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Thermodynamic analysis of a solar aided coal-fired power plant

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Abstract. The combination of traditional coal-fired power plant and solar aided system is analysed in this paper based on a case study of a typical 330MW subcritical power unit. Three different types of combination schemes are proposed and calculated with detailed modelling. It is found that the upper limit of solar aided system capacity would be limited by SCR gas temperature, reheat temperature etc. which could vary between 12.5-35MW. The thermoeconomic performance increase in the sequence of preheat, main steam generation, reheat based on the average heat transfer temperature. Under different load, the coal consumption rate would decrease by about 5t/h. Considering the effect of DNI and actual load change curve, coal rate would decrease by 2.13% with solar aided system.

1. Introduction

In recent years, the renewable energy generation developed in a rapid speed in China, according to the "Renewable Energy Development "13th Five-Year Plan"" from Chinese government, about 25% percent of the electricity in China is provide by renewable energy, it is estimated that by 2020, renewable energy would account for 27% of total electricity generation. Solar energy is one of the most potential renewable energies ^[1-3], which has been studied for decades and some solar thermal power station has been put into commercial operation in America, South Africa etc. ^[4-5]. During the "13th Five-Year Plan", more than 20 solar thermal power stations would be built in China. In the contrary, the traditional coal-fired power plant must face more difficult market environment due to the pollution issues. Considering that the stand-alone solar thermal power plants right now are not competitive with the traditional coal-fired power plants because of the high cost of building solar thermal power station ^[6-8]. So, the integration of solar thermal energy and coal-fired power plant seems to be attractive to solve this contradiction now in China, which not only could decrease the high cost of stand-alone solar thermal power plants, but also decrease the coal consumption in the traditional coal-fired power plant.

1.1. Schemes of the solar aided system

For the traditional coal-fired power plant, it needs retrofit to hybridize solar energy with the coal. The key point of solar aided system is to use the solar energy to replace another heat source in the coal power plant, as shown in Fig.1, there are 3 different processes which are possible to integrate the solar thermal energy into the Rankine cycle.

- 1) Bypass boiler scheme.

The final feedwater out of high pressure preheaters is divided into 2 two fluids which get into the solar aided heating system and boiler separately, these 2 fluids would go into the high-pressure cylinder after being heated to the main steam temperature and mixed evenly.

2) Bypass reheat scheme.

The cold-reheat steam out of the high-pressure cylinder is divided into 2 two fluids which get into the solar aided heating system and reheat separately, these 2 fluids would go into the medium pressure cylinder after being heated to the reheat steam temperature and mixed evenly.

3) Bypass high pressure preheater scheme.

The feedwater out of deaerator is divided into 2 two fluids which get into the solar aided heating system and high-pressure preheaters separately, these 2 fluids would go into the boiler after being heated to the feedwater temperature and mixed evenly.

This paper focuses on the thermodynamic analysis of these 3 schemes in a typical 330MW subcritical power units after integrating the solar energy into the system.

