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Article

Relationship between Water Use and Energy Generation from Different Power Generation Types in a Megacity Facing Water Shortages: A Case Study in Shenzhen

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Abstract: Using less water to generate more power is a goal of the worldwide power industry, but this is difficult to achieve because of the lack of long-term, operational data-based studies. This challenge is especially severe for megacities facing water shortages. This study used long-term data (2005–2015) from Shenzhen, a megacity of over 20 million people that faces severe water shortages, to determine the relationship between water and energy for different types of power generation. It was found that power generation consumed huge amounts of water and that cooling water was the biggest water use category. Smaller power plants, such as the Yueliangwan power plant, which uses the closed cooling method, consume 2.36 million m^3 of tap water per year, equivalent to the water supply of a small reservoir. However, larger power plants, such as the Mawan power plant and Dayawan nuclear power plant (using the open cooling method), use 0.92 and 3.42 billion m^3 of seawater for cooling every year, respectively, equivalent to about 60% and 200% of the total annual water supply in Shenzhen, respectively. Therefore, large thermal power plants and nuclear power plants should be built in coastal areas with rich water resources rather than in arid or semi-arid areas. Additionally, the water use efficiency of nuclear power plants was found to be 0.22 m^3/kWh, which was significantly lower than that of coal-fired power plants (0.10 m^3/kWh) and gas-fired power plants (0.09 m^3/kWh). Third, the water use efficiency of the closed cooling method was ten times higher than that of the open cooling method. Therefore, the closed cooling method is suitable for power plants constructed in areas without rich water resources. These results are useful for balancing the water and energy demands in the changing world.

Keywords: cooling water; megacity; power plants; water and energy; water use efficiency

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1. Introduction

Water and energy are intertwined resources and essential to economic and social development in cities [1,2]. Over the past few decades, there has been a more and more obvious nexus between them, along with the scarcity of water and energy resources. Thus, the water and energy nexus has become one of the most debated topics to promote a sustainable society and has attracted wide attention from scientists, policymakers, urban planners, the resource industry, etc. [2–5]. We can find many related studies about energy use for water supply and know that the urban water system needs to consume a lot of energy for its operation [2,6]. However, studying water use for energy production is not enough, especially for the megacity facing water shortages [1,7,8].

Cities are the largest consumers of energy in the modern world [2,7]. As the main form of urban energy consumption, electricity is widely used in urban industry, construction, public facilities, residential life and the service industry [9]. Urban electricity mainly comes from non-renewable energy power generation, such as coal-fired power, oil-fired power, gas power, and nuclear power generation, as well as from renewable energy power generation, such as solar energy, wind energy, hydropower, biomass energy, tidal energy, and geothermal energy generation [10,11]. Despite having a variety of energy sources, most cities are experiencing shortages of electricity that need to be supplied by external grids [9]. Among the urban energy sources, hydropower generation requires a large number of water resources, and other power plants such as coal-fired power generation, oil-fired power generation, gas power generation, and nuclear power generation plants also use a lot of water in their cooling processes [7,8,12]. Their water consumption varies when they use different cooling methods [13,14]. In contrast, solar power, wind power, and tidal power hardly need to consume any water resources during their power production processes.

The cooling processes used in power generation plants can mainly be divided into open-cycle and closed-cycle water circulation systems. In an open cooling system, water is directly pumped from the water resource to the condenser and is returned to the same source. As a large quantity of water is freely available and the water temperature is almost constant, this cooling method features a low operating cost and a high cooling effect. However, these plants cause greater pressure on the local water supply, which may lead to the eventual destruction of the entire ecosystem. In contrast, a closed cooling system, which circulates water in a closed circuit, requires considerably less raw water and rarely affects the surrounding water environment. These systems require higher capital investment, increased operating costs for the cooling towers, and more maintenance requirements and spares [15]. For instance, the open cooling system of a coal-fired power generation consumes 757–1891 $m^3/10^4$ kWh, while a closed cooling system only requires only 22–34 $m^3/10^4$ kWh [15–19].

To meet the increasing electricity demands in metropolises such as Beijing, Shanghai, Guangzhou, and Shenzhen, more power plants are being planned and built, which will consume a large quantity of water and will lead to more serious water shortages and crises [2,7,10,11]. Hence, it is essential to evaluate the urban water consumption used for electricity production and to identify the main factors affecting the water use intensity of electricity production to reduce water consumption in urban power production, alleviate urban water shortages, and collaboratively develop water and energy resources. Considering the very little proportion of solar and wind power generation used, this paper selected five kinds of typical power generation plants in Shenzhen, namely the Mawan coal-fired power plant, Yueliangwan oil-fired power plant, Shenzhen Eastern gas power plant, Dayawan nuclear power plant and three waste incineration power plants, to analyze the water resource consumption of various power generation plants in a megacity. Meanwhile, the main factors affecting the water use intensity of electricity production were studied in order to provide a reference for the choice of power generation types and cooling methods in a megacity with severe water shortages.

