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Comparative analysis of energy efficiency for three heating and cooling supply schemes in a region with hot summers and cold winters in a chemical industrial park

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Abstract
Building energy consumption in China accounts for 45% of the total national energy consumption, with air conditioning energy consumption representing approximately two-thirds of that. Therefore, energy efficiency in buildings is of utmost importance. This study focuses on a chemical industrial park located along the Fujiang River and compares three heating and cooling supply schemes: the river water source heat pump system, which utilizes river water as the heat source and heat sink; the water cooling unit and boiler system, which uses water-cooled electric compression chillers for cooling and an oil-fired boiler system for heating; and the split air conditioning and gas water heater scheme, which relies on refrigerants such as fluorine-containing compounds for cooling and a gas water heater for heating. By calculating the energy consumption of the above three schemes and conducting a comparative analysis, it is found that the river water source heat pump system exhibits significantly higher energy efficiency throughout the year compared to the water cooling unit and boiler system and the split air conditioning and gas water heater scheme. This highlights the notable energy efficiency advantage of the river water source heat pump system.

Keywords Hot, Summer, Cold, Winter, Chemical, Industry, River, Water, Source, Heat, Pump, Refrigeration, Heating, Energy, Consumption, Air, Refrigerant, Freon, Energy, Rate

Introduction

China, recognizing the increasingly critical global energy situation, has prioritized energy conservation and emission reduction as fundamental national policies. From the 11th Five-Year Plan to the 14th Five-Year Plan, clear goals for energy conservation and emission reduction have been set. Among various sectors, the energy consumption throughout the entire process of building construction is particularly significant, accounting for 45% of the country's total energy consumption and contributing to 50.6% of the national carbon emissions.

Within the realm of building energy consumption, air conditioning energy consumption constitutes a significant proportion, accounting for approximately two-thirds of the total. The strain on power supply caused by air conditioning becomes particularly pronounced each year, highlighting the evident supply-demand imbalance. Researchers such as Xu et al. (Xu et al. 2016) explored the technical routes and development directions of zero-energy buildings in China, taking into consideration the national context. Li et al. (Li et al. 2023) conducted comparative analyses on different forms of air conditioning in nearly zero-energy residential buildings, including split air conditioning with independent fresh air systems, multi-split air conditioning with independent fresh air systems, and heat pump-based integrated fresh air and environmental control systems. Long (Long 2018) established and analyzed mathematical models for combined gas trigeneration and river water source heat pump systems. Chen (Chen 2017) analyzed the design of a river water source heat pump system in a large public building in Chongqing. Schnieders et al. (Schnieders et al. 2015) examined the adaptability of passive houses within different climate zones, revealing variations in energy efficiency performance. In climate zones characterized by higher temperatures, humidity, and prolonged duration, the energy consumption required for latent and sensible heat removal may exceed 70kWh/(m^{2}a). Zhang (Zhang 2019) conducted simulation studies on the three-dimensional numerical modeling of temperature (cold) discharge in river water source heat pump systems. Liu (Liu 2022) studied process improvements in fluorine refrigerant systems. Shi et al. (Shi et al. 2018) analyzed the operation of a combined cooling, heating, and power tri-generation system with a river water source heat pump in Chongqing. Wu (Wu 2020) analyzed the influential factors on the performance of a river water source heat pump system in Chongqing. Chang (Chang 2023) conducted analyses on various issues related to the energy efficiency of chillers.

From the aforementioned studies, it can be observed that there is a wide range of cooling and heating systems available. Most research efforts have focused on the operational performance and energy consumption of various air conditioning systems, or on the analysis of existing engineering cases. However, there are few comparative analyses based on regional characteristics. As a result, it is difficult for users to determine which system is most suitable for their projects. Therefore, this paper aims to provide a comparative analysis on the energy consumption of different systems, taking into account the long-standing concerns of users. The goal is to identify the optimal cooling and heating solution based on specific environmental conditions.

