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Scheduling of the Combined Power and Desalination System

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The combined power and desalination system can improve energy utilisation efficiency and market competitiveness of the production process by adjusting production planning according to the demand load of water and electricity. In this paper, the scheduling model is proposed that addresses the operational optimisation of the combined power and desalination system. The time-dependent electricity price is considered and the proposed model is described as a nonlinear programming (NLP) problem with the maximising total economic benefits. Based on the periodic characteristics of demand load of water and electricity, the typical day of each season is selected as one scheduling time, which is divided into several time intervals according to the change of electricity price. A case study is adopted to demonstrate the presented scheduling model. The results showed: the multi-stage flash (MSF) system keeps running for the total scheduling cycle and the water production varies between 2,000 t/h and 4,000 t/h. A part group's module of reverse osmosis (RO) system would be shutdown/start up following the increasing/decreasing demand for electricity. When the electricity price higher, the more electricity is supplied to the users and the less water is produced. While the electricity price lower, less electricity and more water are produced. The surplus water is stored in the tank to make up for high water demand. Comparing with the stand-alone plant, the load fluctuation of the power plant decreases from 150 MW to 20 MW. The operation stability and efficiency will be improved by the optimal scheduling of the combined power and desalination system.

1. Introduction

Seawater Desalination technology is an important way to solve the shortage of freshwater and has been accepted by the world, but its further development has been restricted by the high energy consumption (Gao and Chen, 2004). The combined power and desalination system can use the waste heat steam and electricity of the power plant to provide energy for the desalination system. It not only takes full advantage of the energy but also further reduces the cost of freshwater produced by desalination method. The integration and optimisation of desalination and the power plant are considered to be the most promising technology (Wu, et al. 2010).

In order to meet the water and electricity demand, the production load of power and desalination system will wave greatly, especially if the power and desalination system run independently, as the water and electricity demand load vary with the time. This problem can be efficiently solved by the production scheduling of the combined power and desalination system. It is important to study the production scheduling of the CPD system. The optimisation of the combined heat and power plant (CHP) or desalination system has been paid much attention. Sumit et al. (2013) presented a general mode model to solve the operational optimisation of the CHP system. Malak et al. (2014) proposed a systematic decision-making process and optimisation model for large scale investment, in which the desalination industry network is regarded as a supply chain. Hariharan and Dragoljub (2015) presented a mixed 0-1 nonlinear programming formulation for short term operational planning of a CHP system. A genetic algorithm method is adopted to solve the model. Kia et al. (2017) presented the optimal day-ahead scheduling problem of combined heat and power plant with electrical and thermal energy storage. Mojica et al. (2017) presented an optimisation framework to study the dynamic scheduling of district energy system. A multi-follower bilevel programming approach for optimal energy management of combined heat and power based microgrid is proposed by Alipour et al. (2018). Rensonnent et al. (2007) presented the mathematical model of the CHP system and studied the economic analysis. A designing and scheduling model

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of biomass-fueled combined heat and power system is put forward by Zheng et al. (2018). Pazouki and Haghifam (2016) proposed an optimal scheduling model of the energy hub, considering operation constraints, electricity price, demand and the deterministic/stochastic performance of wind power. Hawaidi and Mujtaba (2011) had considered the water change for the optimisation of the desalination system. Ehsa et al. (2011) studied the multi-objective optimisation of a power and desalination plant, but they don't consider the change in the demand load of water and electricity. Wu (2012) considered the change of water and electricity demand in the desalination and power plant but did not consider the affection of the timed power tariff.
The novelty of this paper describes a scheduling model of combined power and desalination system that helps decision-makers to optimise their production schedules with respect to operating costs that are due to fluctuations in electricity prices and the demand of water and electricity.

2. Sketch of integration of MSF/RO and power plant

The sketch of the combined power and desalination system proposed in this paper (shown in Figure 1) consists of a multi-stage flash desalination system (MSF), reverse osmosis (RO) and power plant.

