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Article

Scenario-Based Analysis on Water Resources Implication of Coal Power in Western China

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Abstract: Currently, 58% of coal-fired power generation capacity is located in eastern China, where the demand for electricity is strong. Serious air pollution in China, in eastern regions in particular, has compelled the Chinese government to impose a ban on the new construction of pulverized coal power plants in eastern regions. Meanwhile, rapid economic growth is thirsty for electric power supply. As a response, China planned to build large-scale coal power bases in six western provinces, including Inner Mongolia, Shanxi, Shaanxi, Xinjiang, Ningxia and Gansu. In this paper, the water resource implication of the coal power base planning is addressed. We find that, in a business-as-usual (BAU) scenario, water consumption for coal power generation in these six provinces will increase from 1130 million m^3 in 2012 to 2085 million m^3 in 2020, experiencing nearly a double growth. Such a surge will exert great pressure on water supply and lead to serious water crisis in these already water-starved regions. A strong implication is that the Chinese Government must add water resource constraint as a critical point in its overall sustainable development plan, in addition to energy supply and environment protection. An integrated energy-water resource plan with regionalized environmental carrying capacity as constraints should be developed to settle this puzzle. Several measures are proposed to cope with it, including downsizing coal power in western regions, raising the technical threshold of new coal power plants and implementing retrofitting to the inefficient cooling system, and reengineering the generation process to waterless or recycled means.

Keywords: energy-water nexus, coal power generation, water resource, China

1. Introduction

The extensive development mode in China has led to rapid economic growth in a short time, but has been followed by a lot of environmental problems, especially air pollution, in recent years. Taking the increasingly serious air pollution into consideration, the Chinese government announced the ban on new energy-and-pollution intensive projects in eastern regions, among which coal-fired power plants are strictly banned [1].

Meanwhile, China's rapid economic growth has brought growing electricity demand. The national total electricity consumption has ballooned from 2481 trillion Watt hour (TWh) in 2006 to 4200 TWh by 2010, with an average annual growth of 11.1% during the 11th Five-year-plan (FYP) period (2006–2010). Then in 2012, it reached 4950 TWh [2]. In 2020, the total electricity consumption is expected to reach around 8000 TWh, with an average annual growth rate of 6.8% [3].

In order to meet the growing energy demand, five comprehensive energy bases located in Shanxi, Ordos, Xinjiang region, and eastern and southwestern Inner Mongolia will be built, according to the 12th FYP [4]. The 12th Energy Development plan also intended to develop 14 large coal mine bases and 16 coal power bases, and the total size of thermal power capacity is expected to reach more than 600 GW in these bases [5,6].

However, the water resource constraint in the coal power bases and the implication of the coal power bases on regional water resource is not fully considered in the planning. This paper is an attempt to address these two interweaved issues. The structure of the paper is as follows. Section 1 presents the background and purpose of the study. Section 2 will briefly review the water–energy nexus and provide background information on water resource and consumption in China’s coal power base provinces. Section 3 will propose the model for analyzing water usage of thermal power generation. Section 4 will analyze the demand and impact of the coal power planning on water resource in China’s coal power base provinces. Section 5 will provide analysis on water saving measures and an alternative scenario and Section 6 concludes the paper.

2. Literature Review and Research Background

2.1. Energy-Water Nexus

Globally, 80% of electricity generation comes from thermo-electric power stations (such as fossil fuels and nuclear), all of which require cooling for efficient and safe operation [7]. Most of the cooling system is provided by water abstractions from, and thermal discharges to, the natural environment, including rivers, tidal estuaries and coasts. The production of energy requires large quantities of water in processes such as thermal plant cooling systems or raw materials extraction. Analysis on whether water resources in a given region can support energy production will be a critical issue in the near future. The energy-water nexus has been a topic of increasing importance in recent years. In 2003 and 2006, numerous power plants in Europe had to be throttled in summer due to water shortages and high water temperatures caused by a hot and dry summer [8]. The agriculture sector currently has the highest water demand at the global scale, followed by the industry-energy sector that is responsible for 20% of the total water withdrawals [9]. In the U.S., the energy sector is expected to be the fastest growing water consuming sector, being responsible for 85% of the increase in domestic water consumption during 2005–2030 [10]. In some MENA (Middle Eastern and Northern Africa) countries, the interdependencies are already being manifested. For instance, in Saudi Arabia almost all of the natural gas currently produced is consumed domestically, primarily in the petrochemical industry and in seawater desalination [11]. Joint consideration of both water and energy domains can identify new options for increasing overall resource use efficiencies [12]. Gleick calculated the water consumption of different forms of energy [13]. Morgan Bazilian *et al.* (2011) considered the energy, water and food nexus, primarily from a developing country perspective [14]. Hagen Koch *et al.* described how to integrate the calculation of water demand of power plants into water resource management model [15]. Alexander *et al.* [16] studied the relationship between water and energy in an interactive lifecycle framework. Benjamin *et al.* [17] highlighted the most likely locations of severe water shortages in 22 counties because of thermoelectric capacity additions, and identified an assortment of technologies and policies that could respond to these electricity–water tradeoffs. Edward *et al.* [18] presented a model that quantifies current water use of the UK electricity sector, disaggregated by generation type, cooling method and cooling source. Also, it tested six decarbonisation pathways for the UK by combining projections of cooling methods and cooling sources for future thermoelectric generation. Aurelie *et al.* [19] proposed a model to assess optimal "water-energy" mix considering opportunities for water reuse and non-conventional water use in the water-scarce Middle East region. Kuishuang *et al.* [20] applied an integrated hybrid LCA approach to eight different electricity generation technologies in China to calculate their total life-cycle CO_2 emissions and water consumption throughout national supply chains.

China is a drought-hit country. Though total freshwater resources reach 2.8 trillion m^3, accounting for 6% of global water resources, ranking fourth in the world after Brazil, Russia and Canada, per capita water resource is just 2200 m^3, a quarter of the world average, or 1/5 of the United States level [21]. Energy and water have become major factors limiting sustainable development in China. Energy efficiency and optimization of water management are critical for the healthy growth of the Chinese economy [22]. In addition to energy shortages, China is also confronted with numerous water resource challenges, including shortage, pollution and aquatic environment deterioration.

