ENERGY-WATER NEXUS FOR INTEGRATING COOLING WATER WITH DUAL-PURPOSE HEAT PUMPS

A Thesis

by

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ABSTRACT

The energy crisis has gradually become an important issue facing the world. There are limited reserves of coal, oil, natural gas and other resources. Furthermore, fossil-fuel combustion can cause environmental problems such as global climatic changes. In recent years, there has been a growing attention to energy cascade utilization and waste heat recovery. There has also been a recognition that energy and water issues are intertwined. Addressing the shortages of water and energy in an integrated manner is key to economic development and social progress.

Upon the use of once-through cooling water in power plants and industrial facilities, the discharged water may be too hot for immediate discharge to the surrounding water bodies and may cause thermal pollution. This work proposes to extract excess heat from the cooling water leaving the power plant and to effectively use it to drive a heat pump. The net result is the mitigation of thermal pollution and the reduction of external-fuel usage in heat pumps. A theatrical analysis is carried out for the proposed configuration. To illustrate the validity of the recommended system, a case study is solved and a techno-economic analysis is carried out.

ACKNOWLEDGEMENTS

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1 INTRODUCTION

1.1 Water-energy nexus

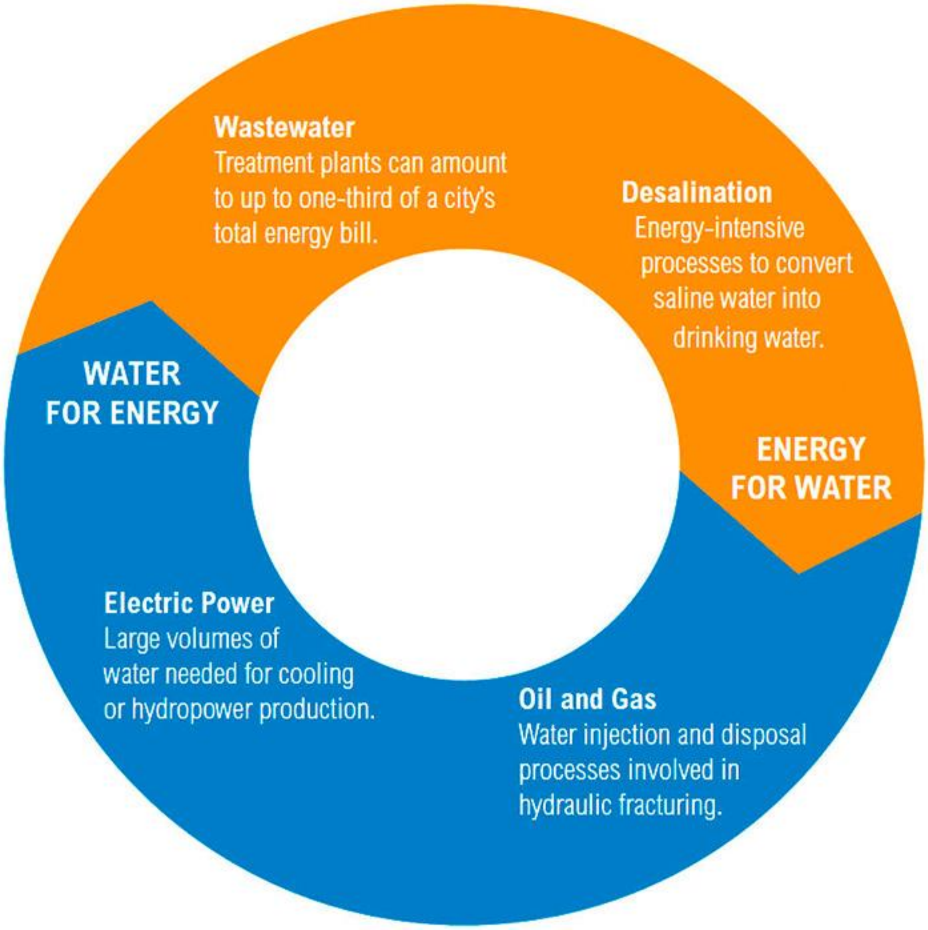

Figure 1. Water-energy nexus [1]

Figure 1 shows the relationship between water and energy. With the development of science and technology, many countries pay more and more attention to energy conservation and emission reduction. The energy crisis has gradually become an important issue across the world. Due to the limited reserves of coal, oil and natural gas, heat recovery has been paid more and more attention in recent years.

Water and energy are both important natural resources, and the relationship between them is very close. At present, almost all energy exploitation and utilization are inseparable from the water, and the use of water resources always be energy-driven. However, with the growing demand for water and energy from economic and social development, water and energy are two major factors that may constrain future economic and social sustainable development. The United Nations set the theme of World Water Day on March 22, 2014 as "Water and Energy", which fully demonstrates the great importance attached to water and energy issues at the global level. The international attention on water resources and energy is gradually increasing, and some researches on water-energy nexus are carried out. The water-energy nexus is of great importance to the world's water and energy security. [1] For the United States, Water-energy nexus is mainly influenced by the following factors. First, climate change has already begun to affect precipitation and temperature patterns across the United States. Second, U.S. population growth and regional migration trends indicate that the population in arid areas, such as the Southwest, is likely to continue to increase, further impacting the management of both energy and water systems. Third, introduction of new technologies in the energy and water domains could shift water and energy demands. [2]

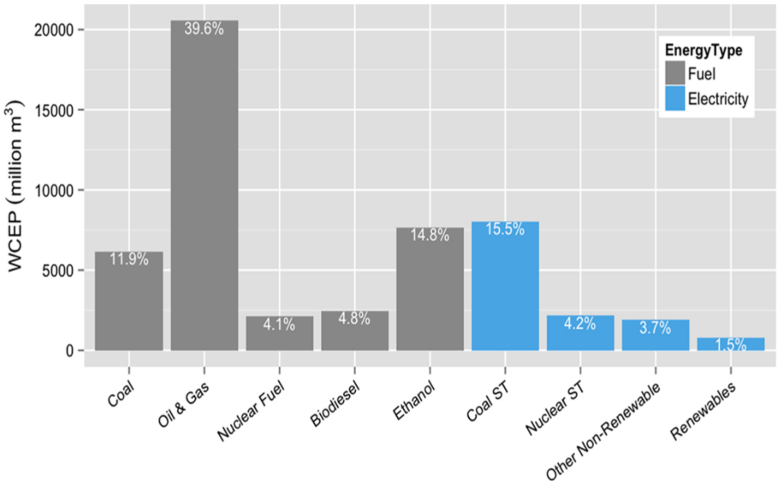

Figure 2. Water consumption of energy production

（Source: iopscience.iop.org）

Figure 2 shows that thermoelectric power accounts for 80% of global electricity production, which is a big water user. In the United States and several Western European countries, 15.5% of the water is used to produce thermoelectric power. The consumption of water by thermoelectric production depends mainly on the choice of cooling technology, not on whether the fuel is coal, natural gas, nuclear energy or oil. In addition, hydroelectric power also needs abundant water resources.

In water-energy nexus, renewable resources are also an important part. At present, 15% of the world's electricity comes from hydropower. Hydropower is being used as a major renewable energy source all over the world. This will result in competition for water resources between different sectors and the environment. After the dam is established, the surrounding land become a lake. This will have an impact on the local rainfall and temperature. In addition, changes in the river may cause the death of local creatures. From a water-saving perspective, the most sustainable source of energy comes from wind and solar, but both are intermittent and the manufacturing process of these devices consumes a lot of water. On the other hand, the exploitation and utilization of water resources consumes energy. The collection and transportation of water resources are inseparable from energy. In general, the relationship between water and energy is complex, and they depend on each other.

Recycling the cooling water heat of the power plant can effectively reduce the energy consumption of the power plant. Besides, this measure can improve the power plants' economic benefits and energy efficiency. This will make the power plant more environmentally friendly.

1.2 Eco-Industrial Park

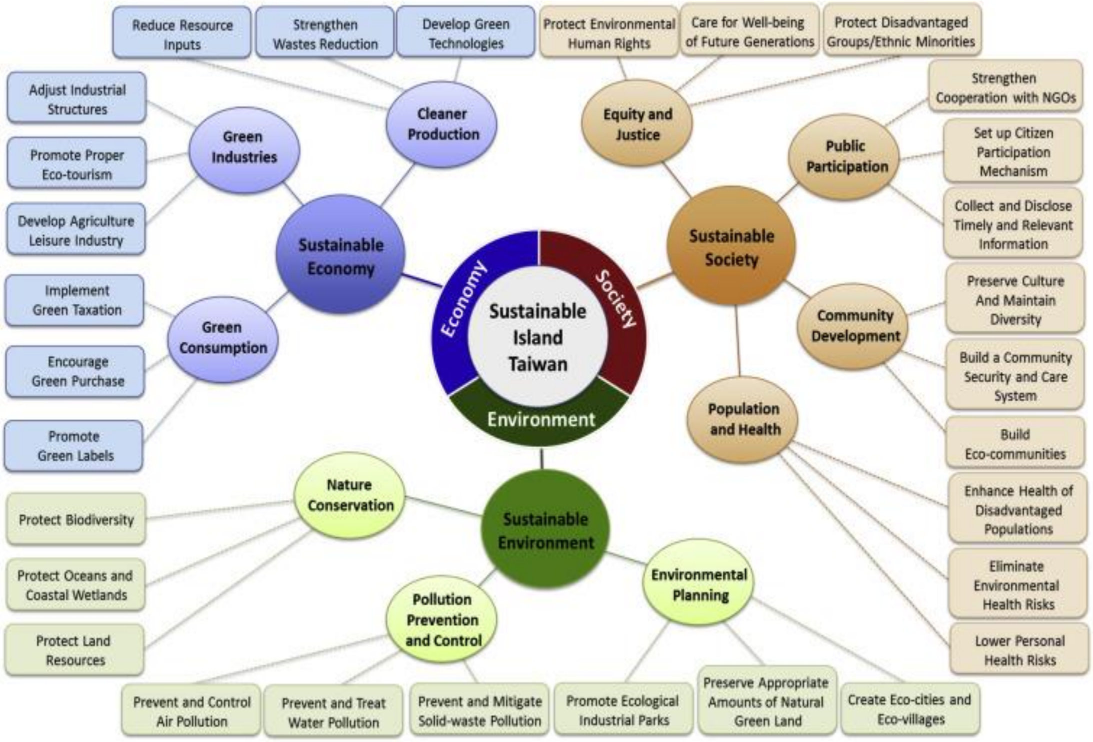

Figure 3. An eco-industrial park's structure [3]

