Study on the performance of two water-side free cooling methods in a semiconductor manufacturing factory

Lizhi Jia[a,b], Junjie Liu[a,*], Shen Wei[b], Jing Xu[c]

[a]Tianjin Key Laboratory of Indoor Air Environmental Quality Control, School of Environmental Science and Engineering, Tianjin University, Tianjin 300072, P.R. China

[b]The Bartlett School of Construction and Project Management, University College London (UCL), London, WC1E 7HB, UK

[c]Tianjin Tranair Technology Co.,Ltd. Tianjin 300392, P.R. China

Abstract: Buildings account for a large portion of global energy consumption and CO_2 emissions. Therefore, reducing the energy demands of buildings has become a global topic for sustainable development. A central cooling system accounts for a significant part of a building's energy consumption. This study proposes a tap water-based free cooling system that recovers heat from spaces for tap water preheating in winter. The tap water-based free cooling and cooling tower free cooling systems integrated with a water-cooled central cooling system were applied in a semiconductor manufacturing factory. Based on the whole-year operation data, the performance of the tap water-based free cooling and cooling tower free cooling systems were compared from thermodynamic, energy, environmental, and economic perspectives. The results showed that free cooling was the dominant cooling method in winter in Tianjin. Compared with the cooling tower free cooling system, the tap water-based free cooling system could provide slightly higher chilled water temperature resulting in 10% shorter operating time. The energy analysis revealed that the coefficient of performance (COP) of the tap water-based free cooling system was approximately 7.4-fold and 2.2-fold higher than that of the mechanical cooling and cooling tower free cooling systems, respectively. Using the two free cooling methods reduced electricity consumption by 6,044 MWh and reached an annual energy-saving rate of 15.1%. Furthermore, the tap water-based free cooling system saved $1.48x10^5$ kg of natural gas for tap water preheating. Energy reductions attributed to two free cooling methods reduced CO_2 emissions by 6,236 tons. The tap water-based free cooling is more environmentally friendly with a 4.4-fold greater CO_2 emission reduction rate than the cooling tower free cooling method. From the economic perspective, with a short payback period (1.4 years), the tap water-based free cooling system is an attractive solution for improving the energy efficiency of central cooling systems.

Keywords: Building energy, Energy-efficient, CO_2 emission reduction, Free cooling, Tap water-based free cooling.

1. Introduction

Nomenclature

c_p	Specific heat capacity, kJ/(kg·°C)	ΔOC	Operation cost savings, RMB
C_{pur}	Purchase cost, RMB	μ	CO2 emission factor, kg/kWh
COP	Coefficients of performance	ρ	Density, kg/m3
$\overline{COP}$	Average COP	τ	The billing period, hours
ES	Electricity savings, kWh	*Subscripts*	
H_{NG}	Heating load reduction, kWh	CH	Chillers
LHV	Lower heating value, kJ/kg	CP	Cooling pumps
m	Mass flow rate, kg/s	CT	Cooling tower
M	Mass of CO_2 reduction, tons	$CTFC$	Cooling tower free cooling
n	Total number of sampling data	Ele	Electricity
p_{Ele}	Price of electricity, RMB/kWh	ExP	Heat exchanger pumps
p_{NG}	Price of natural gas, RMB/m^3	FC	Free cooling
PBP	Payback period, year	i	The number of sampling data
q	Cooling supply, kW	MC	Mechanical cooling
Q	Cooling supply in a period, kWh	NG	Natural gas
r	Installation factor	$PriP$	Primary pumps
R_{CO2}	CO_2 reduction rate, ton/MWh	re	Return chilled water
S	Standard deviation	su	Supply chilled water
SR	Energy Saving rate, %	t	Time
T	Temperature, °C	tap	Tap water
$\bar{T}$	Moving average temperature, °C	$TWF($	Tap water-based free cooling
W	Power consumption, kW	w	Chilled Water
Greek symbols		wet	Wet-bulb
ΔIC	Additional initial cost, RMB		

Buildings account for nearly 40% of global energy consumption and CO_2 emissions [1, 2]. Therefore, reducing the energy demands of and CO_2 emissions from buildings has become a global topic for sustainable development [3, 4]. High-tech manufacturing factories are among the most energy-intensive buildings, which consume 30-50-fold more energy than typical commercial buildings [5]. In these factories, 40%-50% of energy is consumed by process equipment, and the remaining energy is consumed by the facility system [6, 7]. Due to the rigorous control requirements for the indoor environment, the central cooling system is a dominant energy consumer in a facility system, accounting for 20%-30% of the total energy consumed [7-9]. Thus, central cooling system energy savings are crucial for reducing the energy consumption of these factories.