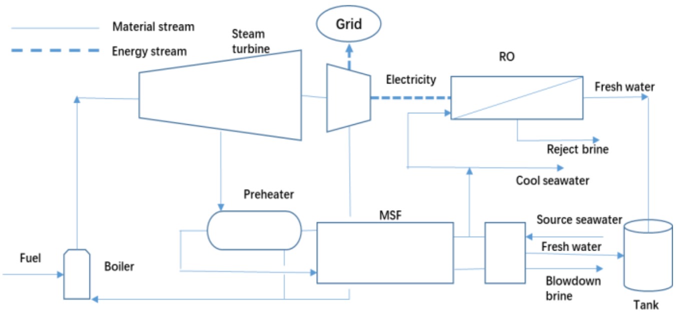

Figure 1: Sketch of integration of MSF/RO and power plant

The superheated steam coming from the boiler with high pressure goes firstly to the NO.1 and NO.2 turbine to produce electricity. And then, it is divided into two parts, one of them is supplied to the MSF system as the heat steam, the other one entrances the NO.3 turbine to produce electricity. The steam condensate coming from the MSF system and the NO.3 turbine returns to the boiler again and is reheated to produce the superheated steam. And then be transported to the turbines to produce electricity.
The seawater is sent to the MSF and heated as they flow through the pre-heater tubes of the heat rejection section. Subsequently, it is divided into two parts. One part is used as the makeup water to the heat recovery section, and the other part is sent to RO as the feed water and return to the sea. The freshwater produced by MSF and RO is blended as the total water production.

3. Scheduling of the combined power and desalination system

The MSF and RO plant could be operated independently in the desalination system. The waste heat from the power plant is supplied to MSF and the remaining electricity is sent to RO. A tank is introduced in this paper to store fresh water when lower electricity demand and to provide water when higher electricity demand. A day is divided into ten-time intervals.

3.1 The model of the combined power and desalination system

The detailed model of the desalination system and the power plant is described in the literature (Wang, 2011). The balance equations for the combined power and desalination system are presented.
The total water production is the sum of the MSF and RO system (Wu, 2010):

$$W_D=W_{DRO}+W_{DMSF} \tag{1}$$

Part of the total electricity is sent to the outside grid, and the rest is supplied to the RO system. So the total electricity is the sum of demands of the RO system and the outside grid.

$$W_e=W_{eRO}+W_{eG} \tag{2}$$

Bottom acreage of the tank:

$$A_T=\frac{\pi\cdot D^2}{4} \tag{3}$$

The volume of the tank is equal to the bottom area times the height and is calculated by Eq(4):

$$V_T=A_T\cdot h_T \tag{4}$$

High level of the water in the tank is equal to the amount of water divided by the base area:

$$h={}^{W_T}\!/_{A_T} \tag{5}$$

The amount of water in the tank at *i* time interval is equal to the sum of the input at *i* time interval and the remainder at *i-1* time interval minus the output at *i* time interval.

$$W_T(i)=W_{D_{in}}(i)+W_T(i-1)-W_{D_{out}}(i) \tag{6}$$

The objective function to be maximised corresponds to the total economic benefits. The total economic benefits consist of electricity, desalination water and the production cost and describe as the Eq(7) to Eq(11):

$$\text{Max: } Pr_O=P_E+P_{MSF}+P_{RO}-C_T \tag{7}$$

$$P_E=\sum_{i=1}^{n}((p_{elec}\cdot W_e(i)\cdot 1,000-\frac{C_{PA}(i)}{360\cdot 24})\cdot\Delta T) \tag{8}$$

$$P_{MSF}=\sum_{i=1}^{n}((p_{wat}\cdot W_{DMSF}(i)-\frac{C_{MSF}(i)}{360\cdot 24})\cdot\Delta T) \tag{9}$$

$$P_{RO}=\sum_{i=1}^{n}((p_{wat}\cdot W_{DRO}(i)-\frac{C_{RO}(i)}{360\cdot 24})\cdot\Delta T) \tag{10}$$

$$C_T=3.1\cdot 0.0963\cdot(2,300\cdot 0.55V_T)/360 \tag{11}$$

Subject to the constraints:

$$W_{D_{in}}(i)+W_T(i-1)\geq W_{D_{out}}(i) \tag{12}$$

$$W_{eT}\geq W_{eD} \tag{13}$$

$$0\leq h_T(i)\leq h_T \tag{14}$$

Where, W_D, *We* and *P* represent the fresh water, power and the economic benefits. *V*, *A*, *h* and W_T are the volume, bottom acreage, water level and water capacity of the tank. *C* and *p* is the cost and unit price. The subscripts *T* is the tank, and the *E* is the electricity.