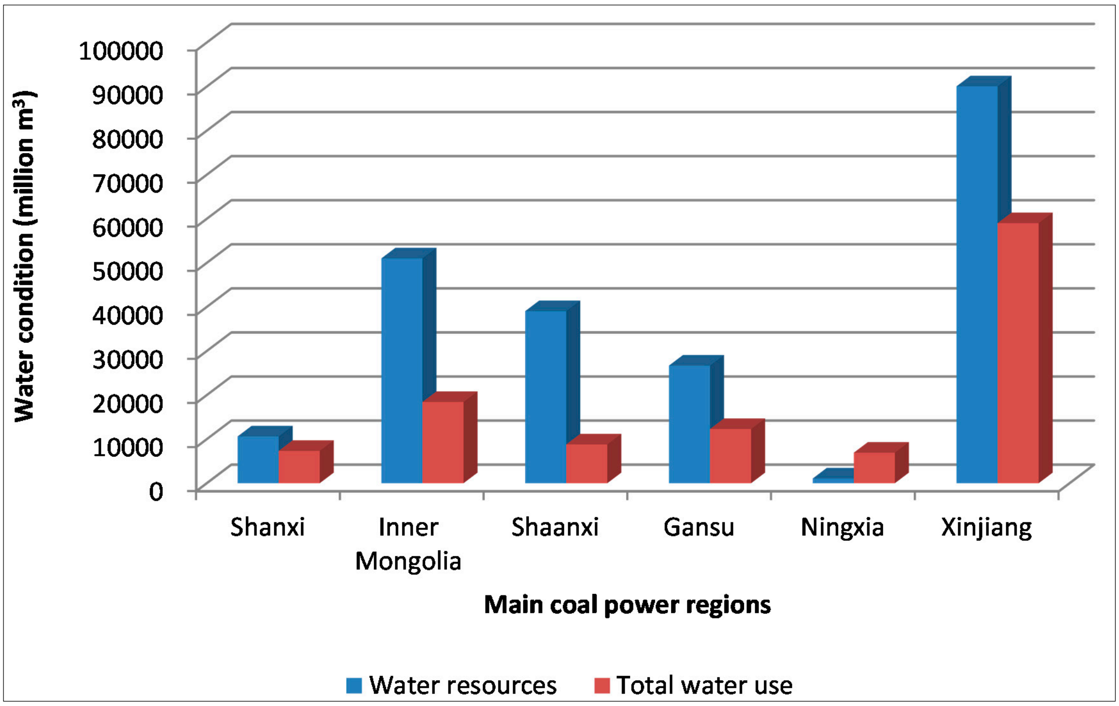
It is noteworthy that the development of China's coal power base is uncoordinated with the distribution of water resources. The coal-rich regions often face water scarcity, while regions with plentiful water resources mostly face coal shortage [23]. According to the 12th Energy Development Plan [5], coal and energy supply in China is relying on the west coal-rich regions, but these areas are mostly located in the dry arid and semi-arid regions. That is to say, water resource conditions will inevitably become an important factor in the development of coal power bases. Because of limited freshwater resources, decision-making has to take the most valuable use of this limited resource into consideration. In water-stressed areas of the coal power bases, power plants will increasingly compete with other water users. Large-scale coal power bases in arid region of northwest will lead to severe water crisis, and the conflicts between coal resources and water are most significant in the following six provinces (autonomous regions), including Inner Mongolia, Shanxi, Shaanxi, Xinjiang, Ningxia and

Gansu. To the best scope of our knowledge, only a book [24] explicitly addressed this issue, but it only raised a question and did not provide a solution to it. It is rightly the study scope of this paper.

2.2. Water Resources in China's Western Coal Power Base Provinces

According to the China Statistical Yearbook 2013, the data of water resources and water use of the main coal power bases is reported in Figure 1. In terms of total water resources, Xinjiang is the richest while Ningxia is the poorest region in these provinces. In particular, the water use in Ningxia is much more than its total water resources, indicating that water is scarce. Though the water resource in Xinjiang Uygur Autonomous Region seems rich, the water resources in Hami (coal power base) is merely 1.696 billion m^3, accounting for only 2.13% of its total water resource endowment [24].

Figure 1. The water resources and water use in China's coal-power base provinces.



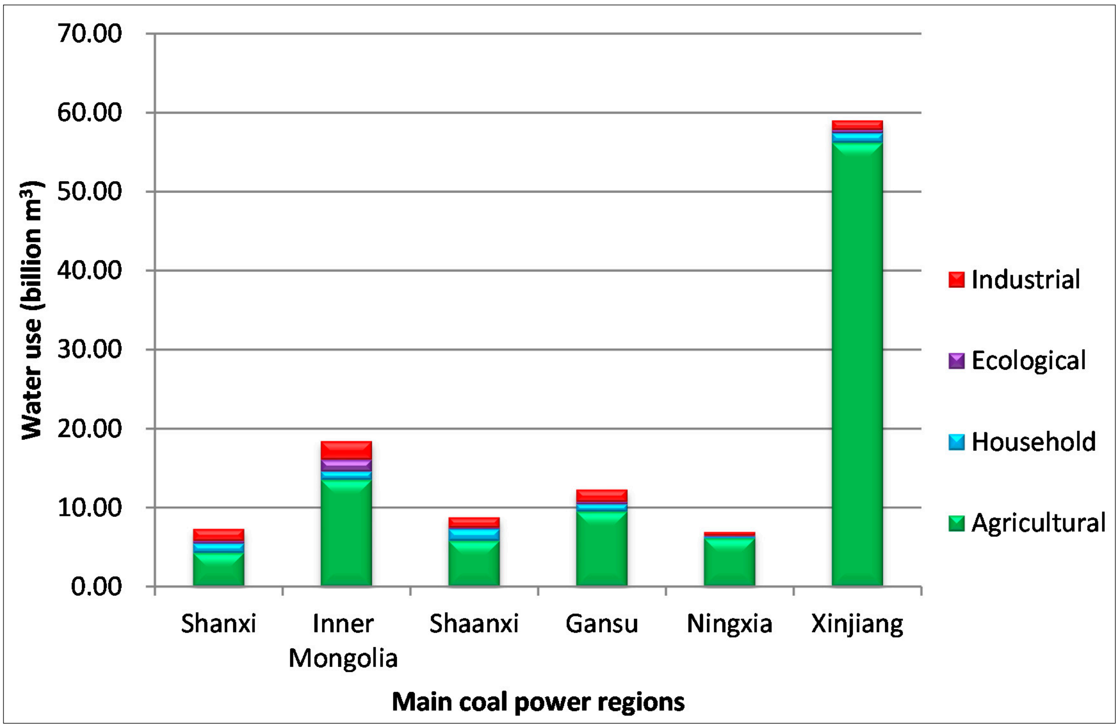
As is shown in Figure 1, the water resource in Inner Mongolia Autonomous Region is second to that of Xinjiang, but its coal power bases' water resources are not as rich. With the exception of Hulunbeir coal power base, other bases all have water shortage issues at varying degrees. For example, water resource in Jungar coal power base account for just 0.67% of Inner Mongolia water endowment [25]. For Xilingol League coal power base, the figure is 5.8%, for Ordos coal power base, 5.4% [26], and for Holingol coal power base, 0.09% [27]. The coal power bases located in the other four provinces all have water shortage issues. Especially, the condition of water shortage in Ningxia is the most serious, whose water resource ranked the last in this country.

2.3. Water Use in the Coal Power Base Provinces of Western China

The consumption of water resources can be divided into the following categories: agricultural water use, household water use, ecological water use and industrial water use. The electricity sector is one of the largest water consumers in China after agriculture [28]. Thus, the electricity sector can be a contributor to water scarcity which has already occurred in many parts of the country, in particular in Northern China [29]. The water use of the main coal power base provinces in 2012 is shown in Figure 2 [30].

From Figure 2, we can easily see that agricultural water use absolutely takes up the most part of whole water use, and industrial use is only second to agricultural use. Though total water use in Shanxi and Shaanxi is not as much as that in Xinjiang, their industrial water use has accounted for much larger share. Because of water shortage and agricultural water demand, Ningxia does not seem to have enough water to support industry development, including coal power bases. Considering total water resources and water use, the potential of developing coal power bases in Shanxi, Gansu and Ningxia does not look optimistic.

Figure 2. Water use of main coal power base provinces in 2012.



2.4. Originality and Novelty of the Study

The energy-water nexus has been a topic of increasing importance in recent years. Indeed, water is needed for the energy sector (fuel production and electricity generation), and energy is used to clean, desalinate and transport water. This relationship is referred to as the water-energy nexus, a concept originally formulated by Gleick in the 1990s with his seminar study [13]. Current studies and research mainly focus on water issues and energy consumption related to water management, and coupled water and energy challenges have been described for the energy production sector, *i.e.*, for the United States [31], Australia [32], Spain [33], the UK [18], Middle East [19], and China [22]. However, though few studies have indicated that China could face water shortages resulting from the addition of thermoelectric power plants, no precise estimate or policy study have been conducted. The goal of the present study is to reveal the potential water issues in China's coal power bases, and to provide a solution for it.