Free cooling is an energy-efficient solution to reduce the cooling system energy consumption using natural cooling sources in suitable climate zones [10]. Free cooling systems can be grouped into three categories: air-side free cooling, water-side free cooling, and heat pipe free cooling [11, 12]. Air-side free cooling systems use the outdoor cold air for space cooling by drawing the outdoor air inside directly or indirectly via economizers. Direct air-side free cooling is simple to use, but it may introduce humidity disturbances, particulates, and gas contaminants inside [13, 14]. Indirect air-side free cooling can overcome those drawbacks, but it is less efficient and incurs higher initial and operational costs. Because of these concerns, water-side free cooling is preferred in some applications, such as for data centers and cleanrooms [15]. Water-side free cooling utilizes natural cold sources through a cooling water infrastructure, which allows the free cooling process to be introduced without compromising the internal environment [11, 16]. Heat pipe free cooling is a special kind of economizer with the ability to transfer heat with small temperature differences. However, this technology is still in the exploratory stage and has not been widely adopted due to its unfamiliarity and reliability concerns [11]. In the literature, studies on free cooling technologies mainly focus on data centers because of the large amount of heat generated all year-round. For electronic cleanrooms, cooling is required 24 hours per day and 365 days per year to remove the heat generated by the process equipment [17]. Due to rigorous indoor environment control requirements, water-side free cooling is a reasonable way to reduce the energy used by the central cooling system. Water-side free cooling can be further classified into direct water-side free cooling, dry cooler, and cooling towers (wet cooler) systems. Direct water-side free cooling systems cool the indoor air by directly pumping natural cold water into cooling coils in air-conditioned zones. Clidaras et al. [18] proposed a seawater-based free cooling system and designed a closed-loop to transfer heat from the indoor environment to seawater. Li et al. [19] employed lake water to cool the data center through a heat exchanger. However, these water-side free cooling methods are limited by the location of the buildings. James and Rubenstein [20] invented geothermal free cooling in which heat exchangers buried in the earth directly to remove heat generated by computer services. Similarly, a water/soil heat exchanger integrated with radiant floor coils was utilized for free space cooling [21]. However, the high initial investment and fouling concerns have hindered the broad application of geothermal free cooling. A dry cooler free cooling system utilizes low-temperature outdoor air to cool chilled water, and the dry cooler is usually integrated into air-cooled chillers [22]. However, the cooling capacity of this free cooling method is limited by the outdoor dry-bulb temperature. Cooling tower free cooling (CTFC) systems are the most widely used because they could produce colder chilled water by evaporative cooling. The CTFC is an energy-efficient solution, and the energy savings are higher in cooler climate zones [23]. In electronic cleanrooms, cooling demands are significant all year round, making free cooling methods sensible for producing chilled water in cold seasons [24].

Combined space cooling with water heating is another method to improve the energy efficiency of the central cooling system. There are numerous studies focused on recovering heat from space cooling systems to heat/preheat water. The space cooling and water heating systems could be combined through a heat exchanger directly or thermal energy storage indirectly [25]. Ji et al. [26, 27] investigated the energy performance of a split-type air-conditioner integrated with a water heater in summer in a subtropical climate zone, and the results have shown that the condensing heat recovery could considerably improve the system energy performance. Jiang et al. [28] studied the dynamic characteristic of a combined system that reuses the condensing heat for domestic hot water heating. This combined system has shown great economic and environmental value, with 38.6% higher energy efficiency. Yi et al. [29] employed a helical heat exchanger to transfer condensing heat from the water-cooled air-conditioner to the domestic hot water system, and the energy efficiency of the system was increased by 12.3%. Chen and Lee [30] conducted questionnaire surveys to obtain the simultaneous consumption characteristic of space cooling and water heating in Hong Kong, and the potential energy savings of the combined system was 50% for typical public rental housing. The success of the combined system depended heavily on the matching degree of space cooling and water heating demands. To solve the mismatch of the demands, thermal energy storage with and without phase change material was employed [31-33]. In summary, the typical system that combined space cooling with water heating utilized the condensing heat from air-conditioners to heat/preheat domestic hot water. These studies were mainly focused on domestic air-conditioners and hot water systems in tropical and subtropical zones. The combined system could only operate in summer with the simultaneous demand for space cooling and water heating.

For semiconductor manufacturing factories, the cleanrooms are required to be cooled all year-round, and the ultrapure water is needed to be heated in winter. Therefore, a tap water-based free cooling method was proposed to combine space cooling and water preheating, and this method was designed to be used in winter. The heat generated by process equipment was directly transferred to the tap water through a heat exchanger rather than energy-consuming air-conditioners. In this system, a small amount of energy was consumed by pumps to overcome the flow resistance, and thus it was named as tap water-based free cooling method. The tap water-based free cooling system and cooling tower free cooling system were integrated into a water-cooled central cooling system in a semiconductor manufacturing factory located in Tianjin. The performance of two free cooling methods was evaluated and compared from different perspectives using whole-year operating data. In Section 2, the principles and the operation strategy of the different cooling methods are described, and the performance metrics are introduced. In Section 3, the performance of tap water-based free cooling and the cooling tower free cooling systems are compared from thermodynamic, energy, environmental, and economic perspectives. The characteristics of the tap water-based free cooling system and its application prospects are discussed in Section 4.

2. Methodology

2.1 System description

This study focuses on a central cooling system that integrated free cooling methods with the mechanical cooling system. This central cooling system with multiple cooling sources was applied in a semiconductor manufacturing factory in Tianjin. The manufacturing of semiconductors requires cleanrooms to meet the environmental requirement of production. In this case, the cleanrooms are required to achieve the cleanness of ISO Class - 5 to Class - 7 for different areas. The main indoor design temperature and humidity are 22±1 °C and 45±5%. The system cooling load mainly includes heat generated by the process equipment and heat bring by fresh air. As the production line works 24 hours per day throughout the year, the cleanrooms require cooling all year-round. In this system, dry cooling coils (DDC) with medium-temperature chilled water were employed to remove the sensible cooling load, and this part of the cooling load is relatively stable. Make-up air units are used to process the fresh air, and their cooling demand varies with the outdoor weather conditions. This study focused on free cooling methods to improve the energy efficiency of the central cooling system. In winter, cooling towers and cold tap water can be used to reduce the energy consumption of chillers and improve the energy efficiency of the central cooling system. Figure 1 shows the central cooling system of the semiconductor manufacturing factory in this study. In this system, three different cooling sources, chillers, cooling towers, and tap water, share the chilled water distribution (CWD) system. In the CWD loop, six variable speed secondary pumps are designed to transport medium-temperature chilled water to terminal cooling coils and three pumps are used for low-temperature coolant distribution. With multiple cooling sources, the system can be divided into three subsystems, mechanical cooling, cooling tower free cooling, and tap water-based free cooling subsystems.