Figure 3 shows an eco-industrial park’s structure. An eco-industrial park's goal is to increase its economic efficiency while minimizing the environmental impact of participating businesses. These approaches include green design, cleaner production, pollution prevention, improving energy efficiency and intra-firm cooperation. The biggest difference between the eco-industrial park and the traditional industrial park is that, guided by the theory of eco-industry, the eco-industrial park focuses on the construction of ecological chain and eco-net in the park to maximize the efficiency of energy using and reduce the emission of pollutants. Different from the traditional "design-production-use-disposal" mode of production, eco-industrial park follows the recycling economy model of "Recycling - Reuse - Design - Production". It is modeled on the natural ecosystem material circulation, so that different enterprises form a symbiotic combination of industries that share resources and exchange by-products. This can achieve the optimal allocation of resources between each other.

Circular principle is an important principle of eco-industrial park, including four aspects.

(1) The material cycles. The resources that industrial development relies on are limited. However, industrial production always consumes these resources continuously, and produces wastes in large quantities after production and consumption. The key to resolving this contradiction is to achieve the recycling of waste materials.

(2) Rational use of energy. Although the energy cannot be recycled, it can be used according to energy quality to achieve cascade energy. Waste heat recovery process or the use of waste energy can increase energy efficiency. This is an important way to save energy.

(3) Information sharing and feedback. The flow of information can reduce the use of energy. This is the guarantee for the steady development of eco-industry.

(4) Diversity is also one of the important principles of eco-industrial park. The principle of diversity is the basis for building the eco-industrial park ecological chain. In the construction of eco-industrial park, different products and different enterprises can be introduced to make use of their differences in energy needs to achieve energy saving.

With the development of industrial system, the structure has become more and more complex. While the direction and ways of contact within the system have increased, the eco-industrial park has gradually become more and more complete. Mutual use of waste between enterprises breaks the original one-way linear model, and it forms a multi-directional flow of non-linear structure. The waste produced in the company's production process is fully utilized in the recycling process, so there is no need to establish a company that specifically deals with pollutants. Compared with the early eco-industrial park, the new eco-industrial park not only has ecologically stable, but also has high market stability. Even if an enterprise is discontinued due to the market, it will not lead to the destruction of the entire eco-industrial park system.

1.3 Energy system

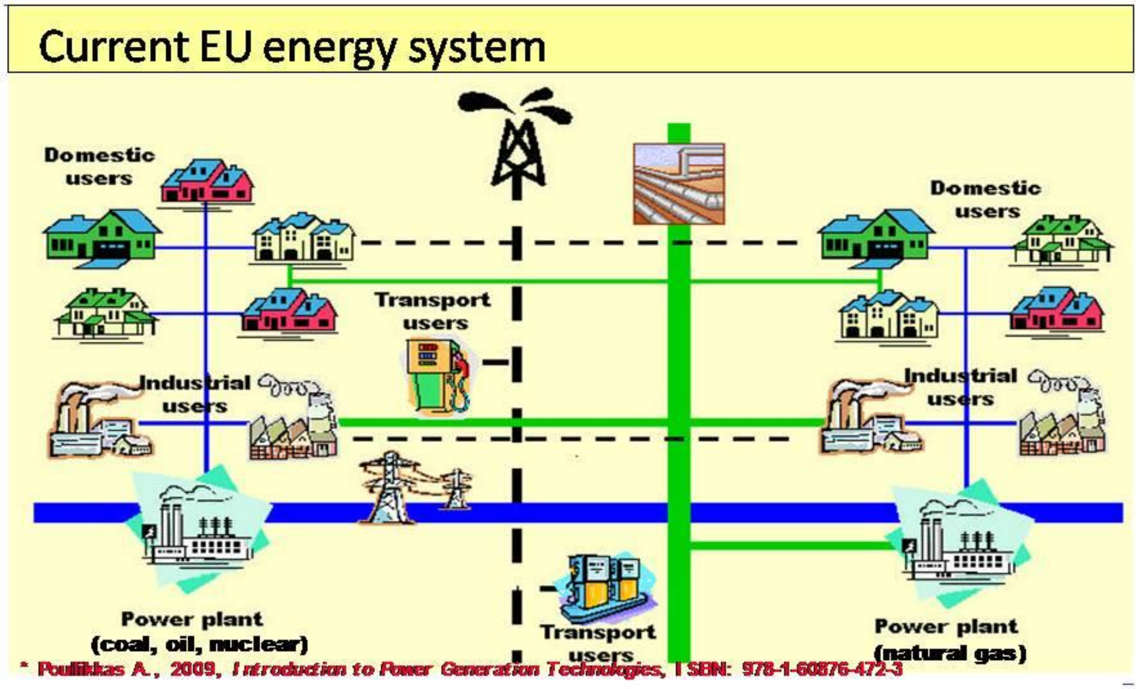

Figure 4. A type of energy system

(Source: http://www.renewablegreenenergypower.com/future-sustainableenergysystems/)

Figure 4 shows the current EU energy system. An energy system is a system that primarily designed to supply energy-services to end-users. [4] From a structural viewpoint, the IPCC Fifth Assessment Report defines an energy system as "all components related to the production, conversion, delivery, and use of energy”. [5] The field of energy economics includes the energy market, which regards the energy system as a technical and economic system that meets consumer demand for heat, fuel, and electricity. Thus, the analysis of energy systems connects the disciplines of engineering and economics. Combining knowledge of these two areas is challenging, especially when it comes to Macroeconomic. [6] From the aspect of structure, energy systems, like any general system, consist of a series of interacting components located in the environment. The composition of the energy system and the determination of behavior depend on the environment, purpose, and function. Therefore, the energy system is an abstract concept. In the process of solving practical problems, the energy system should be designed according to the situation.

1.4 Energy structure

In today's energy structure, non-renewable resources are still the main sources of energy. Fossil fuels impact the environment in two ways. First is global climate change. Fuel combustion produces a mountain of carbon dioxide, which can increase the concentration of carbon dioxide in the atmosphere and resulting in a greenhouse effect. The greenhouse effect will change the global climate and endanger the ecological balance. The second is thermal pollution. Waste heat from thermal power plants is discharged into rivers, lakes, the atmosphere or the sea, which causes heat pollution in most cases. For example, when high-temperature hot water is discharged into a lake, creatures in the lake will die because of a sharp rise in temperature. Therefore, the original ecological balance was destroyed, and then causes many environmental problems.

Figure 5 shows the global energy structure and the Chinese energy structure. It shows that coal still accounts for a large proportion in energy using. In China, coal accounts for more than 60% of the total energy consumption. Coal mining and utilization will consume a lot of water. If the waste heat of fuel combustion is recovered, the system can save a lot of fossil fuels every year. Since water is required for the exploitation and utilization of energy, waste heat recovery also helps save water. At the same time, environmental problems can be alleviated by reducing the amount of fuel used.

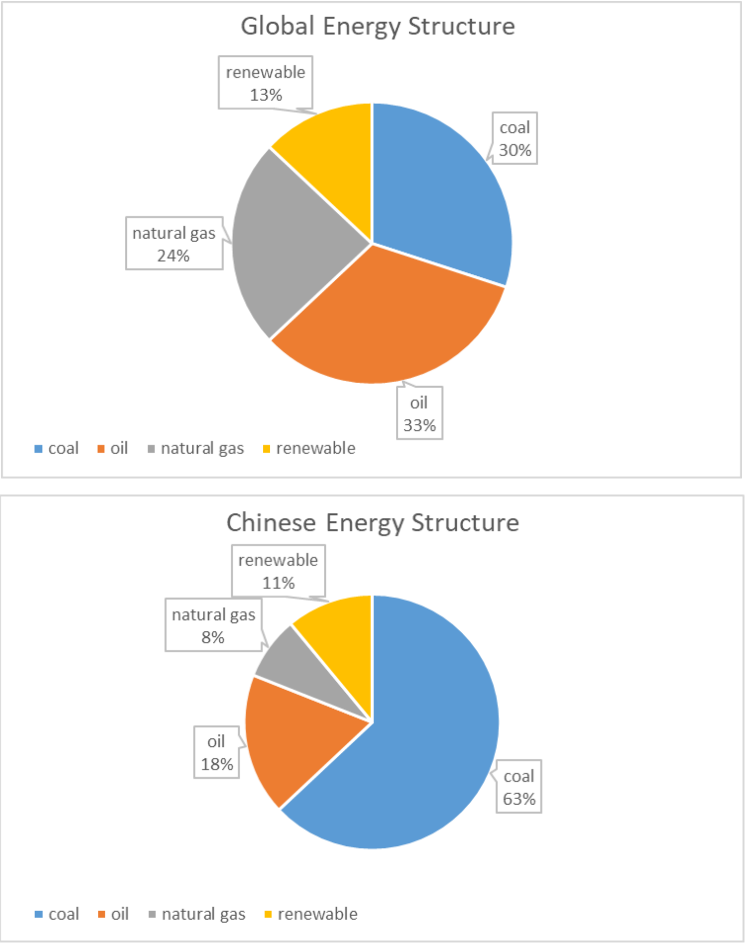

Figure 5. Global and Chinese energy structures

So far, the dominant position of fossil fuel in energy consumption remains irreversible, but its structure is constantly changing. After entering the 20th century, especially since the Second World War, the consumption of oil and natural gas continued to increase. Finally, oil replaced coal as the most important energy source.