3. Methods and Data

According to the US Geological Survey's (USGS) water use survey data, Each kilowatt-hour (kWh) of thermoelectric generation requires the withdrawal of approximately 25 gallons of water (weighted-average for all thermoelectric power generation), which is primarily used for cooling purposes. Power plants also use water for operation of flue gas desulfurization (FGD) devices, ash handling, wastewater treatment, and wash water [34].

When discussing water and thermoelectric generation, it is necessary to distinguish between water withdrawal and water consumption. Water withdrawal represents the total water taken from a source but then returned to it, while water consumption represents the amount of water withdrawal that is not returned to the source. Water withdrawal is defined as the removal of water from any source or reservoir for human use. The water withdrawal constitutes the conveyance losses, consumptive use and return flow. Water consumption is defined as the amount of water extracted from a source that is no longer available for use, because it has evaporated, transpired, been incorporated into products and crops, consumed by man or livestock, ejected into the sea, or otherwise removed from freshwater resources [33]. The industry chain of large coal bases includes coal mining industry, thermal power industry and coal chemical industry. The focus of this paper is on the water consumption of thermal power industry and thus the terminology of "water consumption" is used in our analysis.

3.1. The Water Link of Thermal Power Plant

The composition of water consumption in thermal power plants are as follows: (a) water recharge of the cooling system; (b) ash and slag removal system; (c) boiler water feed system; (d) auxiliary cooling system; (e) desulfurization system; (f) water use of coal yard; and (g) domestic water use [35].

Thermal plants use fossil fuels to generate electricity or heat, and their water needs can vary drastically depending on the type of plant, type of refrigeration system, type of fuel and region [36]. The amount of water withdrawal and consumption depends on the type of technology used at a given plant. According to Meldrum *et al.* [37], water used for cooling purposes dominated the life cycle water use of electricity generation.

Large quantities of cooling water are required for thermoelectric power plants to support the generation of electricity. There are basically three types of cooling system designs: wet recirculating (open-loop and closed-loop) and dry recirculating (air-cooled). Open-loop (once-through) systems do not consume large quantities of water but require large quantities of water withdrawal in the cooling process. Closed-loop systems require smaller withdrawal of water, but most of the water withdrawal is lost in evaporation [13]. Air-cooled systems, also referred to as dry recirculating cooling systems, use either direct or indirect air-cooled steam condensers. In a direct air-cooled steam condenser, the turbine exhaust steam flows through air condenser tubes that are cooled directly by conductive heat transfer using a high flow rate of ambient air that is blown by fans across the outside surface of the tubes. Therefore, cooling water is not used in the direct air-cooled system. In an indirect air-cooled steam condenser system, a conventional water-cooled surface condenser is used to condense the steam, but an air-cooled closed heat exchanger is used to conductively transfer the heat from water to ambient air [38].

3.2. Water Consumption Rate in Coal Power Plants

China Electricity Council (CEC) is responsible for energy efficiency benchmarking in the power industry and releases detailed energy efficiency and water efficiency statistics [39]. By collating and analyzing the data, we calculated the water consumption and coal consumption indexes for power generation in the 600 MW units. Table 1 reports the water consumption rates while Table 2 reports the heat rates of the coal power units with different cooling system (Interested readers may refer to the Appendix for detailed information).

Table 1. Water consumption rates in China's 600 MW coal power units, 2012.

Types of cooling system	Counted units	Proportion (%)	Comprehensive water consumption rate (m^3/MWh)		
			Optimal value	The top 30% average	Average
Closed-loop	128	39.26%	0.23	1.27	1.83
Open-loop	134	41.10%	0.02	0.18	0.29
Air-cooled	64	19.63%	0.18	0.23	0.31

Table 2. Heat rates in China's 600 MW coal power units, 2012.

Types of cooling system	Counted units	Heat rates (gce/kWh)		
		Optimal value	The top 30% average	Average
Closed-loop	128	285.00	296.41	307.80
Open-loop	134	275.85	290.28	303.89
Air-cooled	64	306.90	320.86	331.18

As shown in Table 2, on the average, air-cooled unit performs worst in energy efficiency, with about 25 grams coal equivalent gce/kWh more than water-cooled units; while open-loop water cooling system is with lowest heat rate. Combining the information reported in Tables 1 and 2, we can easily see that the open-loop system is the most efficient, because of the lowest heat rate and the lowest comprehensive water consumption rate. However, the pre-condition for open-loop water-cooled system is the existence of large body of fresh water like rivers or lakes adjacent to the power plant. Also, the direct pollution of freshwater also indicates the infeasibility of open-loop water-cooled system.

3.3. Method

According to the data on installed capacity and comprehensive water consumption rates of thermal power plants by [39], we can calculate the water consumption of thermal power plants in these coal power bases located in western provinces. The water consumption of power plants is calculated by:

$$Q = \sum_{i=1}^{3} MW_i \times H_i \times R_i \div 10^6 \quad (1)$$

where

Q water consumption [10^6 m^3/a]

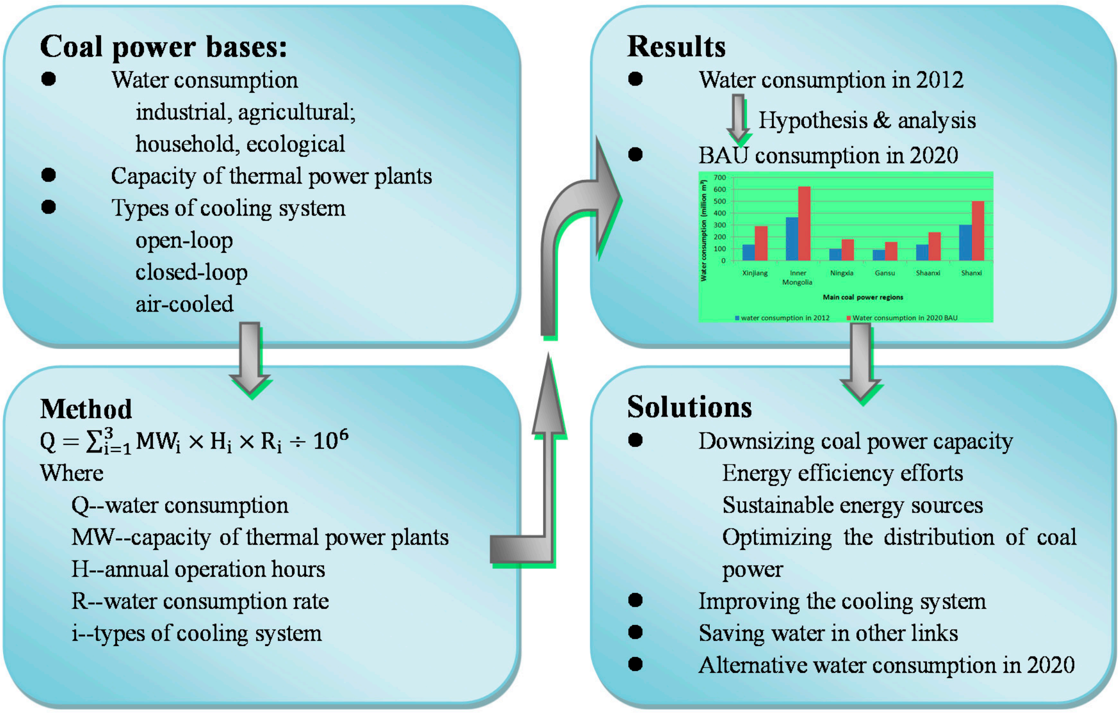
MW installed capacity of thermal power plants [MW]

H Annual operation hours of the thermal power plants

R	comprehensive water consumption rate [m^3/MWh]
i = 1	closed-loop cooling system
i = 2	open-loop cooling system
i = 3	air-cooled cooling system

The methodology for water consumption estimate and scenario study is presented in Figure 3. In its simplest form, water consumption is calculated by multiplying the electricity generated from a certain technology and the consumption factor for that technology, which is subject to various assumptions in our study. Because of the scope of our study, we limit our study in the above-mentioned six western coal power base provinces.