The three commonly used cooling and heating solutions selected for this study in the Chongqing region are as follows: Scheme 1: River Water Source Heat Pump (RWHP) technology, which is a renewable energy technology that utilizes surface water sources such as groundwater, rivers, lakes, reservoirs, and oceans to convert them into usable cooling sources. Scheme 2: Chiller and Boiler system, where cooling is achieved through water-cooled electrically driven compression chillers, and heating is provided by fuel oil hot water boilers. Scheme 3: Split Air Conditioning and Gas Water Heater, which is a widely applied option. The cooling principle of split air conditioning involves compressing refrigerants such as fluorocarbons into high-temperature and high-pressure gaseous state, which is then sent to the condenser for cooling. After cooling, it transforms into a medium-temperature and high-pressure liquid refrigerant that enters the dryer for filtration and dehumidification. The medium-temperature liquid refrigerant then undergoes pressure reduction via the expansion valve, becoming a low-temperature and low-pressure gas-liquid mixture. Through the evaporator, it absorbs heat from the air and evaporates into a gaseous state. It then returns to the compressor to continue the refrigeration cycle. For heating, a gas water heater is utilized.

Scheme selection

Overview of supported project

This project is a chemical park that integrates the chemical factory buildings and supporting equipment rooms, underground parking garage, kindergarten, and commercial service facilities. Its main functions include chemical factory buildings, apartments, kindergarten, commercial, and service offices.

Selection of cooling and heating schemes

The case project is located on the south side of the park, adjacent to Binjiang Road and Fujiang River. During the dry season, the horizontal distance from the surface of the Fujiang River is about 80 m, and the absolute elevation of the river water level is 185.2 m; During the flood season, the horizontal distance from the surface of the Fujiang River is about 60 m, and the absolute elevation of the river water level is 187.4 m. It can be seen that the horizontal distance between this project and Fujiang is relatively close, with a vertical height difference of over 25 m. If the energy station is built on two underground floors, the height difference will be reduced by about 10 m. Relatively speaking, the height difference is not significant, creating good conditions for the application of Fujiang water as a heat pump system cold and heat source for cooling and heating in residential communities.

To analyze the energy-saving performance of the river water source system, this case study selects and compares two contrasting schemes. The three schemes are presented in Table 1:

Based on the conducted literature research (Peng 2013; Fan 2010), the analysis in this paper will be performed using the Dest dynamic load simulation software to simulate and analyze the annual dynamic building loads in the chemical industrial park. The aim is to derive the annual cooling and heating load conditions under typical meteorological year conditions. The loads of all building categories in the entire project will be summarized, considering the simultaneous usage factor, in order to obtain the overall air conditioning and heating loads and their distribution characteristics. By analyzing meteorological data from Chongqing, the air conditioning cooling season is determined to

Table 1 Heating and cooling supply schemes

No.	Schemes	Equipment selection in cooling season	Equipment selection in heating season	Auxiliary equipment
Scheme I	River water source heat pump system	See Table 2	See Table 2	See Table 2
Scheme II	Chiller and boiler system	Water-cooled electric compression water cooling unit	Fuel oil hot water boiler	Air handling units, such as fan coil units or cabinet-type terminal equipment.
Scheme III	Split air conditioning and gas water heater	See Table 4	See Table 4	See Table 4

Table 2 Selection of hot and cooling source units

Water cooling unit	Two centrifugal chillers CVHE-L800 (TRANE)
Screw type water source heat pump unit	SGHP-QAII-400 (Tsinghua Tongfang)
	HSSWR-EIII-60 S (Tsinghua Tongfang)
	30HXC-HP1-130 A(Carrier)

Table 3 Statistical table of energy consumption of cooling and heat source units

Items	Energy consumption in heating season	Energy consumption in cooling season
Maximum hourly energy consumption of the unit (kW)	1425.65	2454.88
Total energy consumption of cooling and heat source units (kWh)	1729502.49	2531954.36

Table 4 Allocation of water intake pipes on the river side

Length of intake pipe (m)	Flow (m^3/h)	Pipe diameter (m)	Flow rate (m/s)
228.49	1477.51	0.600	1.45

span from May 1 to September 30, whereas the heating season is observed from December 1 to February 28.

Energy consumption calculation of three schemes

Scheme 1 river water source heat pump system

Analysis of energy consumption of cooling and heating source units

(1) Selection of units.

The selected chillers and heat pumps for the project are shown in Table 2:

(2) Unit energy consumption calculation

The relationships between the energy efficiency, heating (cooling) capacity, and input energy consumption of the units are provided in references (Li 2011; Gilbong et al. 2021; Lisnianski et al. 2020; Jung et al. 2021). For heating/hot water operation conditions:

$$COP = \frac{Q_r}{p_r} \tag{1}$$

where: Q_r - Heating capacity under heating conditions (kW); P_r - Input power of the unit under heating conditions (kW).