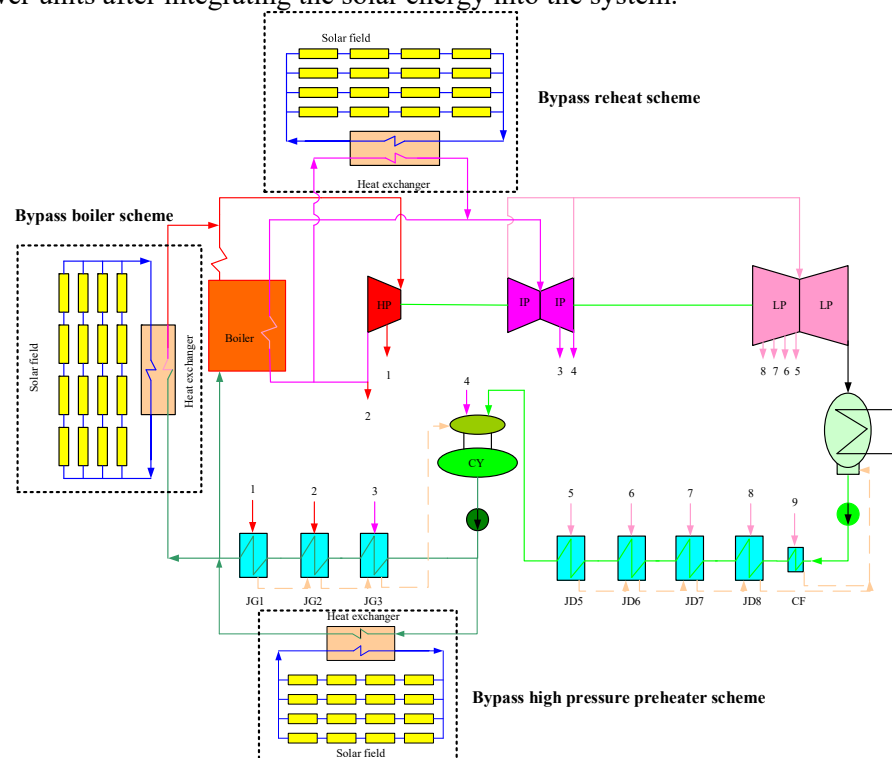


Figure 1 3 different schemes of solar aided coal power plant

2. Modelling of the hybridized system

2.1. Introduction of EBSILON

To analyze the thermodynamic performance of solar aided coal power plant, it is necessary to build the model of traditional coal-fired power plant first, and then integrate the solar heating system into the model. This paper would adopt EBSILON to build the thermodynamics model. Basically, the modelling process is that based on the components provided by EBSILON which describe basic physical processes, build the whole power plant system according to the sequence of components, component groups, subsystems, complete systems.

EBSILON is an "All in One" solution for plant engineering. It can be used for engineering, acquisition and planning for all kinds of power plants and other thermodynamic processes. EBSILON is visualized model builder, which enables building cycles with the graphical user interface. The computing core of EBSILON creates and solves for this a system of equations automatically.

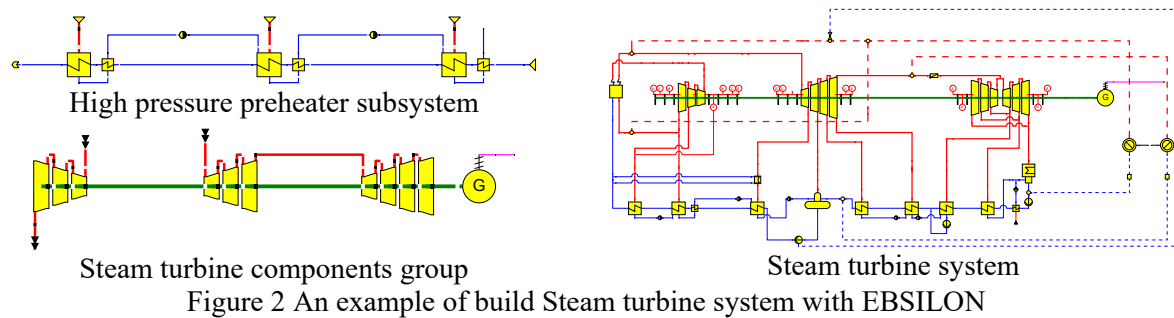


Figure 2 An example of build Steam turbine system with EBSILON

2.2. System design parameters

As mentioned in the chapter 1, to analyse the thermodynamic performance of the solar aided system, taking a typical 330MW subcritical coal-fired power plant as example to build the mathematical model. The design parameters are shown in the Table 1.

Table 1 Design parameters of a typical 330MW subcritical coal-fired power plant

Item	pressure(MPa)	temperature(°C)	mass flow(t/h)
coal	-	-	1210
main steam	16.67	540	1047.93
reheat steam	3.35	540	890.69
exhaust steam	0.00539	-	-
1st extraction steam	6.19	390.84	82.50
2nd extraction steam	3.56	321.20	71.73
3rd extraction steam	1.82	444.87	43.89
4th extraction steam	0.88	341.64	32.95
5th extraction steam	0.51	279.10	28.69
6th extraction steam	0.29	214.56	28.25
7th extraction steam	0.15	148.90	28.41
8th extraction steam	0.07	90.19	63.61

2.3. Modelling and validation

2.3.1. Boiler-turbine integration modelling

A complete mechanism model of solar-aided coal power plant is built in this paper based on EBSILON, which is a professional software for all kinds of power plants and other thermodynamic processes. As shown in Fig.2, This model is set up by using the modulization method, every equipment of a real power plant like boiler, turbines, feedwater preheaters, steam condenser, is built according to the sequence of equipment, subsystem and system.

