sustainability

MDPI

Review

Operational Water Withdrawal and Consumption Factors for Electricity Generation Technology in China—A Literature Review

Jinjing Gao [1], Peng Zhao [1,*], Hongwei Zhang [1,2], Guozhu Mao [1] and Yuan Wang [1]

[1] School of Environmental Science and Engineering, Tianjin University, Tianjin 300072, China; kitegao@126.com (J.G.); hwzhang@tju.edu.cn (H.Z.); maoguozhu@tju.edu.cn (G.M.); wyuan@tju.edu.cn (Y.W.)

[2] School of Environmental and Chemical Engineering, Tianjin Polytechnic University, Tianjin 300287, China

* Correspondence: zhpeng@tju.edu.cn

Received: 13 March 2018; Accepted: 12 April 2018; Published: 14 April 2018

check for updates

Abstract: As two indispensable resources for human development, energy and water are closely related. China, as the world's largest consumer of electricity, is also experiencing very serious water shortages. Understanding the water consumption intensity in various types of electric power production technologies according to China's national conditions is a prerequisite for understanding the potential impact of electrical power production on water resources. Therefore, following the steps of a meta-analysis, this paper provides a literature review on operational water withdrawal and consumption factors for electricity generation technology in China. We observed that 50% of water consumption for electricity generation was for coal power, whereas there was no research on the water consumption intensity of natural gas power generation, and a shortage of studies on water intake during electrical power production. The average water consumption intensity of hydropower is the largest. The results indicate that compared with other fuel types, hydropower is not a sustainable energy with respect to water conservation, and the study of hydropower applications should be improved in China.

Keywords: water–energy nexus; China; electricity generation; freshwater demands; meta-analysis

1. Introduction

The contradiction between the rapidly increasing demand for water/energy and the lack of both resources has gradually become one of the largest obstacles to development in most parts of the world [1–3]. At the same time, water and energy are inextricably and reciprocally linked. The electricity sector is highly dependent on water. By 2035, global water withdrawals for energy production will increase by more than 20% compared to 2010 [4].

China has become the world's largest consumer of electricity. With its rapid development, China's demand for electricity will be further expanded. To achieve sustainable development goals, such as a reduction in carbon dioxide emissions, Chinese government departments are adjusting the structure and technology of electric power production. In China's most important planning initiative—the 13th Five Year Plan—the government clearly noted the goal of establishing a low-carbon electric power industry system and the plan to adjust the working focus in the electric power structure [5].

China is experiencing highly serious water shortages and water contaminations [6,7], while climate change will worsen water availability. What is the impact on water resources of the speed and direction of the electricity demand? Are water resources able to support electricity development goals in the future? Such issues should be considered by the government. Therefore, comprehensive and accurate data on the water consumption intensity of all types of electric power production is the basis for answering the above questions.

With the increasing attention of the academic community on problems of the water and energy nexus all over the world [8–13], more systematic and comprehensive studies on the water consumption of electric power production in China have also emerged. Several studies have calculated the water consumption intensity of the whole process of electric power production using input–output tables, such as Wu [14], Feng [15] and Okadera [16], but these results mostly present the aggregated water footprint of industry sectors, with a lack of spatial and technology details. This shortage of Input-output (IO) analysis was also noted by other researchers, such as Zhang [17], Yuan [18] and Zhang [19], who identify the plant-level water consumption for coal-fired electricity generation, and Liu [20], who calculated the evaporative water consumption for each unit of hydropower generation in China based on data from 209 power plants. However, these results only focused on one kind of energy source or one category of electrical-power-producing technology. Water consumption for power plants with different energy resources needed to be compared to help the government in making decisions on energy resources and to help understand the water impact of their electricity decisions. Thus an overall picture of the water withdrawn and consumption factors for different kinds of energy resources and power generation technologies in China is strongly needed [21].

Therefore, we provide a review of publications that focus on operational water withdrawals and consumption factors for electricity generation technology using a meta-analysis. By classifying and summarizing the relevant literature and data, we present the water use data for China's power plants more clearly [8]. This analysis can more effectively reflect the existing problems of studies of water consumption intensity in electrical power production in China and provide a data foundation for further studies on the energy and water nexus in China.

2. Materials and Methods

2.1. The Scope of the Review

We estimated the two aspects of water usage: water consumption and water withdrawal. According to the US Geological Survey (USGS), 'withdrawal' is defined as the amount of water removed from the ground or diverted from a water source for use, while 'consumption' refers to the amount of water that is evaporated, transpired, incorporated into products or crops, or otherwise removed from the immediate water environment [22].

China's electricity generation primarily relies on coal power [23]. Meanwhile, the government is encouraging the development of hydropower, nuclear power, wind power, solar power, natural gas power and biomass power [5]. Therefore, this article focuses on the water use of power plants during electricity generation utilizing coal, natural gas, nuclear energy, water, wind, solar energy and biomass energy. The electricity generation methods that are not mainstream methods or are not strongly encouraged by the government, such as geothermal power generation and oil-fired power generation, will not be discussed in this article.

Only the water usage for power plant operation, rather than other aspects of the life cycle, such as the fuel cycle or plant construction, was taken into consideration. In this study, operational water use includes all of the press-related needs that occur during electricity generation. Thermal electricity technologies (for example, coal, natural gas, nuclear, concentrating solar power (CSP) and biopower technologies) generally require water as the working fluid as part of the Rankine cycle, the thermodynamic process that drives a steam engine. Fuel-based electricity technologies (for example, coal, natural gas, nuclear and biopower technologies) also require water as the cooling medium to condense steam. In addition, coal power plants also involve water use in desulfurization and flue gas dust removal. Nuclear power plants also involve water use for the nuclear island, and CSP also involves water use in mirror cleaning. For hydroelectricity generation, water is passed straight through with negligible losses at the turbine level. The majority of the water lost in hydropower plants with reservoirs is incurred by evaporation [24–26]. From the point of the working principle [27] and Macknic's work [8], for fuel-based electricity technologies, water withdrawals are different from water consumption, while for other electricity generation technologies, water consumption is equal to water withdrawals. Therefore, in this paper, we focus on water consumption and withdrawal factors for fuel-based electricity technologies and water consumption factors for non-fuel-based electricity technologies.