For cooling conditions:

$$EER = \frac{Q_c}{p_c} \tag{2}$$

where: Q_c - Cooling capacity of the unit under cooling conditions (kW); P_c - Input power of the unit under cooling conditions (kW).

By using the above equations based on the hourly building cooling and heating loads and the hourly load ratios under cooling and heating conditions, the hourly energy consumption of each cooling and heating source unit, as well as the total hourly energy consumption of all units, can be obtained for cooling and heating conditions. The summarized results provide the total energy consumption of the cooling and heating source units under heating, cooling, and year-round hot water conditions, as shown in Table 3.

Table 5 Selection of circulating pump on user side for cooling and heating

	Model of pump	Flow (m^3/h)	Head (m)	Rotational speed (*r*/min)	Power (kW)
Phase I building circulation pump	250–315	550	32	1450	75
Phase II building circulation pump	200-200IA	358	10	1450	18.5

Table 6 Selection of primary water pump at river side for cooling and heating

	Model of pump	Flow (m^3/h)	Head (m)	Rotational speed (*r*/min)	Power (kW)
Primary water pump at river side	200–330	400	128	2900	220

Table 7 Selection of secondary water pump at river side for cooling and heating (one pump for one unit)

	Model of pump	Flow (m_3/h)	Head (m)	Rotational speed (*r*/min)	Power (kW)
1–130 A	80–160 (I)	100	32	2900	15
1–400 A	200-315IA	374	28	1450	45
L800	300-460B	614	45	1450	110

Energy consumption analysis of transmission and distribution systems

The energy consumption of the river water source heat pump distribution system includes the energy consumption of the primary and secondary pumps on the water source side, the circulation pumps for the cold and hot water distribution network (circular), the pumps for the branch pipe network, and the energy consumption of the tertiary pumps on the user side.

(1) Equipment selection.

Based on the relationship between the flow rate, water velocity, flow rate, and diameter of the distribution pipelines on the river water side of the river water source heat pump system, as well as the recommended value for the water flow velocity in the pump suction pipe, the configuration of the river water intake pipeline and each level of pumps is determined as shown in Tables 4, 5, 6 and 7.

(2) Energy consumption model of water pump

According to the similarity law of pumps (Hosseinkhani and Kargari 2022), when the rotational speed of a pump varies within a certain range, there exists the following relationship between power, head, and flow rate:

$$\begin{cases} \dfrac{G_1}{G_2} = \dfrac{n_1}{n_2} \\ \dfrac{N_{z1}}{N_{z2}} = \left(\dfrac{n_1}{n_2}\right)^3 \\ \dfrac{H_1}{H_2} = \left(\dfrac{n_1}{n_2}\right)^2 \end{cases} \tag{3}$$

where: G1, G2 - water flow rates handled by the pump at rotational speeds n_1 and n_2 (m^3/h); H_1, H_2 - pump heads at rotational speeds n_1 and n_2(mH_2O); N_{z1}, N_{z2} - shaft powers of the pump at rotational speeds n_1 and n_2 (kW).

Single pump power:

Table 8 Summary of energy consumption of water source heat pump system (kWh)

	User side			River side		Total energy consumption of transmission and distribution systems
	Three-stage water pump	Secondary water pump	Circulation pump	Heat pump water intake pump	Primary water intake pump	
In heating season	10566.53	7345.70	32405.00	189960.81	41315.00	281593.04
In cooling season	30073.91	20906.94	92229.46	418035.43	146876.07	708121.81
Sanitary hot water supply throughout the year	15207.13	3387.39	10697.44	47827.79	48720.69	125840.44

Table 9 Summary of energy consumption for end devices in the river water source heat pump system (kWh)

Energy consumption of end devices	
In heating season	174538.94
In cooling season	273902.09

$$N_{z\tau} = \left(\frac{G_\tau}{G_0}\right)^3 N_{z0} \tag{4}$$

where: N_{zr} - shaft power of a single pump at time τ after frequency conversion(kW); G_τ - flow rate handled by the pump at time τ(m^3/h); G_0 - rated flow rate of the pump(m^3/h); N_{z0} - rated shaft power of the pump(kW).

The energy consumption of the user side pump during cooling, the energy consumption of the user side pump during heating, the energy consumption of the river side pump during both cooling and heating seasons, and the energy consumption of the pump for supplying sanitary hot water can be calculated according to the above equations. The energy consumption of the distribution system can then be summarized as shown in Table 8.