3.2 Water and electricity demand load in the four seasons

The demand load of water and electricity are changed with time, as shown in Figures 2 and 3 (Xiao, 2013), which have the following characteristics. The demand for water and electricity are different in different seasons. In other words, the change of demand has seasonal, such as the water and electricity demand is highest in summer and lower in spring and autumn.

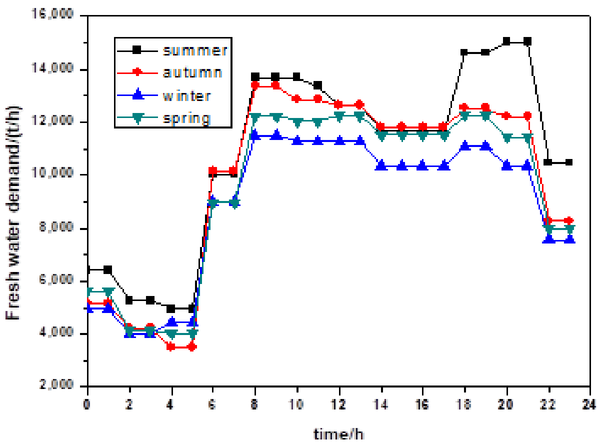

Figure 2: Freshwater consumption of a typical day

The change in water and electricity demand shows the same tendency and periodicities in a day. The water demand is low during 0 - 5 h and 22 - 24 h. It increases from the 6th h and reaches the highest between 8 - 11 h and 18 - 22 h. The characteristics of the above are related to the periodicities of the production and life.

3.3 Timed power tariff

Timed power tariff is a method to decide the electricity price based on the demand load changes in the electricity grid system. The day is divided into some period as the peak, steady and off-peak period, and the electricity price is different in different period. The users can make a reasonable plan based on their electricity demands and the timed power tariff, which could reduce the production cost and the load shifting. The fluctuation of the electricity price is considered in this paper, and the timed power tariff is shown in Table 1 (Xiao, 2013).

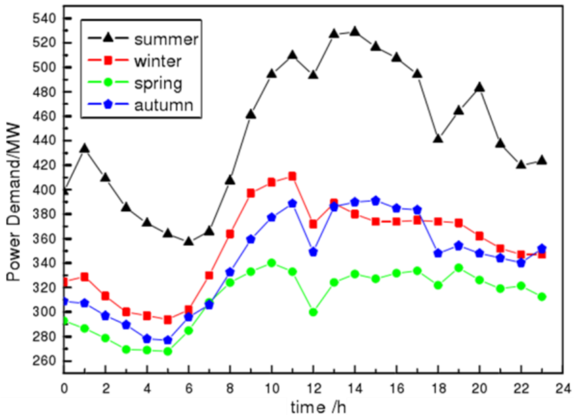

Figure 3: Electricity consumption of a typical day

Table1: Electricity price in each period

Electricity demand	time period	Electricity price /($/kWh)
Peak period	8:00 - 11:00, 18:00 - 23:00	0.19
Steady period	11:00 - 18:00	0.12
Off-peak period	23:00 - 8:00	0.043

4. Case study

Taking summer as an example, the scheduling of the combined power and desalination system is studied based on the demand load of the water and electricity in a typical day, which is divided into ten parts according to the demand and electricity price. The demand load of water and electricity in the typical summer day and the electricity price of different time are shown in Table 2 (Xiao, 2013).
In addition, the MSF is keeping running during all the time with a changeable production load while RO can be shut down or start according to the demand.
The production capacity is 4,000 t/h, 17,000 t/h for MSF and RO, and the capacity of the power plant is 460 MW. The optimal results are shown in Figures 4 and 5.