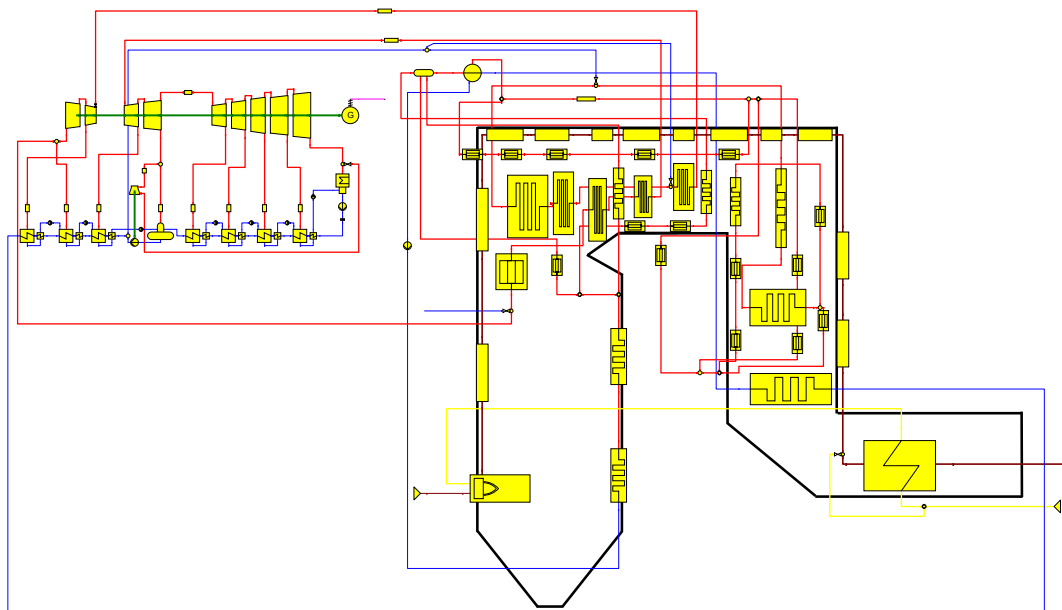


Figure 3 Boiler-Turbine integration calculation model based on EBSILON

2.3.2. Parameters validation

To verify the model's error is good enough to analyze the solar aided system, taking 40%THA load as an example, the comparison of parameters from manufactures and calculation results is listed in Table 2. The results show that the relative error is less than 5%.

Table 2 The comparison of design parameters and calculation results at 40%THA load

Item	unit	Manufacture	Calculation	Error
Power	MW	135.00	132.62	1.76%
heat rate	kJ/kWh	8533.54	8657.95	-1.46%
coal rate	t/h	498.04	507.38	-1.88%
air mass flow	t/h	527.59	527.51	0.01%
exhaust gas mass flow	t/h	583.61	580.13	0.60%
exhaust gas temperature	°C	106.18	109.23	-2.87%
main steam pressure	MPa	7.46	7.25	2.78%
main steam mass flow	t/h	395.29	394.08	0.30%
reheat steam pressure	MPa	1.32	1.38	-4.10%
reheat steam mass flow	t/h	355.34	354.29	0.30%
1st extraction steam	t/h	21.00	20.59	1.96%
2nd extraction steam	t/h	18.94	18.57	2.00%
3rd extraction steam	t/h	13.47	14.09	-4.59%

3. Comparison of different schemes

3.1. Solar thermal energy consumption capacity

In case of the power unit could NOT consume heat provide by solar energy at HIGH operation loads, the solar thermal energy system should be design based on the minimum operation load. In the other hand, based on the different schemes, the solar thermal energy consumption capacity would be affected by the operation safety of boiler and turbine, for example, the maximum temperature of main steam and reheat steam temperature, the minimum temperature of the SCR in the boiler, the maximum exhaust steam humidity etc.