Although the status of fossil energy as a dominant energy will not change in the short term, the future energy structure will change significantly due to the impact of factors such as global climate change and the development of new technologies. On the one hand, in the foreseeable future, the proportion of fossil energy will continue to decline, while the proportion of renewable energy will continue to rise.

On the other hand, due to the development of new technologies, the cost of natural gas exploitation is getting lower and lower. And as a relatively clean and low-carbon fuel, natural gas will replace coal as the second largest fuel. Although there are certain differences in the predictions of different institutions, as long as countries take certain measures to solve the problem of climate change, the trend of energy structure changes in the future is about the same. The proportion of fossil fuel in primary energy consumption has decreased significantly, from the current 85% to about 75%. Among them, oil is expected to grow steadily at an average rate of 0.9% per year, but its proportion in primary energy is declining. Nevertheless, oil is still the most important fuel; natural gas is expected to grow at an average rate of 1.8% per year. Natural gas will become the fastest growing fossil fuel and will replace coal as the second largest fuel by 2030. In addition, the proportion of non-fossil energy has risen rapidly, especially renewable energy. [7]

As the global energy structure gradually changes, the energy structure of various regions of the world has also changed. In the future, due to carbon emissions constraints, the proportion of coal consumption in Asia will be significantly reduced, while the proportion of natural gas and non-fossil energy will tend to rise. Taking China as an example, according to the prediction of the China Energy Research Association, by 2030, the proportion of coal consumption has dropped significantly to 49%, which is a decrease of 15% compared to 2015. The proportion of oil consumption will drop to 17%. Clean energy (including natural gas and non-fossil energy) will account for 34% in total energy using. It can be seen that the optimization of China's primary energy consumption structure is consistent with the changing trend of the world's energy consumption structure. [8]

In general, North America's "shale gas revolution", the rapid development of developing countries, global climate change, and breakthroughs in new energy have prompted a significant change in the world's energy landscape. These changes can be summarized in the following five aspects:

(1) The rapid development of emerging market countries will drive the continuous growth of energy demand.

(2) Natural gas will replace coal as the second largest fuel in the future, and the proportion of renewable energy will rise rapidly.

(3) With the development of shale gas, energy supply has become more polarized and diversified.

(4) The focus of energy trade has shifted from the Atlantic Basin to the Asia-Pacific region.

(5) In the future, global energy supply and demand will tend to balance, and energy prices will gradually increase.

1.5 Heat pump

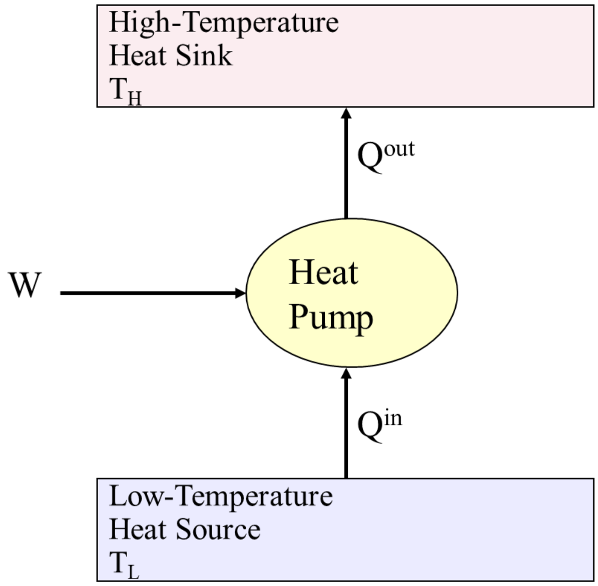

Figure 6. Heat pump

(Source: El-Halwagi, 2017)

A heat pump is a device that transfers thermal energy from a low temperature source to a high temperature source. Figure 6 shows the schematic of a heat pump. The "pump" is a kind of mechanical equipment that can increase the potential energy. For example, a water pump can pump water from a low position to a high position. The heat pump is a device that can take heat from air, water, or soil and then absorb energy from the outside to provide energy that can be utilized. The working principle of the heat pump system is consistent with the refrigeration system.

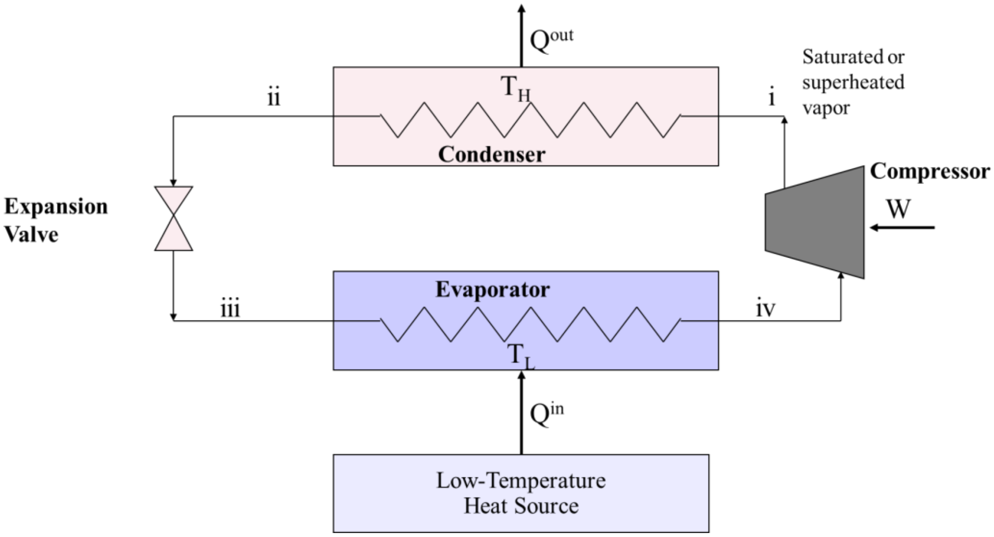

Figure 7. A Vapor-Compression Heat Pump

(Source: El-Halwagi, 2017)

The composition of the heat pump is shown in Figure 7. Heat pump generally consists of four parts: compressor, condenser, expansion valve and evaporator. Its work process consists of the following four parts.

(1) The low-temperature and low-pressure liquid refrigerant first absorbs heat from the low-temperature heat source and vaporizes into low-pressure steam in the evaporator.

(2) The refrigerant gas is then compressed in the compressor and becomes high-temperature, high-pressure vapor.

(3) The refrigerant gas is cooled by the high temperature heat source in the condenser and it becomes high-pressure liquid.

(4) After the refrigerant passing through expansion valve, it becomes a low temperature and low-pressure liquid refrigerant.

Heat pump performance is generally measured by COP. The coefficient of cooling is defined as the ratio of the heat transferred from the low temperature heat source to the high temperature heat source and the required extra work.

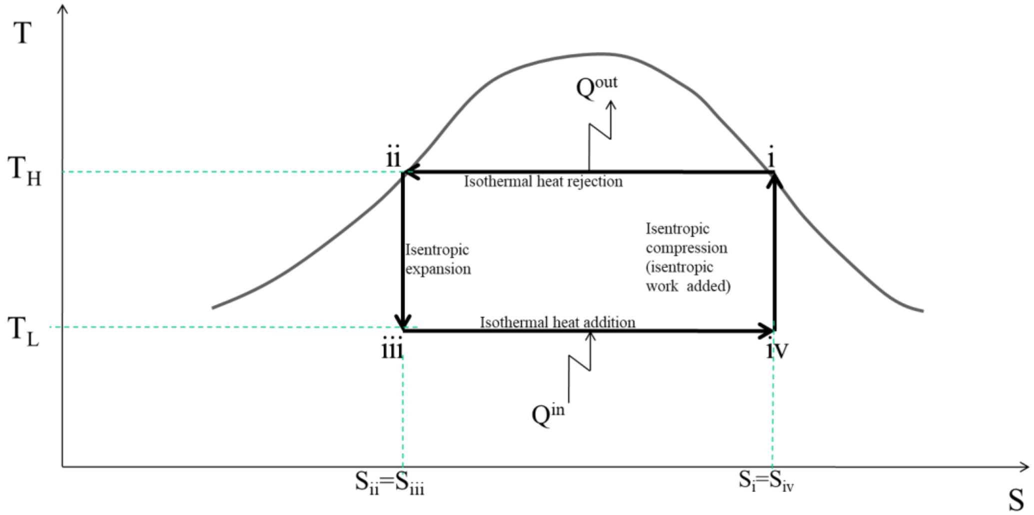

Figure 8. The T-S Mollier Diagram for a Carnot Heat Pump

(Source: El-Halwagi, 2017)

The heat pump works on the reverse Carnot cycle. Its principle is shown in Figure 8. The inverse Carnot cycle includes the following four steps, and all of them are reversible processes.