Analysis of energy consumption of end devices

The strategy for controlling the hourly operating load rate of end devices is proportional to the ratio of hourly cooling and heating loads to the design load, i.e.:

$$N_{md,i} = \frac{Q_i}{Q_{C\max}} N_0 \tag{5}$$

where, N_0 - Rated power of the end device (kW); $N_{md,i}$ - Hourly power of the end device (kW);

Q_{Cmax} - Design load (kW); Q_i - Hourly cooling or heating load (kW).

By considering a coefficient of simultaneous use of 0.4 for end devices in both cooling and heating conditions, the hourly energy consumption of the end devices can be calculated using the above equation. The cumulative energy consumption of the end devices in the river water source heat pump system is shown in Table 9.

Total energy consumption of water source heat pump system

In conclusion, the total energy consumption of the river water source heat pump system for this project is shown in Table 10.

Table 10 Energy consumption summary for the cooling and heating source system (kWh)

	Energy consumption of transmission and distribution systems	Energy consumption of heat pump unit	Energy consumption of end devices	Total energy consumption
In heating season	281593.04	1729502.49	174538.94	2185634.48
In cooling season	708121.81	2531954.36	273902.09	3513978.26
Sanitary hot water supply throughout the year	125840.44	1100228.76	——	1226069.20

Table 11 Design load (scheme II)

Design value of cooling load (kW)	Design value of heating load (kW)	Design value of sanitary hot water load (kW)
10788.13	6246.64	1039.75

Scheme 2 Chiller and hot water boiler scheme

Option 2 adopts a water-cooled electric compression chiller for summer cooling, a fuel fired hot water boiler for winter heating, and other end equipment such as fan coil units or cabinet air handling units.

Water cooling refers to the condenser of its compressor being cooled by water, which requires a set of cooling water system. A fuel vacuum hot water boiler, using diesel as fuel, works by utilizing the low boiling point of water at low pressure to quickly heat the heat medium water filled in a sealed furnace, causing the heat medium water to boil and evaporate into high-temperature water vapor. Water vapor condenses on the heat exchange tube, heating the cold water inside the tube to supply hot water.

Equipment selection

The calculation equation for selecting the capacity of an electric water cooling unit is provided in reference (Liu 2022), as follows:

$$Qe = A1A2A3A4QC \tag{6}$$

where, Q_e - Design capacity of the water cooling unit (kW); Q_c - Design cooling load of the air conditioning system (kW); A_1 - Simultaneous use coefficient of the building, which is influenced by factors such as the functional nature, grade, regulations, and management of the building, and generally ranges from 0.6 to 1.0; A_2 - Coefficient for cooling losses, typically taken as 1.05 to 1.15; A_3 - Correction coefficient for accident standby capacity, considering that during peak load periods with 2–3 units operating, if one unit fails, the remaining units can still sustain approximately 75% of the load; A_4 - Coefficient accounting for equipment heat transfer and output efficiency reduction, provided by the manufacturer's specifications.

In the water system for Scheme 2, the user side is divided into three levels of pipelines, with a total of two phases and eight blocks. Taking into account the factors mentioned above, the values of A_1, A_2, and A_3 are all taken as 1, and the heat transfer loss coefficient A_2 for each level of heat exchange is set to 1.10, the same as in Scheme 1. The calculation of the installed capacity of the fuel boiler follows the same method.

Based on the calculation, the capacities of the water cooling unit and the fuel boiler in Scheme 2 are shown in Table 11.

Table 12 Cooling and heating equipment configuration (Scheme 2)

Cooling and heating source equipment	Items	Number	Capacity of a single unit	Total capacity	Usage
Standard type cooling tower: FBL-600	Power (kW)	2	Inlet water pressure (kPa)	Cooling capacity (m^3/h)	Corresponding to CVHE-L1610
	22		80	600	
Centrifugal chillers: CVHE-L1610 (TRANE)	Cooling capacity (kW)	2	4570.8	9141.6	Cooling
	Input power (kW)		802	1604	
Standard type cooling tower: FBL-300	Power(kW)	1	Inlet water pressure (kPa)	Cooling capacity (m^3/h)	Corresponding to CVHE-L800
	7.5		60	300	
Centrifugal chillers: CVHE-L800 (TRANE)	Cooling capacity (kW)	1	2285	2285	Heating
	Input power (kW)		401	401	
Fuel oil vacuum hot water boiler: ZKW1.05-65/55-Q.Y (Shanghai Bojian)	Heating capacity (kW)	1	1050	1050	Heating and sanitary hot water supply
	Light diesel fuel consumption (kg/h)		99	99	
Fuel oil vacuum hot water boiler: ZKW2.8-65/55-Q.Y (Shanghai Bojian)	Heating capacity (kW)	2	2800	5600	Heating and sanitary hot water supply
	Light diesel fuel consumption (kg/h)		264	528	