According to the scheme diagram in Fig.1, integrate the solar thermal system into the model, the solar resources is described in Table 3. Taking the 40%THA as the minimum load, Fig.4, Fig.5 and Fig.6 shows how to determine the upper limit of design capacity of the solar thermal energy system.

Table 3

Item	unit	value
location	-	Yanqing District,Beijing,China
Latitude	°	40.4
Longitude	°	115.9
DNI	W/m ²	713

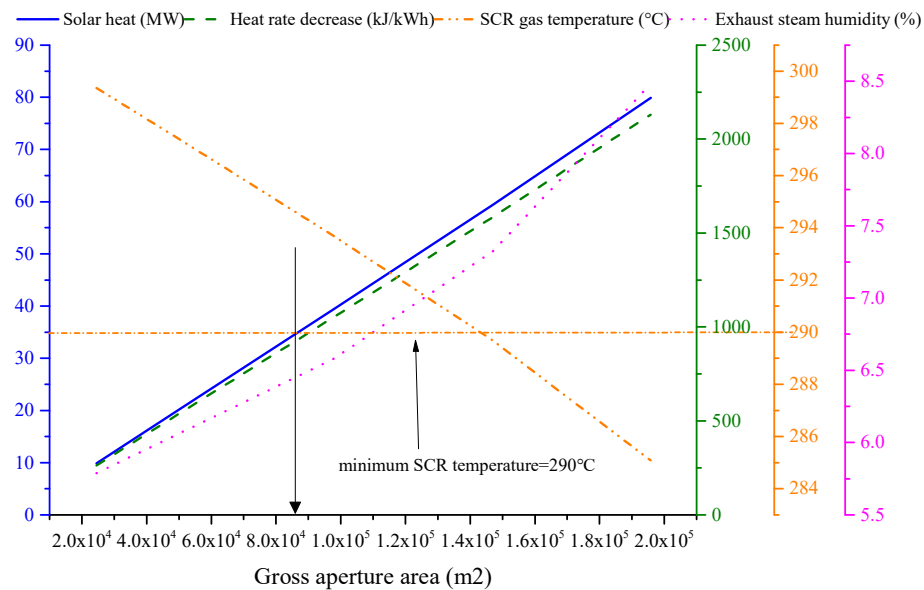


Figure 4 Upper limit of capacity of bypass boiler scheme

As Fig.4 shows that as the gross aperture area increases, the SCR temperature would decrease, but the requirement of SCR needs to make sure the gas temperature is higher than 290°C, so the upper limit of capacity of bypass boiler scheme is determined by the minimum SCR temperature, which is 35MW.

