chemical industries consume considerably more water than do traditional coal conversion technologies. Although many mining enterprises and regional governments consider coal chemical industries a priority for the growth of the local economy (Xie, Li, & Zhao, 2010), regulations on new coal chemical industries will become more and more strict. Currently there are water withdrawal standards for coal to gas, coal liquefaction, coal-derived synthetic ammonia, and the coking industry. Water use standards for coal-derived methanol, ethylene glycol, and olefins have not yet been released. The synthetic ammonia Industry (GB/T 18916.8-2006) has set a water withdrawal standard of no more than 27 m^3 per ton of coal-derived synthetic ammonia produced (Pan et al., 2012). Typical industrial water withdrawal intensity ranges from 9 to 15 m^3/t for converting coal to methanol and from 16 to 37 m^3/t for converting coal to ethylene glycol. Advanced industrial performance consumes about 9 m^3 water per ton of methanol and 17 m^3 per ton of ethylene glycol (China national institute of standardization, 2017). The market access standard (minimal technical requirements) for the coking industry states that freshwater withdrawal for conventional coke ovens should be no more than 2.4 m^3 per ton of coke produced, and the water recycling rate should be no less than 96% (Ministry of Industry and Information Technology, 2014). Currently only 50% of coke production meets these market access standards. By 2020, the coking industry's water withdrawal intensity should be less than 1.5 m^3/t, and the water recycling rate should be more than 98% (China Coking Industry Association, 2016).

Most coal gasification and coal liquefaction technologies already have been commercialized. Various coal to chemicals projects are demonstrated in coal-rich regions (Chang, Zhuo, Meng, Qin, & Yao, 2016). The potentially severe environmental impacts have made developing coal conversion technologies controversial. The government attitude and policy support for the industry has shifted over the past decade, becoming quite conservative (Ministry of Industry and Information Technology of PRC, 2012, 2016). The environmental regulations and industry entry requirements will become more and more stringent, limiting or stifling its growth. The prospects for the coal conversion industry are also highly affected by international and domestic oil and gas prices.

Oil refinery

During the past 10 years, China's petrochemical industry has approached large-scale development. In 2014, crude oil processing capacity reached 503 Mt (Sinopec, 2016). The industry has been facing increasing challenges such as stricter environmental regulations and excess production capacity. Oil refining is joining steel, coal, and other heavy industries as a sector that suffers from overcapacity. The major use of water in a petroleum refinery is for cooling. Relatively small quantities of water are used for boiler feed, processing, sanitary services, fire protection, and miscellaneous purposes (Jr. Otts, 1963). The average water withdrawl intensity of an oil refinery in China is 0.7 m^3/t. The water withdrawal for a high-performance oil refinery is 0.5 m^3/t (Ministry of Industry and Information Technology and Ministry of Water Resource, 2013).

Heat generation and supply

Today China has one of the most extensive district heating networks in the world. In China district heating began in 1950 with the first Five-Year Plan. The district heating network remained small until 1986, when a change in policy priorities promoted rapid expansion. That expansion continues still, showing an average annual growth rate of 9% to 17% in recent decades. In 2013, district heating systems in the provinces of northern China supplied heat to a 5717 km^2 floor area through a network of 178,136 km of pipes. Since 2000, when the "Revised Regulations for Combined Heat and Power (CHP) Development" were adopted, the national government has promoted the deployment of CHP. CHP and boilers account for similar shares of the total heat supply in China (J. Zhang & Lucia, 2015), although in recent years the national government considers the expansion of coal-based CHP one of the primary strategies for improving the efficiency of heat production.

Both steam and hot water are used to supply heat in China, although using steam to supply heat has declined continuously. In 2013, about 83% of district heating was supplied via hot water (National Bureau of Statistics of China, 2015). There are few studies of the water used for generating heat in China. Two articles estimated 0.5 m^3/GJ or 0.6 m^3/GJ for direct water withdrawal intensity in the Chinese heating sector (Xiang & Jia, 2016; C. Zhang & Anadon, 2013). One study assigned 0.08 m^3/GJ to the water consumption intensity for producing the heat (C. Zhang & Anadon, 2013). This report uses those two values to account for the water used in supplying heat via CHP.

Power generation

Power generation technologies in China use water in various ways when producing electricity. Water is used for thermoelectric power (i.e., coal or gas power plants, nuclear, geothermal, biomass, or concentrated solar power). Other power generation methods use steam to spin turbines or convert energy from falling water into electricity (i.e., hydroelectric power plants).

Coal thermal power

Compared to water use in the primary energy production and processing sectors, the water used for power generation, in particular the water resource impacts of coal-based thermal power, has been more widely studied. This use of water for generating power represents an important nexus in China. China's power systems rely largely on coal (73.1% in 2015, a 6.1% decrease since 2010) (China National Renewable Energy Center, 2016). Based on a coal-equivalent calculation, the other power sources of hydro, nuclear, and wind accounted for 19.9%, 2.3%, and 3.3%, respectively, of total production. In 2016, the capacity of coal thermal power was 943 GW; however, the 47.3% utilization rate is low. The coal power capacity must be capped at no more than 1100 GW by 2020 (National Development and Reform Commission, 2016a). Although the proportion of coal thermal power is expected to decrease further, it will continue to be an important part of China's power sector for decades.

Based on China's 13th Five-year renewable energy plan and medium- and long-term renewable energy plans (National Development and Reform Commission, 2007b, 2016b), shifting away from a coal-fueled economy has been supported steadily through governmental policies. China aims to obtain 15% of its primary energy from renewable sources by 2020, and 20% by 2030, based on a coal-equivalent calculation. China has plans to install 210 GW grid-connected wind power capacity, 105 GWh PV solar power, and 15 GW biomass power by 2020. On July 2017, China increased these renewable energy targets to 259, 153.6, and 23.34 GW of wind, solar, and biomass, respectively (National Energy Administration, 2017b).

A previous study showed that, at the end of 2014 the average reserve margin of coal power plants in China as a whole was roughly 28%, almost twice as high as a typical planning reserve margin in the United States (Lin, Kahrl, & Liu, 2018). The central government not only has recently stopped approving new coal mines, but it also is revoking construction permits for coal plants that are under construction (State Council of China, 2016). In 2016, Chinese leaders called a halt to construction on 30 large coal-fired power plants having a combined capacity of 17GW. These actions indicate that the central government is committed to resolving the current issue of excess coal capacity while taking the opportunity to start putting the country's economy on a more sustainable path.

The amount of water used in coal power plants depends greatly on the type of cooling technology used, whether once-through (or open-loop), recirculating (or closed-loop), or dry cooling (air cooling). In some plants, hybrid systems use both wet and dry cooling. According to a recent study (Xinxin Zhang et al., 2017), 12% of coal thermal power plants in China currently utilize once-through cooling, 58% use closed-loop, 18% use air-cooling, and 12% use seawater cooling. All plants having air-cooling systems are located in the north (in particular the northwest), while once-through cooling is more common in the south. According to the policy guidance for the development of the coal thermal power industry (National Development and Reform Commission of China, 2004), the use of groundwater for cooling is banned for new or renovated coal power plants in northern arid regions. In principle, the plants in these regions should adopt air-cooling systems and should achieve a water consumption intensity of less than 0.18 $m^3/s \cdot GW$. In addition, coal thermal plants should be sited near wastewater treatment plants in order to utilize reclaimed water for cooling.

The use of cooling water for coal thermal power plants is regulated. The water use standard for fossil-fired power (GB/T 18916.1-2012) (General Administration of Quality Supervision Inspection and Quarantine & Standardization Administration of China, 2012) specifies water consumption allowances for different sizes of coal thermal power plants having different cooling technologies (Table A1-1). This study applied the average value for water consumption intensity established in the standard. This study applied the values adopted by Qin for water withdrawal intensity (Qin et al., 2015). Compared to the United States, Chinese coal power plants use a much higher percentage of air-cooling technologies (US Energy Information Administration, 2014). Air cooling supports water savings in power plants; however, the lower efficiency of air cooling potentially can increase CO_2 emissions. The median values for thermal efficiency in 600 MW supercritical units, 600 MW subcritical units, and 300 MW subcritical units that use air cooling are 37.9%, 36.9%, and 35.6%, respectively. Those percents are about 1.7% to 2.2% lower than the thermal efficiencies of wet cooling (C. Zhang, Anadon, Mo, Zhao, & Liu, 2014).