2. Materials and Methods

2.1. Study Area

Shenzhen City, located in south China, is a typical representative of China's rapid urbanization. The contradiction between electricity supply and demand in Shenzhen is one of the main problems faced by most cities in China in the process of economic development and social progress. Before 2012, local power generation systems in Shenzhen mainly used various power generation methods based on traditional fossil energy such as coal-fired power, oil-fired power, and gas-fired power generation, and new energy generation such as nuclear energy, biomass energy, solar energy and wind energy generation, which included most of the typical power generation systems in Chinese cities. By the end of 2012, the oil-fired power generation plants in Shenzhen had all completed the "oil to gas" project and converted them to natural gas power generation.

2.2. Data Collecting

According to official documents, including Shenzhen Statistics Yearbook and Shenzhen's 12th Five-Year Plan for Energy Development [20,21], we obtained the relative data on electricity supply and use in Shenzhen and the proportion of different types of power generation to total electricity use. Meanwhile, by means of spot investigation and checking working documents, we also collected monthly data for 2–3 years on the water use and power generation of seven typical power plants in Shenzhen, namely the Mawan coal-fired power plant, Yueliangwan oil-fired power plant (shut down in 2010), Shenzhen Eastern gas power plant, Dayawan nuclear power plant and three waste incineration power plants, representing five typical power generation systems in Chinese cities and two types of cooling methods in electricity generation (Table 1).

Table 1. Profile of typical electricity generation plants in Shenzhen.

Power Plant	Electricity Generation (Billion kWh)	Fuel Types	Cooling Method
Mawan coal-fired power plant	11	Coal	Open cooling
Yueliangwan oil-fired power plant	0.86	Heavy oil	Closed cooling
Shenzhen Eastern gas power plant	4.2	Natural gas	Open cooling
Dayawan nuclear power plant	45.1	Nuclear energy	Open cooling
Waste incineration power plants (namely Nanshan, Yantian, and Bao'an plants)	0.05	Household garbage	Closed cooling

3. Results

3.1. Electricity Supply and Use in Shenzhen

As can be seen in Figure 1, the power structure in Shenzhen gradually optimized from 2005 to 2015, with all the oil-fired power plants being replaced by gas power plants. In 2015, nuclear power became the largest source of electricity production (53%), followed by gas power generation (19%), external electricity (17%), coal-fired power generation (9%), and biomass power generation (2%). Thus, the electricity derived from clean energy exceeded 90% of total electricity use in Shenzhen, which has effectively reduced the emission of air pollutants and carbon dioxide from the power industry (Figure 2).

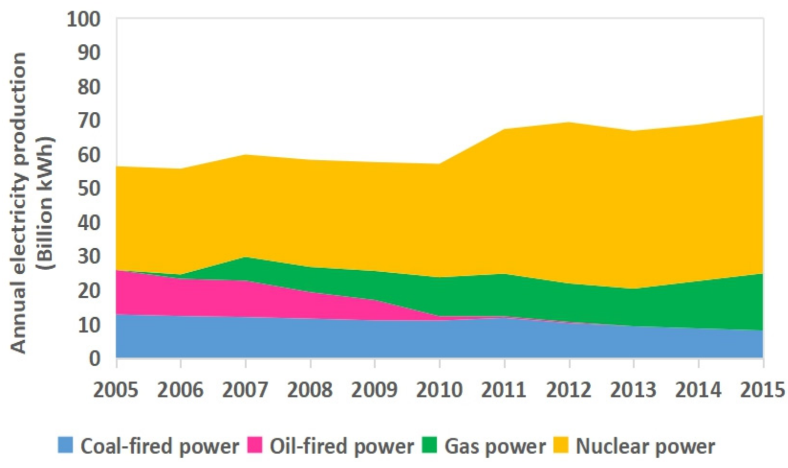

Figure 1. Changes in the energy components from different types of power plants in Shenzhen from 2005 to 2015.

The annual total electricity production in Shenzhen was approximately 57.4 billion kWh from 2005–2010, and this increased to around 68.6 billion kWh when the LingAo nuclear power plant II opened in 2011 (Figure 3). The electricity consumption in Shenzhen increased from 44 billion kWh in 2005 to 85.7 billion kWh in 2015 and showed a significant positive correlation with the gross domestic product (GDP) and the resident population (Figures 4 and 5). This led to a serious electricity shortage of approximately

17.1 billion kWh, and this deficit accelerated with Shenzhen's rapid economic growth and the continuous increase in its population. Thus, about 17% of electricity use in Shenzhen was supplied by non-local power generation plants in 2015, and the proportion of electricity supply from outside Shenzhen increased to more than 30% in 2021.

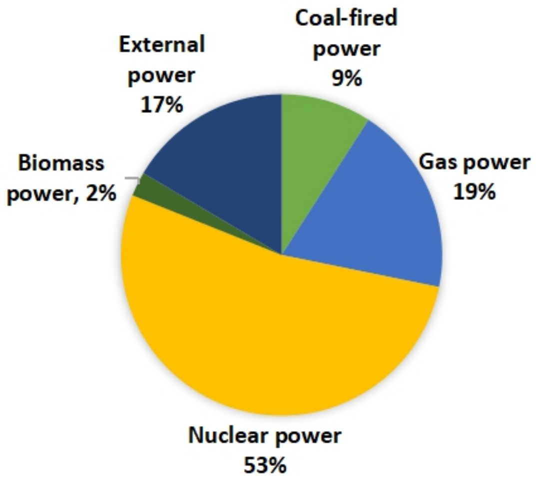

Figure 2. Energy components in Shenzhen in 2015.