Table 13 Cooling water pump selection calculations (Scheme 2)

	Length of cooling water pipe(m)	Circulation pipe flow (m^3/h)	Condenser pipe diameter (m)	Flow velocity (m/s)	Relative friction coefficient RC (Pa/m)	Longitudinal resistance (Pa)	Local resistance (Pa)	Condenser pressure drop (Pa)	Tower inlet pressure drop (Pa)	Pump head (m)	Motor power (kW)
CVHE-L1610	10.00	590.42	0.350	1.70	70	700	385	63,000	80,000	16.91	124.78
CVHE-L800	10	295.16	0.250	1.67	104	1040	572	98,000	60,000	18.73	69.10

Based on Table 12, the selection of cooling and heating equipment for Scheme 2 has been carried out, and the equipment configuration is determined as shown in Table 12.

Calculation of energy consumption in cooling season

Since there have been no changes in the user side load requirements that the system needs to meet, the design and energy consumption of user side distribution systems in both Scheme 1 and Scheme 2 remain the same. The energy consumption on the cooling source side only takes into account the energy consumption of the cooling water pump, as in the chiller and hot water boiler scheme, the cooling water is circulated between the cooling tower and the condenser through the cooling water pump during the cooling process. When it comes to heating and sanitary hot water supply, only the energy consumption of the water intake side distribution system is considered.

(1) Energy consumption of cooling water pump.

Cooling water pump selection calculations (Sanjivy et al. 2023) are shown in Table 13.

The selection of cooling pump is shown in Table 14.

(2) Unit energy consumption

Based on the unit sample parameters, combined with the centrifugal chiller energy consumption model of Scheme 1 and the unit energy consumption method, the hourly

Table 14 Cooling water pump selection calculations (Scheme 2)

	Model of pump	Flow (m^3/h)	Head (m)	Rotational speed (r/min)	Power (kW)
CVHE-L1610	300–400	720	50	1450	132
CVHE-L800	200–400(I)A	374	44	1450	75

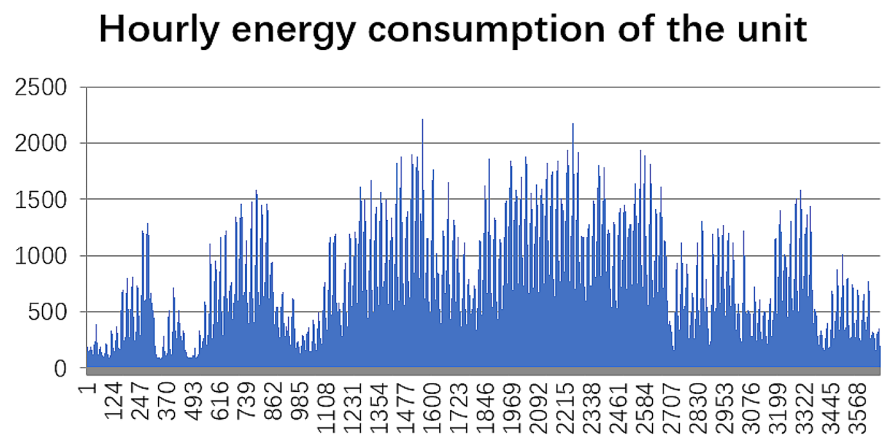

Fig. 1 Hourly energy consumption of centrifugal chiller in cooling season (kW)

Table 15 System energy consumption statistics for the cooling season (Scheme 2)

Energy consumption of transmission and distribution systems (kWh)	Energy consumption of water cooling unit (kWh)	Energy consumption of end devices (kWh)	Total energy consumption (kWh)
375324.20	2463258.08	273902.09	3112484.37

energy consumption of the centrifugal water cooling unit during the cooling season can be calculated, as shown in Fig. 1.

(3) Energy consumption of end devices.