2.2. Meta-Analysis

In the study, we followed the steps of a systematic review—a meta-analysis [28]—and attempted to obtain useful and reliable intensity factors of operational water withdrawal and consumption for electricity generation technology. The guidelines stage of a meta-analysis includes (1) planning the review scope (literature review): construct a search strategy and set inclusion criteria for the relevant articles; (2) data extraction (coding and generation of the databases): tabulate summary data and code the heterogeneity factors; and (3) data analysis: check for heterogeneity, either by performing a meta-analysis if heterogeneity is not a major concern or by explaining the heterogeneity.

To identify eligible studies, the data sources included published academic literature and government agency reports. The literature involved the topics of operational water consumption or withdrawal factors for electricity generation technology in China. A full collection of the key words used in the search process is shown in Appendix A. The collected studies could be included when (1) the study area was located in China; (2) it revealed information on operational water usage factors for individual power plants or statistics for many power plants in China, while the water usage value derived from the input–output table was not included; (3) only the input of the operational phase rather than the life cycle was taken into consideration; and (4) the water resources refer only to freshwater, while sea water and recycled water were excluded.

The selected literature was characterized by the explanatory variables representing different determinants of variations in value. The sub-categories included the fuel type (for example, coal, nuclear, hydropower, biopower, solar power or wind power), production technique, cooling system, and literature type (such as national-level statistics, district-level statistics, individual plant surveys or derived from laboratory experiments), study method (for example, energy balance text, design parameters), study area (accurate to province) and year of publication. The first three sub-categories were used to classify the selected water use value, while the last three were used for the analysis of the selected studies. The reviewed references are shown in Appendix B.

Finally, the water use value collected was statistically classified and summarized, according to which the maximum value, the minimum value, and the intermediate value of the water consumption of the power plants will be determined. In the process of data aggregation, with regard to nationwide data, the authors took the average value or intermediate value of the range as the median of the result, whereas extreme values of the range are taken as extreme values of the results. In regard to the regional average values, a regional average value is regarded as the median if it lacks national level data, whereas if there is a national average value involved, it will be considered the water consumption of a particular power plant. Additionally, regional extreme values are taken as the representative water consumption of power plants and are aggregated together with the water consumption of other specific power plants provided in other documents. After the summarization process was completed, the data were further analyzed.

3. Results

3.1. Overview of Water Usage Factors for the Power Plants Studied

According to the literature collected, there are several problems:

(1) We observed that a limited number of valuation studies have been conducted at the national scale and the compiled statistics from many individual plants in the whole province or country, such as

the work done by Liu [20], who calculated the water footprints of hydroelectricity in China based on data from 209 power plants. Other studies mostly used the data from only one power plant.

(2) The papers focused on coal-fired power plants accounted for 30% of all the papers cited in this study, followed by nuclear power and hydropower both accounting for 12%. We did not find any paper focused on the water consumption intensity of gas-fired power plants. The reason may be that 75% of all of China's electricity is generated by coal-fired power plants [29], while only 4% is from gas-fired power plants [30].

(3) The concepts of "water usage" was not defined precisely in some literature, such as Li's work [31]. They just use the concept of "water usage" without explaining whether the "water usage" was "water consumption" or "water withdrawal". This problem was obvious in the literature written in Chinese.

(4) Furthermore, the statistical system is incomplete in China and lacks comprehensive, official, public statistical reports on the water use for electric power production. In the Statistical Yearbook of China's Power Industry, which is the authority for the statistical results for the power industry in China, there was no information about the water use of electric power plants (except for the 2012 yearbook) [23]. This lack indicates that the government did not mention the importance of the impact on water of electricity generation.

Figure 1 shows the number of papers on water usage factors for power plants. It can be seen that with the increasing attention on the water and energy nexus in international academic circles, such studies in China have also increased and reached a peak in 2014.

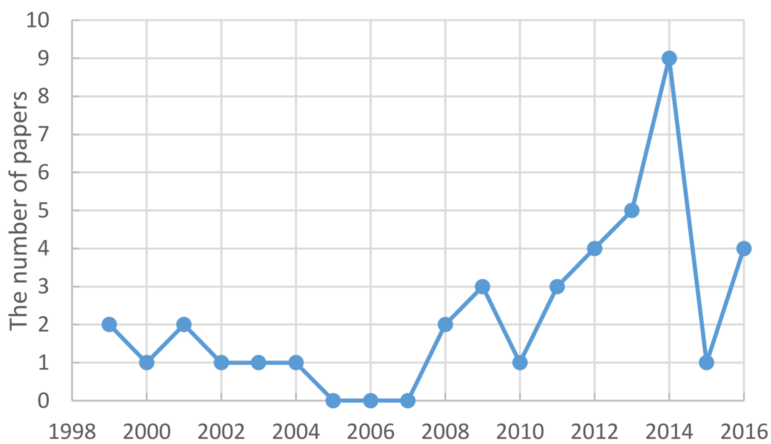

Figure 1. Number of papers describing the water usage factors for power plants in the Science Citation Index (SCI).

3.2. Operational Water Usage Values for Power Plants from Selected Literature

The water usage values were classified by fuel type, production techniques and cooling system. The water withdrawal factors for fuel-based power plants are presented in Table 1, and the water consumption factors for fuel-based and non-fuel-based power plants are presented in Tables 2 and 3, respectively (detailed information on the references is listed in Appendix B). The years of the selected data was shown in Table 4. Hereafter, the collected water use values will be described and analyzed in detail according to each fuel type.

Table 1. The water withdrawal factors for fuel-based power plants.

Fuel Type	Technology	Cooling Type	Median	Mean	Min	Max	N [1]	Sources
			(m^3/MWh)					
Coal	Generic	Closed-loop	3.16	3.8	2.49	7.07	16	[32–40]
	Subcritical	Closed-loop	2.09	2.09	2.09	2.09	1	[41]
Nuclear	Generic	Once-through (using seawater for cooling)	0.05	0.074	0.04	0.13	6	[42–44]

[1] Number of power plant samples.