Figure 3. Methodology framework of our study.



4. Results

4.1. Current Water Consumption Status

Annual Development Report on China's power industry 2013 by CEC has counted the whole-diameter capacity in every province by the end of 2012 [2]. According to this report, by the end of 2012, the installed coal power capacity is 50,110 MW in Shanxi, 60,190 MW in Inner Mongolia, 22,270 MW in Shaanxi, 22,570 MW in Xinjiang; 16,400 MW in Ningxia and 15,510 MW in Gansu.

According to the 2012 basic information and scoring statistics on nationwide 600 MW thermal power units announced by CEC in 2013, we can estimate the distribution of cooling systems in these coal power provinces. There are approximately 75% of units adopting air-cooled system and other 25% of units adopting closed-loop cooling system, as shown in Table 3. Open-loop system, constrained by resource endowment in these western regions, is rarely deployed. According to Equation (1), we can estimate the water consumption by thermal power plants in these provinces, and the results are shown in Table 4.

Table 3. Statistics on different cooling systems in China's coal power base provinces.

Region	**Count of different cooling system**		
	Open-loop	**Closed-loop**	**Air-cooled**
Shanxi	0	4	18
Inner Mongolia	2	12	20
Shaanxi	0	2	13
Gansu	0	0	2
Ningxia	0	0	8
Total	2	18	61

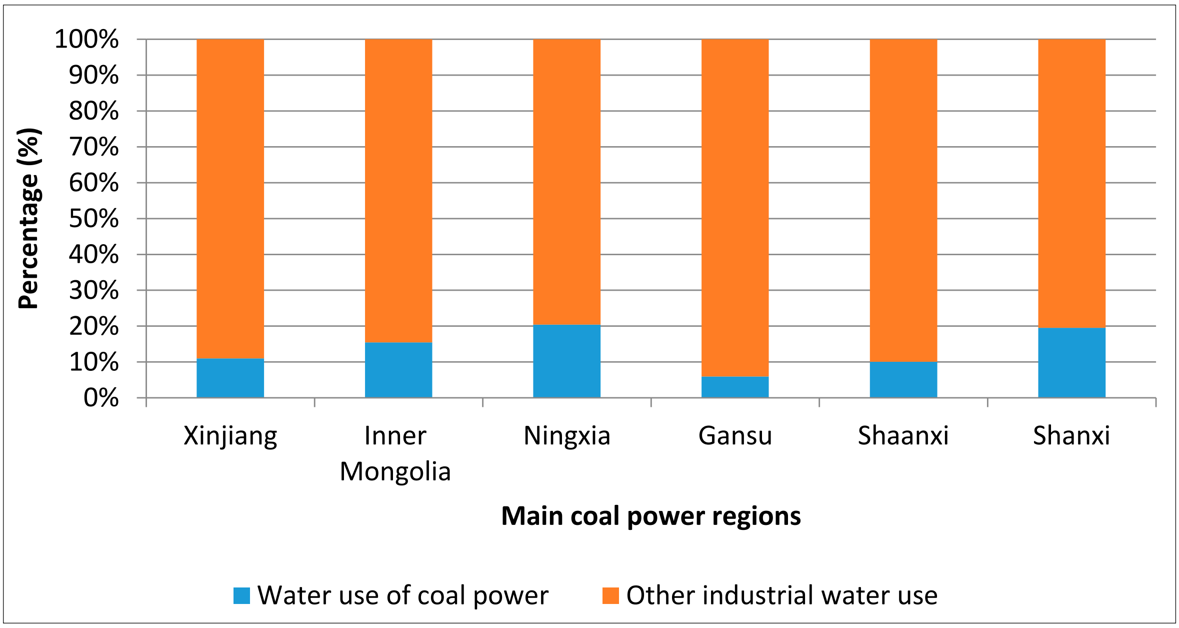
Table 4. Water consumption by thermal power plants in coal power base provinces, 2012.

Province	**Coal power capacity/ MW**	**Types of cooling system**	**Water consumption rate (m^3/MWh)**	**Installed capacity /MW**	**Water consumption (10^6 m^3/a)**	**Total water consumption (10^6 m^3/a)**
Xinjiang	22,570	Closed-loop	1.83	5640	90.414	136.389
		Air-cooled	0.31	16,930	45.975	
Inner Mongolia	60,190	Closed-loop	1.83	15,050	241.264	363.846
		Air-cooled	0.31	45,140	122.582	
Ningxia	16,400	Closed-loop	1.83	4100	65.726	99.128
		Air-cooled	0.31	12,300	33.402	
Gansu	15,510	Closed-loop	1.83	3870	62.039	93.649
		Air-cooled	0.31	11,640	31.610	
Shaanxi	22,270	Closed-loop	1.83	5570	89.292	134.642
		Air-cooled	0.31	16,700	45.351	
Shanxi	50,110	Closed-loop	1.83	12,530	200.866	302.918
		Air-cooled	0.31	37,580	102.052	
Aggregate	187,050				1130.572	1130.572

Then according to the statistical data on industrial water consumption, we can estimate the proportion of thermal power generation in the overall industrial water use in these provinces. The results are shown in Figure 4.

It is found that in both Ningxia and Shanxi provinces, coal power accounts for as high as 20% of industrial water consumption. For Inner Mongolia, coal power consumes 15% of the industrial water use. For Xinjiang and Shaanxi provinces, the percent is 10%. Only in Gansu province the percentage is less than 10%. Because of the scarcity of water resource in these provinces, we assume that further increase in industrial water supply is impossible or is much likely to bring conflicts between industrial water use and other purposes (ecological use or household use, for example) [18]. Therefore, we assume that further big increase in coal power/industrial water use percent is definitely unacceptable in the perspective of sustainable development in these provinces.

Figure 4. Coal power *vs.* industrial water use in the coal power base provinces, 2012.



4.2. BAU Water Consumption Scenario in 2020

According to the "Power Development Strategic Research Report 2013" by CEC, the capacity of China's coal power plants in 2020 is expected to reach 1100 GW, and coal power bases will account for 55% of total newly-constructed plants. The BAU power demand and power planning is shown in Table 5.

Table 5. BAU (business-as-usual) power demand and power planning.