(1) Adiabatic compression, in which the refrigerant is compressed and the temperature rises.

(2) Isothermal compression, the system returns to its original state. During this

process, the system releases heat to the high-temperature heat source, and the temperature remains unchanged.

(3) Adiabatic expansion. In this process, the system produces work to the environment while the temperature of the system decreases.

(4) Isothermal expansion, in which the system absorbs heat from the low-temperature heat source, but the temperature remains unchanged.

1.6 Economic

Economic Evaluation is to evaluate the merits of the object by calculating a series of economic indicators. The core of economic evaluation is economic benefits. At present, there are many economic evaluation indexes and methods put forward around the world. There are more than ten methods used in project evaluation. According to whether the evaluation index considers the time value of funds, it can be divided into static evaluation method and dynamic evaluation method. The static evaluation does not consider the time value of funds to calculate the relevant economic indicators. The dynamic evaluation method is to consider the time value of funds. The dynamic economic evaluation not only considers the time value of funds, but also takes the entire life cycle of the project as the economic analysis. Therefore, the dynamic assessment method is more accurate and scientific than the static assessment method. Dynamic evaluation methods include the dynamic payback period method, the net present value method, the net present value rate method, the net annual value and the net annual value rate method. [9]

2 RESEARCH PROBLEM

2.1 Problem description

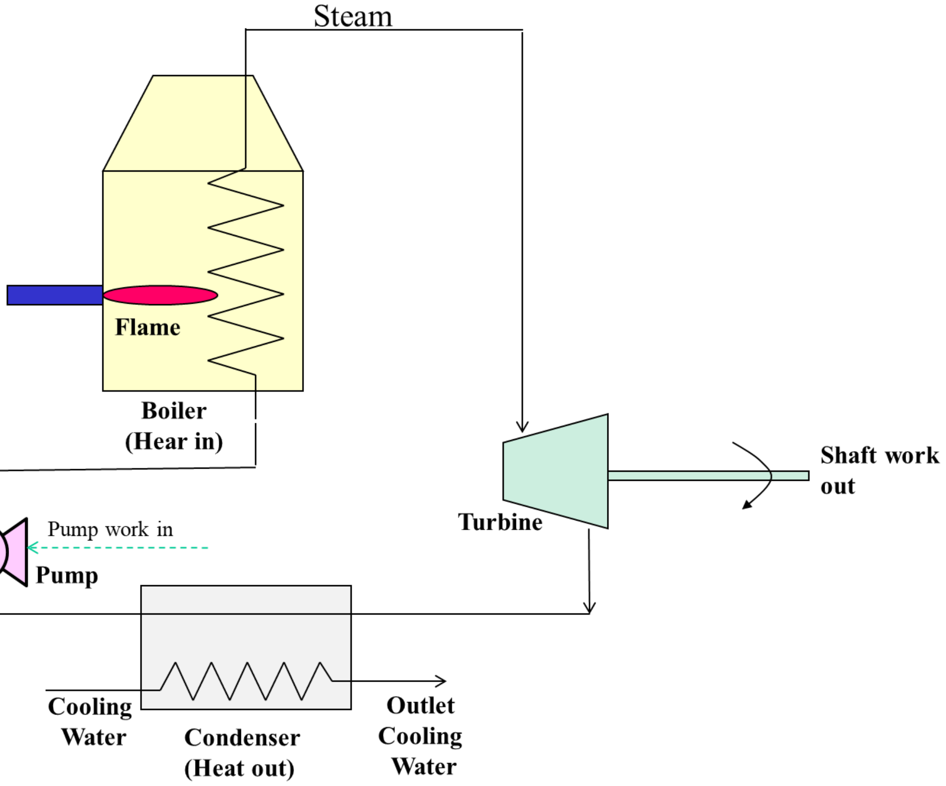

Figure 9. Steam turbines and power plants

(Source: El-Halwagi, 2017)

Figure 9 shows the structure of a steam turbine and power plant. In the process of energy conversion, power plants require a lot of water. After the steam passes through the turbine, the steam changes back to the liquid water and the temperature decreases. Besides, during the cooling process, a portion of the water will be lost in the form of steam. At present, most of the power plants will directly discharge the cooling water. This water, when discharged, still has a certain amount of heat. But the temperature of waste water is low, it is difficult to use. Heat Pump is a device which can transfer heat from low heat source to the high heat source. Power plants produce electricity is generally higher than the actual electricity consumption and excess electricity can drive the heat pump. The heat generated by the waste water through the heat pump can be used to heat the equipment or buildings. The remaining water can be recycled after filtration.

3 SYSTEM INTRODUCTION AND RESEARCH DATA

3.1 System introduction

The working principle of the heat pump is similar with the chiller. The heat pump and the chiller both work according to the reverse Carnot cycle. The difference is that the operating temperature range and the purpose. Heat pump can use low-temperature water to heat buildings. The heat pump system is mainly composed of four parts: the heat pump driving energy (electric energy), the driving device (motor, engine, etc.), the heat pump unit, and the low-temperature heat source. The heat pump is composed of a compressor, a condenser, an evaporator and an expansion valve.

Figure 10 shows the heat pump's working mode during winter. In winter, the heat pump absorbs heat from the low-level heat source (cooling water tank) and releases heat in the condenser. The heating system consumes a small amount of high-level energy to satisfy the energy demand for heating.

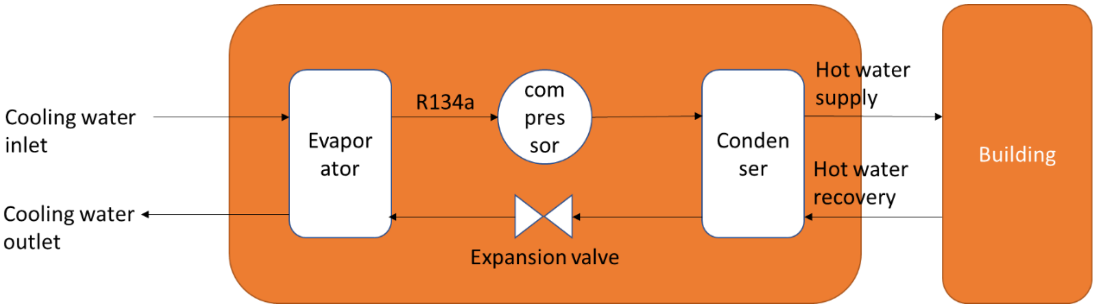

Figure 10. Heating mode in winter

Figure 11 shows the heat pump's working mode during summer. In summer, the system operates in cooling mode, the evaporator becomes the condenser, and the condenser becomes the evaporator. After the refrigerant gas leaving compressor, it enters the condenser and releases heat to the cooling water.

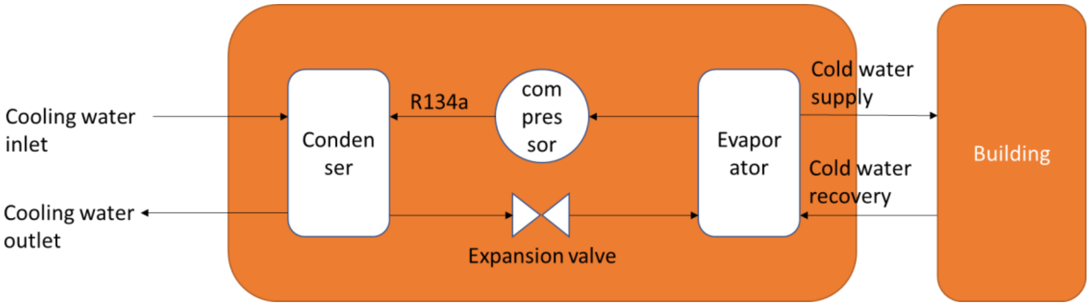

Figure 11. Cooling mode in summer

The heating coefficient εₕ of the heat pump is equal to the ratio of heating capacity Q and power consumption P.

$$\varepsilon_h = \frac{Q}{P} = \frac{Q_0 + P}{P} = \varepsilon + 1$$

The cooling coefficient ε is the amount of cold that can be obtained when consuming one unit of power.

$$\varepsilon = \frac{Q_0}{P}$$

However, in the actual cycling, the heating coefficient and the cooling coefficient are not only related to the temperature of the two heat sources, but also related to the type of refrigerant and other factors in the cycle.

3.2 Research data

The temperature of cooling water in each month is shown in the Table 1. From Table 1, it can be seen that the lowest temperature of cooling water in the winter is 9.8 °C. After water passing the condenser, the temperature rises by about 8 °C. When water enters the cooling tower, the temperature is about 17.8 °C. Therefore, during the winter, the heat pump unit can obtain warm water of approximately 17 °C and the heating coefficient reaches 3.8. When the turbine generator unit stops operating in winter, the heat pump unit also stops operating.

In summer, the highest temperature of the cooling water is 30.3 °C. Therefore, whether turbine generators run normally or stop running, the heat pump can obtain cooling water with the temperature about 27 °C. The cooling coefficient can reach about 4.4. The temperature changes throughout the year are shown in Figure 12.