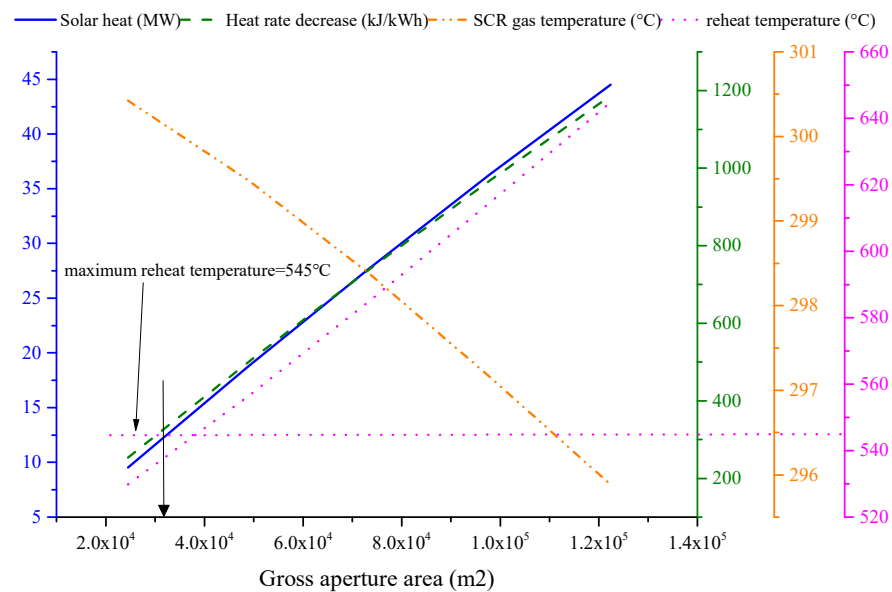


Figure 5 Upper limit of capacity of bypass reheat scheme

As Fig.5 shows that as the gross aperture area increases, the reheat temperature would also increase, but the operation safety of boiler needs to make sure the reheat temperature is NOT higher than 545°C, so the upper limit of capacity of bypass boiler scheme is determined by the maximum reheat temperature, which is 12.5MW.

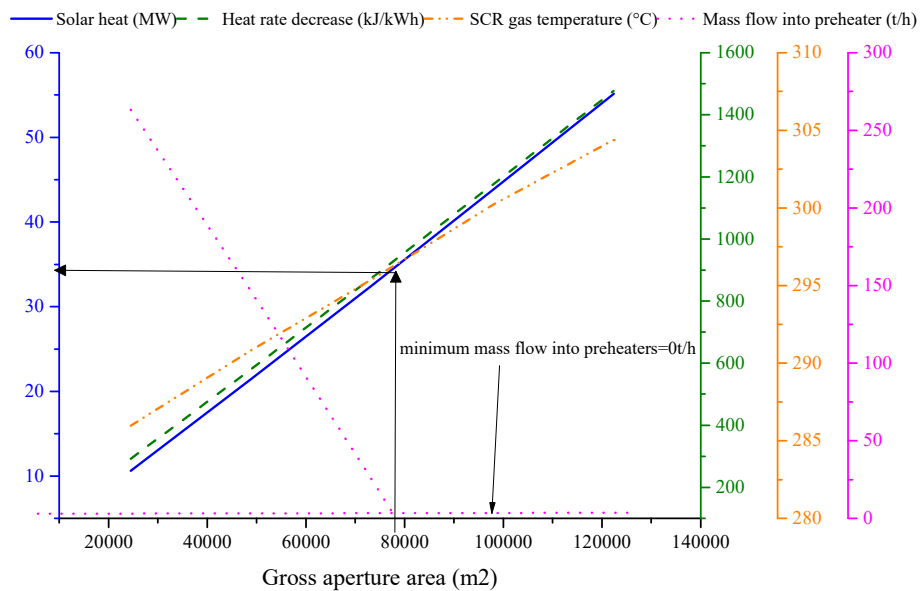


Figure 6 Upper limit of capacity of bypass high pressure preheater scheme

As Fig.6 shows that as the gross aperture area increases, the mass flow into high pressure preheaters would decrease, so the upper limit of capacity of bypass boiler scheme is determined by the minimum mass flow into preheaters(0t/h), which is 33MW.

3.2. Thermoeconomics comparison

As Fig.7 shows, the average heat transfer temperature increases in the sequence of preheat, main steam generation, reheat. So, it is reasonable to deduce that the thermoeconomic performance should also increase in the same sequence, the result from Fig.8 verify that.