Table 2. The water consumption factors for fuel-based power plants.

Fuel Type	Technology	Cooling Type	Median	Mean	Min	Max	N [1]	Sources
			(m^3/MWh)					
Coal	Generic	Closed-loop	1.9	1.6	1.89	2.23	6	[38,40,45,46]
		Once-through	0.64	0.64	0.64	0.64	1	[47]
		Dry		0.24	0.17	0.32	2	[46,48]
	Supercritical	Closed-loop	2.2	2.32	0.15	6.9	45	[49,50]
		Once-through	0.4	0.55	0.31	3	37	[50,51]
		Dry cooling	0.435	0.449	0.18	0.7	7	[50]
Nuclear	Generic	Closed-loop (using fresh water for cooling)		1.7	1.6	1.8	2	[52,53]
Biopower	Steam	Closed-loop cooling	4.47	4.39	2.4	5.53	15	[54,55]

[1] Number of power plant samples.

Table 3. The water consumption factors for non-fuel-based power plants.

Fuel Type	Sub-Category	Median	Mean	Min	Max	N [1]	Sources
		(m^3/MWh)					
Hydropower			13	0.0036	15,244	222	[20,56–59]
CSPr	Wet cooling	3.78	3.65	3.18	4	3	[60,61]
	Dry cooling	0.75	0.75	0.75	0.75	1	[62]
PV		0.019	0.19	0.019	0.019	1	[61]
Wind		0	0	0	0	1	[63]

[1] Number of power plant samples.

Table 4. The years of the selected data.

Fuel Type	Coal	Nuclear	Biopower	Hydropower	CSP	PV	Wind
Year	2002–2013	2010–2015	2014	1998–2014	2013–2014	2014	2012

The largest water consumption of all fuel resources results from the use of hydropower. However, hydroelectricity does not always have a large water intensity. For the Three Gorges Hydroelectric Project, the water consumption per unit of electricity generated was only 4.25 m^3 MW^{-1} h^{-1}, which is 20 times less than hydroelectric projects on the Fenhe River (81.8 m^3 MW^{-1} h^{-1}), but is of the same order of magnitude for other fuel resource categories. The smallest water consumption values result from wind energy and photovoltaic (PV), which are close to zero. Nuclear power plants generally have lower water consumption and water withdrawals than coal-fired power plants with general technology and have greater water consumption than coal-fired power plants with supercritical technology. Coastal nuclear fresh-water withdrawals are only 1/60 of the intensity of water withdrawals of coal power that uses general technology, whereas the water consumption of inland nuclear power is 1/2 the intensity of that of general coal power and slightly larger than the supercritical water consumption of coal power generation (when using closed-loop cooling technology). Biomass power plants consume twice as much water as coal-fired power plants. From this result, we can see that changing the electricity generation technology from coal to other fuels is not always water-friendly.

3.3. The Quality of the Selected Data

For coal power, 352 coal-fired power plants were included in our references, which accounted for 30% of all the thermal power plants in China. Thermal power plants can be found in 30 provinces in China (1191) [23] and the thermal power plant locations in our references were distributed in 26 provinces.

According to the statistical numbers of nuclear power enterprises from the World Nuclear Association, there were 11 nuclear power plants with 30 nuclear power sets in China in 2015; four plants with 10 nuclear power sets were included in the references (Cao [43] and Guo [44]) and were used in this paper. There were also six types of nuclear power sets actively used in China in 2015, which were CNP300, M310, CNP600, Candu HWR, VVER1000, and CPR1000, while four of them (M310, Candu PHWR, VVER1000, CPR1000) were included in the references (Cao [43] and Guo [44]) and were used in this paper.

For biomass-fired power plants, although there were two studies—Zhao [54] and Peng [55]—on the water consumption of electricity generation from biomass combustion, it can be seen in Table A2 that the water consumption data were not very divergent from those in existing studies.

For hydropower, 219 hydropower plants were included in our references, which accounted for 20% of the total number of hydropower plants (1152) [23].

For concentrating solar power, there were also two types of mature concentrating solar power technologies, namely parabolic trough and power tower. The water consumption for the power tower was included in our references.

Both of the studies on water for wind power plants found that there was nearly no water consumption for electricity generation by wind power. They drew this conclusion not only from the power plant but also from the theory of wind power generation [9,63].

4. Discussion

4.1. Status and Knowledge Gaps of Water for Electricity Studies

For coal power, there was only one study that evaluated the water use for electricity production at the national scale, which was in Yuan's work [18]. Besides this, Zuo's study [33] provided the regional power plant statistics for Beijing; the other data all comes from a summary of independent power plant data. The collected literature lacks reports on the water withdrawal of the air-cooling sets. However, its water consumption should be approximately the same as its water intake, considering its operating principle [64]. In the literature, there is also a shortage of reports regarding water withdrawals in once-through cooling technology, which is probably observed because cooling water is discharged into the water pool during the once-through cooling process, where the consumption is negligible. Moreover, China has not explicitly stipulated water withdrawal standards for once-through cooling technology in the Norm on Water Intake, Part1—Electricity Power Production [65] and the technical code for designing fossil fuel power plants [21]. The amount of water intake in direct cooling technologies is a noteworthy issue. During the once-through cooling process, there is almost no consumption of cooling water, but it still occupies local water resources for the purpose of ensuring the safe operation of power plants, which is related to the allocation of local fresh water resources. Therefore, further attention is needed on this type of research.

China's current nuclear power plants are all located in coastal areas. They have adopted once-through cooling technology and use seawater as the cooling water [66]. Therefore, in the literature we can find the fresh water withdrawal intensity data for seawater as the cooling water and the conjectural data of the water consumption intensity of closed-loop water cooling technology, in spite of the lack of literature providing national statistical data.

There are only two independent project studies on the water consumption of China's biomass electricity generation, and the relevant studies on water consumption of garbage power generation and biogas power generation were not found. The search results for the water consumption of biofuel were mainly focused on water consumption for bio-ethanol and biodiesel, such as Gerbens' work [67], Ding's work [68], Hao's work [69] and Yao's work [70]. The biomass energy utilization has grown fast in the past 25 years and there is a huge development potential in biomass energy [71–75]. Thus, the water use of biomass power should receive more attention.