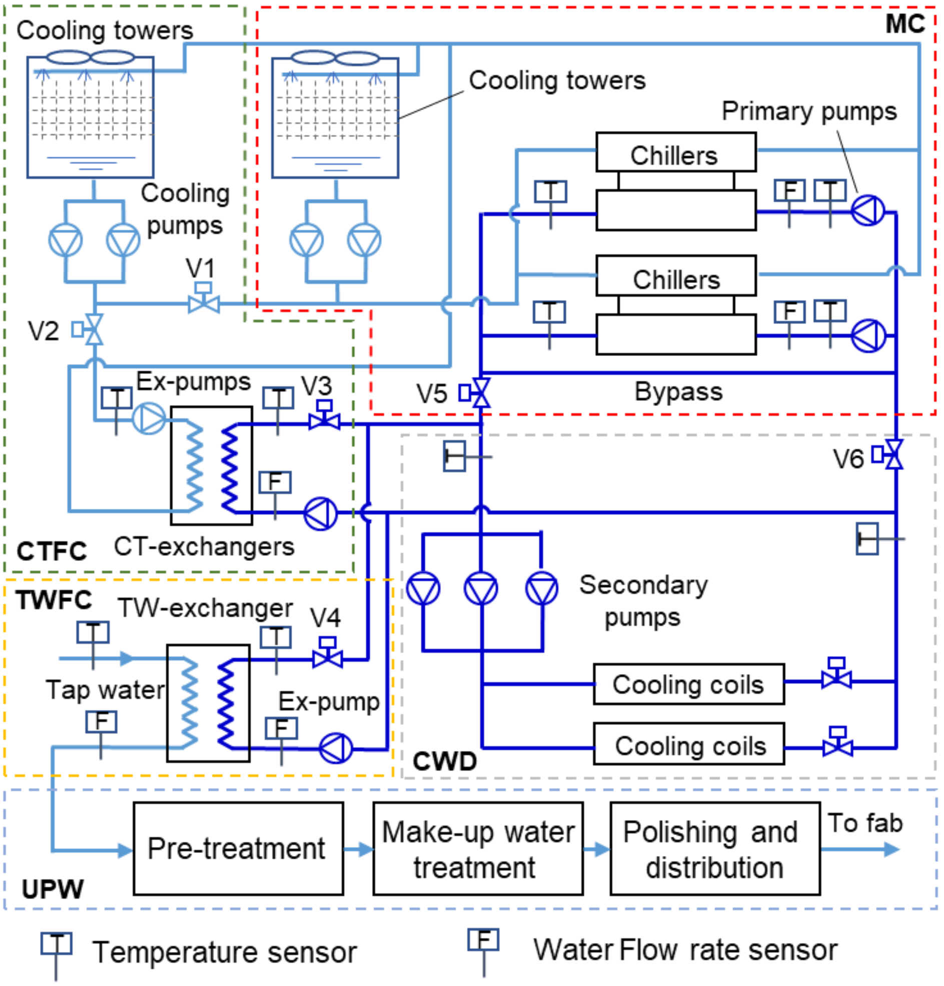


Figure 1: Diagram of the central cooling system and the ultrapure water system

2.1.1 Mechanical cooling

The mechanical cooling system lowers the temperature of chilled water using various refrigerating systems. For large buildings, the water-cooled chillers are generally used to transfer heat from the chilled water loop to the cooling water loop. Then, cooling towers reject heat from cooling water to ambient air by water evaporation. The mechanical cooling system is shown in the red box in Figure 1. In this system, nine medium-temperature centrifugal chillers with dedicated primary pumps are employed to remove the sensible cooling load and precool the fresh air, and three low-temperature centrifugal chillers with dedicated primary pumps are used for fresh air dehumidification in summer. To exhaust heat from chillers, nine cooling towers and nine cooling pumps are configured in the cooling water loop. The specifications of the major equipment used in the central cooling system are listed in Table 1.

Table 1. Specifications of the major equipment of the central cooling system

Equipment	Number	Power (kW)	Capacity (kW)	Flow rate (m^3/h)	Head (kPa)	Area (m^2)
Chiller	9	893	4,572	-	-	-
	3	619	2,286	-	-	-
Cooling tower	8	110	8,272	-	-	-
	1	150	11,030	-	-	-
Primary pump	9	19	-	440	119.5	-
	3	22	-	360	164.3	-
Secondary pump	6	93	-	760	289.7	-
	3	30	-	360	194.2	-
Cooling pump	8	93	-	1,425	194.2	-
	1	250	-	1,900	274.6	-
Ex-pump	10	55	-	650	294.2	-
	1	30	-	420	147.0	-
CT-exchanger	5	-	-	-	-	325
TW-exchanger	1	-	-	-	-	304

2.1.2 Cooling tower free cooling

Cooling tower free cooling is a widely used energy-saving technology in water-cooled central cooling systems. In a cooling tower free cooling system, cooling towers produce cold water and then cool the chilled water through heat exchangers. The green box in Figure 1 shows a schematic of a typical cooling tower free cooling system. In this case, four cooling towers and five plate heat exchangers (named CT-exchangers) are employed to produce chilled water in winter. To overcome the flow resistance of heat exchangers, pumps (named Ex-pumps) are employed on both sides of the heat exchangers.