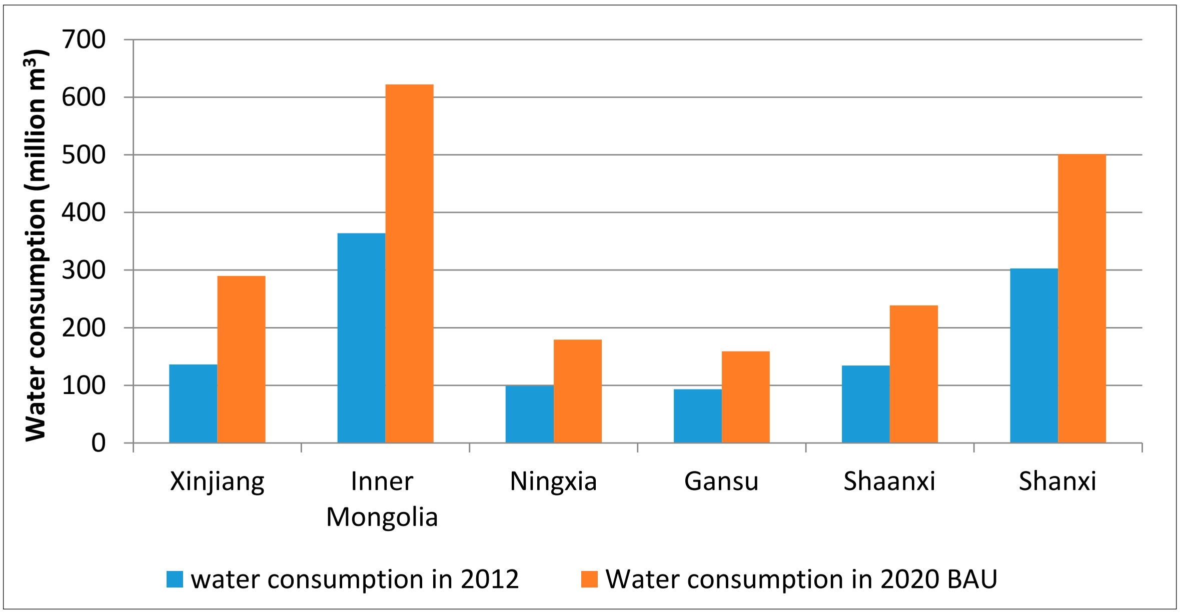
	Capacity (GW)	Electricity production (TWh)
Hydropower	360	1260
Pumped storage	60	48
Coal power	1050	5250
Gas power	100	300
Nuclear power	58	406
Wind power	200	400
Solar power	70	112
Biomass energy	15	67.5
Total	1913	7795.5
Balancing loss	-	90.5
Electricity demand	-	7705

Assume constant water consumption rates, we can estimate the business-as-usual (BAU) scenario of water consumption by coal power plants in these coal power base provinces in 2020 (Table 6). According to the BAU scenario, it is estimated that water consumption for coal power generation will double during 2012–2020, provided that the comprehensive water consumption rates and the composition of cooling system are unchanged (Figure 5). It is worthwhile pointing out that all these coal power bases are puzzled by water shortage, and a double growth in water demand will certainly break the balance of water ecology system in these regions.

Table 6. BAU Water consumption by thermal power plants in coal power base provinces, 2020.

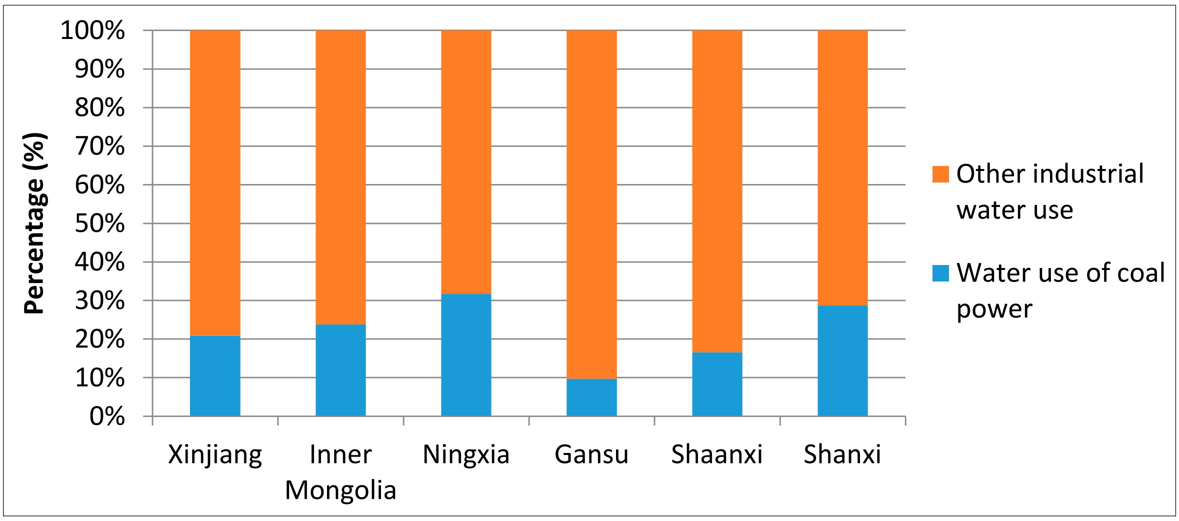
Province	Total capacity /MW	Types of cooling system	Water consumption rate (m^3/MWh)	Installed capacity /MW	Water consumption (10^6 m^3/a)	Total water consumption (10^6 m^3/a)
Xinjiang	47,970	Closed-loop	1.83	11,990	192.209	289.917
		Air-cooled	0.31	35,980	97.707	
Inner Mongolia	102,900	Closed-loop	1.83	25,730	412.472	622.035
		Air-cooled	0.31	77,170	209.563	
Ningxia	29,670	Closed-loop	1.83	7420	118.949	179.371
		Air-cooled	0.31	22,250	60.422	
Gansu	26,300	Closed-loop	1.83	6580	105.483	159.034
		Air-cooled	0.31	19,720	53.552	
Shaanxi	39,520	Closed-loop	1.83	9880	158.384	238.875
		Air-cooled	0.31	29,640	80.490	
Shanxi	82,950	Closed-loop	1.83	20,740	332.479	501.416
		Air-cooled	0.31	62,210	168.937	
Total	329,310			329,310	1990.648	1990.648

Figure 5. 2020 BAU *vs.* 2012 water consumption by coal power in coal power base provinces.



Furthermore, current water consumption by the power generation is substantial in volume and critical to its operation, but pressures of population growth, hydrological variability and climate change will complicate the issue. Water consumption in these provinces is always constrained by available supply and consumption in other industries is relative stable in the past. Hence, we hypothesize that water consumption in other industrial sectors will hold constant during 2012–2020, and then we can update the percentage of coal power/industrial water use for these provinces in 2020 (Figure 6). According to the estimate, with the exception of Gansu province, in the other five provinces, the percentages of coal power/industrial water use will be largely enlarged. In Shanxi and Ningxia provinces, coal power is expected to consume 30% of industrial water use in the BAU scenario; while in Xinjiang, Inner Mongolia and Shaanxi, coal power is expected to consume around 20% of industrial water use. In other words, the BAU scenario envisions higher possibility of water resource conflicts in these provinces.

Figure 6. Percentage of coal power/industrial water use in the BUA scenario.



5. Water Conservation Measures and Alternative Scenario

Our projected result in these provinces has clearly indicated that serious water crisis will be likely to erupt in the BAU scenario. A strong implication is that the Chinese Government must take water resource constraint into consideration as a critical point in its overall sustainable development plan, in addition to energy supply and environment protection. The point is that an integrated energy-water resource plan with regionalized environmental carrying capacity as constraints is a desideratum to settle this puzzle. Hence, in this section, firstly possible measures to cut down (or avoid) water consumption will be discussed. Then, an alternative scenario will be proposed to guide the sustainable energy development in these coal power base provinces.

5.1. Water Conservation Measures

5.1.1. Downsizing Coal Power Capacity

The most effective measure to cope with water resource crisis caused by power generation is cutting down the scale of coal power capacity in western provinces. In other words, an alternative power plan is needed. The following strategies can be employed in developing the power sector plan:

- Reducing electric power demand by active energy efficiency efforts. Energy efficiency has been regarded as the fifth energy source besides coal, oil, gas and hydropower. Worldwide experience has also clearly demonstrated the efficacy of energy efficiency in optimizing energy system. We estimate that with active energy efficiency efforts, the demand growth for electric power can be slowed down by 2%–3% and results in energy conservation at 200–300 TWh annually. The energy efficiency potential into 2020 by various active efforts is shown in Table 7.

Table 7. The energy efficiency potential of active efforts into 2020.