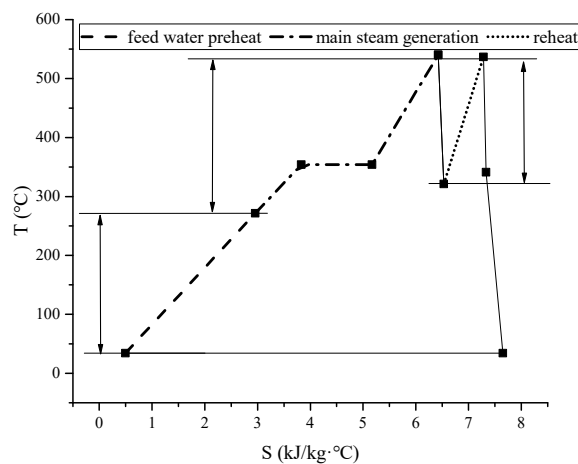


Figure 7 T-S diagram of Rankine cycle

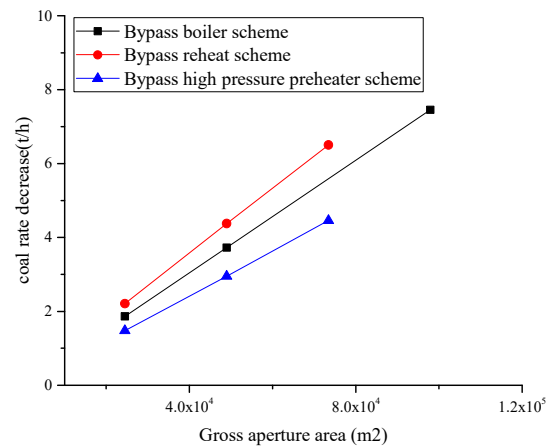


Figure 8 Thermoeconomics comparison of different schemes

3.3. Summary

Based on the thermoeconomic performance comparison result, the bypass reheat scheme and bypass boiler scheme are relatively better but considering that this scheme requires retrofit and rebuilt of boiler heating surfaces, the complexity and excessive cost of the system make these schemes less competitive, the bypass high pressure preheater scheme is recommended.

4. Thermodynamic performance analyses

4.1. Solar aided system operating characteristics

Under higher loads, the feedwater into the solar thermal block would be higher, if the mass flow doesn't change, the outlet temperature of feedwater would higher too. To keep the feedwater temperature, the same as before the retrofit, it is necessary to adjust the mass flow into the solar thermal block. As shown in Fig.9, Although the final feedwater temperature increases as the load increases, but the mass flow into solar thermal block would decrease linearly. Comparing the change of extraction mass flow before and after the retrofit, as shown in the Fig.10, the extraction steam mass flows decrease by 10-20t/h on average. As shown in Fig.11, the heat rate would decrease by 200-700kJ/kWh and the coal consumption rate would decrease by 40-42t/h with the solar aided system running.