2.1.3 Tap water-based free cooling

Additional to being energy-intensive, high-tech manufacturing is a water-intensive industry because of the large amount of water involved in the rinsing and cleaning procedures of the production lines [34-36]. In these procedures, ultrapure water is generally used, and ultrapure water use accounts for approximately 70% of the total factory water use [37]. To produce ultrapure water, a series of processes, including pretreatment, make-up water treatment, and polishing, are conducted on tap water (raw water), as shown in the blue box in Figure 1 [38]. In the pretreatment process, tap water is usually heated over 20 °C to improve the productivity of the ultrapure water system [37, 39]. In some special cases, the ultrapure water is required to be heated to 70 °C [39]. Considering the simultaneous demand of heating and cooling, a tap water-based free cooling system was proposed to reduce the energy consumption of the factory. The tap water-based free cooling system consists of a heat exchanger that transfers heat from the chilled water loop (cooling side) to the cold tap water (heating side), as shown in the orange box in Figure 1. This approach reduces both the energy consumption for chilled water cooling and tap water heating. In this case, a plate heat exchanger is employed for tap water-based free cooling (TW-exchanger), and an Ex-pump is employed to overcome the resistance of the exchanger on the cooling side. The specifications of the major equipment are listed in Table 1.

2.2 System operation strategy

The operation of a central cooling system with multiple cooling sources is complicated. As the cooling load in winter is mainly sensible heat generated by the process equipment, the two free cooling methods can efficiently generate medium-temperature chilled water. The operation strategy of different cooling sources is shown in Table 2. The free cooling system could be enabled when the downstream water temperature of economizers is lower than the chilled water supply temperature setpoint (12 °C in winter). For the cooling tower free cooling system, the downstream temperature of the economizer can be estimated by the sum of the outdoor wet-bulb temperature and the approach temperatures of the cooling tower (5.5 °C) and the heat exchanger (2.0 °C). Thus, the critical point of the system switching is the outdoor air wet-bulb temperature of 4.5 °C. To prevent short cycling CTFC system, a deadband of 1.0 °C was employed in the real application. When the outdoor wet-bulb temperature is low enough, the cooling tower free cooling system starts with valves V2 and V3 open and V1 closed (Figure 1). For the tap water-based free cooling system, the inlet tap water temperature should be lower than the chilled water temperature setpoint minus the approach of the heat exchanger. In this case, when the tap water temperature is lower than 10 °C, the tap water-based free cooling system begins with valve V4 open. The two free cooling systems can operate simultaneously when both operation conditions are meted. When the cooling capacity of the free cooling systems is insufficient, chilled water from chillers is mixed with that from economizers before entering the secondary pumps to satisfy the cooling demand and maintain the chilled water supply temperature. In this scenario, valves V2 to V6 are opened, and V1 is closed. When both free cooling methods are disabled, the system operates in a fully mechanical cooling mode with valves V1, V5, and V6 open.

Table 2. Operating strategy for the central cooling system

Cooling sources	Operating conditions
Cooling tower free cooling	$T_{wet} < 4.5$ ℃
Tap water-based free cooling	$T_{tap} < 10$ ℃
Fully mechanical cooling	$T_{wet} \geq 4.5$ ℃ & $T_{tap} \geq 10$ ℃

2.3 Data collection and performance metrics

2.3.1 Data collection

In this study, two free cooling methods are integrated into the central cooling system to reduce the system energy consumption. To evaluate the performance of the system, water temperature, water flow rate, and the electricity consumption of different cooling systems were monitored, which span over one year (2018). The location of the major sensors is shown in Figure 1. The specification of sensors and their accuracy were listed in

Table 3.

Table 3. The specification of sensors

Sensors	Range	Accuracy
Water Temperature	-20 - 80 °C	±0.3 °C
Water flow rate	0.1 - 15 m/s	±1%
Electric meter*	0 - 100 V, 1.5 - 6 A	±0.5%

* Transformers are required for equipment with high input voltage and current.

2.3.2 Performance metrics

Based on the measured data, the analysis from the perspectives of energy, environment, and economic were taken to evaluate the two free cooling systems' performance. The performance metrics are introduced below.

1. Features of the cooling sources

The water supply temperature, operating hours, and cooling capacity of two free cooling systems were evaluated and compared.

1) Water supply temperature

The water supply temperature and its stability impacted the use of the different free cooling methods in terms of volume and operating hours. The fluctuation of the water temperature can be described by the standard deviation of the data. As the variation of the supply water temperature shows a clear trend, the mean temperature is replaced by the moving average temperature to calculate the standard deviation, as defined in Equation (1),

$$S = \sqrt{\sum_{i=1}^{n} \frac{(T_i - \bar{T})^2}{n-1}} \tag{1}$$

2) Cooling supply

The cooling supply of different cooling sources can be estimated based on Equation (2),

$$q = c_p m_w (T_{re} - T_{su}) \tag{2}$$

2. Energy performance

The coefficients of performance (COPs), energy savings, and energy-saving rate were used to evaluate the energy performance of different cooling systems.

1) COP

The COPs of different cooling methods are evaluated based on the cooling supply and the total power consumption of associated equipment according to Equations (3) to (5). Since these three cooling systems share the chilled water distribution system, the energy consumption of secondary pumps is excluded.