Technology/sector	Energy efficiency potential (TWh)
Green lighting	108.51
High efficiency motor	130.00
Energy-saving transformer	8.87
Frequency converter	97.70
High efficiency appliance	442.00
Ground source heat pump technology	18.00
Total	805.08

- Optimizing generation mix by deploying clean and sustainable energy sources. On one hand, in China the hydropower development is yet to reach its economically developable resource limit. On the other hand, China is endowed with abundant renewable energy sources like wind power and solar power, and active support of renewable energy development can make a big difference.
- Optimizing the regional distribution of coal power. With the development of zero emission technology, coal power can generate electricity at emission levels (SO_2, NOx and dust) closer to or even lower than gas power [40]. Hence, the government can lift the ban on the new construction of coal power plants in east regions and plan to build some coal power plants with cutting-edge pollutant control technologies in the load centers. The benefits are twofold. First, China's potential water resource crisis in western can be partly relieved. Second, the demand on long-distance electric power transmission—another important concern of decision-makers—can also be reduced.

5.1.2. Saving Water by Improving the Cooling System

The cooling system consumes most of water in the power generation process. Therefore, another priority of water conservation is to improve the cooling system in coal power plants. In the existing coal power fleet, these plants with advanced closed-loop water cooling system perform as effectively as those with air-cooled system in terms of the comprehensive water consumption rate while enjoying super energy efficiency advantage. Here, an important measure is to raise the technical threshold of new coal power plants and require that all the newly-constructed coal power plants perform better in their water consumption than the existing records. For existing plants, technical retrofitting can be implemented in those plants with below than average water efficiency performance.

5.1.3. Saving Water in Other Links

The demand on water quality in the other links of power plants is not as strict as in the cooling system. For example, treated wastewater, instead of fresh water, can be used in the desulfurization system and the coal yard. Use of nontraditional water sources, such as secondary-treated municipal wastewater, provides an option to reduce freshwater usage in thermal power production [41]. In the subsequent subsection, concrete water conservation measures are proposed from many links in the generation process.

- Ash and slag removal system: Dry-type ash and slag removal system, which consumes no water at all, is a mature option. On the other hand, with this process, the produced ash and slag can be reclaimed as building material [41].
- Cooling system of auxiliary systems: The cooling water for the auxiliary systems can be processed in a centralized way. Similarly, a small-scale wet recirculating or dry recirculating cooling system can be employed for the cooling of the pooled water.
- Desulfurization system: Dry desulfurization process consumes much less water than wet process. For the wet desulfurization process, the cyclic utilization of processing water is a feasible option. Other option is to use the reclaimed water in the cooling system for the auxiliary systems in desulfurization process.
- Water use of coal yard: The water quality demand in the coal yard is much lower. Retreated industrial wastewater or domestic wastewater can be collected for this purpose. Besides, the wastewater produced in coal yard can also be reutilized to further cut down water consumption.

5.2. An Alternative Water Consumption Scenario

In the alternative water consumption scenario, with energy efficiency efforts, electricity demand is projected to drop from 7705.5 TWh to 7560 TWh. In addition, with more clean and sustainable energy sources, the demand for thermal power is reduced by almost 100 GW, as shown in Table 8.

Table 8. Alternative power demand and power planning.

	Capacity (GW)	**Power production (TWh)**
Hydropower	360	1260
Pumped storage	70	56
Coal power	959.91	4799.6
Gas power-centralized	70	350
Gas power-distributed	50	125
Nuclear power	60	420
Wind power	230	460
Solar power-centralized	40	64
Solar power-distributed	60	72
Biomass energy	14	63
Total	1913.91	7594.9
Balancing loss	-	34.9
Electricity demand	-	7560

Due to technological advances and structural optimization, the comprehensive water consumption rate could be cut down by a large extent in the alternative scenario. Our estimate is that the water consumption rate could be cut down by 30% from the existing level. In addition, we project that more air-cooled units would be built. The details of the alternative scenario are reported in Table 9.

Table 9. Alternative water consumption in coal power base provinces.

Province	Total capacity /MW	Types of cooling system	Water consumption rate (m^3/MWh)	Installed capacity /MW	Water consumption (10^6 m^3/a)	Total water consumption (10^6 m^3/a)
Xinjiang	45,050	Closed-loop	1.27	9010	100.238	172.851
		Air-cooled	0.23	36,040	72.613	
Inner Mongolia	100,000	Closed-loop	1.27	20,000	222.504	383.688
		Air-cooled	0.23	80,000	161.184	
Ningxia	27,580	Closed-loop	1.27	5520	61.411	105.858
		Air-cooled	0.23	22,060	44.446	
Gansu	24,390	Closed-loop	1.27	4880	54.291	93.600
		Air-cooled	0.23	19,510	39.309	
Shaanxi	38,140	Closed-loop	1.27	7630	84.885	146.357
		Air-cooled	0.23	30,510	61.472	
Shanxi	80,950	Closed-loop	1.27	16,190	180.117	310.595
		Air-cooled	0.23	64,760	130.478	
Aggregate	316,110			316,110	1212.949	1212.949

In the alternative scenario, planned coal-fired generation capacity in these provinces would be 13 GW lower than in the BAU scenario. Also, the comprehensive water consumption rate of the closed-loop cooling system would be lowered to 1.27 m^3/MWh. The water consumption by coal power in these provinces will be 1212 million m^3, with only a slight increase relative to 2012 level. In this way, the envisioned water crisis caused by the electric power industry in these water-deprived provinces could possibly be avoided. However, we should not be too optimistic about it. Great risk exists in the implementation of water conservation measures and their actual effects.

6. Concluding Remarks

Coal power is an inevitable choice for meeting the increasing electric power demand in China. Considering the ever worsening atmospheric pollution, the Chinese Government has to adhere to the path of developing large-scale coal power bases in western provinces. However, the analysis presented in this paper clearly indicates that there will be furious water-energy conflicts in the development of coal bases, and water resource constraints will seriously restrict their development. An integrated planning of energy and water resources which takes regionalized environmental carrying capacity as the constraint is a final resort to this sustainable development puzzle. Several concrete water conservation measures are proposed to address the water crisis in China's coal power bases.

Certainly, our study is suffering from some limitations. For example, the perspective employed in the study is water resource constraint. Other important factors, such as the deployment cost of new cooling system and the retrofitting cost of existing cooling system, the economic appraisal of water conservation in links other than cooling system, are not addressed in the study. Water issue is only projected to worsen in the future, as a consequence of climate change. Therefore, further and more in-depth analysis on the issues presented here is needed to provide guidance for Chinese government and other stakeholders.

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Author Contributions

Jiahai Yuan contributed to the research idea and the framework of this study. Other authors contributed equally to the study.

Appendix

Table A1. Energy efficiency and water efficiency statistics on coal-fired power plants in China, 2012.