	January	February	March	April	May	June
Circulating cooling water temperature (℃)	10.67	15.89	18.72	20.72	24.11	28.06
	July	August	September	October	November	December
Circulating cooling water temperature (℃)	30.33	29.11	27.01	20.89	16.89	9.83

Table 1. Temperature of cooling water

(Source: https://www.weather.gov/fwd/dmotemp)

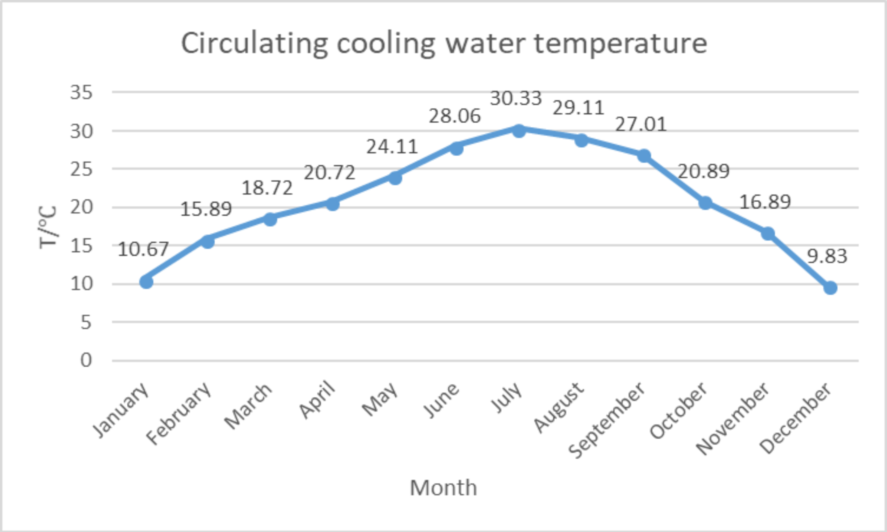

Figure 12. Temperature of cooling water in each month

Table 2 and Table 3 show the investment costs and the useful life period of the equipment. The device's quantity and salvage value are also displayed in tables. By comparison, it can be seen that the investment cost of the heat pump system is lower.

Items	Number	Useful life period	Price ($)	Salvage value (10%) ($)
Heat pump unit	2	20	190000*2	19000*2
Circulating water pump	4	20	3200*4	320*4
Total	6		392800	39280

Table 2. Heat pump equipment investment

Items	Number	Useful life period	Price ($)	Salvage value (10%) ($)
Screw chiller units	2	20	118960*2	11896*2
Cooling tower	2	20	71380*2	7138*2
Circulating water pump	4	20	3200*4	320*4
Heat exchanger	1	20	47600	4760*1
Recovery device	1	20	13000	1300*1
Total	10		454080	45408

Table 3. Screw chiller + heat exchanger equipment investment

If the machine is running at full load, Table 4 shows the energy consumption of the heat pump. Assuming that the cooling capacity is 2500kw and the heating capacity is 3500kw. When calculating, the standard coal’s calorific value is 7000 kcal/kg (29302 kJ/kg). The efficiency of power plants is 40%. Table 5 shows the energy consumption of a screw chiller + heat exchanger system. Assuming that the steam loss is 10% and the power plant boiler efficiency is 95%. By comparison, it can be seen that, heat pump has a higher efficiency when under the same conditions.

Cooling Mode		Heating Mode	
Items	Power consumption(KW)	Items	Power consumption(KW)
Heat pump unit	290*2=580	Heat pump unit	420*2=840
Circulating water pump	50*4=200	Circulating water pump	50*4=200
Total	780	Total	1040
Primary energy consumption		Primary energy consumption	
780/40%=1950kw		1040/40%=2600kw	
Standard coal consumption rate		Standard coal consumption rate	
1950*860/7000=239.57 kg/h		2600*860/7000=319.43 kg/h	

Table 4. Heat pump energy consumption

Cooling Mode		Heating Mode	
Items	Power consumption(KW)	Items	Power consumption(KW)
Screw chiller	310*2=620	Steam	3500/0.9=3888
Circulating water pump	50*4=200	Circulating water pump	50*2=100
Cooling Tower	50*2=100		
Total	920	Total	100(Electricity)+3888(Steam)
Primary energy consumption		Primary energy consumption	
920/40%=2300kw		100/0.4+ 3888/0.95=4342.63kw	
Standard coal consumption rate		Standard coal consumption rate	
2300*860/7000=282.57 kg/h		4342.63*860/7000=533.52 kg/h	

Table 5. Screw chiller + heat exchanger energy consumption

Assume that the system is operating throughout the year. The number of heating days per year is 155, and the number of cooling days is 210. During heating mode, the average power is 70% of full load. During cooling mode, the average power is 50% of full load. Compared to screw chiller + heat exchanger system, the standard coal that is saved by using heat pump system during heating is

$$(533.52 - 319.43) \times 24 \times 155 \times 70\% = 557490.36 \text{ kg} = 557.49 \text{ tons}$$

The standard coal that is saved during cooling is

$$(282.57 - 239.57) \times 24 \times 210 \times 50\% = 108360 \text{ kg} = 108.36 \text{ tons}$$

The standard coal saved in one year is

$$557.49 + 108.36 = 665.85 \text{ tons}$$

From the above calculation, compared to cooling mode, the heat pump system can save more energy in heating mode. Besides, 3500kw can meet the heating demand of 40,000 square meters of buildings.

In heating mode, standard coal can be saved annually is

$$557490.36 \div 40000 = 13.94 \text{ kg}/(\text{yr} \cdot m^2)$$

4 ECONOMIC ANALYSIS

4.1 Cash flow analysis

The composition of equipment investment is shown in the figure 13.

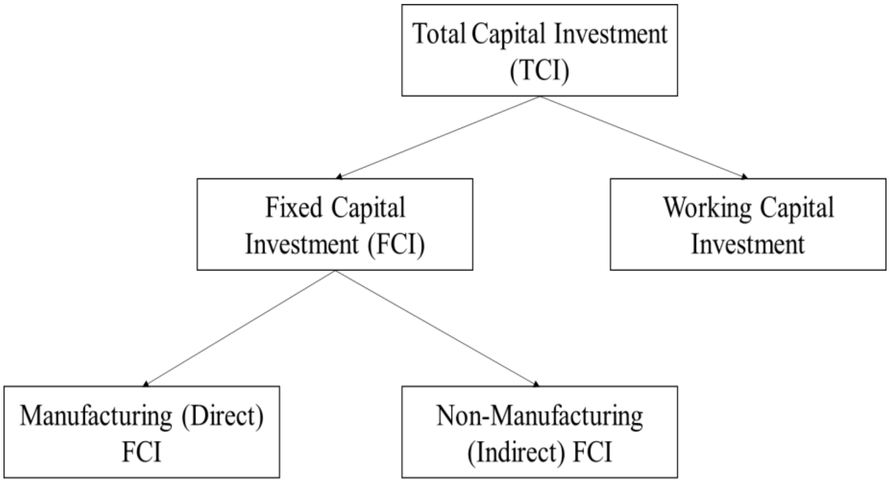

Figure 13. The composition of equipment investment

For the heat pump system, fixed capital investment (FCI) is

$$392800 \text{ dollars}$$

Total Capital Investment (TCI) is

$$392800 \div (1 - 15\%) = 462118 \text{ dollars}$$

Working Capital Investment (WCI) is about 15% of TCI

$$462118 \times 15\% = 69318 \text{ dollars}$$

Total operating cost (20% of FCI) is

$$392800 \times 20\% = 78560 \text{ dollars}$$

Depreciation is

$$(392800 - 39280) \div 20 = 17676 \text{ dollars/year}$$

Table 6 shows the cost calculation result of each item.

Items	Cost ($)
Fixed Capital Investment (FCI)	392800
Total Capital Investment (TCI)	462118
Working Capital Investment (WCI)	69318
Total operating cost (per year)	78560
Depreciation/annualized fixed cost (per year)	17676

Table 6. Cost calculation for heat pump system

For a screw chiller + heat exchanger system, Fixed Capital Investment (FCI) is

$$454080 \text{ dollars}$$

Total Capital Investment (TCI) is

$$454080 \div (1 - 15\%) = 534212 \text{ dollars}$$

Working Capital Investment (WCI) is about 15% of TCI

$$534212 \times 15\% = 80132 \text{ dollars}$$

Total operating cost (20% of FCI) is

$$454080 \times 20\% = 90816 \text{ dollars}$$

Depreciation is

$$(454080 - 45408) \div 20 = 20434 \text{ dollars/year}$$

Table 7 shows the cost calculation result of each item.

Items	Cost ($)
Fixed Capital Investment (FCI)	454080
Total Capital Investment (TCI)	534212
Working Capital Investment (WCI)	80132
Total operating cost (per year)	90816
Depreciation/annualized fixed cost (per year)	20434

Table 7. Cost calculation for screw chiller + heat exchanger system

The costs of the two systems is shown in Figure 14.