Table A1-1. Water use requirements for fossil fired power production (GB/T 18916.1-2012)

Cooling types by capacity		Water use intensity per unit of electricity production ($m^3/MW \cdot h$)			Water use intensity per unit of installed capacity ($m^3/s \cdot GW$)
		Advanced	Average	Controlled	Threshold
Recirculating cooling	<300 MW	2.20	2.7	3.2	0.88
	>300 MW	2.03	2.39	2.75	0.77
	>600 MW	1.94	2.13	2.4	0.77
Once-through cooling	<300 MW	0.60	0.90	0.79	0.19
	>300 MW	0.38	0.42	0.54	0.13
	>600 MW	0.33	0.43	0.46	0.11
Air cooling	<300 MW	0.5	0.65	0.95	0.23
	>300 MW	0.38	0.41	0.63	0.15
	>600 MW	0.35	0.44	0.53	0.13

Natural gas combined cycle

Gas power plants do not have the issues of intermittency faced by renewable energy, and they are cleaner than coal thermal power plants. In 2015, the capacity of gas power in China was 66 GW. Despite a recent slow-down in natural gas consumption due to the slower economy, plans call for increasing the installed gas power capacity to 110 GW by 2020 (National Development and Reform Commission of China, 2016a). Power generation and combined heat and power utilizing natural gas accounts for only 20% of the total demand for gas demand in China (Farina & Wang, 2013). Most natural gas power plants in China are used to provide peaking shaving during periods of high electricity demand. Gas supply and pricing are the major issues faced by natural gas power plants. Because of the current high gas price, most gas power plants are located in more developed regions of China. The levelized cost of the natural gas combined cycle (NGCC) in China is calculated to be 83.6 $/MWh, which is about twice as much as the cost for pulverized coal-fired technology. In the past decade the gas sector has focused on pricing reforms. Despite the recent launch of nationwide gas pricing reform that links the price of natural gas to oil prices, the national government continues to benchmark local prices based on the end user's economic sector (Ratner, Nelson, & Lawrence, 2016). In addition to the distorted pricing structure, China's gas infrastructure lags behind its demand requirements. Even if the China National Petroleum Corporation (CNPC)succeeds in doubling the extent of transmission pipelines in the next five years, China will still have less pipeline length than Germany, given a demand that is 2.5-fold higher (J. Zhang & Lucia, 2015).

A typical NGCC plant first combusts gas to generate electricity, then recovers the waste heat to make steam that can generate additional electricity. An NGCC plant uses much less water per unit of electricity output than does a coal or nuclear plant, because no cooling is required for gas combustion turbines. This study will apply the water consumption/withdrawal intensity found in U.S. case studies (Table 7). We assume that NGCC plants use the same percent of the different cooling technologies as do coal power plants.

Nuclear Power

China started developing its nuclear energy industry in the 1980s. Development slowed down after the Fukushima accident in 2011. After that time, the government implemented stricter policies and delayed approval of new projects. Two years later, given new safety policies and continued environmental, climate, and energy pressure on other energy sources, nuclear construction gradually resumed (Ming, Yingxin, Shaojie, Hui, & Chunxue, 2016). Nuclear energy has been controversial in many countries. The current dominant attitude toward developing nuclear energy in China has more to do with the speed at which nuclear expansion should occur and how to deal with the challenges associated with that expansion (Xu, 2014). The national government has planned to double the installed capacity of nuclear power to at least 58 GW by 2020, possibly 200 GW by 2030, and 400 GW by 2050 (Sun, Zhu, & Meng, 2016). In the short term, development remains limited by diverse technological options, shortage of uranium resources, weak market competitiveness, and low public acceptance (X. Guo & Guo, 2016). As a response to the public concern for the security of nuclear power after the Fukushima accident, the government has been asked to improve policy transparency (Sun et al., 2016).

Producing nuclear power is water-intensive, using water throughout the production life cycle—from fuel extraction to electricity production and waste handling. Depending on the type of cooling system installed, the generation of nuclear power uses about 50% more water than the quantity consumed by coal-fired thermal power plants (L. Guo, Huang, Qiu, & Qiu, 2013). The two types of nuclear reactors (boiling water reactors and pressurized water reactors) both boil water to make steam. Then water is needed to cool the steam, as well as to keep the reactor core and used fuel rods cool. For this study we excluded the water needed for fuel production, because most of China's nuclear power fuel is imported from Australia and other countries (Cai, Zhang, & Bi, 2014). Because of the water requirements, most nuclear plants in China are located on the east coast, including Jiangsu, Zhejiang, and Guangdong provinces, and all of them utilize seawater-based cooling systems. In 2015, the seawater used for cooling both thermal coal and nuclear power plants amounted to 112.6 billion tons, 95% of which came from nuclear power cooling systems (State Oceanic Administrion of China, 2016). According to one study (Cai et al., 2014), the seawater withdrawal intensity for nuclear power ranged from 14.7 to 17.8 m^3/MWh in 2011. In China, there currently is no water use intensity requirement associated with nuclear power. The freshwater withdrawal intensity is reported to be 0.1 m^3/MWh (Xiang & Jia, 2016). If nuclear power plants were to be built inland in the future, we would assume that the average water consumption and withdrawal intensity would achieve the current minimum level for recirculating cooling systems in U.S. nuclear power plants (2.2 m^3/MWh and 3 m^3/MWh, respectively, for water consumption and withdrawal) (Macknick, Sattler, Averyt, Clemmer, & Rogers, 2012). Safety concerns make dry cooling uncommon in nuclear power generation. By consolidating the current proposals for nuclear power plants in China, we estimate that about 62% of nuclear power plants (total capacity 157.3 GW) are to be built in inland regions by 2050 (China electric power statistical yearbook editorial board, 2017; World Nuclear Association, 2017). In September 2015, it was reported that 31 inland sites had cleared NDRC's preliminary approval and awaited State Council approval (World Nuclear Association, 2017).

- Power from biomass

According to NDRC, residues from agriculture and forestry can supply an estimated 145.5 EJ of energy annually (Han, 2013). By 2015, the total capacity of biomass power in China was 10.3 GW, including 5.3 GW of biopower sourced from agricultural and forestry wastes, 4.7 GW of biopower produced from solid waste, and the rest (0.3 GW) biomass gasification power (National Energy Administration, 2016a). The 13th Five-year biomass development plan set the 2020 target at 15 GW. As mentioned, in July 2017 the National Energy Administration revised the biomass energy target to 23.34 GW (National Energy Administration, 2017b). Biomass development to date has been inhibited by factors such as a lack of strategic planning for large-scale biomass power plants, appropriate siting, cost, and transportation of fuel resources.

As other thermal power plants do, biomass power generation uses water to create steam and water to cool the steam. In this study we focus on the operational water use for different types of biopower plants. Based on an earlier study, the water consumption intensity for biopower ranges from 1.4 to 2.5 m^3/MWh (0.4 to 0.7 m3/GJ) when using residues and 0.36 m^3/MWh (0.1 m^3/GJ) for gasification plants (N. Jiang & Ning, 2009). Other studies determined the water consumption intensity for biopower in China to be 2.1 m^3/MWh (Xiang & Jia, 2016) and 3.19 m^3/MWh (Zhou, Li, Wang, & Bi, 2016). This study adopted the median value (2.3 m^3/MWh) from previous studies having values that range from 1.4 to 3.19 m^3/MWh for non-gasification biomass power. If the water used to produce the biomass crops is considered, crop production can account for more than 95% of total water consumption for biomass plants (Feng, Hubacek, Siu, & Li, 2014).

- Geothermal power

According to the latest geological survey performed in 2015 by China's Ministry of Land and Resource (MLR), the exploitable hydrothermal and geothermal resources in the major sedimentary basin total about 41.3 EJ (with a potential annual production of 0.06 EJ). Most of the resources represent intermediate- and low-temperature geothermal energy. Hot dry rock geothermal energy (also called an enhanced geothermal system) having a depth of between 3000 and 10,000 meters totals 28,251 EJ (National Development and Reform Commission of China, 2017a). The higher-temperature geothermal resources (i.e., usually more than 150 °C) are located in the south of Tibet and west of Yunnan and Sichuan provinces. Abundant hydropower resources are also available in those regions, making large-scale geothermal power less competitive. In the 1970s, four geothermal power plants were built in China, including Yangbajain in Tibet and the lower- and intermediate-temperature plants in Guangdong, Hebei, and Jiangxi. In 2015 the total capacity of those four plants was 27.28 MW. According to the 13th five-year plan on geothermal energy, the sector is expected to grow substantially to 527.28 MW by 2020 (National Development and Reform Commission of China, 2017b). This production, coming after a long period of stagnation, is almost 20 times the 2015 level.

Depending on the availability and characteristics of the local resource, geothermal electricity generation can utilize four types of systems: direct-dry steam, flash and double-flash cycle, binary cycle, and enhanced geothermal (California Energy Commission, 2017; C. E. Clark, Harto, Sullivan, & Wang, 2011). Because dry-steam reservoirs are rare, and the enhanced geothermal system in China is still at stage of very early research and geological exploration, this study will focus on the two conventional hydrothermal systems: the flash and double-flash cycle (operating at between 175 and 300 °C) and the binary cycle (operating at between 74 and182 °C) (C. E. Clark et al., 2011).