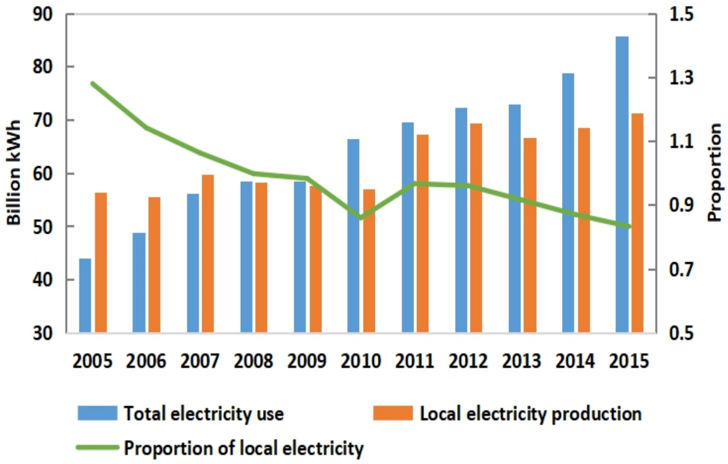

Figure 3. Local electricity generation and its proportion to total electricity use in Shenzhen during 2005–2015.

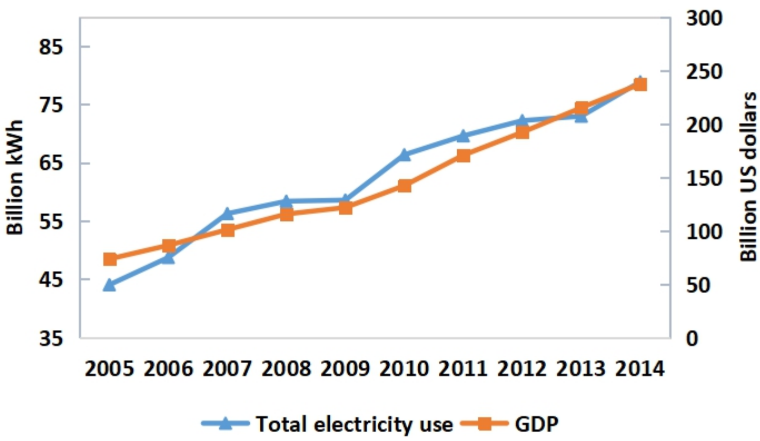

Figure 4. Relationship between GDP and total electricity use in Shenzhen during 2005–2014.

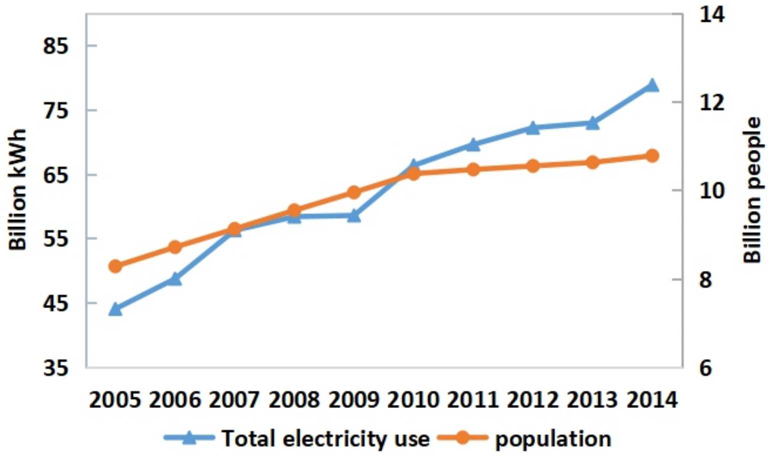

Figure 5. Relationship between population and total electricity use in Shenzhen during 2005–2014.

3.2. Water Consumption of an Oil-Fired Power Plant

The Yueliangwan power plant used heavy oil and adopted tap water in a closed-cycle circulating water system. As shown in Figure 6, its mean annual water consumption intensity for 2006–2008 was 23 $m^3/10^4$ kWh, of which cooling water consumption was 10.5 $m^3/10^4$ kWh, working water consumption was 0.38 $m^3/10^4$ kWh, and miscellaneous water consumption was 12.12 $m^3/10^4$ kWh. As the cooling water is recycled in the closed cooling system, cooling water consumption only accounted for about 45.7% of the total water consumption, which was lower than the consumption of miscellaneous water (52.7%). The monthly consumption of the working water and miscellaneous water showed small variations, while the cooling consumption varied seasonally, with a relatively small consumption occurring from January to March, which may be attributed to the low temperature of tap water in winter.