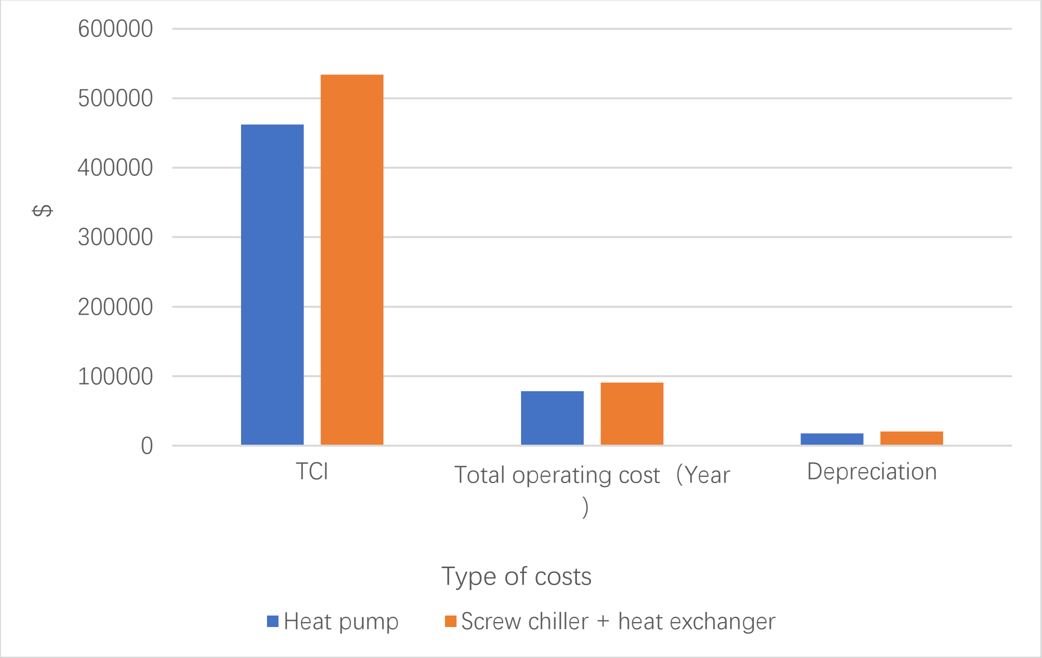

Figure 14. Different costs of the two systems

The above analysis shows that the heat pump system saves 665.85 tons of coal annually. The current coal price is about 65.14 dollars per ton. The money that the system saves per year is

$$668.85 \times 65.14 = 42714.2775 \approx 42.7 \text{ thousand dollars}$$

Items	Income number
Coal Saving	665.85 tons/year
Coal Price	$64.15/ton
Total save (per year)	$42.7 Thousand

Table 8. Money saving

Annualized fixed cost(AFC) is

$$\text{AFC} = \frac{392800-39280}{20} \approx 17.7 \text{ thousand dollars/year}$$

The variable annual operating cost at maximum production capacity is obtained as follows.

$$\mathrm{AOC}^{\mathrm{Max}} = 15 \times [(533.52 - 319.43) \times 24 \times 155 + (282.57 - 239.57) \times 24 \times 210] \div 1000 \approx 15 \text{ thousand dollars}$$

So, the break-even point analysis as shown in Figure 15.

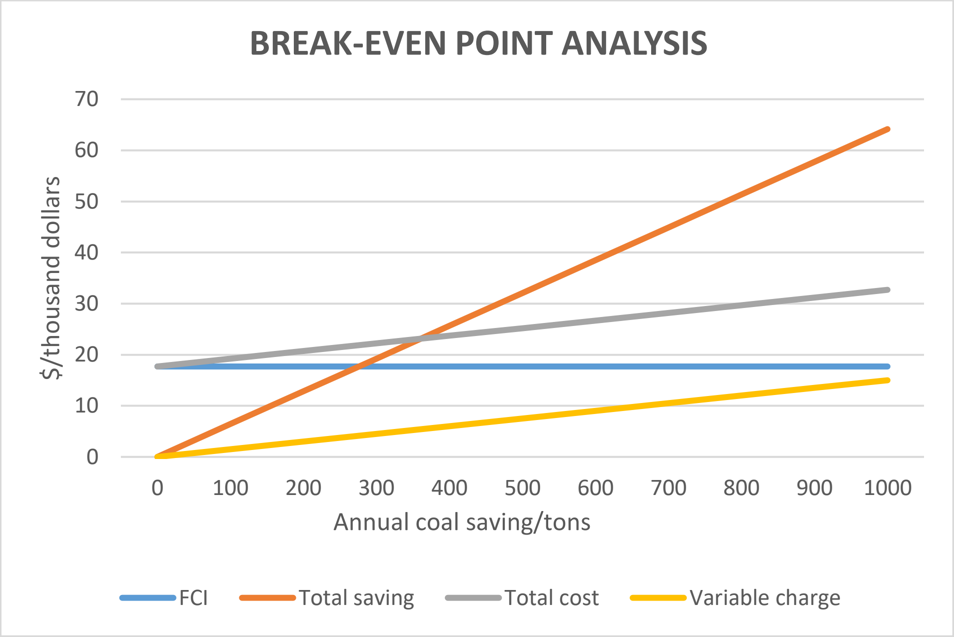

Figure 15. Break-even point analysis

The break-even point analysis indicates that the total saving of the coal should be at least 350 tons per year to make profit.

The system's cash flow during 20 years is shown in Figure 16.

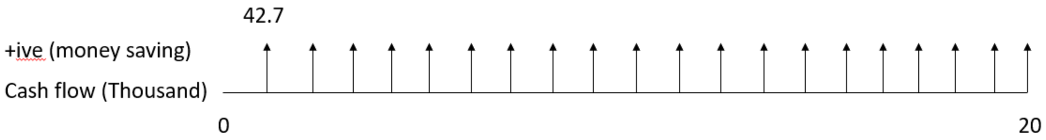

Figure 16. Cash flow of heat pump system

In this study, assuming that the discount rate is 10%. The present value is

$$\mathrm{P} = \sum_{\mathrm{N}=1}^{20} \frac{42.7}{(1+0.1)^{\mathrm{N}}} = 363.53 \text{ Thousand Dollars}$$

P −Present value

N −Time(year)

Return on investment (ROI) is

$$\mathrm{ROI} = \frac{\text{Annual Saving}}{\text{Total Capital Investment}} \times 100\% = \frac{42.7}{462} \times 100\% \approx 9.24\%$$

Return on investment (ROI) refers to the value that should be returned through investment. ROI is the profit that an enterprise obtains from an investment activity. It covers the economic goals of the company. Profits are related to the assets necessary to invest in operations. Compared to the screw chiller + heat exchanger system, the heat pump system has higher economic benefits.

According to statistics, burning a ton of coal produces about 2.9 tons of carbon dioxide. (Source: B.D. Hong and E. R. Slatick, 1994)

So, the annual reduction in CO_2 emissions of the heat pump system is

$$665.85 \times 2.9 \text{ ton } \mathrm{CO_2}/\text{ton coal} = 1{,}931 \text{ tons } \mathrm{CO_2}/\text{yr}$$

At present, the carbon credit of carbon dioxide is about $30/ton. (Source: https://en.wikipedia.org/wiki/Carbon_credit)

The annual saving is

$$1931 \times 30 \approx 57.9 \text{ Thousand dollars}$$

The $\mathrm{ROI}_{\mathrm{co}_2}$ is

$$\mathrm{ROI}_{\mathrm{co}_2} = \frac{42.7 + 57.9}{462} \times 100\% = 21.77\%$$

From the above calculations, it can be seen that the heat pump system has a high ROI when considering CO2 emissions. The calculation results show that the heat pump system has a good economic potential. The heat pump system is worthy of application.

4.2 Life cycle process

The life cycle process refers to a design theory that takes into account all aspects of the product's life history at the design stage. All relevant factors are comprehensively planned and optimized in the stage of product design. Life cycle cost (LCC) originated from the cost management model proposed by GE in the 1940s. Life cycle cost is the total cost of ownership, operation, maintenance and demolition over a period of time.

In the design and application process, some traditional design ideas only consider the initial investment cost. These methods are only to minimize the initial investment. However, operating cost is an important part of the total cost. The operating cost of the system cannot be ignored. Because many factors are considered, the results of the life cycle cost method are more accurate. Based on this situation, life cycle cost analysis method has gradually been used and promoted.

For this project, the life cycle cost method is used to analyze the total cost. The entire life cycle of the system includes installation, operation, recovery and demolition. This research uses the discount coefficient method to calculate the cost of the system.

The life cycle cost is the sum of the initial investment and operating cost.

$$C_T = C_i + C_c$$

C_T − Total cost
C_i −System initial investment
C_c − Operating cost

$$C_c = PWF \times C_y$$

PWF − Discount factor
C_y −Annual operating cost of the system

$$PWF = [1 - (1 + I)^{-N}]/I$$

N − usage time
I − discount rate, %

The two systems are analyzed and the results are shown in Figure 17.

