Exergy analysis and economic evaluation of the steam superheat utilization using regenerative turbine in ultra-supercritical power plants under design/off-design conditions

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Design/off-design conditions, economic analysis, exergy destruction, regenerative turbine, steam superheat utilization, thermodynamic analysis

Abstract
In order to effectively utilize the steam superheat of ultra-supercritical power plants, a regenerative turbine (RT) system was proposed. In the RT system, a portion of the high-pressure turbine exhaust steam is sent to an extra turbine termed as RT, and the extracted steam of several regenerative heaters (RHS) would be extracted from the RT instead of the intermediate-pressure turbine. The superheat degree of related extracted steam would decrease and the exergy destruction of the heat transfer process in RHS would be reduced. Thermodynamic and economic analyses of the RT system in a typical 1000 MW power plant were carried out. The results showed that the heat consumption rate would be reduced as compared to the conventional configuration. When the RT isentropic efficiency is set to 85%, the heat consumption rate of the RT system could decrease by 46.9 kJ/kWh as compared to that of the reference system without RT under design condition. The heat consumption rate decrement will be greater with higher RT isentropic efficiency. Meanwhile, thermodynamic analysis of the RT system under off-design condition showed that the energy saving effect of the RT system would be decreased when the design conditions are no longer met. The exergy analysis showed that the total exergy destruction decrement of related RHS in the RT system decreases as the load drops down. Moreover, the economic analysis revealed that the net economic benefit of the RT system could reach 0.57 M$ per year, and would perform economically within a wide range fluctuations of power market conditions.

Nomenclature

| Symbol | Description |
|--------|-------------|
| E_total | total energy input per unit time |
| P_gen | generated electric power |
| ΔE_ex | exergy destruction |
| E_ex,in | exergy input |
| W_in | power input |
| E_ex,out | exergy output |
| W_out | power output |
| E_ex,loss | exergy loss caused by energy loss |
| ΔI_net | net economic benefit |
| ΔI | income of energy saving |
| ΔC_O&M | annual operating and management costs |
| CRF | capital recovery factor |
| Δq | reduction in the heat consumption |
| P_f | fuel price |
| h_eq | equivalent operation hours per year |
| P_gen | power output of the power plant |
| η_i,rt | isentropic efficiency of regenerative turbine |
| k | the discounted rate |
| n | the equipment life span |
| C_O&M | operation and maintenance cost |
| γ | proportionality coefficient |

Abbreviations

RT regenerative turbine
USC ultra-supercritical
Introduction

Coal-fired power generation provides over 40% of electricity supply worldwide and is expected to continue to play a predominant role in the global energy mix in the near future [1, 2]. In China, it provides nearly 80% of the total electricity requirement and accounts for more than half of total coal consumption. Consequently, these power plants contribute nearly 50%, 37%, 33% and 50% to the total SOx, NOx, dust, and CO2 emission volumes, respectively, for the entire country [3, 4]. Encountering these emissions necessitates the need to implement strategies and plans to mitigate the impacts of coal-fired power plants on air quality and global environment [5]. In view of recent regulations concerning emission reduction, electric power industries have been required to improve the energy efficiency of coal-fired power plants, which could both lessen the impacts on the environment and increase the economic viability, particularly for developing countries where electric power consumption is rapidly rising [6, 7]. Improvements in efficiency would be satisfied, using larger units and higher steam parameters. As a result, a lot of large ultra-supercritical (USC) units are widely applied in recent years.

On a global scale, USC power generation technology is entering a fast-development stage. The parameters of the live steam in USC power plants has rapidly increased worldwide, resulting in improved parameters of the extracted steam with increased superheat degree. Moreover, the increased superheat degree of the extracted steam leads to large temperature difference and exergy destruction during the heat transfer process of the regenerative heater (RH) [8]. Appropriate superheat utilization of extracted steam by reducing the superheat degree is an effective approach to further improve the thermal efficiency of USC power plants. Generally, an outer steam cooler is mostly used to effectively utilize the superheat of extracted steam, which involves setting a surface-type heat exchanger before the regenerative heater [9]. The superheated extracted steam enters the outer steam cooler, and some of its superheat is used to heat the feed water, which reduces the superheat degree and improves the feed water temperature. Liu et al. [9] investigated the thermal performance of a steam cycle employing an outer steam cooler. Li et al. [10] conducted the thermodynamic and techno-economic analysis of a double reheat power plant with an outer steam cooler. A heat circulation calculation model for a power plant employing an outer steam cooler was established in Ref. [11]. These studies have demonstrated that using the outer steam cooler is an effective superheat utilization measure in power plants. Using the outer steam cooler can reduce the superheat degree of extracted steam by more than 100°C. However, the outer steam cooler could only utilize the superheat of special extracted steam.