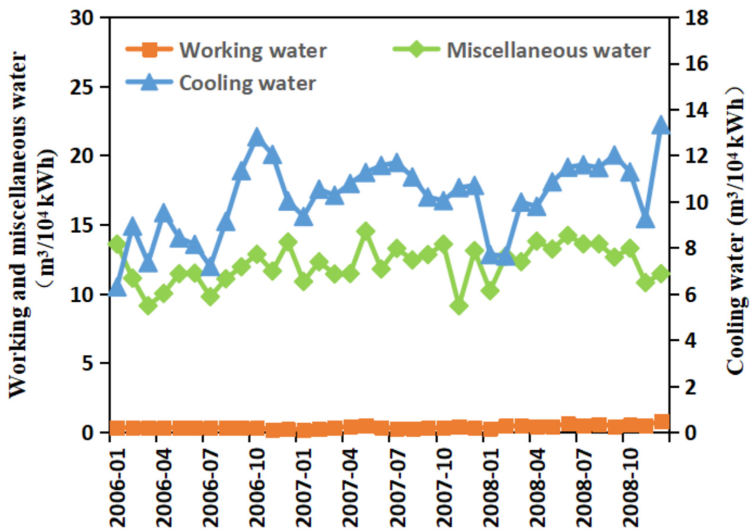

Figure 6. Water use efficiency in different sections for electricity generation at the Yueliangwan oil-fired power plant (from January 2006 to December 2008).

3.3. Water Consumption of a Coal-Fired Power Plant

The Mawan power plant is a coal-fired power generation plant with an open cooling system, which uses seawater as its cooling water. As shown in Figure 7, its average water consumption intensity in 2011–2013 was about 993 $m^3/10^4$ kWh. Its consumption of cooling water, working water and miscellaneous water was 990.1, 0.54, and 1.89 $m^3/10^4$ kWh, respectively. In such an open cooling system, the cooling water cannot be recycled, and therefore almost all the water consumption was used as cooling water (99.7%). Compared to the Yueliangwan power plant, which used a closed-cycle circulating water system, the Mawan power plant consumed dozens of times the amount of cooling water and total water consumption per unit of power generation.

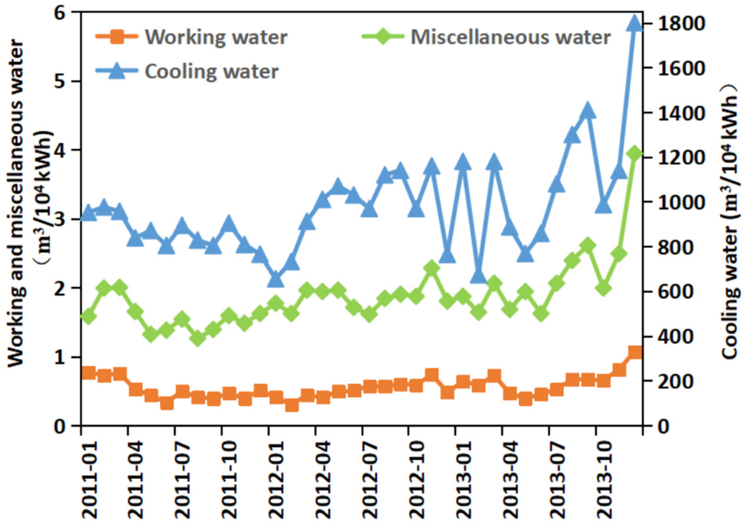

Figure 7. Water consumption for electricity generation at the Mawan coal-fired power plant from January 2011 to December 2013.

3.4. Water Consumption of a Gas Power Plant

The Shenzhen Eastern power plant is a gas power generation plant that uses seawater in an open cooling system. As can be seen in Figure 8, its water consumption intensity was about 869 $m^3/10^4$ kWh, and its consumption of cooling water, working water and miscellaneous water was 868, 0.36 and 0.46 $m^3/10^4$ kWh, respectively. Cooling water accounted for more than 99.9% of its water consumption. Although its cooling water consumption and total water consumption did not vary seasonally, its consumption of working water and miscellaneous water showed a similar seasonal variation.

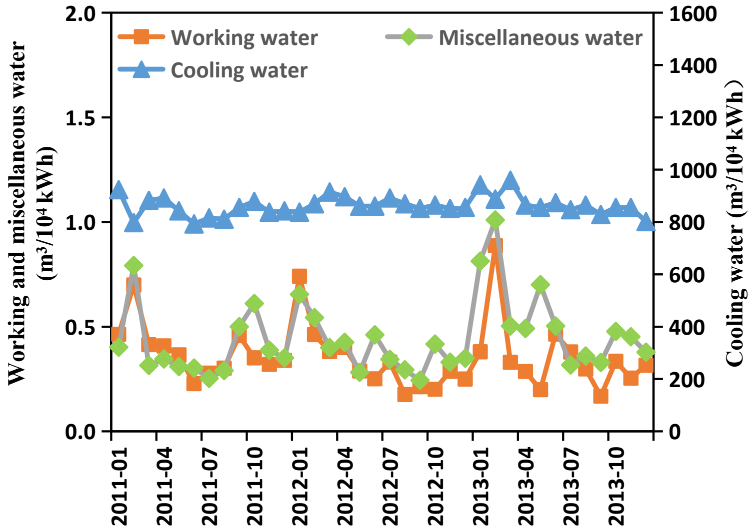

Figure 8. Water consumption for electricity generation at the Shenzhen Eastern gas-fired power plant from January 2011 to December 2013.