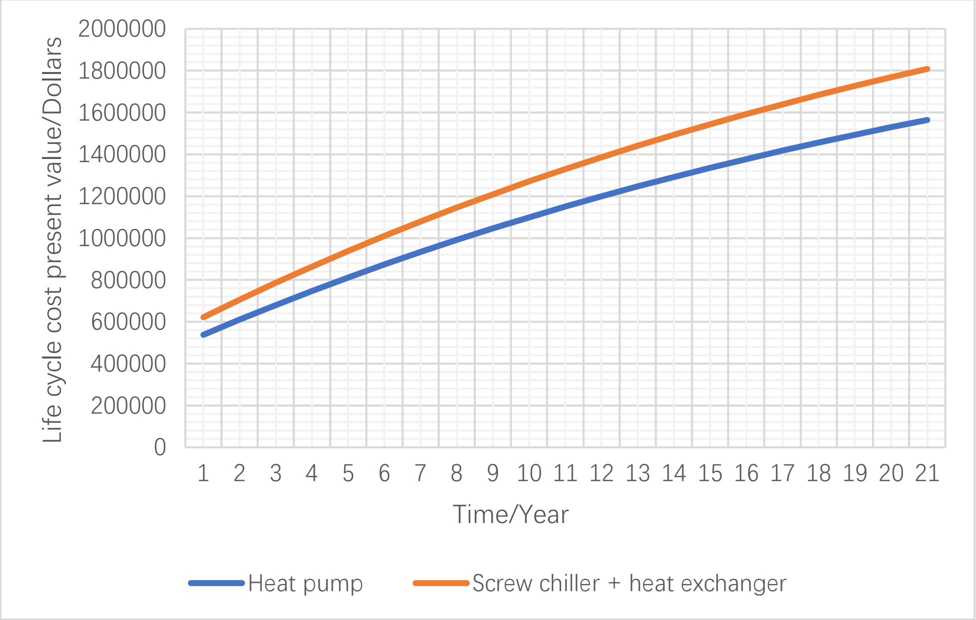

Figure 17. The current life cycle cost of two systems

This chapter uses the life cycle cost method to analyze two systems. It is mainly analyzed from the perspective of economy. From the above analysis, it can be seen that the heat pump system is more suitable for this project. Its operating cost is significantly less than the screw chiller + heat exchanger system. In addition, the initial investment of the heat pump system is lower. For the economic analysis of the two systems, it is not enough to only consider the initial investment. The result demonstrates that the heat pump system has a lower life cycle cost. In this research, the lifetime of the air-conditioning system is set to 20 years. From the view of the total cost, the heat pump system is more suitable.

5 SYSTEM OPTIMIZATION

5.1 Optimization process

System optimization is an important part. Optimization is based on demands trying to achieve the best performance of the system. The optimization design consists of a large number of design options finding a set of solutions to meet a variety of constraints (such as the most cost-saving, minimum energy consumption, etc.). The goal of the optimization of the air conditioning system in this paper is to minimize the energy consumption of the entire system. Therefore, all the energy consumption included in the system should to be considered. System optimization can make the system run efficiently. Through the system optimization, the consumption of the system can be reduced to achieve the purpose of energy saving.

For an air-conditioning unit, the unit's power is affected by the evaporation temperature and the condensing temperature. The evaporation temperature and the condensing temperature are related to the cooling water flow. Therefore, the method is to control the cooling water flow. Subsequently, the total energy consumption of the system can be obtained.

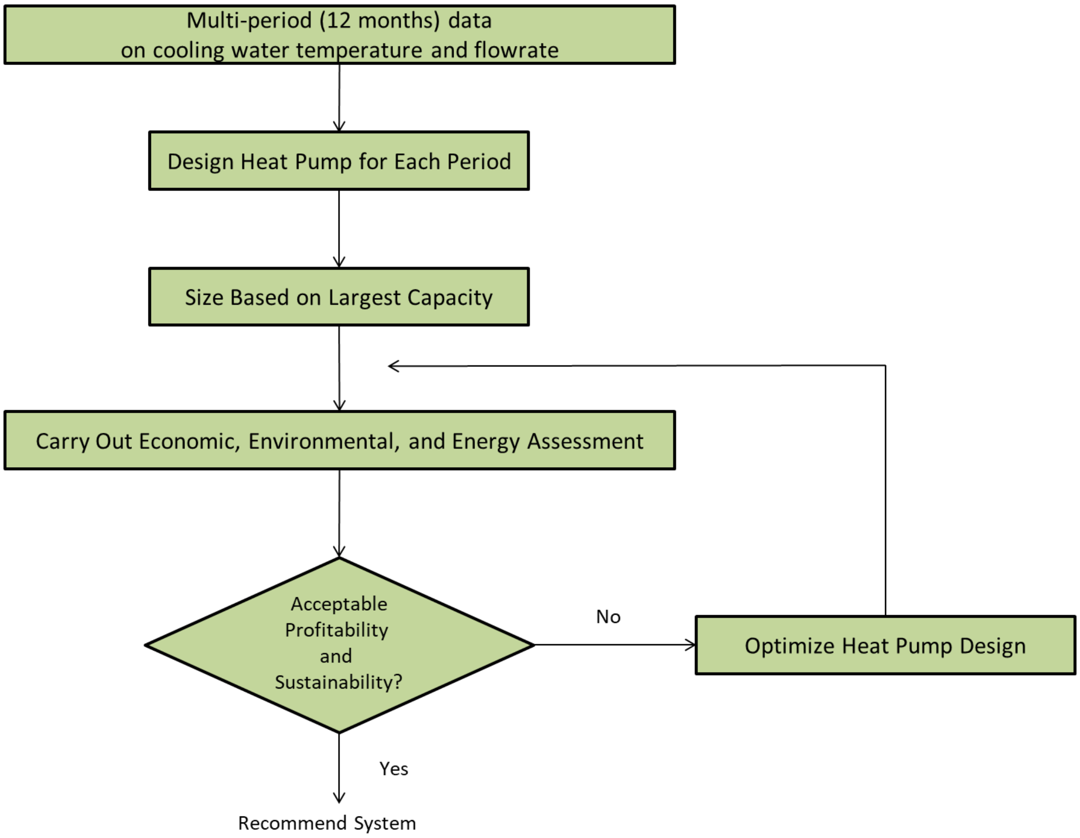

Figure 18. A Vapor-Compression Heat Pump

(Source: El-Halwagi, 2018)

The flow chart of system optimization is shown in Figure 18. Because water's temperature varies from month to month, system optimization needs to be performed according to different circumstances.

5.2 Model

The model was designed by Yuan Xudong. [10]

In this study, the objective function is

$$\mathrm{Min(P)} = \mathrm{P}_r + \mathrm{P}_\mathrm{h}$$

P_r − Pumps' power, k W

P_h – Heat pump unit's power, k W

P – Total power of the system, k W

The cooling water quantity is the optimized parameter of the water pumps' power.

The condenser's model is shown in Figure 19.

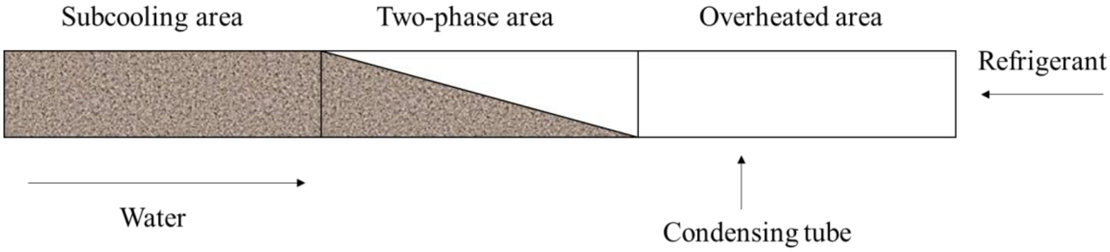

Figure 19. Condenser model

This model is based on the following assumptions.

(1) One-dimensional axial flow in the heat-transfer pipe.

(2) Only consider the radial heat exchange of the refrigerant, tube wall and water. Ignoring the axial heat transfer and thermal conductivity of the tube wall.

(3) When the refrigerant is in the two-phase zone, the liquid and gas are evenly mixed.

(4) Ignoring the impact of impurities on heat transfer.

(5) The refrigerant and water are both incompressible fluids whose parameters do not change with time.

(6) Does not consider the pressure loss in the condenser.

(7) The heat transfer process is a reversible process.

When the condenser is under the cooling mode, the formulas are as follows.

$$Q_e = G_f C_p \times (2t_c - 2\Delta t_c - 2t_{c,i})$$

$$\Delta t_c = t_c - \frac{t_{c,i} - t_{c,o}}{2}$$

$$Q_e = Q_{cl} + N_i$$

Q_{cl} − System's cooling load, k W
G_f − Cooling water flow, Kg/s
C_p − Specific Heat Capacity, kJ/kg·°C
Δt_c − Temperature difference of heat transfer in condenser, °C
t_c − Condensation temperature, °C
$t_{c,i}$ − Cooling water inlet temperature, °C
$t_{c,o}$ − Cooling water outlet temperature, °C
Q_e − Condenser heat release
N_i − Compressor's input power

When the condenser is under the heating mode, the formula is as follows.

$$Q_h = G_f C_p \times (2t_c - 2\Delta t_c - 2t_{c,i})$$

Q_h − Heating load, kW

The evaporator's model is shown in Figure 20.

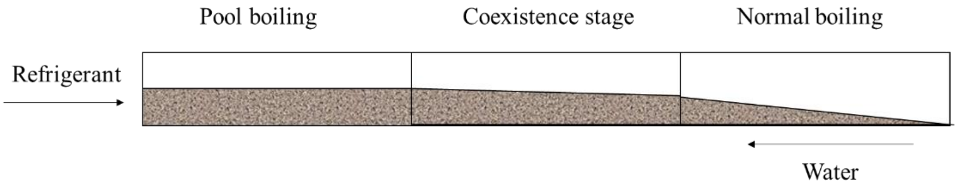

Figure 20. Evaporator model

Pool boiling is a type of boiling that liquid boiling above the saturation temperature. The boiling process is limited by the boiling space and the boiling vapor. During pool boiling, liquid and vapor are mixed together to form a two-phase flow. It is also known as limited space boiling or forced convection boiling.