Another effective method for superheat utilization of extracted steam is to employ a regenerative turbine (RT). In this system, part of the exhaust steam from the high-pressure turbine (HPT) flows directly into a RT without entering the reheater [12, 13]. Several extracted steam points are set in the RT to replace those in the intermediate-pressure turbine (IPT). The extracted steam from the RT is not reheated, and thus, the superheat degree of multistage extracted steam is effectively reduced in this system. This could achieve a reduced exergy destruction of the regenerative heaters (RHS) and improve the thermal performance of the whole power plant. Ploumen et al. [14] compared the thermal performance between a common steam cycle and the RT system. Cai et al. [15] conducted thermodynamic analysis of a RT system in a double reheat USC power plant. Xu et al. [16] also investigated the energy effect of double reheat power plants. The results of these studies indicated that the thermal efficiency could increase by employing a RT to utilize superheat of extracted steam.

Moreover, large USC power plants often operate under partial load for peak regulation. Han et al. [17] conducted a simulation study of a lignite-fired power system integrated with flue gas drying and waste heat recovery to present performances under variable power loads. Thermodynamic analysis of a solar aided coal-fired power plant under design/off-design conditions was studied in Ref. [18]. The superheat degree of extracted steam increases when the load decreases under the sliding pressure operation mode. Thus, it is necessary to conduct thermodynamic analysis of superheat utilization under off-design conditions. The RT system needs new equipment and facilities, resulting in an increased power plant investment. Rovira et al. [19] investigated thermodynamic and techno-economic analyses of combined cycle gas turbine power plants. However, few studies have focused on thermodynamic and techno-economic analysis of the RT system to utilize the superheat of the extracted steam in 1000 MW USC power plants, especially under off-design operation conditions. In addition, the isentropic efficiency of the
RT could influence the energy saving effect of superheat utilization, few studies have investigated the RT system with different isentropic efficiency.

Against this backdrop, in the present work, thermodynamic and techno-economic analyses of superheat utilization using the RT in a 1000 MW USC power plants were conducted under design/off-design conditions, to achieve the following objectives: (1) to conduct thermodynamic evaluation of superheat utilization system with different RT isentropic efficiency under design/off-design conditions; (2) to reveal the energy saving mechanism of the RT system based on exergy analysis of superheat utilization of the extracted steam; and (3) to assess the economic performance of the superheat utilization system using the RT.

**Steam Superheat Utilization Using a Regenerative Steam Turbine in a Typical 1000 MW USC Power Plant**

**Reference system description**

A typical USC power plant is selected as the reference system in this study. The simplified process flow diagram of the USC power plant is shown in Figure 1. The plant consists of one single-flow high-pressure turbine (HPT), one double-flow intermediate-pressure turbine (IPT), and two double-flow low-pressure turbine (LPT). All the HPT, IPT, and LPT sections in the turbine are connected to the generator by a common shaft. The steam from the exhaust of the HPT is returned to the boiler for reheating and sent to the double flow IPT. The exhaust steam from the IPT flows through the LPT system and goes into the condenser (CON). The regenerative system of the steam cycle has eight-stage regenerative heaters (RHs), including four low-pressure RHs, three high-pressure RHs, and one deaerator (DEA).

The power plant is designed to generate live steam at the nominal conditions of 26.25 MPa and 600°C. The power output of the reference system under design condition which can be also termed as turbine heat acceptance (THA) condition is 1000 MW. The reheat steam is heated to 600 °C, and the exhaust steam pressure of LPT is set to 5.75 kPa. Table 1 lists major parameters of the extracted steam in the reference system.

**Configuration of the RT system**

As shown in Table 1, the superheat degree of the extracted steam in RH3, DEA and RH5 is higher than other extracted steam. Obviously, the extracted steam of RH3, DEA and RH5 is extracted from the IPT. Because the steam has been reheated during the reheat process and then enter the IPT, the temperature of the extracted steam from the IPT is high. If the superheat degree of the extracted steam in RH3, DEA and RH5 can be effectively utilized, the thermal performance of the reference system will be improved effectively. Using the RT is an appropriate approach to achieve the superheat utilization of the extracted steam in the reference system.