For the mechanical cooling system, the power consumption of chillers, primary pumps cooling pumps, and cooling towers are included, as defined in Equation (3),

$$COP_{MC} = \frac{q_{MC}}{W_{CH}+W_{PriP}+W_{CT}+W_{CP}} \quad (3)$$

For the cooling tower free cooling system, cooling towers, cooling pumps, and heat exchanger pumps are the major energy-consuming equipment.

$$COP_{CTFC} = \frac{q_{CTFC}}{W_{CT}+W_{CP}+W_{ExP}} \quad (4)$$

For the tap water-based free cooling system, the heat exchanger pump is the only energy-consuming component.

$$COP_{TWFC} = \frac{q_{TWFC}}{W_{ExP}} \quad (5)$$

2) Energy savings

Compared with the mechanical cooling method, the electricity savings of free cooling methods in a billing period can be estimated according to Equation (6),

$$ES = \sum_{t=0}^{\tau}\left(\frac{q_{FC,t}}{COP_{MC}} - W_{FC,t}\right) \quad (6)$$

For the tap water-based free cooling method, the heat absorbed from the chilled water is used to preheat the tap water in the ultrapure water system. Thus, in addition to the electricity savings on cooling side, the tap water-based free cooling system also reduces natural gas (NG) consumption. The reduction in natural gas consumption is the ratio of heat load reduction to the lower heating value of the natural gas（42700 kJ/kg) [40], as expressed in Equation (7). The natural gas savings can be converted to equivalent electricity savings according to Equation (8).

$$m_{NG,t} = \frac{q_{TWFC}}{LHV} \quad (7)$$

$$ES_{NG} = \frac{p_{NG} \times \sum_{t=0}^{\tau} m_{NG,t}}{\rho_{NG} \times p_{Ele}} \quad (8)$$

3) Energy-saving rate

Taking the mechanical cooling method as the baseline, the energy-saving rate of the different free cooling methods can be estimated according to Equation (9),

$$SR = \frac{ES}{\sum_{t=0}^{\tau}\frac{q_{FC,t}}{COP_{MC}}} \times 100\% \quad (9)$$

3. CO2 emission reduction

The reduction of energy use helps to reduce CO_2 emissions. The CO_2 emission reduction using different free cooling methods can be estimated from the electricity savings and the natural gas heating load reductions by multiplying the CO_2 emission factors, as expressed in Equation (10). The CO_2 emission factor of electricity consumption is 0.968 kg/kWh, and the CO_2 emission factor of natural gas is 0.220 kg/kWh [40].

$$M_{CO_2} = \mu_{CO_2,Ele} ES + \mu_{CO_2,NG} H_{NG} \tag{10}$$

Since the design capacities of two free cooling systems differ greatly, the CO_2 emission reduction levels are not comparable. Thus, the CO_2 emission reduction per cooling capacity is proposed and named as the CO_2 emission reduction rate, as defined in Equation (11),

$$R_{CO2} = \frac{M_{CO_2}}{Q} \tag{11}$$

4. Economic analysis

The simple payback period (PBP) is the amount of time it takes the consumer to recover the cost to purchase and install additional equipment as a result of the reduced operating costs. The PBP is the ratio of the additional initial cost to the annual operating cost savings, as defined in Equation (12). The initial cost can be estimated by multiplying the purchase cost with an installation factor, as defined in Equation (13). The operational cost savings consist of the savings from electricity reductions and natural gas savings as defined in Equation (14).

$$PBP = \frac{\Delta IC}{\Delta OC} \tag{12}$$

$$\Delta IC = C_{pur} \times r \tag{13}$$

$$\Delta OC = ES \times p_{Ele} + \frac{p_{NG}}{\rho_{NG}} \times \sum_{t=0}^{\tau} m_{NG,t} \tag{14}$$

3. Results and analysis

3.1 Features of the cooling sources

1) Water supply temperature

The inlet and outlet water temperatures of heat exchangers in different free cooling loops are shown in Figure 2. The varying outdoor wet-bulb temperature led to an unstable supply water temperature of cooling towers (standard deviation of 0. 7 °C). The outlet water temperature of the cooling tower free cooling system was relatively stable with a standard deviation of 0.4 °C. The variation of inlet tap water temperature was relatively stable (standard deviation of 0.1 °C) since the tap water loops buried in the soil had less impact from short-term outdoor temperature variations. The lowest tap water inlet temperature occurred in February. However, the outlet water temperature of the tap water-based free cooling system fluctuated significantly (standard deviation of 0.9 °C). It is because the tap water flow rate fluctuates significantly with the user's demand for ultrapure water. Compared With the cooling tower free cooling, the tap water-based free cooling system outlet temperature was approximately 2.0 °C higher, resulting in a smaller cooling capacity and fewer operating hours.