3.5. Water Consumption of a Nuclear Power Plant

The Dayawan nuclear power plant was built on the seashore and uses seawater as its cooling water in an open system. As shown in Figure 9, its water consumption intensity was 2238 $m^3/10^4$ kWh, and almost all of its water consumption was used as cooling water (2237.9 $m^3/10^4$ kWh). Only 0.012 $m^3/10^4$ kWh of its water was used as working water. The cooling water consumption intensity of this nuclear power plant was 2–2.8 times that of the conventional power plants adopting an open cooling system, and 70–100 times that of the conventional power plants using a closed cooling system. Further, its cooling water consumption and total water consumption did not vary seasonally, but they became relatively lower from January to March every year, which may be attributed to seawater having lower temperatures during these months.

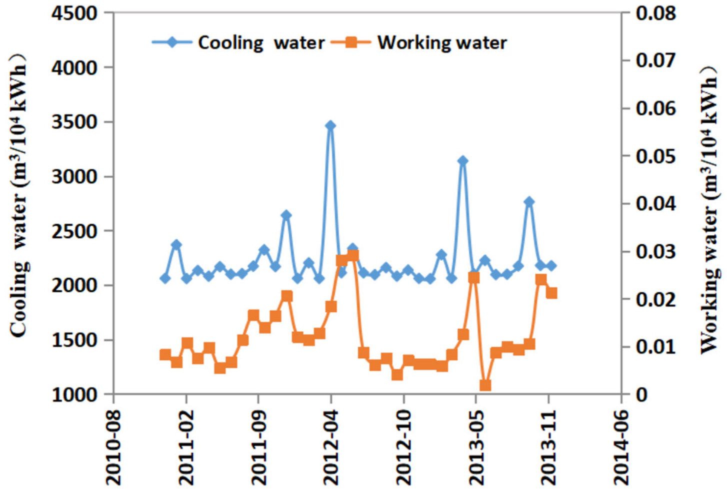

Figure 9. Water consumption for electricity generation per month at the Dayawan nuclear power plant from January 2011 to December 2013.

3.6. Water Consumption of a Biomass Power Plant

The three waste incineration power plants in this study were located, respectively, in the Bao'an District, Nanshan District, and Yantian District in Shenzhen. All of them use a closed-cycle circulating water system. As shown in Figure 10, their water consumption intensity was about 63.2 $m^3/10^4$ kWh, and almost all of their water consumption was used as cooling water (63.1 $m^3/10^4$ kWh). Only 0.062 and 0.03 $m^3/10^4$ kWh of water were used as working water and miscellaneous water, respectively. The annual cooling water consumption intensity in the Nanshan plant and Yantian plant was almost the same for three years continuously, while it decreased at the Bao'an plant as the second phase of the Bao'an plant began in early 2013. These results indicate that the water consumption intensity of a waste incineration power plant could benefit from its scale effect.

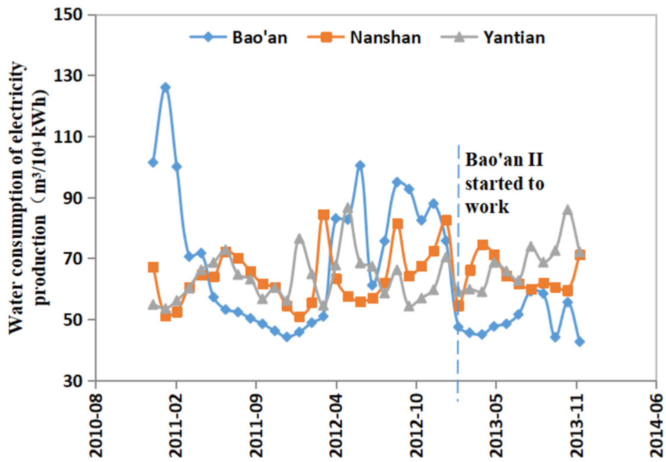

Figure 10. Cooling water use of three waste incineration power plants from January 2011 to December 2013.

4. Discussion

4.1. Water Consumption of Power Plants

Electricity generation consumes a large amount of water and the cooling process was the main water consumption sector of the power plants studied. Except for the Yueliangwan oil-fired power plant, which had been shut down, the cooling water accounted for more than 99% of the total water consumption (Tables 2 and 3 and Figure 11). The Yueliangwan oil-fired power plant, using a closed cooling system, had a total annual electricity generation of about 1.024 billion kWh, and consumed a total of 2.356 million m^3 of tap water every year, which is equivalent to the annual water supply of a small or medium-sized reservoir, and about half of the daily water supply of all waterworks in Shenzhen. Similarly, the biomass power plants, using a closed cooling system, had an annual total electricity generation of about 1.16 billion kWh and total annual consumption of water resources of about 7.331 million m^3, which is equivalent to the annual water supply of a large reservoir, and the total water supply of all waterworks in Shenzhen for more than a day and a half (Table 2).