Figure 2 depicts a simplified process flow of steam cycle in the RT system. A portion of the exhaust steam of the HPT is sent to a RT instead of the reheater, and therefore, the extracted steam in RH3, DEA and RH5 will be extracted from the RT instead of being extracted from the IPT.
In this configuration, the superheat degree of the extracted steam in RH3, DEA and RH5 is significantly reduced because this portion of extracted steam will not be reheated. As a consequence, the temperature difference of the heat transfer process will be also dramatically reduced. Likewise, the steam entering the reheater of the boiler can be obviously reduced, and, as a result, the heat absorption of the boiler decreases with the reduction in the heat capacity of the reheater.

**Thermodynamic Analysis of Steam Superheat Utilization Using RT Under Design/Off-Design Conditions**

**Main models considerations and thermodynamic evaluation criteria**

The thermodynamic cycles of the power plant are simulated using EBSILON Professional in this study [20]. The selection of an accurate method is essential to ensure the precision and reliability of simulation results. EBSILON Professional is a widely used power plant simulation tool whose main purpose is to calculate thermodynamic quantities including enthalpies, pressures and mass flows in the steam cycle, and is restricted to thermodynamic equilibrium states to describe plant components [21–23]. Thermodynamic models of power plants, which can create a set of heat balance data that complies with mass and energy balances, are utilized in the simulation process.

In the present study, the model descriptions of the main components are as follows. The boiler with double reheating is modeled as a black box. The inlet pressure and the isentropic efficiencies are defined in the steam turbine. In most cases, the outlet pressure is determined by the inlet pressure of the following turbine stage. In the last turbine stage, the outlet pressure is determined by the inlet pressure of the condenser. For the RHs, the terminal temperature difference of the primary heater (i.e., the temperature difference between the saturated steam and the heated primary water) and the terminal temperature difference of the after-cooler (i.e., the temperature difference between the drain and the heated primary water) are to be specified. The inlet temperature and pressure of the cooling medium for the condenser are also specific.

In addition, the operation of the power plant is considered to be in a steady state and the mean isentropic efficiencies of the HPT, IPT, and LPT are equal to 0.90, 0.93, and 0.89, respectively.

The heat consumption rate and thermal efficiency are commonly used in the electric power industry to evaluate

![Figure 2. Process flow diagram of the steam cycle in RT system.](image)
the thermal performance of power generation units, which can be defined as follows:

\[ q = \frac{E_{\text{total}} \times 3600}{P_{\text{gen}}} = 3600 \div \frac{P_{\text{gen}}}{E_{\text{total}}}, \quad (1) \]

\[ \eta = \frac{P_{\text{gen}}}{E_{\text{total}}}, \quad (2) \]

where \( E_{\text{total}} \) refers to the total energy input per unit time. \( E_{\text{total}} \) is the total energy input including the chemical energy of coal, the energy of air and the energy of makeup water. To simplify the calculation, the quantitative value of \( E_{\text{total}} \) is considered as the chemical energy of coal, which is equivalent to the lower heating value (LHV) of coal input per unit time.

\( P_{\text{gen}} \) refers to the generated electric power. The number 3600 refers to 3600 kJ/kWh. The unit of heat consumption rate \( q \) is kJ/kWh.

**Thermodynamic evaluation of the RT system under design condition**

Thermodynamic analysis for the RT system and the reference system is conducted through the simulation. The isentropic efficiency of the RT is set to 85%. The extracted steam pressure of the RT system is equivalent to that of the reference system in simulation. Table 2 gives the major parameters of the steam cycle and thermal performance of the reference system and the RT system under design condition.

Table 2 shows that the live steam flow rate increases in the RT system because the mass flow of the extracted steam increases as the superheat degree decreases. The heat consumption rate of the RT system is significantly reduced by 46.9 kJ/kWh. The thermal efficiency of the RT system is increased by 0.27%-points.

Figure 3 compares the superheat degree of extracted steam in the two systems. The temperatures of the related extracted steam of RH3, DEA and RH5 are reduced after employing the regenerative steam turbine. Consequently, the superheat degree of the related extracted steam is also reduced. The superheat degree of the related extracted steam in RH3, DEA and RH5 extracted from the IPT is high in the reference system, which is effectively reduced by extracting from the regenerative steam turbine without being reheated in the RT system.

**Thermodynamic evaluation of the RT system under off-design conditions**

Considering that large USC power plants need to frequently operate under off-design operation condition, it is necessary to study the thermal performance of a 1000 MW USC power plants under off-design conditions. Four typical operation conditions, including THA load, 75% THA load, 50% THA load, and 40% THA load conditions are selected for analysis in this study. Table 3 presents the superheat degree of extracted steam in the reference system under design and off-design operation conditions.