4.2. Factors That Influence the Water Consumption Factors of Electricity Generation

For fuel-based electricity technologies, the cooling system employed is often a greater determinant of the water consumption than the technology and fuel type. For coal-fired power plants, the difference in values between water consumption factors for general technology and supercritical technology with the same cooling type is smaller than that between the closed-loop cooling type and other cooling types with the same technology. For closed-loop technologies, biopower plants have the largest water consumption factors, which are three times greater than the lowest water consumption factors of coal-fired power plants with supercritical technology. However, for the same fuel type, the water consumption factors of the closed loop were four times (for coal-fired power with supercritical technology), five times (for concentrating solar power) and six times (for coal-fired power with generic technology) that of dry cooling.

Liu [20] calculated hydroelectric water footprints, that is, the evaporative water consumption for each unit of hydropower generation in China based on data from 875 representative reservoirs (209 with power plants). In addition, we collected the evaporation data in the Three Gorges area [56], the large and medium-sized reservoirs of the Yellow River area [54], and the Fenhe reservoir [58] and the electricity generation data from the corresponding power plants. The results are all within the range of Liu's results [20]. At the same time, the water consumption of the hydropower projects in the Three Gorges area is 10 times lower than those in the Yellow River area and Fenhe area, as shown in Table 5. The reason for the huge difference in water consumption between different hydropower projects may be because of the vast differences in the evaporation conditions in China. In the context of China's vigorous promotion of hydropower projects, the impact of the hydropower projects on the local water resources through the evaporation of reservoir water should receive considerable attention.

Table 5. The comparison of the results from Sun [56] (2012), Tian [57] (2005) and Yang [58] (2005).

Water Consumption of Hydropower Plants	Hydropower Plant Area
4.25 [56]	Three Gorges Hydroelectric Project
51.9 [57]	Yellow River
81.8 [58]	Fenhe

A summary of the geographic distribution of the selected water consumption intensities for electricity generation are presented in Figure 2 (except hydropower). The size of the signs reflects the relative value of the water consumption intensity. There are no considerable differences among the different provinces, which means that the water consumption intensity is mainly related not to province factors but rather to technology factors (except hydropower). This could be due to the characteristics of China's electric power production enterprises. In China, 17 state-owned large-scale electric power companies take charge of all the responsibilities of electricity generation [23]. Each company's power plants are not concentrated in a single region but are spread widely in multiple regions. At the same time, power plants from the same company have small differences in their electricity generation technologies. Therefore, the differences in the water usage intensity resulting from regional differences is not remarkable.

Figure 2. Geographical distribution of the selected data.

4.3. The Effect of the Energy Development Trend on Water Resources in China

A transition to a less carbon-intensive electricity sector in China [73] would influence water resources in China. As shown in Table 6, nuclear and hydropower are more advantageous than other fuel types. However, according to our results, small-capacity hydropower plants with thermal electricity technologies could result in more water consumption per unit of electricity generated. Nuclear power plants built inland and utilizing freshwater as a cooling medium have no advantage over coal with wet cooling systems. Therefore, when making decisions about the power industry's impact on climate change, we need consider water resource restrictions.

Table 6. The analysis of the renewable energy development trend in China.

Fuel Type	The Technical Maturity in China	The Irrigation Needs	The Perspectives of Economies of Scale Achievement	Source
Nuclear	++	+++	+++	[76]
Biomass	–	—	-	[69,71,72,74,77]
Hydropower	+++	-	++	[71]
Solar	++	+++	–	[71,74]
Wind	—	+++	+	[71]

"+++" represents the positive impact on the energy development and "—" represents the negative impact on the energy development.

According to the results in this paper, hydropower has greater water use intensity than other forms of generation most of the time. Besides, climate change is influenced by hydropower [78,79] and may lead to an increase in evaporation from reservoirs [31], which increases the water consumption of hydroelectricity. Thus, hydropower development has a negative impact on water security. Fortunately, it is possible to reduce the gap between the water consumption of hydropower plants and of other plants. For instance, the Three Gorges Hydroelectric Project had 12–20 times less water consumption than other hydroelectric projects (see Table 5) and was of the same order of magnitude as other fuel-resource categories (see Tables 2 and 3). One reason for this was that most other hydroelectric data were from the Yellow River. The Yellow River Basin is in arid and semi-arid areas, where the evaporation capacity is very large [54]. The other reason was that compared with other hydroelectric plants, the Three Gorges Hydroelectric Project has more generating capacity with similar surface evaporation [54,56]. Therefore, to solve the problem, hydropower development requires coordinated implementation among geographic regions to improve efficiency, as well as a trade-off analysis between reducing greenhouse gas emissions and water use sustainability [80,81].

5. Conclusions

Following the steps of a meta-analysis, in this study we reviewed the literature that reports on the operational water withdrawal and consumption factors for electricity generation technology in Chinese power plants. Through a relevant literature review, we observed that studies on the water use intensity of electrical power production in Chinese power plants are still very incomplete. There are several main problems. There is a lack of national-level investigation into the water consumption of power plants in China to represent the conditions of the whole country. There is a lack of reports aimed at examining the water use intensity of some electricity production technologies, such as power generation from natural gas. Studies on the water intake intensity of electrical power production are inadequate, as well. Hence, several conclusions can be drawn from the results of the existing reports. For fuel-based power plants, the difference in water consumption intensity resulting from the difference in cooling methods is greater than that resulting from different energy sources. For the water consumption intensity of hydropower, which results from reservoir evaporation, its average value is the largest. Therefore, it can be seen that in the process of China's transition to low-carbon electricity generation, the government should pay special attention to whether it will increase the regional water crises with the use of hydropower. The water consumption intensity of wind power and solar power generation is close to zero. Thus, these two technologies are water-friendly power generation sources. In addition, the water intake intensity of coastal nuclear power plants and the water consumption intensity of inland nuclear power are both less than that of coal power. The water consumption intensity of biomass power generation was generally no more than that for coal-fired plants. It can be conjectured that the water consumption in power plants is not an obstacle to biomass application. In the meantime, since coal power's position in China's electric power production structure will not change in a short period of time, the change of its cooling modes will certainly and significantly reduce the pressure on water resources in the process of coal power generation.