When the evaporator is under the cooling mode, the formulas are as follows.

$$t_e = \frac{2t_{x,i} - \frac{Q_c}{G_f c_p}}{2} - \Delta t_e$$

$$\Delta t_e = \frac{t_{x,i} + t_{x,o}}{2} - t_e$$

Q_c – Cold load, kW
t_e – Evaporation temperature, °C
G_f – Cooling water flow, kg/s
$t_{x,i}$ – Recirculating water inlet temperature, °C
$t_{x,o}$ – Recirculating water outlet temperature, °C
Δt_e – Temperature difference of heat transfer in evaporator, °C

When the evaporator is under the heating mode, the formulas is as follows.

$$t_e = \frac{2t_{x,i} - \frac{Q_{he} - N_i}{G_f c_p}}{2} - \Delta t_e$$

Q_{he} – Heat load, kW

For a compressor, its power is related to the evaporation temperature and the condensation temperature.

When the evaporation temperature changes.

$$\Delta P_{co} = -\frac{Q_e \times T_c}{T_e^2} \times \Delta T_e$$

When the condensing temperature changes.

$$\Delta P_{co} = \frac{Q_e}{T_e} \times \Delta T_c$$

$$P_{co} = P_{co,0} + \Delta P_{co}$$

$$\Delta T_e = T_e - T_{e,0}$$

$$\Delta T_c = T_c - T_{c,0}$$

Q_e – Heat load

ΔP_{co} – Change in compressor's power, kw

$P_{co,0}$ – Compressor's original power, kw

P_{co} – Compressor power consumption, kw

ΔT_e – Change in evaporating temperature, K

T_e – Evaporating temperature, K

$T_{e,0}$ – Original evaporating temperature, K

ΔT_c – Change in condensing temperature, K

T_c − Condensing temperature, K

$T_{c,0}$ − Original condensing temperature, K

The relationship between compressor's power and evaporating temperature is shown in Figure 21.

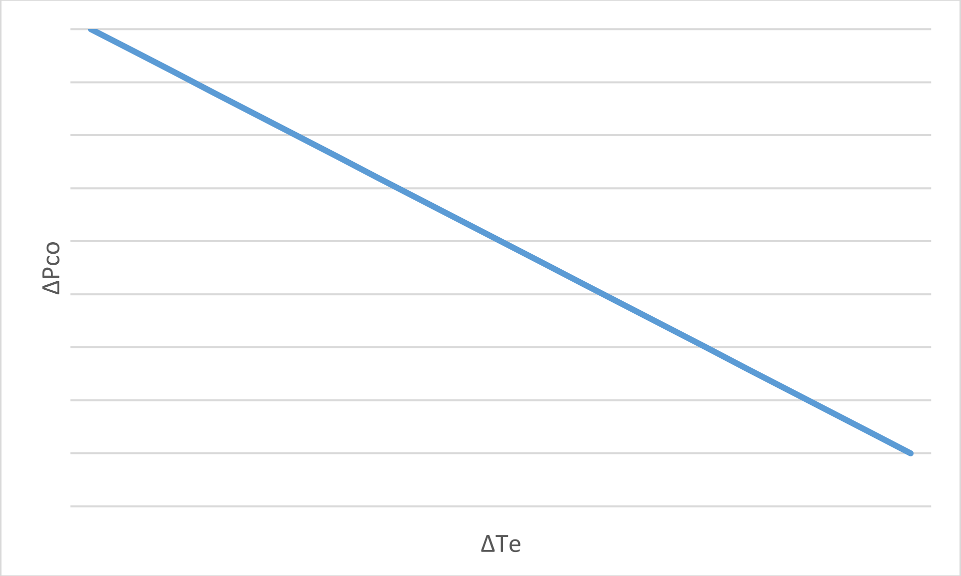

Figure 21. Compressor power and evaporation temperature

The relationship between compressor's power and condensing temperature is shown in Figure 22.

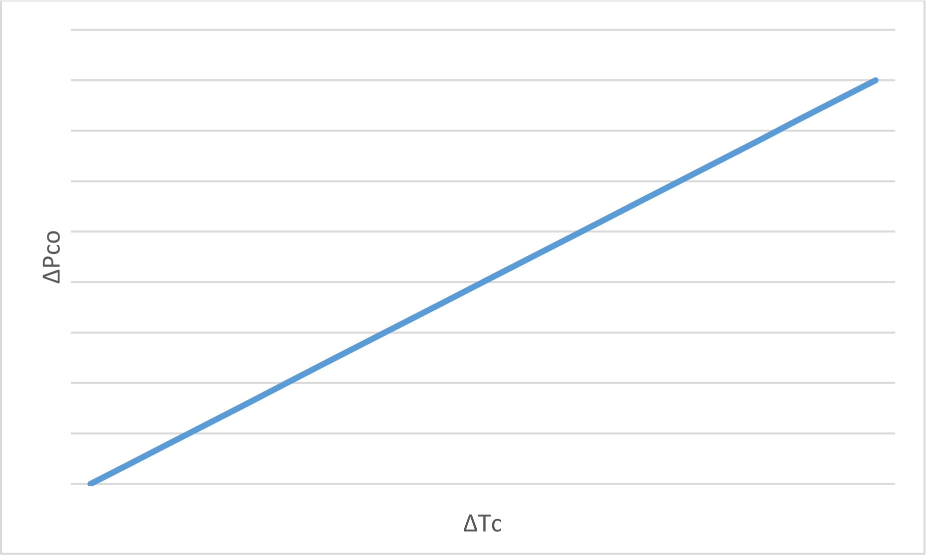

Figure 22. Compressor power and condensation temperature

Through the above analysis, the conclusions can be reached. When the evaporating temperature increases, the compressor power drops. When the condensing temperature increases, the compressor power rises.

The flow rate of the cooling water is adjusted through the valve. The schematic diagram of the characteristics of the pipeline and the flow characteristic curve of the pump is shown in Figure 23.

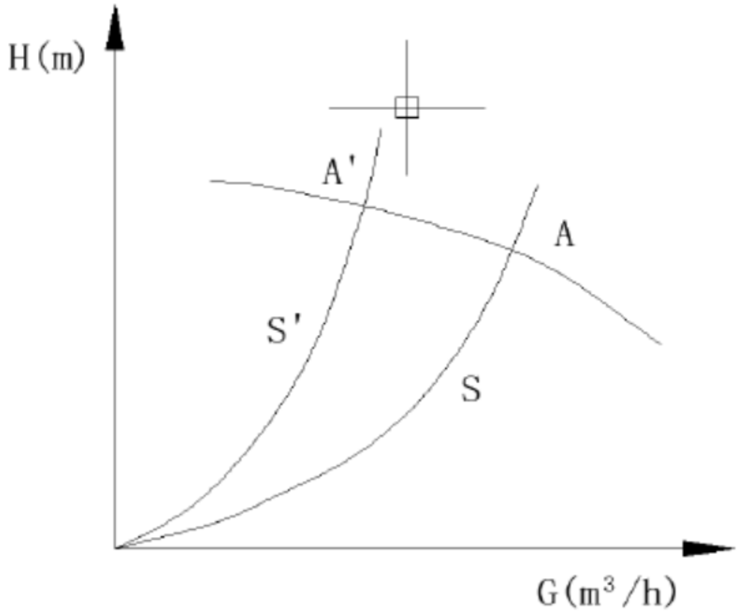

Figure 23. Pipeline and pump head curve characteristics

(Source: Qiu Yurong, 2012)

The parameters of the pump indicate the performance of the pump. However, the parameters are not isolated. For a specific pump, there is a regular pattern between the various parameters. The variation between them is usually represented by a curve, which is called the pump performance curve.

In the figure 23, S and S' are the characteristics of the pipeline. When the valve is closed, the pipeline characteristic curve changes from S to S', and the curve becomes steeper. The intersection of the two lines changes from A to A'. Therefore, when the flow rate changes, the operating point of the pump will change.

5.3 Model analysis

The model for this study is based on the following assumptions. [11]

(1) During the cooling or heating operation, assuming that the difference between the evaporating temperature and the condensing temperature does not change.

(2) The return water’s temperature does not change.

(3) When adjusting the flow rate on one side, the flow rate on the other side remains unchanged.

6 CONCLUSION

This thesis has assessed the feasibility of heat pump systems for recovering waste heat from cooling water in power plants. An integrated configuration has been proposed to cool the discharged water and to use the excess heat in driving a heat pump. A case study has been solved to evaluate the energy saving, environmental benefits, and techno-economic performance of the proposed configuration. Besides, this paper introduces the structure and operational principle of heat pumps. In addition, this paper analyzes the economics of the heat pump system and introduces the system optimization model. The following are the key conclusions from the study:

(1) Direct discharge of cooling water from power plants can cause thermal pollution.

(2) Heat pumps can serve as effective heat sinks to recover excess heat from the discharged cooling water. The recovered heat is sufficient to drive a heat pump which can be used for refrigeration or other industrial purposes. Savings in fossil fuels usage can be accomplished. In the addressed case study, the heat pump system can save 665.85 tons of coal per year compared to the screw chiller and a heat exchanger system. In addition, a heat pump system can reduce CO_2 emissions. When considering CO_2 emissions, the heat pump's return on investment is 21.77%.

(3) Because of the continuous change in the cooling-water temperature, the system design and optimization must be handled through a multi-period approach to account for the variability in water temperature and heat-pump performance.

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