The amount of water used in geothermal processes varies based on the type of resource, type of plant, type of cooling system, and type of waste heat reinjection system (Geothermal energy Association, 2014). Both flash and binary cycle systems use hot water from an underground reservoir to generate steam and power. Some plants also require cooling water. The common industrial practices is to utilize geothermal fluids as the primary medium for cooling (Macknick, Newmark, Heath, & Hallett, 2012a). For flash-cycle systems, outside water sometimes must be added to the reservoir, because some steam enters the atmosphere. For this use the outside water does not need to be freshwater. The major geothermal power plant currently in China (Yangbajain) adopted the double-flash cycle (Shanben, Steam, Works, & Province, 1989). On the other hand, the binary cycle is a closed-loop system, emitting virtually nothing to the atmosphere. Still, however, water sometimes is added to the reservoir to compensate for any operational losses and maintain reservoir pressure. The binary-cycle system is expected to be the dominant form in geothermal power plants, because moderate-temperature water is by far the most common geothermal resource (C. E. Clark et al., 2011). In the United States, water consumption intensity during geothermal plant operation ranges from 0.02 to 0.04 m^3/MWh for a flash-cycle system and from 0.3 to 1 m^3/MWh for a binary cycle system. These values assume that the water used to make up for operational losses is a small percentage of the total operational loss of geofluid) (C. E. Clark et al., 2011). This study applied the U.S. median value (0.03 m^3/MWh) to the geothermal flash-cycle system in China. For estimating future water consumption intensity, we assumed systems added from 2020 onward will be binary-cycle systems having a water consumption intensity of 0.65 m^3/MWh.

- Hydropower

China's installed hydropower capacity currently represents about 46% of the total exploitable potential resource, of which 70% is located in the southwest part of the country (National Development and Reform Commission, 2007a). The percentage of hydropower capacity that has been exploited in China is lower than in many countries in the developed world; for example 82% of hydropower resources have been exploited in the United States (Y. Li, Li, Ji, & Yang, 2015). In the 13th FYP for renewable energy (National Development and Reform Commission, 2016b), the installed capacity of hydropower is expected to increase from 320 GW (including 20 GW pumped-storage hydropower) in 2015 to 0.380 GW (including 40 GW pumped-storage hydropower) in 2020. The development of China's hydropower capacity has not been smooth. Policies on utilizing the resource and for performing environmental reviews were formulated early on. Today hydropower faces many challenges, however, such as the social and economic impacts of large-scale migration of the population that could be served and the competition for priority status in the national strategic plans for energy (Kang, 2010; Y. Li et al., 2015).

Accounting for the water use associated with hydropower is different from accounting for water use in processing other energy resources, because that water use is associated with evaporation and unrecoverable seepage from reservoirs rather than with extractive and cooling operations (Grubert, 2016). The literature displays an inconsistent view of the water footprint of hydroelectricity. Many studies applied the gross evaporative consumption to estimate the water consumption attributable to hydroelectricity. However, gross reservoir evaporation does not represent the anthropogenic increase in water flux to the atmosphere, because it overlooks the background evapotranspiration from the land surface prior to dam construction (Lampert, Lee, Cai, & Elgowainy, 2015). Common accounting methods also often ignore the many purposes of reservoirs, therefore failing to allocate the water consumption burden to the other economically beneficial purposes of reservoirs such as navigation, flood control, municipal water supply, irrigation, and recreation. About one-fourth of the world's reservoirs that have a dam higher than 15 m provide multiple services, and more than 40% of the 8689 reservoirs that provide hydropower are also used for other purposes (J. Liu, Zhao, Gerbens-Leenes, & Guan, 2015). These debatable issues of system boundaries cause some researchers to exclude the water consumption for hydroelectricity when accounting for the water impacts of electricity generation. Recent studies proposed an accounting method that improves upon the gross evaporation approach. For example, Grubert (Grubert, 2016) suggested assessing system wide evaporative water consumption based on each reservoir's primary purpose and by considering net rather than gross evaporation. Using this approach and accounting for long-term averages of climate data, generation data, and reservoir characteristics, Grubert estimated that the net hydroelectric water consumption in the United States is 1.7 m^3/GJ (6.0 m^3 /MWh). This value is about 2.5 times the median estimates for coal power and about 8 times the median estimates for NGCC in the United States. Because most of the dams are built in water-intensive areas, the gross consumption intensity actually may be about 38m^3/MWh. In China, hydroelectric water consumption intensity (gross evaporation) differed widely, from 0.001 m^3/GJ for the Hongyi plant to 4234 m^3/GJ for the Zhanggang plant, both of which lie in the Yangtze river basin (J. Liu et al., 2015). Liu estimated the average hydroelectric water consumption intensity in China to be about 3.6 m^3/GJ (12.86 m^3/MWh). Although this result considered the multipurpose aspects of the reservoirs, it did not account for the anthropogenic changes before and after the dams were constructed. Based on previous research and the estimates for the United States, for China our study applies a 1.8 m^3/MWh water consumption intensity (H. Yang, Ji, & Shi, 2015) and a 0.08 m^3/MWh water withdrawal intensity (Davies, Kyle, & Edmonds, 2013).

- Photovoltaic Systems and Concentrated Solar Power

For other types of renewable energy such as wind and solar, this study covers only the water resource impacts of solar photovoltaic (PV) systems and concentrated solar power (CSP). Wind systems require little, if any, water for cleaning (Macknick, Newmark, Heath, & Hallett, 2012b). PV systems may require water for occasional panel washing, although common industry practice indicates that most PV system operators do not wash panels. For CSP operations, water is needed during construction, in the steam cycle, for cooling purposes, and for the occasional cleaning of solar collectors or mirrors (Bracken et al., 2015). There are four main types of CSP technologies: parabolic troughs, power towers, linear Fresnel systems, and parabolic dish systems. As for coal and nuclear power plants, the first three technologies rely on a steam Rankine power cycle that requires a cooling system to condense steam back into water. Although most of the water is reused in the cycle, water is still needed for the steam cycle make-up (Bracken et al., 2015). Parabolic trough systems are the most commonly used CSP technology. As with thermal power technologies, wet, dry, or hybrid cooling systems are available for CSP technologies. Recirculating evaporative cooling is the most common type of cooling used. For CSP facilities that utilize dry cooling technologies, initial work suggested (Turchi, Wagner, & Kutscher, 2010) that they might cause an annual reduction in electricity output of 2% to 5% compared with wet-cooled facilities, depending on local climatic conditions.

China's ambitious 13th FYP for solar energy identifies a target CSP capacity that is almost 360 times the 2015 level (Table 5). Among current CSP technologies, the solar trough dominates, making up roughly 77% of the total for tower and trough; towers make up 16% (Table A1-2). In China most of the planned CSP facilities will be in the northern and western parts of the country where water resources are limited. In this study, we assumed that all CSP facilities will adopt dry cooling systems.

Table A1-1. Current and Future Targets for Concentrated Solar Power in China

		2015	2020
Capacity (MW)	PV capacity	43180	105000
	CSP capacity	13.9	5000
	Total	43190	110000

Total production (Twh)		39.6	150

Source: (National Energy Agency of China, 2016).

Table A1-2. Concentrated Solar Power projects in China

	Start	Completion	Location	Size (MW)	Technology
Finished	2004	2005	Nanjing (Jiangsu)	0.07	Solar tower
Finished	2010	2013	Yang qing (Beijing)	1	Solar tower
Finished	2011	2013	Jia yu guan (Gansu)	10	Solar trough
Not finished	2010		De Zhou (Shandong)	2.5	Fresnel
Not finished	2009		Mon ding (Yunnan)	10	PV & thermal
Not finished	2011		Golmud (Qinghai)	200	Solar tower
Not finished	2009		Golmud (Qinghai)	1000	Solar tower
Not finished	2010		Yulin (Shanxi)	2000	Solar tower
Not finished	2016		Dunhuang (Gansu)	10	Solar tower
Not finished	2011		Ordos (Inner Mongolia)	50	Solar trough
Not finished	2010		Ruan lin (Hunan)	50	Solar trough
Not finished	2011		Delingha (Qinghai)	50	Solar trough
Planned			Gansu	100	Multidish
Planned			Sanya (Hainan)	100	Solar tower
Planned			Lhasa (Tibet)	50	Solar tower
Planned			Turpan (Xinjiang)	300	Solar trough
Planned			Wuwei (Gansu)	100	Solar trough
Planned			Ningxia	100	Solar trough
Planned			Jinta (Gansu)	50	Solar trough
Planned			Hangzhou (Zhejiang)	100	Tower & heliostats
Planned			Aba (Sichuan)	100	Tower & trough
Total				4384	

Source: (Wang, Yang, Jiang, Zhang, & Lund, 2017a).

Summary

Table 7 summarizes the water intensity values adopted in our model. The intensities we assigned to nuclear power and CSP are much lower than those seen in international research, because our accounting excludes seawater cooling for nuclear power and we assume that in China all CSP facilities utilize dry cooling systems. Producing energy from biomass or hydropower generally is water intensive, but that intensity depends greatly on the fuel sources and local climate. Considering primary energy production, in China water use for transforming coal to liquid and for producing shale gas are on the higher end of international practices (Figure A1-3).

Figures A1-2 shows a broad comparison of the water use intensity for generating electricity and heat in China (left) and the global levels developed by the International Energy Agency (International Energy Agency, 2016). When comparing the two charts, note that the types and percentages of cooling technologies for thermal coal, CHP, NGCC, CSP, nuclear, and geothermal have been accounted for in our analysis of current practices in China. Figure A1-3 presents a similar comparison for energy production. Again, the water intensity for biofuel has been taken into account in valuing that fuel source.