Acknowledgments: This research was supported by the National Natural Science Foundation of China (No. 41571522).

Author Contributions: Jinjing Gao made substantial contributions to the acquisition of data, calculation and results interpretation. Peng Zhao made substantial contributions to the logical structure of the manuscript. Hongwei Zhang, Guozhu Mao and Yuan Wang provided useful advice for the structure and grammar revision the paper.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. The keywords introduced in the systematic review regarding the three main fields: study location, economic valuation technique and ecosystem services.

Field	Main Words
Study location	"Chinese" or "China"
Water consumption for power plants	"water use *" or "water balance" or "water consumption" or "water saving" or "water demand" or "consumption of water" or "water resource *" "fossil-fired power plant *" or "thermal power plant *" or "power plant *" "hydropower" or "evaporation and reservoirs" "nuclear plant" or "nuclear power" "biomass power" or "biomass" or "wind power" or "renewable power" or "non-fossil power"
Water and energy nexus	"water -energy nexus" or "water electricity nexus"

Wildcard (*) is used here to find plurals and word variants

Appendix B

Table A2. The publications included in the analysis conducted and their detailed information—water use intensity of electricity generation.

Fuel Type	References	Study Method	Production Techniques	Cooling Type	Study Area	Water Withdraw Value/Water Consumption Value (m^3/MWh)
Coal	[41]	Water balance treatment	Steam turbine	Closed loop	Shanxi	2.09/N
	[46]	Water balance treatment and design parameters of main structure	Steam turbine	Closed loop, once through and dry	Shandong and northern China	0.41–2.41/N
	[32]	Water balance treatment	Steam turbine	Once through	Shanxi	2.3, 4.68–6.01/N
	[33]	Plant official data statistics	Steam turbine	Once through	Beijing	3.16/N
	[36]	Design parameters of main structure		Closed loop	Neimenggu	2.9/N
	[47]	Water balance treatment	Steam turbine	Once through	Fujian	N/0.64
	[48]	Water balance treatment	Steam turbine	Dry	Neimenggu	N/0.32
	[37]	Water balance treatment	Steam turbine	Closed loop	Shandong	2.69/N
	[38]	Water balance treatment	Steam turbine	Closed loop	Henan	2.49/2.11
	[51]	Water balance treatment	Supercritical steam turbine	Once through	Zhejiang	N/0.33
	[39]	Water balance treatment	Steam turbine	Closed loop	Liaoning	2.86/2.08
	[45]	Water balance treatment	Steam turbine	Closed loop	Neimenggu	N/1.89
	[49]	Water balance treatment	Supercritical steam turbine	Closed loop	Hubei	N/1.34
	[40]	Water balance treatment	Steam turbine	Closed loop	Shandong	2.7/2.17
	[50]		Supercritical steam turbine	Closed loop/Open loop/Air cooling	Whole country	N/0.06–6.9
Hydropower	[56]	Tested evaporation capacity multiplied by conversion factor	Hydro generator		Chongqing	N/4.8, 4.64, 3.69
	[57]	Tested evaporation capacity multiplied by conversion factor	Hydro generator		Huanghe	N/32.32, 14.06,5.74, 65.89, 67.15, 90.66
	[58]	Tested evaporation capacity multiplied by conversion factor	Hydro generator		Shanxi	N/81.82
	[20]	Water foodprint divided by annual power production	Hydro generator		All of China	N/0.0036–1524
	[59]	Water foodprint divided by annual power production	Hydro generator		Beijing	N/0.45
Nuclear	[42]	Water balance treatment	Steam turbine	Once through with sea water	Guangdong Zhejiang Jiangsu	0.13/0.1

Table A2. *Cont.*

	[43]	Water balance treatment	Steam turbine	Once through with sea water		0.04,0.13,0.05/N
	[44]	Water balance treatment	Steam turbine	Closed loop with fresh water		0.054/N
	[52]	Water balance treatment	Steam turbine	Closed loop with fresh water		N/1.8
	[53]	Water balance treatment	Steam turbine	Once through with fresh water		N/1.6
Biopower	[54]	Water balance treatment	Straw combustion	Closed loop	Heilongjiang	N/2.4
	[55]	Water balance treatment	Straw combustion	Closed loop	Anhui	N/3.43–5.53
Solar power	[62]	Design parameters of main structure	Concentrating solar power	Dry	Neimenggu	N/0.75
	[60]	Design parameters of main structure	Concentrating solar power	Closed loop	Northwest China	N/4
	[61]		CSP PV	Closed loop		N/3.18–3.78 N/0.019
Wind	[63]	LCA				0