The user side load requirements that the system needs to meet have not changed, and the end system design and energy consumption for Scheme 2 are the same as Scheme 1. Therefore, summarizing the above results, the system energy consumption during the cooling season can be obtained as shown in Table 15.

Based on the system characteristics, the total water demand on the cooling source side during the cooling season can be calculated using the water demand equation as 1,676,981.87 m^3.

Calculation of energy consumption for heating and sanitary hot water supply

In this paper, the energy consumption of the boiler under ideal conditions is considered as the energy consumption for heating and sanitary hot water supply. This means that the heat generated by the boiler can exactly meet the heat demand on the user side. The thermal efficiency of the hot water boiler is assumed to be 0.92.

Calculation of boiler fuel consumption:

$$\mathrm{M} = \frac{3600\mathrm{Q}}{\gamma \times \eta} \tag{7}$$

Table 16 Energy consumption statistics for Scheme 2 during heating and sanitary hot water supply

	Energy consumption of transmission and distribution systems (kWh)	Fuel consumption of gas boiler (kg)	Energy consumption of end devices (kWh)	Total energy consumption (kWh)
Heating	50317.23	655562.21	174538.94	7973601.51
Sanitary hot water supply	29291.96	272242.43		3247197.50

Table 17 Configuration of split air conditioners and gas water heaters

Items		Phase I project			Phase II project	Total (unit)	Purchase fee (Yuan)
		chemical park (m^2)	Service, offices (m^2)	Kindergarten (m^2)	Housing (households)		
Construction scale		**19752.37**	**4941.28**	**2207.31**	**620**		
Split air conditioner configuration	1P wall-mounted unit	0	1642	0	1240	2882	7,205,000
	2P wall-mounted unit	0	821	0	620	1441	4,755,300
	3P cabinet unit	494	924	55	620	2093	12,662,650
Gas water heater configuration	RUS-16E22CWNF	494	924	55	620	2093	7,116,200

Table 18 Main performance parameters of split air conditioners and gas water heaters

	Cooling capacity (W)	Cooling power (W)	Heating capacity (W)	Heating power (W)
3P cabinet unit	7200	2337	7850	2350
2P wall-mounted unit	5000	1538	5500	1617
1P wall-mounted unit	2650	815	2920	810
Gas heater	Heat efficiency		85%	

where: M - Diesel consumption (kg); Q - Heat load(kW); - Diesel calorific value, taken as 42,552 kJ/kg; - Boiler coefficient, taken as 0.92.

After calculation, the diesel consumption for heating and sanitary hot water supply in this scheme is 655,562.21 kg and 272,242.43 kg respectively. The energy consumption of the distribution system and end-use devices is calculated as shown in Table 16.

Scheme 3 Split air conditioner and gas water heater

Split air conditioners are greatly influenced by the ambient temperature. As a result, the operating efficiency of the units is not high, and the Coefficient of Performance (COP) value is typically below 3.0 (Menekşe et al. 2022).

Equipment selection

Based on the usage habits of split air conditioners in the project's location, equipment selection and configuration for this scheme are shown in Table 17.

The performance parameters of the split air conditioners and gas water heaters units are shown in Table 18.

Table 19 Energy consumption of split air conditioners and gas water heaters

	Heating	Cooling	Sanitary hot water supply
Power consumption (kWh)	2219181.56	5975940.36	0
Gas consumption (kg)	0	0	358693.05

Table 20 Energy efficiency ratios for Scheme 1 to Scheme 3

Energy efficiency ratios	Scheme 1	Scheme 2	Scheme 3
Cooling	4.42	4.54	1.87
Heating	4.12	0.92	3.21
Annual domestic hot water	2.69	0.92	0.85

Energy consumption calculation

After conducting hourly analysis, the energy consumption (Menekşe et al. 2022) for cooling, heating, and hot water supply in chemical industrial park Scheme 3 is shown in Table 19.

System energy efficiency and energy-saving analysis

The coefficient of performance (COP) refers to the ratio of the actual cooling or heating capacity to the actual input power during the operation of the unit or system. It is a comprehensive indicator that reflects the cooling heat produced by the input power of the unit or system during operation.

Energy efficiency ratio

The Energy Efficiency Ratio (EER) for cooling and the Coefficient of Performance (COP) for heating are ratios of cooling capacity and heating capacity to the energy consumption of the cooling and heating units, respectively. In other words:

$$EER = \frac{Q_c}{E_c} \tag{8}$$

$$COP = \frac{Q_h}{E_h} \tag{9}$$

where, Q_c - cooling capacity (kWh); Q_h - heating capacity (kWh); E_c - energy consumption for cooling by the unit (kWh); E_h - energy consumption for heating by the unit (kWh).