![Figure 3. Superheat degree of the extracted steam in RT system and reference system under design condition.](image)

Table 2. Comparisons of major parameters and thermal performances of reference system and RT system under design condition.

| Items                                      | Reference system | RT system  |
|--------------------------------------------|------------------|------------|
| Live steam flow rate (kg/sec)              | 750.0            | 770.3      |
| Live steam pressure (MPa)                  | 26.25            | 26.25      |
| Live steam temperature (°C)                | 600.0            | 600.0      |
| Reheated steam pressure (MPa)              | 5.0              | 5.0        |
| Reheated steam temperature(°C)             | 600.0            | 600.0      |
| Feed water pressure (MPa)                  | 32.7             | 32.7       |
| Feed water temperature (°C)                | 295.4            | 295.4      |
| Heat consumption rate (kJ/kWh)             | 7969.8           | 7922.9     |
| Decrease of heat consumption rate (kJ/kWh) | –                | 46.9       |
| Thermal efficiency (%)                     | 45.17            | 45.44      |
| Increase in thermal efficiency (%-points)  | –                | 0.27       |

Obviously, the superheat degree increases at off-design conditions because the large power generation units always adopt the sliding pressure operation mode [24]. That is, the live steam pressure and live steam mass flow decrease correspondingly as the power output decreases. However, live steam temperature normally remains constant when the load decreases. Therefore, the pressure of extracted steam decreases gradually as the load decreases while the temperature remains almost unchanged. This indicates that the super heat degree will even greater and the
superheat utilization of extracted steam is more important under off-design condition.

Table 4 compares the heat consumption rate comparison of the reference system and the RT system under design and off-design conditions. The heat consumption rate of each system increases when the load decreases. Through adopting the RT, the heat consumption rate decreases more significantly than that of the reference system. In addition, the heat consumption rate of the regenerative system will further decrease when the isentropic efficiency of the RT increases.

Considering that the isentropic efficiency of the RT has important influence on the thermal performance of the RT system, Figure 4 illustrates the decrement of the heat consumption rate between the reference system and the RT system with different RT isentropic efficiency under design and off-design conditions. It can be observed that the decrement of heat consumption rate of each RT system increases when the load increases. Therefore, the energy saving effect of RT system is more obvious as the load increases. Moreover, the energy saving effect of the RT system becomes greater with higher RT isentropic efficiency.

### Exergy analysis of RT system and reference system

As mentioned above, the thermodynamic evaluation shows that the RT system can effectively utilize the superheat of extracted steam, that is, the superheat degree of the related extracted steam is reduced obviously by adopting the RT. As a result, the energy saving effect of the RT system is considerable to achieve the superheat utilization. When the load increases, the energy saving effect of the RT system is more obvious. To further reveal the mechanism of superheat utilization, the comparison of exergy analysis of the related regenerative heaters is performed for the reference system and the RT system.

Clearly, the heat transfer temperature difference and the superheat degree of the extracted steam in RH3, DEA and RH5 will be reduced, leading to a decrease of exergy destruction of the heat transfer process in the regenerative heater.

Figure 5 illustrates the T-S diagram of the heat transfer process between the extracted steam and the feed water or condensate water in the regenerative heater. The entropy generation and the exergy destruction are the measurement indicators of the thermodynamic irreversibility. Entropy on the abscissa represents the entropy of the working medium. T on the ordinate denotes the temperature of the working medium. T₀ represents the environment temperature. The process 5-4-3 represents the exothermic process of the extracted steam, and the process 1-2 represents the endothermic process of the feed water or condensate water. The entropy increase during the heat transfer process in the regenerative heater is ΔS. When the superheat degree of the extracted steam decreases, the exothermic process of the extracted steam can be exhibited as 6-7-3 and the endothermic process of the feed water or condensate water is still shown as 1-2. Obviously, the entropy increase will be reduced by ΔS caused by the reduced heat transfer temperature difference. As a result, the exergy destruction will be reduced, which can be represented by the shaded part in Figure 5.

The general exergy balance of the system components can be expressed as:
In equation (3), $\Delta E_{ex}$ refers to the exergy destruction; $E_{ex,\text{in}}$ and $W_{in}$ refer to the exergy input and the power input, respectively; $E_{ex,\text{out}}$ and $W_{out}$ denote the exergy output and the power output, respectively. $E_{ex,\text{loss}}$ represents the exergy loss caused by energy loss. However, in this study, there is very little heat dissipation during the energy conversion process, therefore, the simulation models of the systems are considered as adiabatic process and the heat dissipation is reasonably ignored, and $E_{ex,\text{loss}}$ in the energy conversion process is zero [25, 26].