References

1. King, C.W.; Holman, A.S.; Webber, M.E. Thirst for energy. *Nat. Geosci.* **2008**, *1*, 283–286. [CrossRef]
2. Sovacool, B.K.; Sovacool, K.E. Identifying future electricity-water trade-offs in the United States. *Energy Policy* **2009**, *37*, 2763–2773. [CrossRef]
3. Schaeffer, R.; Szklo, A.S.; de Lucena, A.F.P.; Borba, B.S.M.C.; Nogueira, L.P.P.; Fleming, F.P.; Troccoli, A.; Harrison, M.; Boulahya, M.S. Energy sector vulnerability to climate change: A review. *Energy* **2012**, *38*, 1–12. [CrossRef]
4. Power Reactor Information System-Reactor Details: Hongyanhe 1. Available online: https://www.iaea.org/pris/CountryStatistics/ReactorDetails.aspx?current=904 (accessed on 11 March 2016).
5. 13th Five-Year Plan of Power Industry Development. (In Chinese). Available online: http://www.ndrc.gov.cn/fzgggz/fzgh/ghwb/gjjgh/201706/t20170605_849994.html (accessed on 20 July 2017).
6. Zhang, S.; Mao, G.Z.; Crittenden, J.; Liu, X.; Du, H.B. Groundwater remediation from the past to the future: A bibliometric analysis. *Water Res.* **2017**, *119*, 114. [CrossRef] [PubMed]
7. Zhang, S.; Hou, Z.; Du, X.M.; Li, D.M.; Lu, X.X. Assessment of biostimulation and bioaugmentation for removing chlorinated volatile organic compounds from groundwater at a former manufacture plant. *Biodegradation.* **2016**, *27*, 223–236. [CrossRef] [PubMed]
8. Macknick, J.; Newmark, R.; Heath, G.; Hallett, K.C. Operational water consumption and withdrawal factors for electricity generating technologies: A review of existing literature. *Environ. Res. Lett.* **2012**, *7*, 045802. [CrossRef]
9. Meldrum, J.; Nettles-Anderson, S.; Heath, G.; Macknick, J. Life cycle water use for electricity generation: A review and harmonization of literature estimates. *Environ. Res. Lett.* **2013**, *8*, 015031. [CrossRef]
10. Macknick, J.; Sattler, S.; Averyt, K.; Clemmer, S.; Rogers, J. The water implications of generating electricity: Water use across the United States based on different electricity pathways through 2050. *Environ. Res. Lett.* **2012**, *7*, 045803. [CrossRef]
11. Wang, S.; Wang, S. Implications of improving energy efficiency for water resources. *Energy* **2017**, *140*, 922–928. [CrossRef]
12. Shaikh, M.A.; Kucukvar, M.; Onat, N.C.; Kirkil, G. A framework for water and carbon footprint analysis of national electricity production scenarios. *Energy* **2017**, *139*, 406–421. [CrossRef]
13. Averyt, K.; Macknick, J.; Rogers, J.; Madden, N.; Fisher, J.; Meldrum, J.; Newmark, R. Water use for electricity in the United States: An analysis of reported and calculated water use information for 2008. *Environ. Res. Lett.* **2013**, *8*, 015001. [CrossRef]
14. Wu, X.D.; Chen, G.Q. Energy and water nexus in power generation: The surprisingly high amount of industrial water use induced by solar power infrastructure in China. *Appl. Energy* **2017**, *195*, 125–136. [CrossRef]
15. Feng, K.; Hubacek, K.; Siu, Y.L.; Li, X. The energy and water nexus in Chinese electricity production: A hybrid life cycle analysis. *Renew. Sustain. Energy Rev.* **2014**, *39*, 342–355. [CrossRef]
16. Okadera, T.; Geng, Y.; Fujita, T.; Dong, H.; Liu, Z.; Yoshida, N.; Kanazawa, T. Evaluating the water footprint of the energy supply of Liaoning Province, China: A regional input-output analysis approach. *Energy Policy* **2015**, *78*, 148–157. [CrossRef]
17. Zhang, C.; Anadon, L.D.; Mo, H.P.; Zhao, Z.N.; Liu, Z. Revealing water stress by the thermal power industry in China based on a high spatial resolution water withdrawal and consumption inventory. *Environ. Sci. Technol.* **2016**, *50*, 1642–1652. [CrossRef] [PubMed]
18. Yuan, J.; Lei, Q.; Xing, M.; Guo, J.S.; Zhao, C.H. Scenario-based analysis on water resources implication of coal power in Western China. *Sustainability* **2014**, *6*, 7155–7180. [CrossRef]
19. Zhang, X.; Liu, J.; Tang, Y.; Zhao, X.; Yang, H.; Gerbens-Leenes, P.W.; van Vliet, M.T.H.; Yan, J. China's coal-fired power plants impose pressure on water resources. *J. Clean. Prod.* **2017**, *161*, 1171–1179. [CrossRef]
20. Liu, J.G.; Zhao, D.D.; Gerbens-Leenes, P.W.; Guan, D. China's rising hydropower demand challenges water sector. *Sci. Rep.* **2015**, *5*, 11446. [CrossRef] [PubMed]
21. Li, M.; Dai, H.; Xie, Y.; Tao, Y.; Bregnbaek, L.; Sandholt, K. Water conservation from power generation in China: A provincial level scenario towards 2030. *Appl. Energy* **2017**, *208*, 580–591. [CrossRef]