Table 2. Relationships between total power generation and total water use for different power plants in Shenzhen.

Power Plants	Water Consumption per Unit of Power Generation ($m^3/10^4$ kWh)	Total Electricity Production (10^8 kWh)	Total Water Use (10^4 m^3)
Yueliangwan plant	23	10.24	235.6
Waste incineration plant	63.2	11.6	733.1
Mawan plant	990	92.5	91,575
Eastern plant	869	12.5	10,862
Dayawan plant	2238	153	342,414

Table 3. Water consumption for electricity generation of typical power plants in Shenzhen.

Power Plants	Fuel Types	Cooling Method	Cooling Water ($m^3/10^4$ kWh)	Working Water ($m^3/10^4$ kWh)	Miscellaneous Water ($m^3/10^4$ kWh)
Yueliangwan plant	Heavy oil	Closed cooling	10.5 ± 1.2	0.38 ± 0.11	12.12 ± 1.25
Waste incineration plant	Biomass energy	Closed cooling	63.1 ± 8.3	0.06 ± 0.02	0.03 ± 0.012
Mawan plant	Coal	Open cooling	990.1 ± 185.9	0.54 ± 0.15	1.89 ± 0.35
Eastern plant	Natural gas	Open cooling	867.9 ± 34.8	0.36 ± 0.16	0.46 ± 0.16
Dayawan plant	Nuclear energy	Open cooling	2237.9 ± 304.6	0.012 ± 0.007	

Despite the different fuel types, the total annual electricity generation for the Mawan power plant and Shenzhen Eastern power plant was 9.25 billion kWh and 1.25 billion kWh, respectively, and their total water consumption was 916 million and 109 million tons, respectively, leading to similar water consumption intensities (990 and 896 $m^3/10^4$ kWh, respectively). Comparably, the Dayawan nuclear power plant consumed 34.3 billion m^3 of cooling water for a total annual electricity generation of 15.3 billion kWh. These large water consumption figures exceed the annual water transfer from other cities to Shenzhen through the Eastern Water Diversion Project and Dongshen Water Diversion Project (1.39 billion m^3). As Shenzhen is a coastal city, all three plants used seawater as cooling water in an open system, which would not have had a big impact on Shenzhen's freshwater resources. However, it is worth noting that, after the cooling process, high-temperature seawater would have been discharged directly into the sea, which might have affected the ecological environment of the surrounding sea areas. In summary, the quantity of water consumption for energy production varied substantially by the technology used for fuel extraction and cooling processing, which is consistent with the results of other studies [7,12]. The total water consumption for energy production was approximately 52 billion m^3 of fresh water annually for over 150 countries [7]. These results indicate that the magnitude of water use for energy production at the city, national, and global scales is essential for local, regional, and global sustainable water management.

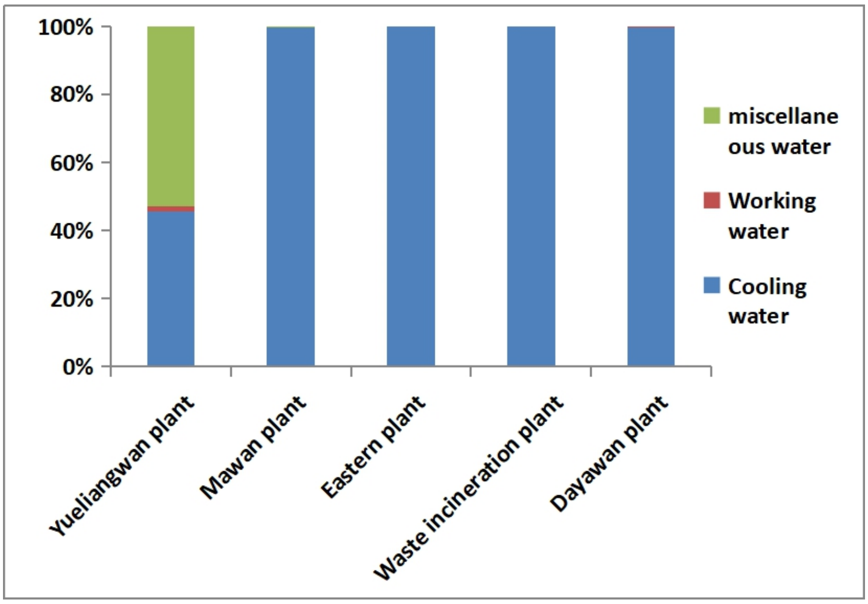

Figure 11. The proportion of water consumption for typical power plants in Shenzhen.