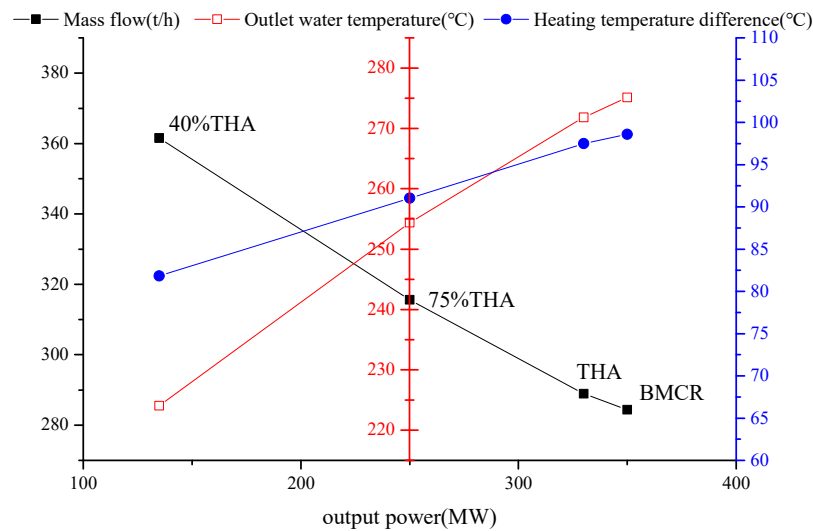


Figure 9 Solar aided system off-design parameter adjustment

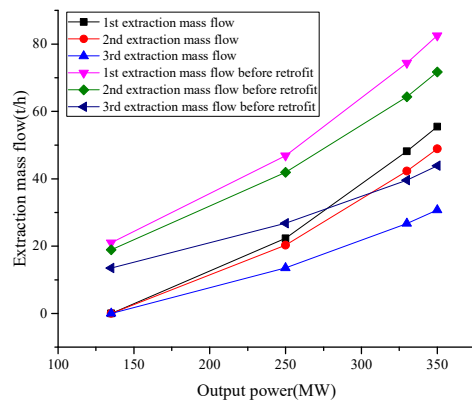


Figure 10 The mass flow change of extraction steam

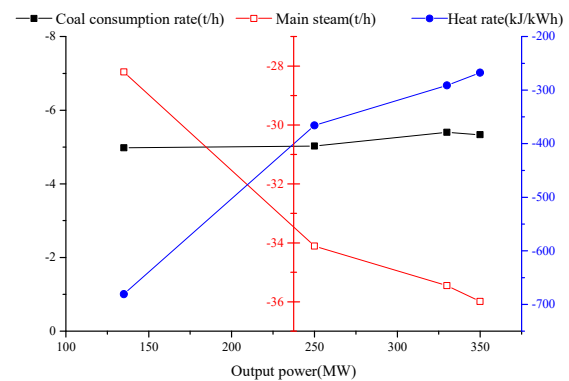


Figure 11 The effect on thermo-economy of solar aided system

4.2. DNI effect

Considering the DNI would change during day and night, the solar aided system would have to stop operating in the night without energy storage system, Fig.12 shows a typical load curve for 24 hours, take the DNI change and load curve into consideration, the calculation result of coal rate decrease is showed in Fig.13. Table 4 shows the total coal rate difference in one day between solar aided power plant and traditional power plant, the result shows that coal rate would decrease by 2.13% with solar aided system.

Table 4 Coal rate decrease under a typical load curve

Item	unit	value
Solar aided coal-fired power plant	t/h	2626.2
Coal-fired power plant	t/h	2683.4
coal rate decrease	t/h	57.2
coal rate decrease percentage	%	2.13

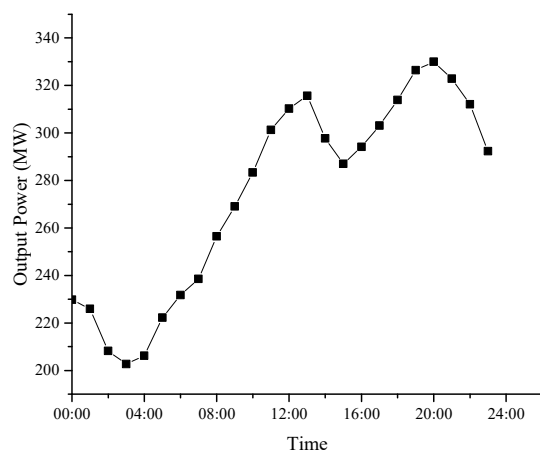


Figure 12 Typical output power curve

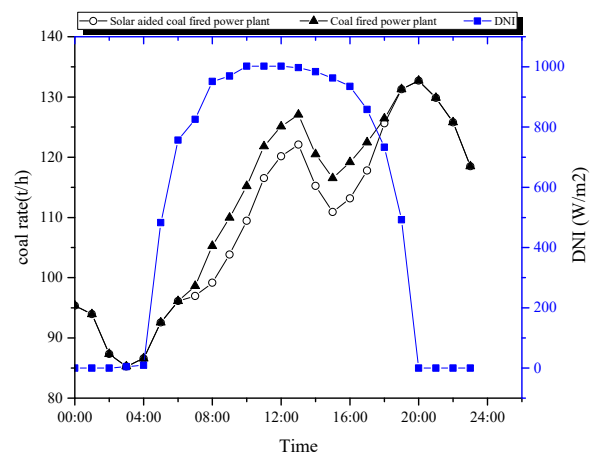


Figure 13 Coal rate decrease for one day

5. Conclusions

In this paper, a typical 330MW subcritical solar aided coal-fired power plant was evaluated. It is found that the design baseload of solar aided system should be the minimum operation load of the coal-fired power plant. Based on the adopted schemes, SCR gas temperature, reheat steam temperature etc. could be the possible factor of the upper limit of solar aided system capacity, and according to the calculation result, the solar aided system capacity could be between 10-35MW.

The thermoeconomic performance increase in the sequence of preheat, main steam generation, reheat based on the average heat transfer temperature.

Under off design conditions, the mass flow into solar aided system should be adjusted to keep the final feedwater temperature unchanged compared with the temperature before the retrofit. After installation the solar aided system, the extraction steam mass flows decrease by 10-20t/h on average, the heat rate would decrease by 200-700kJ/kWh and the coal consumption rate would decrease by about 5t/h.

Considering the effect of DNI and actual load change curve, coal rate would decrease by 2.13% with solar aided system.

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