22. Kenny, J.F.; Barber, N.L.; Hutson, S.S.; Linsey, K.S.; Lovelace, J.K.; Maupin, M.A. *Estimated Use of Water in the United States in 2005(US Geological Survey Circularvol*; Geological Survey: Reston, VA, USA, 2009; Volume 1344, pp. 25–40.
23. National Bureau of Statistics of China. *Statistical Yearbook of China's Power Industry*; China Statistics Press: Beijing, China, 2013. (In Chinese)
24. Gleick, P. Water and energy. *Annu. Rev. Energy Environ.* **1994**, *19*, 267–299. [CrossRef]
25. Wang, B. *Comprehensive Assessment of the Three Gorges Project's Impact on the Eco-environment in Reservoir Area*; Beijing Forestry University: Beijing, China, 2009. (In Chinese)
26. Cao, Y.Q.; Ni, G.H.; Hu, H.P. Analyze impacts on the eco-environment of the hydraulic and hydropower projects. *Yellow River* **2005**, *1*, 56–58. (In Chinese)
27. Ministry of Housing and Urban-Rural Development of the People's Republic of China (MOHURD). *Code for Design of Fossil fired Power Plant*; M. E. Sharpe: Beijing, China, 2011; pp. 160–169.
28. Pullin, A.S.; Stewart, G.B. Guidelines for systematic review in conservation and environmental management. *Conserv. Biol.* **2006**, *20*, 1647–1656. [CrossRef] [PubMed]
29. Jia, X.; Li, Z.; Wang, F.; Foo, D.C.Y.; Tan, R.R. Multi-dimensional pinch analysis for sustainable power generation sector planning in China. *J. Clean. Prod.* **2016**, *112*, 2756–2771. [CrossRef]
30. The Data List of 2015 Chinese Electricity Statistics. Available online: http://www.cec.org.cn/guihuayutongji/tongjxinxi/niandushuju/2016-09-22/158761.html (accessed on 30 April 2016).
31. Lv, M.-Q.; Chen, J.-L.; Mirza, Z.A.; Chen, C.-D.; Wen, Z.-F.; Jiang, Y.; Ma, M.-H.; Wu, S.-J. Spatial distribution and temporal variation of reference evapotranspiration in the Three Gorges Reservoir area during 1960–2013. *Int. J. Climatol.* **2016**, *36*, 4497–4511. [CrossRef]
32. Li, B.; Pi, J.G.; Zhang, S.X. Investigation and analysis of water resources and water consumption conditions in large-scale thermal power plant of Shanxi province. *Shanxi Electr. Power* **2002**, *108*, 8–10. (In Chinese)
33. Zuo, J.B.; Liu, C.M.; Zheng, H.X. Analysis on water consumption and water saving countermeasures of thermal power industry in Beijing. *Water Wastewater Eng.* **2008**, *34*, 56–60. (In Chinese)
34. Su, W.J. Water economizing problem in Zhongning electric power plant Ningxia. *Electr. Power* **2001**, *4*, 21–24. (In Chinese)
35. Wang, F. Analysis on water consumption level of the power plants in China and water-saving measures. *Hebei Electr. Power* **2001**, *20*, 6–9. (In Chinese)
36. Qian, W.X.; Xu, R.W. The measures and proposal for sustainable development water supply of power industry in eastern inner Mongolia Inner. *Mong. Environ. Prot.* **2004**, *16*, 9–14. (In Chinese)
37. Zhang, L. Coal-fired thermal power plant technical analysis and transformation for water-saving, emission reduction, efficiency improvement. *China Plant Eng.* **2013**, *6*, 5–7. (In Chinese)
38. Cai, J.M.; Fan, X. Water balance test example and analysis in thermal power plant. *Electr. Power Technol. Environ. Prot.* **2013**, *29*, 28–30. (In Chinese)
39. Du, J.; Du, F. Discussion on water saving method of fossil-fired power plants in consideration of water balance testing. *Northeast Electr. Power Technol.* **2011**, *4*, 15–17. (In Chinese)
40. Zhang, Y.; Wang, C.L.; Zhang, W.; Xin, H.C. Water balance test and water saving measur of 300 MW unit Shandong. *Electr. Technol.* **2008**, *163*, 77–80. (In Chinese)
41. Xu, H.; Yu, T.Q.; Tian, J.; Zhang, G.B. Research and analysis test of water balance in Hejin power plant. *Shanxi Electr. Power* **2003**, *112*, 12–14. (In Chinese)
42. Qiu, J.; Huang, B.S.; Ma, R.; Ji, H.X. Experience and rationality analysis of water use by nuclear plant. *China Water Resour.* **2011**, *17*, 35–39. (In Chinese)
43. Cao, X.Q.; Huang, B.S.; Qiu, J. Water use rationality analysis and guideposts discussion of nuclear power station near the sea. *Guangdong Water Resour. Hydropower* **2012**, *6*, 12–14. (In Chinese)
44. Guo, L.; Huang, B.S.; Qiu, J.; Qiu, S.X. Research on the characteristics of fresh water consumption in nuclear power plant. *J. Hydraul. Eng.* **2013**, *44*, 615–621. (In Chinese)
45. Wang, W.J.; Liu, T.X.; Liu, X.M. Water balance testing and its saving analysis in a themal power plant water. *Conserv. Sci. Technol. Econ.* **2009**, *15*, 225–230. (In Chinese)
46. Han, M. Analysis and countermeasures on water consumption in thermal power plants. *Ind. Water Treat.* **2010**, *30*, 3–6. (In Chinese)
47. Zeng, Z.W. Analysis on water consumption and water saving countermeasures of thermal power industry in Fujian. *Fujian Power Electr. Eng.* **2000**, *20*, 39–40. (In Chinese)