Figure A1-2. Water use intensity for electricity and heat generation: China (left) and international (right)

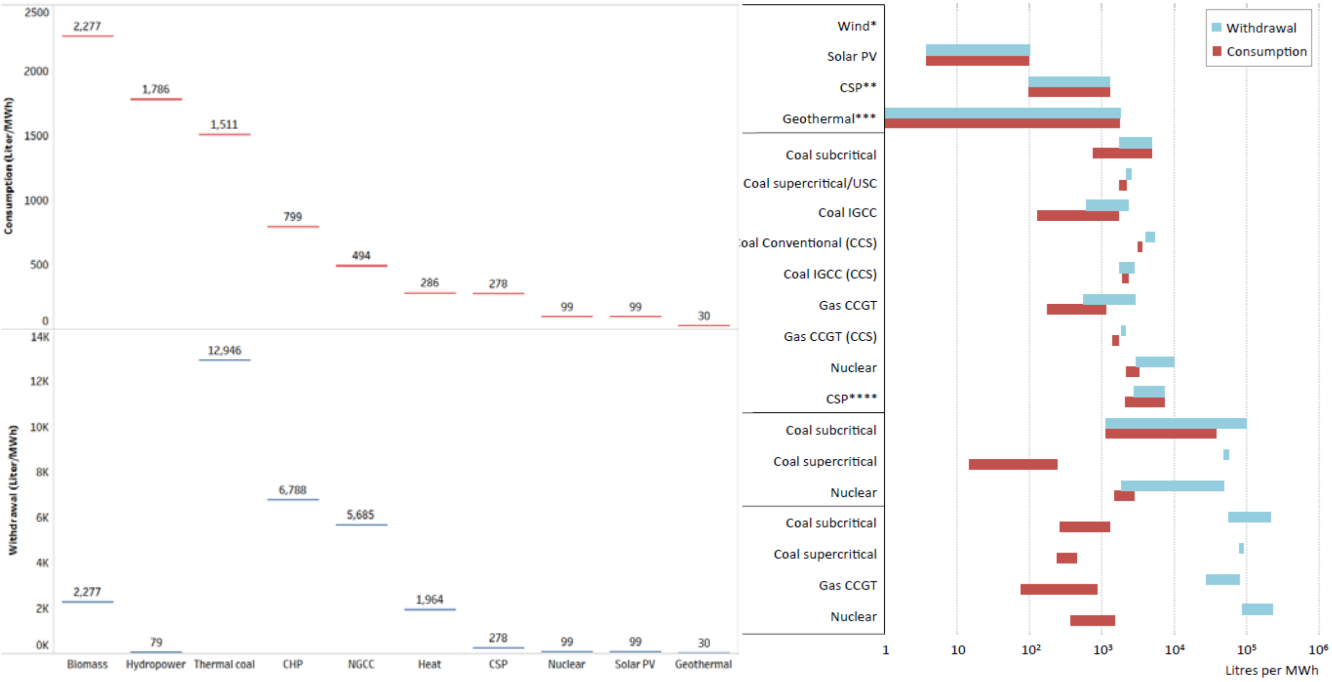


Figure A1-3. Water use intensity for energy production and conversion: China (left) and international (right)

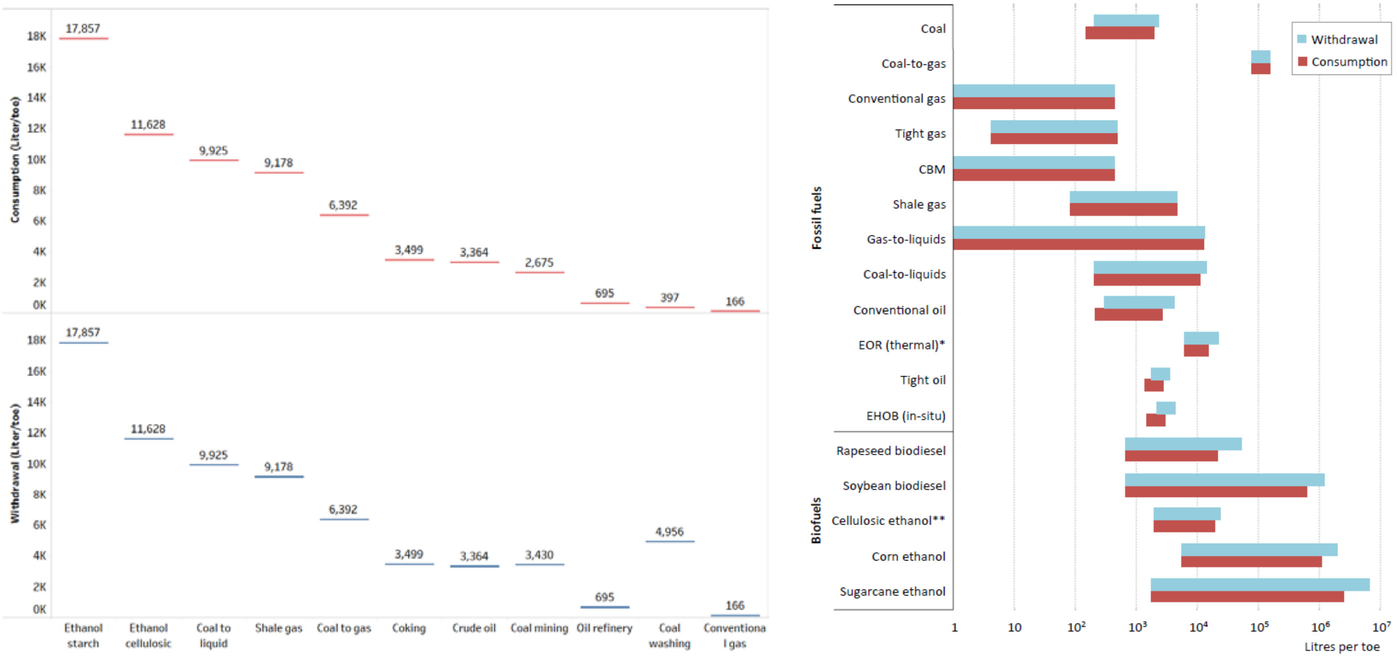


Table A1-3 Water consumption and withdrawal intensity for energy and related sectors

Energy and related sector		Water consumption	Water withdrawal	Unit	Notes	Reference
Primary energy production	Coal mining	0.78*1.73	0.06-3.4 (median: 1.73)	m^3/t	22% of water is recycled and reused; use median intensity value	(Qin et al., 2015)(Pan et al., 2012)
	Coal washing	0.2	2.5	m^3/t	About 66% of coal in China was washed in 2014	(Pan et al., 2012)(China Industry Information, 2015) (National Development and Reform Commission of China, 2016b).

Energy and related sector		Water consumption	Water withdrawal	Unit	Notes	Reference
	Crude oil extraction	0.036-0.14 (median: 0.081)	Same as consumption	m^3/GJ	Use median intensity value	(Spang et al., 2014)
	Conventional gas extraction	0.001-0.027(median: 0.004)	Same as consumption	m^3/GJ	Use median intensity value	(Spang et al., 2014)
	Shale gas extraction	0.003-0.221	Same as consumption	m^3/GJ	Use maximum value for China	(Spang et al., 2014)
	Biofuel	7.9-12.6 for starch-based ethanol; 3.79-9.5 for cellulosic ethanol; biodiesel from waste cooking oil: 0	Same as consumption	m^3/t	Use median value	(Hao et al., 2017)(T. Zhang et al., 2014)
Primary energy transformation	Coal to gas	6	Same as consumption	m^3/10^{3}m^3		(National Energy Administration, 2017a)
	Coal to liquid	6.5 (direct); 10 (indirect)	Same as consumption	m^3/t		(China national institute of standardization, 2017)
	Coal to ammonia	27	Same as consumption	m^3/t		(Pan et al., 2012)
	Coal to olefins	26-32 (median 29)	Same as consumption	m^3/t		(China Society of Environmental Science, 2017)

Energy and related sector		Water consumption	Water withdrawal	Unit	Notes	Reference
	Coal to ethylene glycol	16-37 (current mean 31)	Same as consumption	m^3/t		(China national institute of standardization, 2017)
	Coking	2.4	Same as consumption	m^3/t		(Ministry of Industry and Information Technology, 2014).
	Oil refining	0.7	0.7	m^3/t		(Ministry of Industry and Information Technology and Ministry of Water Resource, 2013)
	Heat generation and supply	0.08	0.5-0.6 (median: 0.55)	m^3/GJ		(C. Zhang & Anadon, 2013)
Power generation	<300 MW thermal power	Once-through 0.9; recirculating 2.7; air cooling 0.32	Once-through 100; recirculating 2.6	m^3/MWh	12% for once through, 58% closed loop, 18% air cooling, and 12% seawater cooling	(General Administration of Quality Supervision Inspection and Quarantine & Standardization Administration of China, 2012);(Qin et al., 2015)
	>300 MW &<600 MW thermal power	Once-through 0.42; recirculating 2.39;	Once-through 100; recirculating 2.6	m^3/MWh	12% for once-through, 58% closed loop, 18% air	(General Administration of Quality Supervision Inspection and