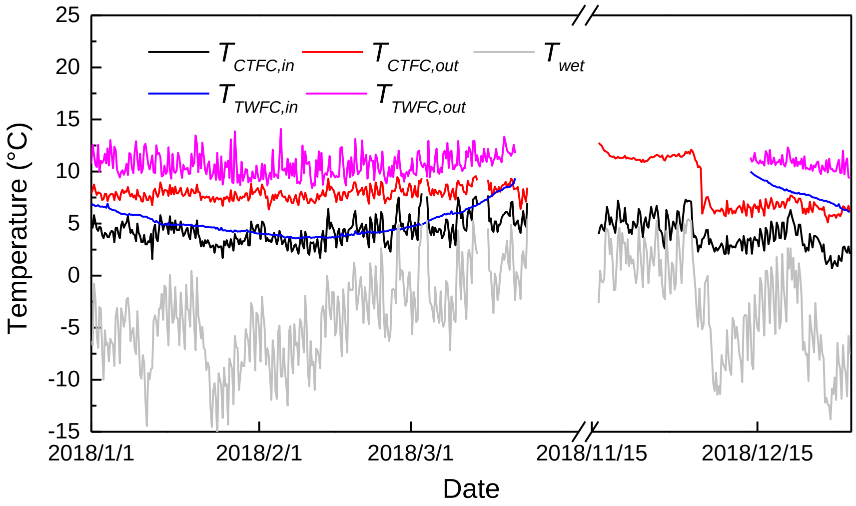


Figure 2: The inlet and outlet water temperature of the two free cooling systems

2) Operating hours

The operating hours of different cooling systems in each month are shown in Figure 3. The cooling tower free cooling system started to work in mid-November and ended in late March. There were 3,248 operating hours of cooling tower free cooling, accounting for 37% of a year. The tap water-based free cooling system started later and ended slightly earlier than the cooling tower free cooling system due to the slightly higher water supply temperature. There were 2,361 hours, nearly 27% of a year, that the tap water could be employed as a cooling source. The cooling capacity and the chilled water supply temperature of the free cooling system vary with outdoor conditions and tap water flow rate. When the cooling capacity of free cooling systems was insufficient, chillers were employed to provide the remaining cooling demand and maintain the chilled water supply temperature. Due to the great cooling demand and strict temperature control of end-users, there were only 57% hours in January and 41% hours in February when all chillers were turned off. In summer, the mechanical cooling system comprised of medium-temperature chillers and low-temperature chillers was in operation all the time.

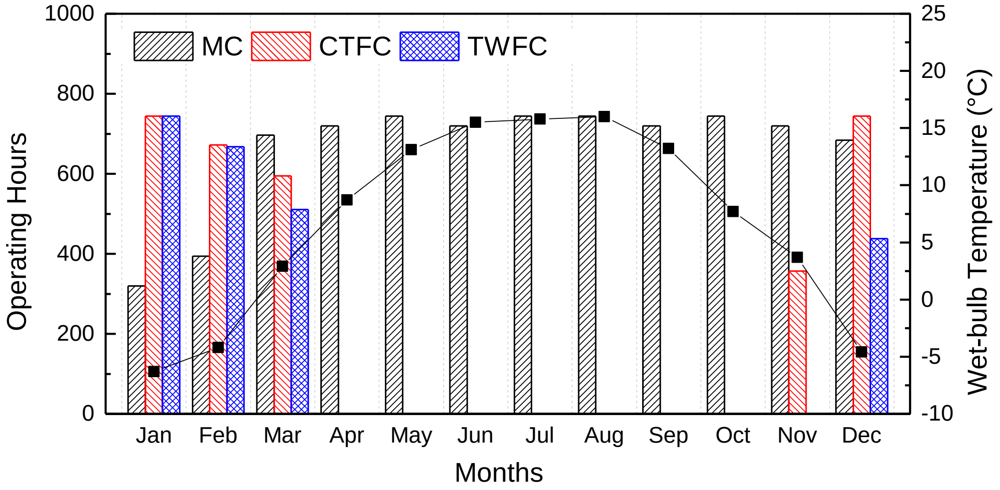


Figure 3: Operating hours of different cooling systems

3) Cooling supply

The cooling load distribution of different cooling systems is shown in Figure 4. In January, February, and December, free cooling was the dominant cooling method which provided 91%, 86%, and 68% of the total cooling demand, respectively. The proportion of tap water-based free cooling was very small, approximately 2%, limited by its small design capacity. In November and March, both mechanical cooling and free cooling were important to satisfy the cooling demand of users. In other months, the mechanical cooling system removed all the sensible and latent cooling loads.

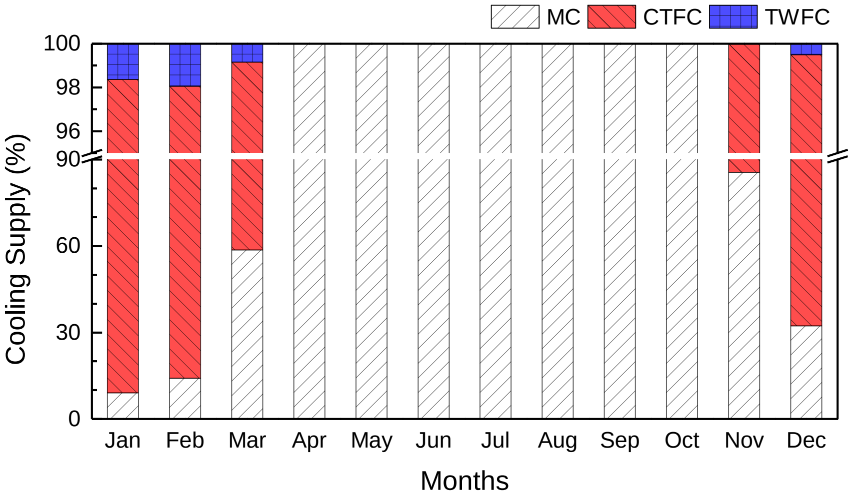


Figure 4: Cooling load distribution of the central cooling system

3.2 Energy performance

1) COPs

The COPs of the different cooling methods are shown in Figure 5. In winter, the COP of the mechanical cooling system achieved an average value of 6.3. In other months, the COP for mechanical cooling decreased with the increase of outdoor wet-bulb temperature and reached the lowest value of 4.3 in July. The COPs of the two free cooling methods were significantly greater than those of the mechanical cooling method, especially the tap water-based free cooling. For cooling tower free cooling, the COP of the system ranged from 12.7 to 22.8 and reached its maximum COP in January since the lower outdoor wet-bulb temperature helped to reduce the energy consumption of the cooling towers. The COP of the tap water-based free cooling system ranged from 26.5 to 62.4, and its maximum COP occurred in February, corresponding to the lowest tap water temperature. In comparison, the COP of tap water-based free cooling was approximately 7.4-fold higher than the mechanical cooling system and 2.2-fold higher than the cooling tower free cooling system. It is because that the cold tap water is a free natural cooling source, and no energy-consuming equipment is required for cold water production. However, cooling towers and/or chillers were required for the cooling tower free cooling and mechanical cooling systems to produce chilled water.