48. Song, J.H.; Yang, X.R. Reduce power plant water consumption by plant water conservation. *Inner Mong. Sci. Technol. Econ.* **2014**, *24*, 45–46. (In Chinese)
49. Peng, T.B. Water balance test and energy saving and emission reduction in dabieshan thermal power plant. *Cent. China Electr. Power* **2009**, *22*, 46–49. (In Chinese)
50. China Electricity Council (CEC). Notification of energy efficiency benchmarking and competition data of 2012 national 600 MW thermal power sets. Available online: http://kjfw.cec.org.cn/kejifuwu/2013-04-07/99877.html (accessed on 1 March 2017).
51. Yao, L.; Feng, L.K.; Yu, Z.Y.; Cao, Q.X. Water balance test and water saving analysis of a thermal power plant. *Ind. Water Wastewater* **2011**, *42*, 54–57. (In Chinese)
52. Chen, Q.W.; Qi, Q.B.; Jiang, Q.; Zhan, D. Nuclear power development and water resources management. *J. Hohai Univ.* **2010**, *38*, 25–28. (In Chinese)
53. Guo, Y.; Cao, Y.Q.; Xian, T.; Zhang, C.R. Brief analysis on water consumption index of inland nuclear power station. *Water Resour. Hydropower Eng.* **2012**, *43*, 119–122. (In Chinese)
54. Zhao, H.X.; Zhong, J.; Liu, Z.G. Water resources argumentation of a biomass power generation project in Heilongjiang Province. *J. Eng. Heilongjiang Univ.* **2014**, *5*, 14–17. (In Chinese)
55. Peng, B. Analysis the water-used of biomass power generation project. *Zhihuai* **2014**, *3*, 42–43. (In Chinese)
56. Sun, Z.Y. Estimation of the three gorges reservoir water loss. *China Three Gorges* **2012**, *20*, 68–69. (In Chinese)
57. Tian, J.H.; Cui, Q.; Xu, J.H.; Zhou, X. Surface-evaporation of large and middle reservoirs affects the cunount of water resource in the Yellow River valley. *J. Shandong Agric. Univ.* **2005**, *36*, 391–394. (In Chinese)
58. Yang, H.X. Calculation of Evaporation and Seepage Loss in Fenhe Reservoir. *Shanxi Hydrotech.* **2005**, *158*, 34–36. (In Chinese)
59. Zhao, D.D.; Liu, J.G.; Zhao, X. A new approach to assess the water footprint of hydropower: A case study of the Miyun reservoir in China. *Acta Ecol. Sin.* **2014**, *34*, 2787–2795. [CrossRef]
60. Wu, Z.Y.; Hou, A.; Chang, C.; Huang, X.; Shi, D.; Wang, Z.F. Environmental impacts of large-scale CSP plants in North-western China. *Environ. Sci. Process. Impacts* **2014**, *16*, 2432–2441. [CrossRef] [PubMed]
61. Liao, S.; Wang, X.Y.; Zhu, L.; Yang, W.H. Research of water consumption in concentrated solar power system. *Ningxia Electr. Power* **2013**, *1*, 35–40. (In Chinese)
62. Qiu, Z.S.; Lei, X.Y.; Zhang, B.J. The water supplement and wastewater treatment system design of one parabolic trough concentrated solar power plant. *Water Wastewater Eng.* **2014**, *40*, 264–266. (In Chinese)
63. Li, X.; Kuishuang, F.; Yim, L.S.; Klaus, H. Energy-water nexus of wind power in China: The balancing act between CO_2 emissions and water consumption. *Energy Policy* **2012**, *45*, 440–448. [CrossRef]
64. Mielke, E.; Anadon, L.D.; Narayanamurti, V. *Water Consumption of Energy Resource Extraction, Processing, and Conversion*; A Review of the Literature for Estimates of Water Intensity of Energy-resource Extraction, Processing to fuels and Conversion to Electricity; Energy Technology Innovation Policy Discussion Paper No. 2010-15; Belfer Center for Science and International Affairs, Harvard Kennedy School, Harvard University: Cambridge, MA, USA, 2010; pp. 29–38.
65. National Standard of the People's Republic of China. *Norm of Water Intake Part 1: Electric Power Production*; M. E. Sharpe: Beijing, China, 2002; pp. 1–2.
66. World Nuclear Performance Report 2016. Available online: http://www.world-nuclear.org/our-association/publications/online-reports/world-nuclear-performance-report-2016.aspx (accessed on 7 September 2017).
67. Gerbens-Leenes, P.W.; Lienden, A.R.V.; Hoekstra, A.Y.; van der Meer, T.H. Biofuel scenarios in a water perspective: The global blue and green water footprint of road transport in 2030. *Glob. Environ. Chang.* **2012**, *22*, 764–775. [CrossRef]
68. Ding, N.; Yang, Y.; Cai, H.; Liu, J.; Ren, L.; Yang, J.; Xie, G.H. Life cycle assessment of fuel ethanol produced from soluble sugar in sweet sorghum stalks in North China. *J. Clean. Prod.* **2017**, *161*, 335–344. [CrossRef]
69. Hao, M.; Jiang, D.; Wang, J.; Fu, J.; Huang, Y. Could biofuel development stress China's water resources? *GCB Bioenergy* **2017**, *9*, 1447–1460. [CrossRef]
70. Yao, Y.; Chang, Y.; Huang, R.; Zhang, L.; Masanet, E. Environmental implications of the methanol economy in China: Well-to-wheel comparison of energy and environmental emissions for different methanol fuel production pathways. *J. Clean. Prod.* **2018**, *172*, 1381–1390. [CrossRef]
71. Hu, Y.; Cheng, H. Development and bottlenecks of renewable electricity generation in China: A critical review. *Environ. Sci. Technol.* **2013**, *47*, 3044–3056. [CrossRef] [PubMed]

72. Guo, M.; Song, W.; Buhain, J. Bioenergy and biofuels: History, status, and perspective. *Renew. Sustain. Energy Rev.* **2015**, *42*, 712–725. [CrossRef]
73. Zhang, D.; Wang, J.; Lin, Y.; Si, Y.; Huang, C.; Yang, J.; Huang, B.; Li, W. Present situation and future prospect of renewable energy in China. *Renew. Sustain. Energy Rev.* **2017**, *76*, 865–871. [CrossRef]
74. Qin, Z.; Zhuang, Q.; Cai, X.; He, Y.; Huang, Y.; Jiang, D.; Lin, E.; Liu, Y.; Tang, Y.; Wang, M.Q. Biomass and biofuels in China: Toward bioenergy resource potentials and their impacts on the environment. *Renew. Sustain. Energy Rev.* **2018**, *82*, 2387–2400. [CrossRef]
75. Ye, B.; Yang, P.; Jiang, J.; Miao, L.; Shen, B.; Li, J. Feasibility and economic analysis of a renewable energy powered special town in China. *Resour. Conserv. Recycl.* **2017**, *121*, 40–50. [CrossRef]
76. Yun, Z. Why is China going nuclear? *Energy Policy* **2010**, *38*, 3755–3762. [CrossRef]
77. Shen, L.; Liu, L.; Yao, Z.; Liu, G.; Lucas, M. Development potentials and policy options of biomass in China. *Environ. Manag.* **2010**, *46*, 539–554. [CrossRef] [PubMed]
78. Liu, X.; Tang, Q.; Voisin, N.; Cui, H. Projected impacts of climate change on hydropower potential in China. *Hydrol. Earth Syst. Sci.* **2016**, *20*, 3343–3359. [CrossRef]
79. Zhang, X.; Li, H.-Y.; Deng, Z.D.; Ringler, C.; Gao, Y.; Hejazi, M.I.; Leung, L.R. Impacts of climate change, policy and Water-Energy-Food nexus on hydropower development. *Renew. Energy* **2018**, *116*, 827–834. [CrossRef]
80. Liu, J.; Zuo, J.; Sun, Z.; Zillante, G.; Chen, X. Sustainability in hydropower development—A case study. *Renew. Sustain. Energy Rev.* **2013**, *19*, 230–237. [CrossRef]
81. Wang, G.; Fang, Q.; Zhang, L.; Chen, W.; Chen, Z.; Hong, H. Valuing the effects of hydropower development on watershed ecosystem services: Case studies in the Jiulong River Watershed, Fujian Province, China. *Estuar. Coast. Shelf Sci.* **2010**, *86*, 363–368. [CrossRef]

© 2018 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).