4.2. Effect of Fuel Types on Water Consumption

The water consumption intensity was generally affected by the fuel types and the cooling methods of the power plants. For example, although both the Yueliangwan power plant and the biomass plants adopted a closed cooling system, their water consumption intensities all differed (Figure 12). The water consumption intensity of the former oil-fired power plant was 2.75 times that of the latter waste-to-energy plant and six times larger with regard to the cooling water. For the plants with an open cooling system, the water consumption intensity of the Mawan oil-fired power plant was about 15% larger than that of the Shenzhen Eastern power plant using natural gas. The Dayawan nuclear power plant had the largest water consumption intensity, which was 2.64 times that of the oil power plant and 2.31 times that of the gas power plant (Figure 13). Therefore, the water consumption intensity varied significantly depending on the fuel types for power generation used.

4.3. Effect of Cooling Methods on Water Consumption

The cooling methods of power plants had a significant impact on their water consumption intensities. The cooling water consumption intensities of the plants that used an open cooling system, the Mawan power plant, Shenzhen Eastern power plant and Dayawan nuclear power plant, were 990, 869 and 2238 $m^3/10^4$ kWh, respectively (Figure 14). Their cooling water consumption accounted for more than 99% of their total water consumption. In contrast, the cooling water consumption intensities of the plants that used a closed cooling system, the Yueliangwan power plant and the biomass power plants, were 23 and 63 $m^3/10^4$ kWh, respectively, which were less than 1/10 of the power plants with an open cooling system. These results are in line with those of previous studies in China, which reported water consumption of 757–1891 $m^3/10^4$ kWh for the open cooling system of coal-fired power generation and 22–34 $m^3/10^4$ kWh for the closed cooling system [15–19]. Therefore, closed cooling methods can save a lot of water and are more suitable in areas with insufficient water resources. The open cooling methods are generally more suitable in coastal power plants that can directly pump seawater for the cooling process, which may not have a large impact on the local freshwater resources.

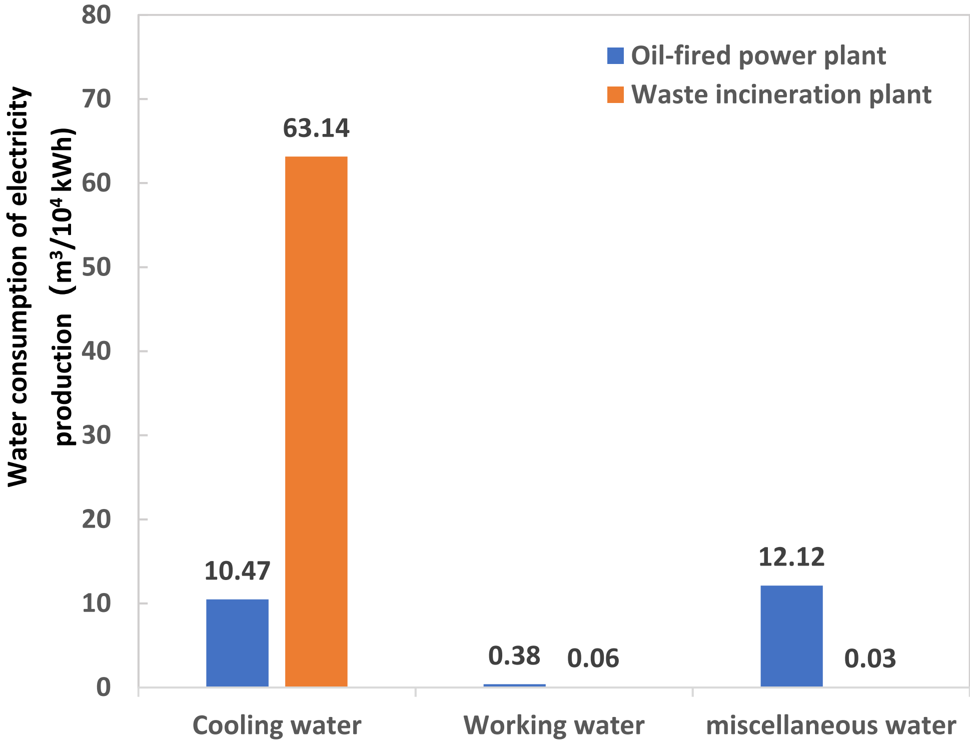

Figure 12. Water consumption of power plants using a closed cooling system.