According to the above equations, the energy efficiency ratios for cooling, heating, and sanitary hot water for Scheme 1 to Scheme 3 are presented in Table 20.

As observed from Tables 8 and 9, Scheme 2 has a higher EER compared to Scheme 1 primarily due to the centrifugal water chiller in Scheme 2 having a higher rated EER than the screw-type river water heat pump unit in Scheme 1.

For heating and sanitary hot water supply in Scheme 2, a hot water boiler is utilized. Based on the assumption of ideal operation and boiler samples, the heating efficiency of the boiler is assumed to be 0.92, which is significantly lower compared to the EER of 4.12 for the river water heat pump unit in Scheme 1. Scheme 3 cannot be directly compared with Scheme 1 as its energy efficiencies are lower across all seasons.

Table 21 PER of Schemes 1 to 3

Season PER	In cooling season	In heating season	Annual supply of domestic hot water	Annual PER
Scheme 1	0.88	0.90	0.61	0.84
Scheme 2	1.00	0.83	0.89	0.92
Scheme 3	0.52	0.89	0.85	0.64

Table 22 Energy consumption of Schemes 1 to 3

	Power consumption (kW)	Fuel/gas consumption (kg, Nm^3)	Water consumption (m^3)
Scheme 1	7052940.37	0.00	2934147.76
Scheme 2	3366632.50	927804.64	16769.82
Scheme 3	8195121.92	358693.05	0.00

Primary energy utilization efficiency analysis

To better evaluate the energy-saving performance of the three schemes, further analysis is conducted using the primary energy utilization efficiency (PER). This analysis involves converting the secondary energy or energy-consuming working fluid in the total supplied energy into equivalent heat value in order to calculate the energy utilization efficiency.

The primary energy utilization efficiency (Kim et al. 2020) (PER) is defined as the ratio of the obtained energy to the primary energy consumed in obtaining that energy. The expression for PER is as follows:

$$PER = \frac{Q_{gain}}{E_{primary}} \tag{10}$$

where, Q_{gain} - Energy obtained by the system; $E_{primary}$ -Primary energy consumption of the system.

For the design of different cooling and heat source systems in various energy forms, the expression for PER is as follows:

$$\mathrm{PER} = \frac{Q_{\mathrm{c}} + Q_{\mathrm{h}}}{\frac{(E_C+E_H)}{\eta_f \times \eta_w} + \frac{\sum_{i=1}^{n} M_i \times q_i}{3600}} \tag{11}$$

where, η_w - Efficiency of electricity transmission grid, assumed to be 92%; η_f - Efficiency of power plants, assumed to be 30.1% (coal consumption for power generation is 404 g standard coal per kWh); M_i - Consumption of the i-th type of other energy in the system (kg or m^3); q_i - Calorific value of the i-th type of other energy consumed in the system (kJ/kg or kJ/ m^3). Other symbols remain the same.

By calculating the above equations, the PER of Schemes 1 to 3 for each season and the entire year are presented in Table 21.

Energy saving analysis

The energy consumption comparison of Schemes 1 to 3 is shown in Table 22.

The water consumption of Scheme 2 in the table is calculated based on a drift rate of 10‰ for the closed cooling tower.

Conclusions

Based on the analysis and calculations above, it can be concluded that the energy efficiency of Scheme 1, the river water source heat pump system, is significantly higher than that of the hot water boiler in Scheme 2 under heating conditions. However, under cooling conditions, the energy efficiency of Scheme 1 is slightly lower than that of Scheme 2, primarily due to the lower energy efficiency of the screw-type heat pump unit in Scheme 1 compared to the centrifugal water cooling unit in Scheme 2. As for Scheme 3, its energy efficiency is lower than that of Scheme 1 in all operating conditions.

In terms of overall annual performance, the river water source heat pump system in Scheme 1 has a much higher annual energy efficiency compared to Scheme 2 and Scheme 3. This indicates that Scheme 1 demonstrates a significantly higher energy efficiency.

Author contributions

K.W. Jiang wrote the main manuscript text and W. Zhang contributed to methodology and formal analysis.

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Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical approval

Not applicable.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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