Plant No.	Capacity (MW)	Comprehensive water consumption rate (m^3/MWh)	Types of cooling system	Heat rates (gce/kWh)
1	640	1.91	Closed-loop	298.29
2	640	2.10	Closed-loop	297.71
3	1000	0.30	Open-loop	275.85
4	630	1.31	Closed-loop	296.2
5	640	1.98	Closed-loop	297.85
6	630	0.35	Open-loop	296.77
7	640	1.99	Closed-loop	298.36
8	600	0.23	Open-loop	306.28
9	630	1.31	Closed-loop	297.33
10	640	1.92	Closed-loop	298.15
11	1000	0.30	Open-loop	276.44
12	630	2.20	Closed-loop	296.78
13	600	0.23	Open-loop	308.21
14	500	1.83	Closed-loop	306.05
15	600	2.00	Closed-loop	307.3
16	660	0.25	Air-cooled	310.21
17	600	0.29	Open-loop	298.97
18	500	1.60	Closed-loop	324.06
19	700	2.10	Closed-loop	307.61
20	600	2.00	Closed-loop	309.35
21	600	0.24	Air-cooled	326.41
22	600	1.72	Closed-loop	302.35
23	600	2.00	Closed-loop	298.51
24	600	1.70	Closed-loop	302.12
25	600	0.24	Air-cooled	326.7
26	600	1.57	Closed-loop	310.03
27	1000	0.23	Closed-loop	287.18
28	1000	0.10	Open-loop	282.
29	600	0.23	Air-cooled	330.13

Table A1. *Cont.*

Plant No.	Capacity (MW)	Comprehensive water consumption rate (m^3/MWh)	Types of cooling system	Heat rates (gce/kWh)
30	600	0.47	Air-cooled	318.14
31	600	0.25	Open-loop	310.5
32	600	0.23	Air-cooled	330.05
33	900	0.43	Open-loop	299.82
34	500	1.83	Closed-loop	306.28
35	630	1.47	Closed-loop	300.58
36	630	0.35	Open-loop	298.53
37	600	0.24	Air-cooled	327.53
38	630	0.35	Open-loop	300.3
39	600	0.33	Air-cooled	329.62
40	660	0.32	Open-loop	288.2
41	660	1.73	Closed-loop	298.01
42	630	1.99	Closed-loop	305.3
43	700	2.10	Closed-loop	311.39
44	600	2.83	Closed-loop	310.97
45	660	0.19	Air-cooled	323.55
46	660	0.43	Open-loop	291.51
47	670	2.07	Closed-loop	301.11
48	640	1.88	Closed-loop	305.12
49	670	2.07	Closed-loop	302.07
50	600	0.26	Air-cooled	328.14
51	680	0.19	Open-loop	298.6
52	600	0.26	Air-cooled	327.11
53	660	1.31	Closed-loop	291.34
54	600	1.90	Closed-loop	307.57
55	600	1.87	Closed-loop	302.45
56	680	0.11	Open-loop	289.98
57	600	0.24	Air-cooled	331.9
58	630	1.85	Closed-loop	301.08
59	1000	2.01	Closed-loop	285.71
60	600	2.10	Closed-loop	315.48
61	1000	2.01	Closed-loop	286.11
62	660	0.41	Open-loop	311.3
63	600	2.03	Closed-loop	301.49
64	630	0.42	Air-cooled	323.42
65	600	0.24	Open-loop	311.66
66	630	0.42	Air-cooled	323.39
67	600	2.81	Closed-loop	319.58
68	600	1.85	Closed-loop	300.86
69	1000	0.26	Open-loop	285.58
70	630	2.26	Closed-loop	304.13
71	600	0.34	Open-loop	300.71
72	660	0.43	Open-loop	291.51

Table A1. *Cont.*

Plant No.	Capacity (MW)	Comprehensive water consumption rate (m^3/MWh)	Types of cooling system	Heat rates (gce/kWh)
73	600	0.29	Open-loop	312.11
74	600	0.24	Open-loop	299.99
75	600	0.20	Open-loop	310.03
76	900	0.43	Open-loop	301.01
77	1000	0.27	Open-loop	285.55
78	600	0.24	Air-cooled	330.73
79	650	0.33	Closed-loop	303.07
80	660	0.17	Open-loop	294.85
81	600	2.46	Closed-loop	304.26
82	630	1.99	Closed-loop	306.8
83	600	0.41	Air-cooled	330.38
84	600	2.83	Closed-loop	311.91
85	600	0.29	Open-loop	313.48
86	600	0.24	Open-loop	301.48
87	600	0.24	Air-cooled	331.15
88	600	2.46	Closed-loop	304.87
89	600	1.78	Closed-loop	302.49
90	600	1.57	Closed-loop	314.35
91	660	1.62	Closed-loop	297.16
92	600	1.85	Closed-loop	308.1
93	1000	1.65	Closed-loop	288.77
94	630	2.20	Closed-loop	301.75
95	600	1.75	Closed-loop	315.73
96	660	0.19	Air-cooled	323.41
97	630	0.41	Open-loop	302.36
98	600	0.49	Air-cooled	320.25
99	650	0.28	Open-loop	302.93
100	600	0.24	Open-loop	300.39
101	600	1.76	Closed-loop	306.17
102	600	0.20	Open-loop	313.97
103	600	2.01	Closed-loop	305.2
104	600	1.95	Closed-loop	320.04
105	1000	0.31	Air-cooled	306.9
106	600	1.57	Closed-loop	314.62
107	600	0.29	Open-loop	302.52
108	630	1.97	Closed-loop	303.66
109	600	2.90	Closed-loop	319.42
110	600	1.57	Closed-loop	314.97
111	1000	0.32	Open-loop	283.93
112	660	0.41	Open-loop	315.05
113	1000	0.81	Closed-loop	285.
114	600	1.75	Closed-loop	316.69
115	600	0.19	Open-loop	313.92

Table A1. *Cont.*

Plant No.	Capacity (MW)	Comprehensive water consumption rate (m^3/MWh)	Types of cooling system	Heat rates (gce/kWh)
116	600	1.76	Closed-loop	306.39
117	600	0.24	Open-loop	301.66
118	600	2.05	Closed-loop	318.
119	660	0.32	Open-loop	293.12
120	640	2.10	Closed-loop	302.07
121	600	2.03	Closed-loop	303.19
122	660	0.36	Air-cooled	314.82
123	600	1.76	Closed-loop	305.96
124	1000	0.19	Open-loop	289.61
125	600	1.83	Closed-loop	306.03
126	660	0.26	Open-loop	298.98
127	660	0.31	Open-loop	292.89
128	600	0.36	Open-loop	305.13
129	1000	0.23	Closed-loop	291.46
130	600	0.41	Air-cooled	332.7
131	600	2.46	Closed-loop	305.95
132	600	0.27	Air-cooled	331.91
133	630	0.35	Open-loop	303.38
134	600	0.24	Open-loop	304.19
135	600	1.75	Closed-loop	319.14
136	630	0.14	Open-loop	306.29
137	630	1.67	Closed-loop	305.48
138	600	0.23	Air-cooled	337.29
139	600	0.34	Open-loop	303.17
140	600	2.46	Closed-loop	305.71
141	680	0.19	Open-loop	303.58
142	600	0.24	Open-loop	311.64
143	660	0.18	Open-loop	298.47
144	600	0.41	Air-cooled	333.87
145	1000	0.16	Open-loop	286.6
146	680	0.11	Open-loop	294.31
147	600	2.00	Closed-loop	318.28
148	600	1.80	Closed-loop	307.34
149	600	0.29	Closed-loop	313.94
150	650	0.33	Closed-loop	306.63
151	600	0.24	Open-loop	304.92
152	600	2.16	Closed-loop	311.51
153	600	1.83	Closed-loop	305.74
154	600	0.29	Open-loop	303.69
155	1000	0.29	Closed-loop	290.67
157	650	0.30	Open-loop	305.25
158	660	1.03	Closed-loop	324.
159	660	0.28	Open-loop	292.09