Energy and related sector		Water consumption	Water withdrawal	Unit	Notes	Reference
		air cooling 0.32			cooling, and 12% seawater cooling	Quarantine & Standardization Administration of China, 2012); (Qin et al., 2015)
	>600 MW thermal power & supercritical	Once-through 0.43; recirculating 2.13; air cooling 0.32	Once through 90; recirculating 2.3	m^3/MWh	12% for once-through, 58% closed loop, 18% air cooling, and 12% seawater cooling	(General Administration of Quality Supervision Inspection and Quarantine & Standardization Administration of China, 2012); (Qin et al., 2015)
	NGCC	Once-through 0.07-0.38 (median 0.38) recirculating 0.49-1.14 (median 0.78)	Once-through 2.84-75.7 (median 43.1) recirculating 0.57-1.07 (median 0.97)	m^3/MWh	Shares of cooling technologies used assumed to be the same as for coal thermal power	(Macknick, Newmark, et al., 2012a)
	Nuclear	0.1	Same as consumption	m^3/MWh	Only freshwater use considered	(Xiang & Jia, 2016)(L. Guo et al., 2013)
	Biomass	1.4-3.19 m3/MWh (median: 2.295)	Same as consumption	m^3/MWh		(Zhou et al., 2016) (N. Jiang & Ning, 2009) (Xiang & Jia, 2016)

Energy and related sector		Water consumption	Water withdrawal	Unit	Notes	Reference
	Geothermal	0.03 (flash cycle); 0.65 (binary cycle)	Same as consumption	m^3/MWh	U.S. median value	(Macknick, Newmark, et al., 2012a)
	Hydropower	1.8	0.08	m^3/MWh		(Davies et al., 2013) (H. Yang et al., 2015)
	Combined heat and power	Power: use mean water consumption intensity for thermal power; heat: use water consumption intensity for heat generation	Use mean water withdrawal intensity for thermal power; use water withdrawal intensity for heat generation		Heat and power portions are 56% and 44%, respectively	
	PV	0.1	Same as consumption	m^3/MWh	U.S. median value	(Macknick, Newmark, et al., 2012a)
	CSP	0.1 for tower; 0.3 for trough	Same as consumption	m^3/MWh	U.S. median value; current percentages of technologies in China: 10% tower, 90% trough	(Macknick, Newmark, et al., 2012a) (Wang, Yang, Jiang, Zhang, & Lund, 2017b)

Energy Use in Water Systems

Water supply

This section summarizes the base year activities and energy intensity used to obtain surface and groundwater supplies, as well as highlighting the policies and technical trends that form the basis for assumptions about the future.

Surface water supply

Energy use related to surface water supplies usually encompasses water lifting, water storage, water transfer via gravity, and inter-basin water transfer. In 2014, those activities accounted for about 31.3%, 32.7%, 32.1%, and 3.9%, respectively, of activities related to surface water withdrawal (Ministry of Water Resources of the People's Republic of China, 2014).

Pumps can lift water from a lower elevation to higher one to supply end users (e.g., buildings or a community). The average elevation in each Chinese province ranges from 2.54 m (Tianjin) to 650.17 m (Yunnan), resulting in an estimated average national energy intensity for water lifting of 0.53 Kwh/m^3 (S. Jiang, 2017).

Reservoir construction in China increased during the past 30 years. The pace of construction accelerated from 4.4 large reservoirs (of a capacity greater than 0.1 km^3) each year from the 1970s to 1990s, to an average of 11.8 large reservoirs each year during the 2000s (Miao, Borthwick, Liu, & Liu, 2015). By 2011, China had built 97,246 reservoirs (having a total capacity of 810.4 km^3), of which 20866 (having a total capacity of 217 Twh) are used to produce hydropower (Ministry of Water Resources of the People's Republic of China, 2013). The reservoirs are used for one or multiple purposes. Globally, 75% of registered large dams and reservoirs are classified as single purpose. The most common single purpose is irrigation (47%), followed by hydropower (19%), water supply (11%), flood control (9%), with the rest devoted to recreation, navigation, and "unclassified" (Bakken, Killingtveit, & Alfredsen, 2017). According to a field study by the China Institute of Water Resources and Hydropower Research (IWHR) (S. Jiang, 2017), the average distance water must travel from reservoirs to irrigation sites is between 2 and 5 km; the average distance between reservoirs and urban water supply utilities is 15 to 50 km. Accounting for the accepted 5% in frictional head loss, the energy intensity for agricultural water supply from reservoirs is calculated to be 0.018 kWh/m^3, and the intensity for urban and industrial water supply from reservoirs is 0.18 kWh/m^3.

Inter-basin water transfers are often the most energy-intensive type of surface water supply. The energy consumption of such projects depends primarily on the length and elevation changes in each stage of the transfer project. The energy consumption also depends, to some extent, on the material and resistance of the pipes (Plappally & Lienhard V, 2012). In this study, we applied results of a previous study that calculated the energy intensity for water transfer projects in China to be 0.0045 kWh/m^3 per km (J. Gao, 2012)(X. Li, Liu, Zheng, Han, & Hoff, 2016). Table A1-5 presents details regarding the amount of water transferred from various river basins to end users, and the average lengths of the transfer projects.

Table A1-4. Amounts of water transferred and average lengths of transfer projects (2014)

Project name	Source	Destination	Length (km)	Purpose of water transfer	Water quantity (billion m^3)
South-North	Hebei	Beijing, Tianjin	342	Residential, Industrial	0.09
Yin Huang Ji Qing	Yellow River	Shandong	252	Residential, Industrial	6.23
	Yellow River	Henan	200	Residential, irrigation	1.86
Yin Huang Ru Jin	Yellow River	Shanxi	450	Residential, Industrial	0.05
Xi Jiang Yin Shui	Xijiang	Guangdong	71.5	Residential	1.353
Yin Jiang Ji Huai	Yangtze River	Jiangsu	60	Ecological, Residential	9.61
Yin Jiang Ji Huai	Yangtze River	Anhui	1280	Residential, Industrial	0.6
Zhe Dong Yin Shui	Yangtze	Zhejiang	294	Residential, Industrial	1.248
Ping Tan Yin Shui	Min River	Fujian	160	Residential, Industrial	0.02
Qian Zhong Diao Shui	Yangtze River	Guizhou	395.62	Residential, Industrial and irrigation	0.04
Total					21.1

Source: (S. Jiang, 2017).

According to the inter-basin water transfer Masterplan, by 2030 the three routes (central, eastern, and western) of the South-North Water Transfer project will provide as much as 45 billion cubic meters of freshwater to nearly 100 cities north of the Yangtze basin (Pohlner, 2016). Only the eastern and central routes are in operation (since 2014). This study calculated only the energy required by the eastern route

(Table 8), because the water transferred via the central route is lifted mostly by gravity without pumping. We assumed the lifting pumps are electric. Figure A1-7 shows the current completed and planned South-North Water Transfer projects.

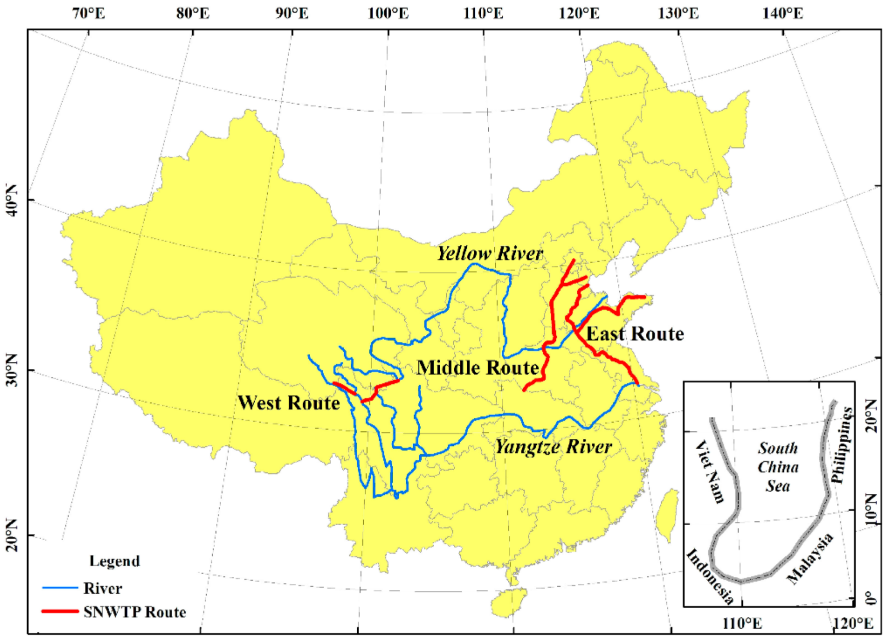


Figure A1-4. South-North Water Transfer Projects. Source: (Wilson, Li, Ma, Smith, & Wu, 2017)

Regarding future water demand and supply, the "three red line" policy[1] requires that total national water withdrawal be capped at 670 billion m^3 by 2020 and peak at about 700 billion m^3 by 2030. According to the Action Plan for Synchronous Control over the Total Amount and Intensity of Water Consumption in the 13th Five-year plan (Ministry of Water Resource and National Development and Reform Commission of China, 2016), by 2020 the cap on total water withdrawal will stand at 670 billion m^3. In addition, water withdrawal per industrial GDP should see a 20% improvement between 2015 and 2020, and irrigation efficiency should exceed 0.55. By 2030 water withdrawal should be less than 40 m^3 per 10000 RMB industrial GDP, and irrigation efficiency should exceed 0.6. These values suggest that the agriculture sector's share of total water consumption is expected to decline in order to accommodate the demand coming from the residential and industrial sector. These targets will serve as the basis for the water demand scenario analyzed in this paper.