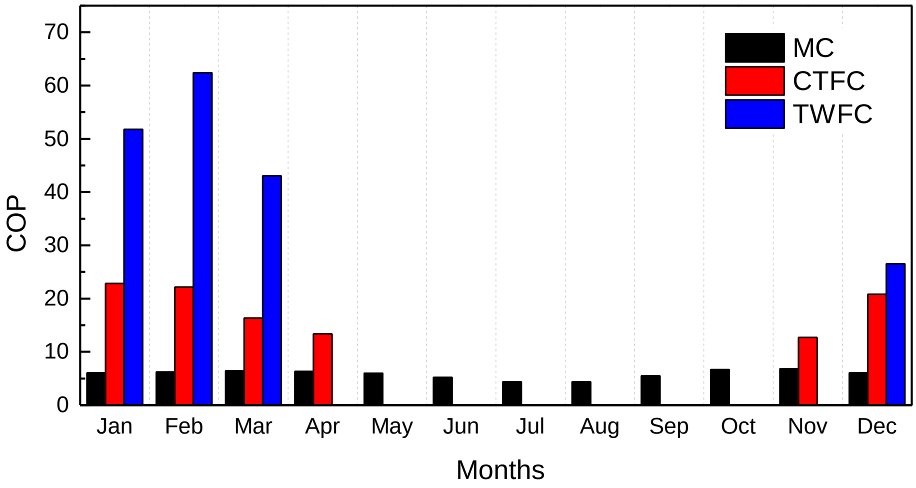
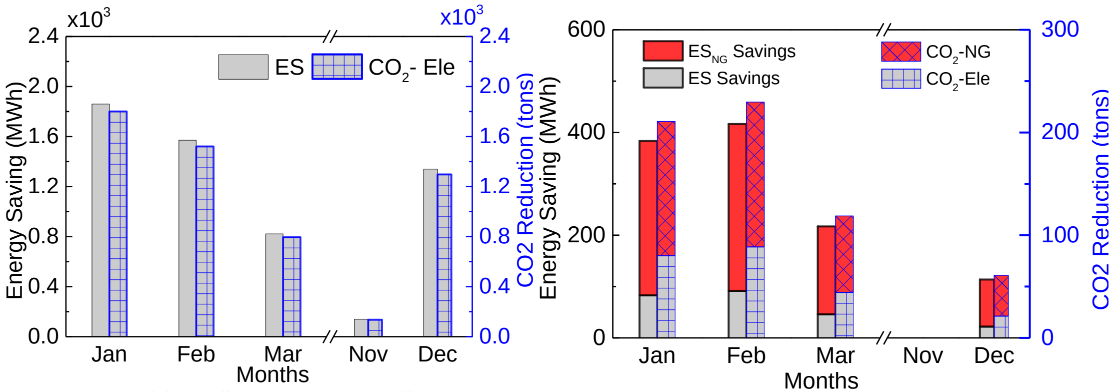


Figure 5: The COPs of different cooling systems

3) Energy savings

According to Equations (6) to (8), the energy savings of two free cooling methods were evaluated, as shown in Figure 6. Compared with mechanical cooling, the electricity savings of the cooling tower free cooling system ranged from 139.4 MWh to 1860 MWh in winter months, as shown in Figure 6 (a), and the energy-saving rates ranged from 49.9% to 72.3%. Additional to the electricity savings, tap water-based free cooling could reduce the natural gas consumption for tap water preheating. The natural gas savings could be converted to equivalent electricity savings according to Equation (8). The total electricity savings of the tap water-based free cooling system were ranged from 113.5 MWh to 416.5 MWh energy, as shown in Figure 6 (b). The energy savings on the heating side (natural gas reduction) was much larger than they were on the cooling side since the energy efficiency of the cooling system was normally higher than that of the direct heating system. The monthly electricity-saving rate on the cooling side ranged from 76.3% to 89.9%. Compared with cooling tower free cooling, the tap water-based free cooling method showed a higher energy-saving rate. In summary, the total electricity savings of two free cooling methods were 6,044 MWh, and the corresponding annual energy-saving rate was 15.1% (cooling side only). The annual total natural gas savings were 1.48×10^5 kg.



(a) Cooling tower free cooling

(b) Tap water free cooling

Figure 6: Energy savings and CO2 reduction of two free cooling methods

3.3 CO_2 emission reduction

Figure 6 also shows the CO_2 emission reductions of two free cooling methods. The annual CO_2 emission reductions were 5,616 tons for the cooling tower free cooling system and 620 tons for the tap water-based free cooling system. The CO_2 emission reduction from the cooling tower free cooling system achieved its peak value in January along with its highest energy savings. For tap water-based free cooling, the CO_2 emission reduction reached its peak value in February, which also aligned with its energy savings. The CO_2 emission reductions from natural gas savings were greater than those from the electricity savings, as shown in Figure 6 (b). With a large cooling capacity, the cooling tower free cooling system reduced a greater amount of CO_2 emissions than the tap water-based free cooling system. However, the CO_2 emission reduction rate of tap water-based free cooling system (0.44 ton/MWh) was 4.4-fold higher than that of the cooling tower free cooling (0.10 ton/MWh), indicating more environmentally friendly.