Table A1. *Cont.*

Plant No.	Capacity (MW)	Comprehensive water consumption rate (m^3/MWh)	Types of cooling system	Heat rates (gce/kWh)
160	660	1.73	Closed-loop	302.49
161	1000	0.16	Open-loop	288.99
162	1000	1.65	Closed-loop	289.5
163	1000	0.28	Open-loop	289.07
164	600	1.60	Closed-loop	309.03
165	600	2.03	Closed-loop	310.84
166	660	2.05	Closed-loop	309.78
167	630	0.34	Open-loop	308.04
168	600	1.84	Closed-loop	307.46
169	600	0.29	Open-loop	303.06
170	600	1.76	Closed-loop	306.29
171	660	0.24	Open-loop	299.56
172	1000	0.28	Open-loop	285.09
173	600	2.49	Closed-loop	309.85
174	660	0.24	Open-loop	296.98
175	600	0.39	Air-cooled	338.06
176	660	0.02	Open-loop	294.52
177	600	0.41	Air-cooled	334.8
178	1000	0.28	Open-loop	289.2
179	1000	0.89	Closed-loop	285.05
180	660	2.05	Closed-loop	309.78
181	630	0.34	Open-loop	316.79
182	1000	0.31	Air-cooled	308.01
183	1000	0.28	Open-loop	289.02
184	600	0.36	Open-loop	309.38
185	660	0.31	Air-cooled	320.86
186	660	0.18	Open-loop	299.94
187	600	2.00	Closed-loop	306.58
188	630	0.43	Open-loop	312.91
189	1000	0.40	Open-loop	289.51
190	630	0.39	Open-loop	309.73
191	500	1.60	Closed-loop	327.8
192	600	0.23	Air-cooled	335.44
193	600	0.24	Open-loop	304.24
194	1000	0.19	Open-loop	291.34
195	660	0.02	Open-loop	295.42
196	600	0.31	Air-cooled	337.53
197	600	0.27	Open-loop	309.85
198	600	2.13	Closed-loop	321.41
199	660	0.18	Open-loop	301.81
200	1000	0.39	Open-loop	292.2
201	660	1.03	Closed-loop	324.7
202	600	1.75	Closed-loop	309.03

Table A1. *Cont.*

Plant No.	Capacity (MW)	Comprehensive water consumption rate (m^3/MWh)	Types of cooling system	Heat rates (gce/kWh)
204	660	1.65	Closed-loop	300.1
205	600	2.13	Closed-loop	321.41
206	600	1.84	Closed-loop	308.99
207	660	0.17	Open-loop	306.56
208	630	0.34	Open-loop	308.87
209	600	2.20	Closed-loop	318.28
210	1000	0.40	Open-loop	288.15
211	660	0.41	Open-loop	314.32
212	1000	0.21	Open-loop	284.56
213	600	1.75	Closed-loop	320.92
214	600	0.40	Air-cooled	330.38
215	660	0.28	Open-loop	292.8
216	660	0.31	Air-cooled	321.15
217	650	0.32	Open-loop	307.82
218	600	1.71	Closed-loop	320.74
219	600	0.33	Air-cooled	338.41
220	600	1.78	Closed-loop	307.04
221	660	1.74	Closed-loop	305.11
222	1000	0.32	Open-loop	293.25
223	600	0.39	Air-cooled	338.4
224	680	0.39	Open-loop	302.96
225	660	0.28	Open-loop	302.73
226	660	0.36	Air-cooled	328.9
227	660	0.35	Air-cooled	333.58
228	600	0.18	Open-loop	297.56
229	660	0.31	Air-cooled	325.03
230	600	2.07	Closed-loop	320.33
231	630	2.26	Closed-loop	308.05
232	600	2.07	Closed-loop	313.43
233	660	0.31	Air-cooled	328.35
234	630	0.63	Open-loop	306.7
235	660	0.34	Air-cooled	329.91
236	660	1.30	Closed-loop	291.34
237	660	1.71	Closed-loop	305.72
238	630	0.14	Open-loop	306.36
239	600	1.96	Closed-loop	320.28
240	600	0.31	Air-cooled	338.79
241	600	2.02	Closed-loop	308.06
242	630	0.41	Open-loop	303.68
243	600	1.81	Closed-loop	313.89
244	660	0.24	Open-loop	310.58
245	600	3.83	Closed-loop	327.47
246	600	0.27	Air-cooled	339.18

Table A1. *Cont.*

Plant No.	Capacity (MW)	Comprehensive water consumption rate (m^3/MWh)	Types of cooling system	Heat rates (gce/kWh)
247	600	0.25	Open-loop	322.2
248	600	0.28	Open-loop	306.39
249	600	0.22	Air-cooled	337.27
250	660	0.17	Open-loop	308.22
251	600	0.26	Open-loop	322.76
252	600	0.22	Air-cooled	338.28
253	630	0.39	Open-loop	319.89
254	630	0.63	Open-loop	307.89
255	600	0.28	Open-loop	313.82
256	600	0.19	Open-loop	306.97
257	660	1.55	Closed-loop	308.27
258	660	0.24	Open-loop	311.67
259	600	1.86	Closed-loop	315.92
260	660	0.31	Air-cooled	328.35
261	1000	0.31	Open-loop	284.56
262	1000	0.19	Open-loop	295.69
263	600	0.40	Open-loop	322.3
264	600	2.03	Closed-loop	310.84
265	600	0.40	Air-cooled	330.15
266	600	2.05	Closed-loop	317.36
267	600	0.44	Air-cooled	344.06
268	660	0.50	Open-loop	305.45
269	1000	0.39	Open-loop	294.82
270	660	0.30	Open-loop	291.2
271	660	0.31	Air-cooled	324.62
272	600	0.31	Air-cooled	326.92
273	600	0.27	Air-cooled	338.92
274	600	0.40	Open-loop	318.71
275	600	0.10	Open-loop	313.33
276	600	0.20	Open-loop	310.75
277	600	0.44	Air-cooled	344.06
278	600	2.10	Closed-loop	316.79
279	700	0.41	Open-loop	321.73
280	700	0.49	Open-loop	310.74
281	660	0.38	Air-cooled	328.51
282	600	2.08	Closed-loop	323.87
283	600	1.86	Closed-loop	316.44
284	660	0.55	Air-cooled	325.81
285	600	0.40	Open-loop	318.23
286	600	0.20	Open-loop	310.77
287	660	0.45	Open-loop	303.24
288	600	2.07	Closed-loop	318.
289	600	0.27	Air-cooled	338.82

Table A1. *Cont.*

Plant No.	Capacity (MW)	Comprehensive water consumption rate (m^3/MWh)	Types of cooling system	Heat rates (gce/kWh)
290	600	2.16	Closed-loop	311.67
291	600	0.40	Open-loop	324.25
292	600	3.83	Closed-loop	326.53
293	600	0.19	Open-loop	306.98
294	600	0.26	Open-loop	317.15
295	600	0.26	Open-loop	318.05
296	600	0.31	Air-cooled	339.33
297	600	0.38	Open-loop	313.76
298	600	0.24	Open-loop	303.91
299	1000	1.87	Closed-loop	291.08
300	1000	0.32	Open-loop	298.1
301	600	1.71	Closed-loop	322.59
302	600	0.25	Open-loop	322.2
303	600	1.61	Closed-loop	332.22
304	600	0.31	Air-cooled	326.75
305	630	0.39	Open-loop	309.04
306	600	0.25	Open-loop	322.2
307	600	0.28	Open-loop	308.48
308	630	0.42	Open-loop	317.64
309	600	0.23	Open-loop	309.43
310	600	1.79	Closed-loop	331.2
311	700	0.41	Open-loop	322.14
313	600	0.76	Closed-loop	303.75
314	600	0.26	Open-loop	320.52
315	660	1.71	Closed-loop	304.94
316	600	0.27	Air-cooled	339.58
317	600	0.76	Closed-loop	305.18
318	600	0.18	Air-cooled	346.8
319	600	1.78	Closed-loop	316.43
320	600	0.23	Open-loop	314.1
321	600	0.35	Air-cooled	349.18
323	800	0.51	Open-loop	355.23
324	600	0.28	Air-cooled	341.09
327	600	0.25	Open-loop	325.51
328	700	0.50	Open-loop	312.49
330	600	0.35	Air-cooled	351.6
331	600	0.28	Air-cooled	339.29
333	600	0.27	Air-cooled	333.16
334	600	0.18	Air-cooled	346.8

Conflicts of Interest

The authors declare no conflict of interest.

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