Groundwater supply

According to IWHR's calculation (S. Jiang, 2017), groundwater withdrawal for the agriculture sector was about 88.32 billion m^3 in 2014, while withdrawal for the residential and industrial sectors was about 23.39 billion m^3. Because it lacks adequate surface water resources, the North is generally 5 times more reliant on groundwater than is the South of China (Tan, Hu, Thieriot, & McGregor, 2015). This situation has

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[1] In 2010, China's Communist Party Central Committee and State Council promulgated a "three red lines" policy intended to establish clear and binding limits on water quantity usage, efficiency, and quality.

resulted in over-extraction of groundwater. When groundwater is pumped out faster than it can be recharged, more electricity must be used to pump deeper wells. In addition, the risks increase for environmental consequences such as saltwater intrusion, land subsidence, and reduction in aquifer storage capacity. On the other hand, based on a Ministry of Water Resources' survey in early 2016[2] (Ministry of Water Resources of the People's Republic of China, 2016), more than 80% of the shallow groundwater in China exceeds the national water quality standards for IV and V class, meaning that it is not suitable to be used as potable water. Most of the groundwater pumped for potable use comes from deep underground, where water quality issues are of lesser concern. Climate change is a force-multiplier for groundwater, however (Shah, 2009); that is, it tends to increase demand while reducing recharge. Considering the current over-extraction of groundwater resources, this study does not consider further increasing exploitation of groundwater to provide future water supply. By 2030 and 2050, the volume of groundwater pumped nationwide is assumed to be the same as today, although we recognize that groundwater usage differs significantly among regions.

The energy required for pumping groundwater depends on the depth of the well, the distance transported, volume, pump types, pump efficiency, etc. We consider the energy loss via distribution to be 10% for residential and industrial users. According to the statistical yearbook produced for the national geological monitoring of groundwater, the average depth to groundwater ranges from 4.86m (Liaoning province) to 50.93m (Shanxi province). To estimate residential and industrial energy use, the national average energy intensity is back-calculated to 0.19 kWh/m^3, while the energy intensity of groundwater pumping for irrigation is calculated to be 0.4 kWh/m^3 (S. Jiang, 2017). Based on a previous study (X. Zou et al., 2013), we assumed that 76% percent of agricultural pumping relies on diesel and the rest employs electric pumps.

Water treatment system

The energy use for water treatment systems encompasses energy used for raw water distribution and treatment at urban water supply utilities, wastewater collection, treatment and discharge systems, recycling water systems, and desalination.

Water treatment and distribution

When raw water is conveyed to urban water supply utilities from sources such as lakes, rivers, reservoirs, and groundwater, the raw water must be treated to potable standards or to relevant industrial standards depending on ultimate use for the water. Much of the energy used by conventional water treatment plants in China is for pumping water into the plant (sourcing) and for (pressurizing) water before it leaves the plant. The average distribution intensity is calculated to be 0.41 kWh/m^3 (S. Jiang, 2017). Standard treatment for surface water and groundwater in China is a combination of coagulation (and sedimentation), filtration, and disinfection. Sludge produced during drinking water treatment is handled the same way as sludge produced from wastewater treatment plants.

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[2] Note that the latest groundwater quality is only reported in Groundwater Monthly Issue of January 2016.

The energy intensity of raw water treatment can be calculated given the amount of water delivered by urban water supply utilities annually and the utilities' annual electricity consumption, data obtained from the Urban Water Supply Statistical Yearbook. The national average energy intensity of water treatment is 0.32 kWh/m^3, within a ranging of from 0.162 (Qinghai) to 0.754 (Chongqing) (S. Jiang, 2017).

Wastewater treatment

China's daily wastewater treatment capacity approximately doubled between 2005 and 2015. The daily wastewater treatment capacity increased from 0.057 billion m^3/day in 2005 to 0.127 billion m^3/day by the end of 2015 (National Bureau of Statistics of China, 2005; NRDC and MOHURD, 2016). Today there are nearly 4000 wastewater treatment plants (WWTPs) in China (MOHURD, 2016). Not all plants are operating at an optimal loading level. The average loading rate is approximately 83%; 52% of WWTPs operate at loadings of <80%. WTTPs in China treat as much as 40% of the wastewater generated (Q. H. Zhang et al., 2016).

Anaerobic-anoxic-oxic (AAO) and oxidation ditch (OD) are the most common technologies used by WTTPs in China; together those technologies treat about 46% of the total volume of wastewater generated. One-quarter of the remaining wastewater is treated by traditional activated sludge and a sequencing batch reactor (SBR); 28% is treated by other processes (e.g., anoxic-oxic (AO), biological film, chemical, and physicochemical) (Q. H. Zhang et al., 2016). The choice of treatment technology depends on the composition of the wastewater, treatment affordability, and other factors. For example, OD is resistant to shock loadings and excess sludge production; AAO and AO are technologies of choice for high-performance nutrient removal; and SBR is preferred for treating domestic wastewater in rural areas and wastewater from industrial enterprises (China Water Risk, 2014).

The energy demand of a wastewater treatment plant depends on such factors as the plant's location; its size (population equivalent, organic, or hydraulic load); type of treatment process and aeration system; requirements for effluent quality; age of the plant; and abilities of the plant managers. For individual utilities, the conflicts in the water-energy nexus are particularly evident. In a conventional WWTP, about 25% to 40% of operating costs are reported to be attributable to energy consumption (Gu et al., 2017). Of the total energy consumed within a wastewater treatment plant in China, about 25% can be attributed to pretreatment, whereby energy is used primarily for pumping against gravity at the inlet of the plant (Smith & Liu, 2017). The common secondary treatment processes used in China are biological and involve significant aeration, which produces a large energy demand. In 2006 Yang et al. (L. Yang, Zeng, Chen, He, & Yang, 2010) studied the energy consumption of secondary treatment plants that used different treatment technologies. Those researchers found that the energy intensity of wastewater treatment ranges from 0.219 kWh/m^3 for an absorption-biology system to 0.34 kWh/m^3 for extended aeration systems (Gu et al., 2017). Figure A1-8 shows the electricity intensity for various treatment technologies based on their scale. Generally, intensity decreases with increasing treatment scale. For WWTPs less than 10,000 m^3/d in capacity, the average electricity intensity is 0.37 kWh/m3; the intensity is 0.22 kWh/m3 for plants larger than 1000,000 m^3/d (Zeng, Chen, Dong, & Liu, 2017). According to a surveyed performed by MOHURD in 2012, the national electricity intensity for wastewater treatment ranges from approximately 0.21 to 0.32 KWh/m^3, with a national average of 0.24 KWh/m^3 (Fu & Zhong, 2014). More advanced wastewater treatment technologies consume higher amounts of energy because they apply nutrient removal processes. For example, the energy intensity of conventional municipal WWTPs in the United States typically is about 0.43 kWh/m^3 (Gu et al., 2017). Currently, few WWTPs in China provide tertiary treatment. According to a 2011 survey (Zeng et al., 2017), 153 urban WTTPs (having a total capacity of 4.34*10^6 m^3/d) out of 1079 urban WTTPs (having a total capacity of 53.95*10^6 m^3/d) provided tertiary treatment following the secondary biological processes, such as biofilter and ultrafilter.

Sludge treatment in a WWTP is also an energy-intensive process. A study (G. Yang, Zhang, & Wang, 2015) showed that in 2013 more than 80% of the sludge produced by wastewater treatment was disposed of by improper dumping. Disposal in a sanitary landfill is the most common method for properly handling sludge (50%), followed by composting (16%), combustion (10%), and recycling of materials (9%) (Q. H. Zhang et al., 2016). In most Chinese WWTPs sludge is treated by a “thickening-coagulation-mechanical dewatering” process. This sludge treatment can account for about 4.1% to 13.9% of the energy consumption within a WWTP (Smith & Liu, 2017). In this study, we assumed that by 2050 China will have adopted proper sludge treatment and handling, which will increase the energy intensity by about 0.1 Kwh/m^3 (International Energy Agency, 2016) . Note that the energy input to sludge treatment generally is far outweighed by the energy recovered in the form of heat and/or electricity from biogas production. This practice currently is relatively uncommon in China, however.