3.4 Economic analysis

The payback periods of both free cooling methods were analyzed according to Equations (12) to (14). As analyzed in Section 3.2, both free cooling methods achieved significant energy savings. However, additional heat exchangers and pumps are required, thus increasing initial costs. The initial costs were estimated by multiplying the purchase cost of equipment by an installation factor to cover all piping, sensors, electrical installations, foundations, and enclosures, and the installation factor of 3 is used in this study according to a similar economic analysis of the free cooling system in [41]. This results in the installed cost of 7.14x10^6 RMB for the cooling tower free cooling system and 9.45x10^5 for tap water-based free cooling system, as listed in Table 4. The initial cost of cooling towers was excluded since cooling towers were also required in the mechanical cooling system in summer. The operation cost savings was the energy cost savings minus maintenance and repair costs of the system. However, the major maintenance tasks for heat exchangers and pumps are mainly performed at relatively low frequency, such as quarterly, semiannually, or annually, according to ASHRAE standard 180-2018 [42]. In addition, the free cooling systems only operate in winter, which would help to reduce the maintenance and repair cost further. Thus, the maintenance and repair costs were neglected in estimating operation cost, as defined in Equation (14). The operation cost savings are 3.54x10^6 RMB and 6.90x10^5 RMB for the cooling tower free cooling and the tap water-based free cooling system, respectively. The payback period of tap water-based free cooling was 1.4 years, which was slightly shorter than the cooling tower free cooling system (2 years) due to higher COP on the cooling side and natural gas reductions on the heating side. A shorter payback period makes the tap water-based free cooling method an attractive solution for improving the energy efficiency of central cooling systems.

Table 4. Parameters used in the economic analysis

Items	CTFC	TWFC
Heat exchangers (RMB)	1.25x10^6	2.5x10^5
Pumps (RMB)	1.13x10^6	6.5x10^4
Installed Cost (RMB)	7.14x10^6	9.45x10^5
Electricity Saving (MWh)	5802	242
Natural gas savings (m^3)	-	2.06x10^5
Electricity price (RMB/kWh)	0.61	0.61
Natural gas (RMB/m^3)	-	2.63
Operation Cost Saving (RMB)	3.54x10^6	6.90x10^5
PBP (years)	2.0	1.4

4. Discussion

In this study, the potential of a tap water-based free cooling method was explored, and its performance was compared with the widely used cooling tower free cooling system. According to the analysis above, the tap water-based free cooling shows good performance with higher energy efficiency, greater CO2 reduction rate, and shorter payback period. These features make the tap water-based free cooling system an attractive solution for reducing energy consumption of the cooling system. However, the variation of tap water flow rate leads to fluctuations in the supply water temperature, complicating system control and operation. The fluctuation in the supply temperature can be mitigated by controlling the flow rate through the exchangers, such as a three-way control valve. Furthermore, the cooling capacity of the tap water-based free cooling system may be insufficient due to the limited tap water flow rate, necessitating the use of other cooling sources to compensate for the remaining cooling demand. There is considerable water consumption in industrial and domestic uses. For example, China's industrial water consumption was 126.16 billion m^3 and 85.99 billion m^3 for domestic uses in 2019, accounting for 21.0% and 14.3% of the national water consumption, respectively [43]. When the city water network in a district or larger scale is used as the natural cooling source, the cooling capacity will be greater and more stable. The proposed free cooling system also could reduce the heat demand of downstream users, and thus, considerable energy-saving potentials exist.

5. Conclusions

This study proposed a tap water-based free cooling system and explored its energy-saving potential. The proposed tap water-based free cooling system integrated with a cooling tower free cooling and mechanical cooling system was applied in a semiconductor manufacturing factory in Tianjin. The performance of the tap water-based free cooling system was compared with the widely used cooling tower free cooling from thermodynamic, energy, environmental, and economic perspectives. The following conclusions can be founded.

1) Compared with the cooling tower free cooling, the inlet temperature of the tap water-based free cooling system was more stable with a smaller standard deviation of 0.1 °C. However, its outlet water temperature fluctuated significantly with a

standard deviation of 0.9 °C due to the tap water flow rate variation. The operating hours of the tap water-based free cooling system accounted for 27% of a year, which was 10% shorter than the cooling tower free cooling system due to slightly higher outlet water temperature.

2) From the energy analysis, both free cooling systems showed significantly higher energy efficiency than the mechanical cooling system, especially the tap water-based free cooling system. The COP of the tap water-based free cooling system was approximately 7.4-fold higher than that of the mechanical cooling system and 2.2-fold higher than that of the cooling tower free cooling system. Using these two free cooling methods together saved 6,044 MWh electricity for cooling and achieved an annual energy-saving rate of 15.1%. In addition, the tap water-based free cooling system saved 1.48×10^5 kg of natural gas for ultrapure water preheating.
3) Energy reductions from the two free cooling systems reduced 6,236 tons of CO_2 emissions in a year. The CO_2 emission reduction rate of the tap water-based free cooling system was 4.4-fold higher than that of the cooling tower free cooling system, indicating that the tap water-based free cooling method was more environmentally friendly.
4) From the economic analysis, the tap water-based free cooling showed a shorter payback period, which makes it an attractive solution for improving the central cooling system efficiency.

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