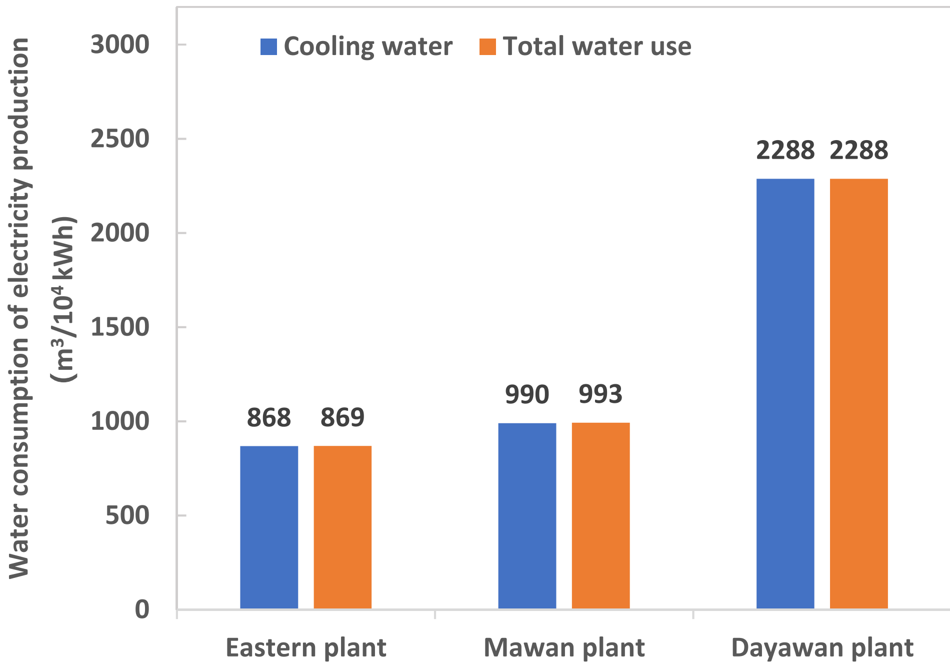

Figure 13. Water consumption of power plants using an open cooling system.

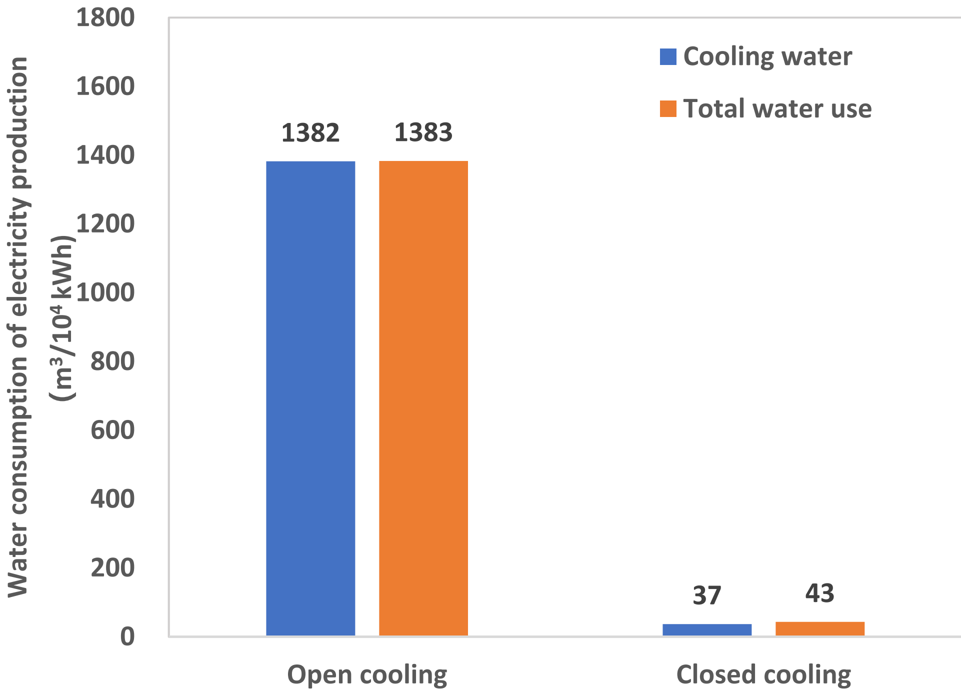

Figure 14. Water consumption of power plants using open and closed cooling systems.

5. Conclusions

In order to study the water consumption of power generation in a megacity facing water shortages, this paper collected data on the electricity production and water consumption of seven typical power generation plants in Shenzhen, including power plants using fuels such as coal, oil, natural gas, nuclear energy, and waste incineration. It was found that the power production process consumed a lot of water resources and that cooling water was the primary type of water used. Water consumption was found to vary significantly by generation technology, fuel type and cooling type at the scale of the individual power plants. The Yueliangwan power plant, a small power plant using the closed cooling method, consumes about 2.36 million tons of tap water per year, equivalent to the water supply of a small reservoir. Furthermore, the Mawan power plant and the Dayawan nuclear power plant, both of which use the open cooling method, use about 0.92 billion tons and 3.42 billion tons of seawater for cooling every year, respectively, equivalent to about 60% and 200% of the total annual water supply in Shenzhen, respectively. Therefore, large thermal power plants and nuclear power plants should be built in coastal areas with rich cooling water resources rather than in arid or semi-arid areas. Secondly, water consumption for different types of power plants was significantly different, and the unit water consumption of the nuclear power plant (0.22 m^3/kWh) significantly exceeded that of the coal-fired power plants (0.10 m^3/kWh), the gas-fired power plant (0.09 m^3/kWh) and the waste incineration power plant (0.01 m^3/kWh). Third, the choice of cooling methods could also have a significant impact on the unit water consumption of power plants. The unit water consumption of the power plant using the closed cooling method was less than 1/10 of that used in the open cooling method. Therefore, the closed cooling method is more suitable for power plants constructed in areas without rich water resources.

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