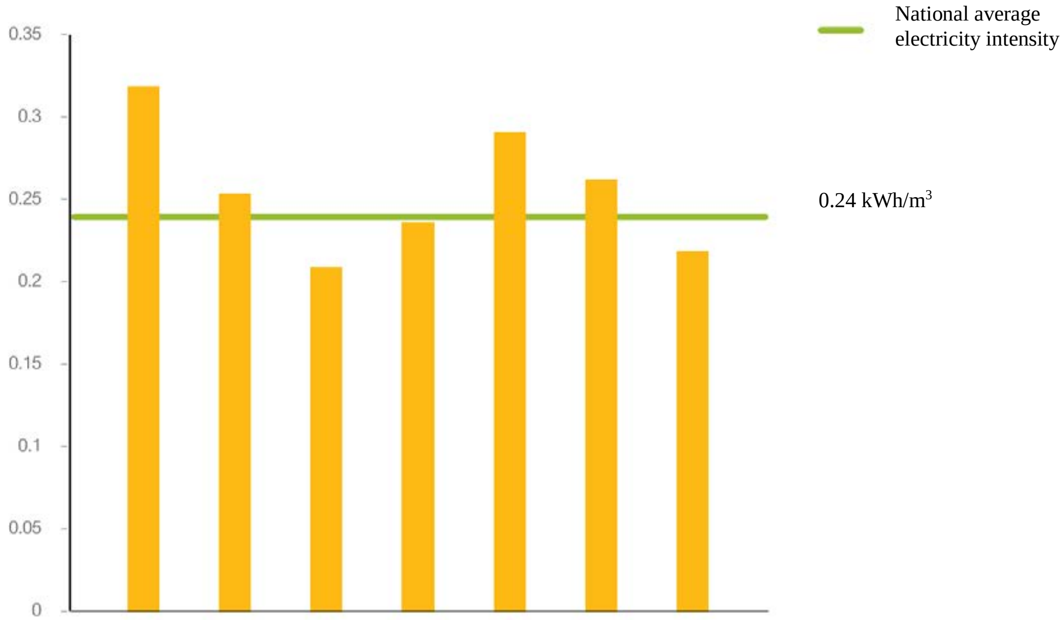

Figure A1-5. National average electricity intensity of wastewater treatment by region in 2012
Revised from (Fu & Zhong, 2014).

Water reclamation

A topic related to wastewater treatment that is receiving increasing attention is the topic of water reclamation, also termed water recycling or water reuse. Although technically it is possible to re-use recycled water for potable purposes, it most commonly is used for non-potable purposes, such as agriculture, landscape, cooling water for power plants and oil refineries, or industrial processes (USEPA, 2017). Utilities in Southern California were first to develop indirect potable reuse (i.e., introducing purified wastewater into a surface or underground drinking water reservoir). An expert panel in California currently is assessing the feasibility of deploying direct potable reuse widely (i.e., adding recycled water directly to the drinking water supply immediately upstream or downstream of a drinking water treatment plant) (Harris-Lovett, Binz, Sedlak, Kiparsky, & Truffer, 2015). In this study we do not consider direct portable reuse as a feasible option for China.

The reuse of water is energy intensive, but the amount of energy involved is difficult to quantify. For example, Israel and Singapore recycle 87% and 50% of their wastewater, respectively, a practice that consumes between 0.72 and 0.93 kWh/m^3 (Wakeel, Chen, Hayat, Alsaedi, & Ahmad, 2016). Wastewater treatment plants usually are located in a city's lower elevations, while the end users receiving the recycled water are usually at higher elevations. Thus additional energy is required for pumping the water to end users. This re-distribution dominates the electricity consumption of the recycling process, as shown in a California study (Horvath & Stokes, 2013). Quantifying the energy intensity of water reuse is difficult because of the breadth of inflow and water quality requirements. For example, water reuse can range from a homeowner collecting bath water to water potted plants, to a California utility injecting reclaimed wastewater into an aquifer or use in industrial processes or the irrigation of golf courses or parks (Pabi, Amarnath, Goldstein, & Reekie, 2013). These unknowns mean the energy intensity of water reuse can range from 0.2 to 2.5 kwh/m^3 (United National World Water Assessment Programme, 2014). This study adopted the median value of 1.25 kwh/m^3.

In 2014, only 4.61 billion cubic meters of wastewater reportedly was recycled in China, or about 10% of treated wastewater (Ministry of environmental protection of PRC, 2015). By 2020, the total capacity of recycling facilities must reach 41.6 million tons/day—a 56% increase from the 2015 baseline (National Development and Reform Commission of China and Ministry of Housing Urban and Rural Development of China, 2016). The use of recycled water was encouraged in 2015 when the "Water Pollution Prevention & Control Action Plan" (the “Water Ten”) declared that no new water use permits would be issued to thermal power plants that do not fully utilize the potential of reclaimed water. There have been indications of success. One study found that reclaimed water from wastewater treatment plants accounted for 58% of the water withdrawal quotas issued to new coal power plants in the Yellow River Basin from 2009 to 2014 (Tan et al., 2015).

Desalination

Before 2005, China's capacity for seawater desalination increased very slowly; after that it increased rapidly, achieving an average annual growth rate of 73.32% during the 11th FYP period (Q. Zou & Liu, 2016). According to the latest report from the State Oceanic Administration of China (State Oceanic Administrion of China, 2017), by the end of 2016 China had about 131 desalination plants having a total capacity of 1.19 Mt per day. Most of the desalination plants are located along the northern coastal region, such as Tianjin, Hebei, Shandong, and Liaoning. The desalinated water that is produced is supplied to water-intensive industries such as thermal power and steel plants. In the south, desalination has been constructed for residential use in remote islands. Table A1-6 and Figure A1-9 present statistics for the overall development of desalination plants across regions, the types of technologies that have been adopted, and the percentages of various users that utilize desalinated water. Reverse osmosis (RO) and low-temperature multi-effect distillation (MED) are the most prevalent technologies adopted in China.

The largest low-temperature MED plant currently produces 200,000 m^3/d of desalinated water, and the largest RO facility produces 100,000 m^3/d of desalinated water (Q. Zou & Liu, 2016). In 2014, 64.7% of desalination plants used RO, and 34.6% used MED. Of the desalination plants in China, two were built in the 1980s that utilize multi-stage flash distillation (MSF) and electrodialysis (ED) technologies, respectively. In the 13th five-year plan for desalination of seawater (National Development and Reform Commission of China and State Oceanic Administration of China, 2017), the stated target is to attain a 2.2 Mt per day capacity by 2020. The targets include developing the capacity to desalinate 1 Mt per day of brackish water. The plan emphasizing the expansion of desalination capacity in water-scarce areas such as northern coastal cities, islands, and industrial parks.

Table A1-5. Desalination capacities and types of technologies adopted in each jurisdiction 2014

Region	Million tons/year	MED (%)	RO (%)	MSF (%)	ED (%)
Tianjin	115.79	66	32	2	
Hebei	61.14	64	36		
Liaoning	32.00	1	99		
Jiangsu	1.86		100		
Zhejiang	51.65		100		
Fujian	3.99		100		
Shandong	60.30	2	98		
Guangdong	11.25		100		
Hainan	0.34	3	76		21

Source: (State Oceanic Administrion of China, 2015a).

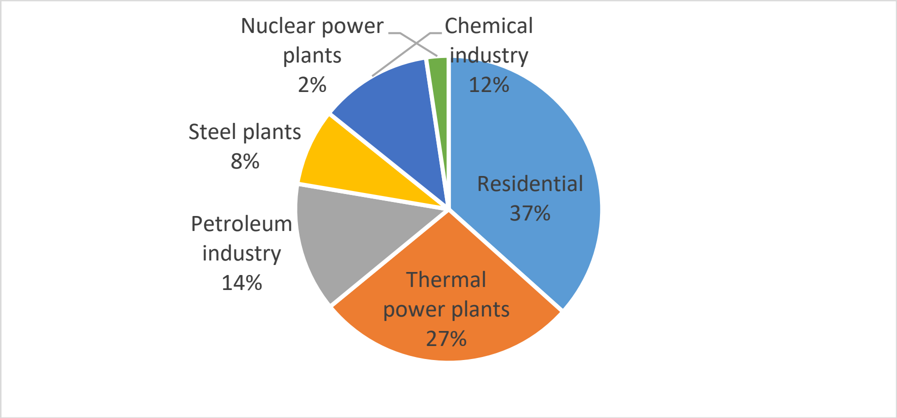

Figure A1-6. Users of desalinated water (percents), 2014

Data sourced from (State Oceanic Administrion of China, 2015b).

Reverse osmosis is the most economical desalination technology for end uses such as high-temperature gas-cooled nuclear plants, thermal power plants, chemical and petrochemical plants, and domestic municipal supply when energy is reliable and there are established methods for dealing with potential membrane blockages and the providing for periodic cleaning. MED is often utilized in low-temperature nuclear plants, thermal power plants, and steel and metal plants when there is sufficient heat to support distillation (Wastewater & Water International, 2017).

Desalination usually is energy intensive (table A1-7). A large amount of energy is needed for high-pressure pumping using a membrane technology such as RO. Many plants have systems for recovering energy for pumping. RO can be applied worldwide for many desalination projects, but ED can be a cost-effective technology for many industrial applications (Strathmann, 2010). ED is particularly appropriate for desalinating brackish water having low total dissolved solids (TDS) (Ghalavand, Hatamipour, & Rahimi, 2015). Unlike RO systems, ED systems operate at atmosphere pressure. ED systems consume electricity primarily to enable ion transport across membranes. The energy intensity of desalination using either ED or RO depends on the salt concentration, composition, and temperature of the feed water. The distillation processes used in MSF and MED require two types of energy—low-temperature heat and electricity. Producing the low-temperature heat consumes most of the energy input; the electricity is used to drive the system’s pumps. Many MED desalination plants in China were constructed jointly with power plants, which provide the needed electricity. MED plants are constructed so they can use waste heat from iron or steel plants. Because many more nuclear power plants are expected to be constructed in China, MED desalination could receive more attention and market share (Zheng, Chen, Wang, & Zhang, 2014). Given the great uncertainty regarding future trends in deploying desalination technologies, this study assumes that new desalination facilities will adopt RO and MED systems according to their current market shares of 35% and 65%, respectively.