Table 2: Electricity and freshwater consumption and electricity price in each period in summer

Time interval	hours	Electricity price ($/kWh)	Water demand load (t/h)	Electricity demand load (MW)
0-2	2	0.043	6,404.4	416
2-4	2	0.043	5,261.4	397
4-6	2	0.043	4,950	368
6-8	2	0.043	10,038.6	361
8-11	3	0.19	13,672.8	454
11-14	3	0.12	12,876.6	510
14-18	4	0.12	11,700	512
18-20	2	0.19	14,607	453
20-23	3	1.18	13,500	447
23-0	1	0.26	10,454.4	424

5. Results and analysis

As shown in Figure 4, the MSF system keeps running for the total scheduling cycle and the water production varies between 2,000 t/h and 4,000 t/h. A part groups module of RO system will be shutdown/start up following the increasing/decreasing demand for electricity. When the power demand is lower (0-8 h), The RO runs at full load, the total water production increases, and the level of water tank rises as the water demand is lower at this period. When the power demand is higher (from 8 to 18 h), the RO production decreases as the electricity is provided to the users. Between 11 to 18 h, the RO system is shutdown. But the water demand is high. The total water production does not meet the demand, so the water stored with the tank begins to release water to meet the shortage. The level of the water tank decreases and reaches the lowest from 18 to 23 h. In this period, the water demand and electricity demand both decreases, the RO process starts to produce water. The water production increases during 23 - 0 and 0 - 8 h, and the level of the tank increases again.

The cost of desalination water reduced and the total economic benefits increased by producing more water when the power demand is lower. Although the electricity price is a little higher during 18 - 23 h, but the water production of the desalination system increases in order to maintain the stability of the power plant, and the water demand is satisfied.

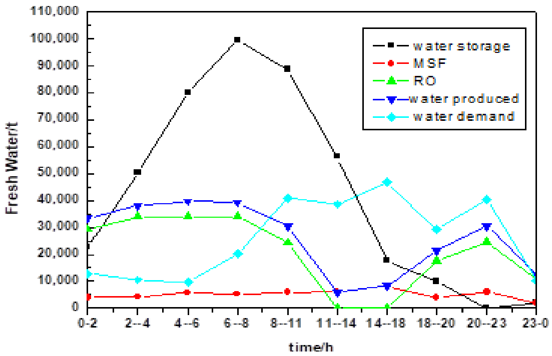

Figure 4: Optimal scheduling result of summer

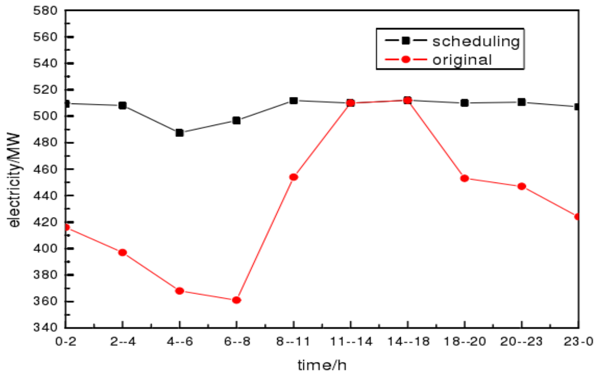

Figure 5: Comparison of a stand-alone power plant and cogeneration system

As shown in Figure 5, the load fluctuation of the power plant significantly reduced by the scheduling of the combined power and desalination system. The stability and efficiency of the combined power and desalination system are proved. The optimal scheduling of combined power and desalination system can not only meet the demand for water and electricity but also can greatly reduce the load fluctuations of the power plant. Comparing with the stand-alone plant, the load fluctuation of the power plant decreases from 150 MW to 20 MW.

6. Conclusions

In this paper, the scheduling model of combined power and desalination system is presented with the maximising total economic benefits, which is described as a nonlinear programming problem and solved by GAMS. The timed power tariff is proposed to coordinate the contradiction between demand and supply. The results showed: during the scheduling period, the MSF system keeps running for the total scheduling cycle and

the water production varies between 2,000 t/h and 4,000 t/h. A part groups module of RO system will be shut down/startup following the increasing/decreasing demand for electricity. When the power demand is low, the water production of RO and the total water production increase. The surplus water is stored in the tank. On the contrary, water production decrease. When the water demand is high and/or the water production rate cannot meet demand, then the water stored in the tank is released to make up the shortage. When the electricity demand is lower, the more water is produced. When the electricity demand is higher, more power and less water produced. Comparing with the stand-alone plant, the load fluctuation of the power plant decreases from 150 MW to 20 MW and the stability and efficiency of the power plant are improved.
Future work will focus on the optimisation of the integrated system of power, heat and desalination, including the use of multiple types of demand, available renewable energy sources and the incorporation of novel storage systems for water and energy.

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