In the United States, most of the installed desalination capacity is used to treat brackish water using RO (J. Yang & Yamazaki, 2013). Brackish water is a mixture of freshwater and seawater, thus being more saline than freshwater and less saline than seawater. Because brackish water contains much lower concentrations of TDS than does ocean water, desalinating brackish water has a lower energy intensity (can range from 0.37 to 0.48 kWh/m^3) (Bennett, Park, & Wilkinson, 2010). In China, the practice of desalinating brackish water began in the 1970s (W. Li & Lv, 2012) as a way of meeting residential and industrial water quality standards and increasingly is used as a way to resolve local water scarcity problems.

Table A1-6. Energy intensity of desalination technologies

Kwh/m^3	Current range	This study (base year 2014)	Capacity share in China (2014) (State Oceanic Administrion of China, 2015a)	Future projection

RO (seawater)	4-6 (Semiat, 2008)	5	34.64%	3 (2020); 2.1-2.4 (2035) (International Water Association, 2016)
MED	40-65 (thermal); 2-2.5 (electric)(Shahzad, Burhan, Ang, & Ng, 2017)	54.75	64.69%	15 (2030) (Semiat, 2008)
MSF	53-70 (thermal); 2.5-5 (electric) (Shahzad et al., 2017)	65.25	0.65%	21 (2030) (Semiat, 2008)
ED (brackish water)	1.5-4 for feed water having 1500-3500 ppm solids (IEA-ETSAP and IRENA, 2012)	2.75 (brackish) (IEA-ETSAP and IRENA, 2012)	0.02%	

Summary

Among water services in China, seawater desalination, water reclamation, and inter-basin water transfer are the most energy intensive (Table A1-8 and Figure A1-10). Because desalination distillation technologies such as MED and MSF require thermal energy, many MED plants are built near thermal power plants or steel plants to take advantage of their waste heat. Water reclamation is also energy intensive because it often requires significant energy to distribute the reclaimed water to end users. The energy consumed by the inter-basin water transfer projects depends greatly on the differences in elevation and the distance between the source and end users. In this study the energy intensities of inter-basin water transfer projects are aggregated at the national level for analytical purposes. Of course the energy intensity of any water services can differ significantly among regions and localities.

The energy consumed for water services in China differs in some ways from typical international levels (Figure A1-11). Treating raw water appears to consume more energy in China than elsewhere, but this result might be explained by different accounting boundaries applied in the studies. For instance, in China electric usage data are obtained at the utility meter ends, and so reflect some of the energy for obtaining and pumping water and for discharging water. The different scopes of the 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 (approximately 8% in 2011) (Zeng et al., 2017). We also note that the energy used for wastewater collection and discharge in China might be underestimated, because this study applied average international values. Lastly, the average energy intensity for inter-basin water transfer in China (an aggregated value of 0.815 kWh/m^3) represents only the water that is pumped through the eastern route, because the central routes transfer water using primarily gravity. To provide a 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 the place where water is delivered (Klein, Krebs, Hall, O'Brien, & Blevins, 2005).

Table A1-7. Energy intensities of water services in China, 2014

Water service	Water process	Sector/ technology	Source	Energy intensity adopted in this study (KWh/m^3)	Source
Water supply	Source/ conveyance	Agriculture	surface water_storage	0.018	(S. Jiang, 2017)
			surface water_lifting	0.53	(S. Jiang, 2017)
			groundwater	0.4	(S. Jiang, 2017)
		Industrial & municipal	surface water_storage	0.18	(S. Jiang, 2017)
			surface water_lifting	0.53	(S. Jiang, 2017)
			groundwater	0.19	(S. Jiang, 2017)
		Inter-basin (the volume that requires pumping)	surface water	0.815	Calculated based on (J. Gao, 2012)
	Water treatment	Industrial & municipal	surface water/groundwater	0.32	(S. Jiang, 2017)
	Water distribution	Industrial & municipal	surface water/groundwater	0.41	(S. Jiang, 2017)

Water service	Water process	Sector/ technology	Source	Energy intensity adopted in this study (KWh/m^3)	Source
	Desalination	MSF	seawater	3.75 (electric) + 61.5 (thermal)	(Shahzad et al., 2017)
		MED	seawater	2.25 (electric) + 52.5 (thermal)	(Shahzad et al., 2017)
		RO	seawater	5	(Semiat, 2008)
		ED	brackish water	2.75	(IEA-ETSAP and IRENA, 2012)
Wastewater (WW) system	WW collection	Industrial & municipal	surface water/groundwater	0.06	(Y. Liu et al., 2016)
	WW treatment	Industrial & municipal	surface water/groundwater	0.24	(Fu & Zhong, 2014)
		Recycled water	surface water/groundwater	1.25	(United National World Water Assessment Programme, 2014)
	WW discharge	Industrial	surface water/groundwater	0.06	(Y. Liu et al., 2016)

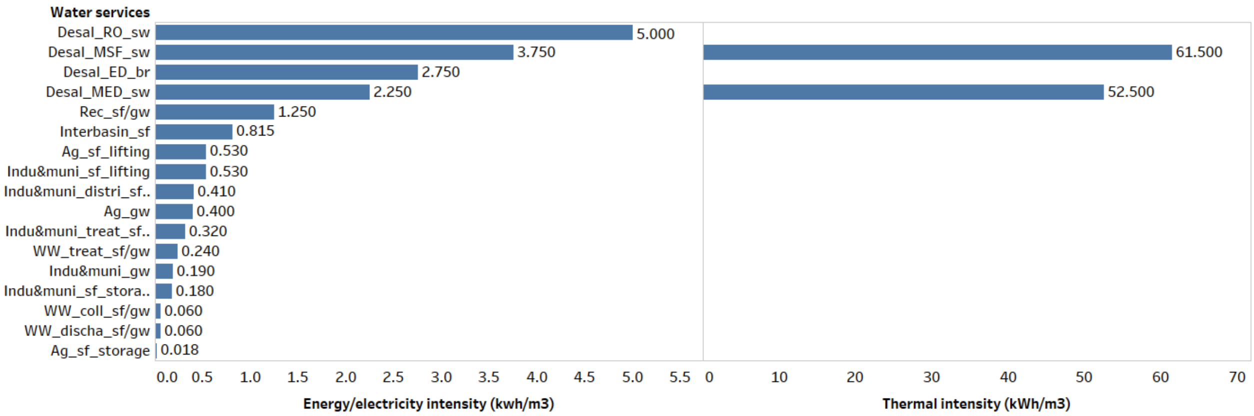

Figure A1-7. Energy intensities of water services in China, 2014

Note: the abbreviation is formatted as "water process_sector/technology_source" in Table 11. sf: surface water; gw: groundwater; br: brackish water.

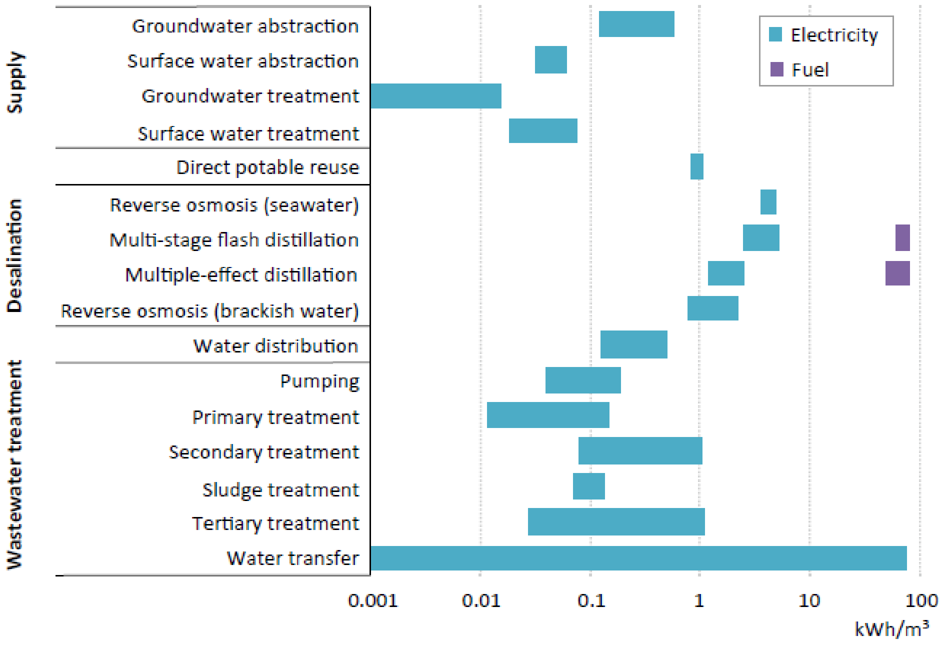

Figure A1-8. International energy intensity values for various processes in the water sector

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

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