The exergy destruction within a special component of the energy conversion system can be derived from the exergy balance equation. For the regenerative heater, there is no $W_{in}$ and $W_{out}$ during the heat transfer process. As a result, the general exergy balance of the regenerative heater can be expressed in the following rate form:

$$\sum E_{ex,\text{in}} + \sum W_{in} = \sum E_{ex,\text{out}} + E_{ex,\text{loss}} + \Delta E_{ex}.$$  \hfill (3)

In equation (3), $\Delta E_{ex}$ refers to the exergy destruction; $E_{ex,\text{in}}$ and $W_{in}$ refer to the exergy input and the power input, respectively; $E_{ex,\text{out}}$ and $W_{out}$ denote the exergy output and the power output, respectively. $E_{ex,\text{loss}}$ represents the exergy loss caused by energy loss. However, in this study, there is very little heat dissipation during the energy conversion process, therefore, the simulation models of the systems are considered as adiabatic process and the heat dissipation is reasonably ignored, and $E_{ex,\text{loss}}$ in the energy conversion process is zero [25, 26].

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$$\sum E_{ex,\text{in}} = \sum E_{ex,\text{out}} + \Delta E_{ex}.$$  \hfill (4)

Figure 6 shows the total exergy destruction of RH3, DEA and RH5 in the RT system and the reference system under design and off-design conditions. The two solid line denotes the total exergy destruction of related RHs (RH3-RH5) in the reference system and the RT system, respectively. The total exergy destruction of RH3, DEA and RH5 in the RT system is effectively reduced as compared to that of the reference system. In addition, the total exergy destruction decrement of related RHs between the reference system and the RT system decreases as the load drops down, as shown by the dashed line in Figure 6.

To further study the reason of different energy saving effect between the RT system and the reference system under off-design conditions, the exergy destruction decreases the coefficient of RHs, which represents the ratio of the RHs’ exergy destruction difference between the RT system and the reference system to the RHs’ exergy destruction of the reference system, is proposed in this study. Figure 7 gives the decrease coefficient of the exergy destruction of the RT system. It can be observed that the exergy destruction decrease coefficient of the RHs increases as the load increases in the RT system. Thus, the decrement of heat consumption rate of RT system increases when the load increases and the energy saving effect becomes more obvious as the load increases.

Economic Analysis of the RT System

Basic evaluation

As discussed above, the RT system can effectively utilize the superheat of extracted steam in related RHs. As such, it is expected that new equipment and facilities, such as RT and steam pipes, will be added to the reference system. This will lead to the increasing power plant investment with rising equipment cost and the operating and management cost.

In the RT system, the net economic benefit can be defined as follows:

$$\Delta I_{net} = \Delta I_{es} - \Delta ICC \times CRF - \Delta C_{O&M},$$  \hfill (5)

where $\Delta I_{net}$, $\Delta I_{es}$, $\Delta ICC$ and $\Delta C_{O&M}$ denote the net economic benefit, the income of energy saving, total additional installed capital costs and the annual operating and management costs, respectively, and CRF is the capital recovery factor.
The $\Delta I_{es}$ is calculated as follows:

$$\Delta I_{es} = \Delta q P_F h_{eq} P_{gen},$$

where $\Delta q$ refers to the reduction in the heat consumption (kJ/kWh), $P_F$ refers to the price of fuel ($/J$ LHV), $h_{eq}$ denotes the equivalent operation hours per year (h), and $P_{gen}$ is the power output of the power plant (MW).

The capital recovery factor (CRF) is related to the discounted rate ($k$) and the equipment life span ($n$). Because $k$ refers to the fraction interest rate per year, and $n$ refers to the number of years that the capital has been borrowed over a fixed rate of interest [27]. CRF can be calculated with the following as follows:

$$CRF = \frac{[k \cdot (1+k)^n] / [(1+k)^n-1].}$$

The operating and management cost ($C_{O&M}$) is assumed to be proportional to ICC, with the proportionality coefficient of $\gamma$ set to 4% [28].

The basic assumptions for net economic benefit calculation are listed in Table 5.

The values for total additional installed capital costs (ICC) associated with added equipment and the construction of the RT system to achieve steam superheat utilization are illustrated in Table 6 [29, 30]. ICC includes the investment cost of the added equipment and related auxiliary fees (e.g., construction and installation cost) in the project. As illustrated in Table 6, when the RT is implemented, the additional ICC of the power plant increased by $3.02 \text{M}$.

Table 7 presents the results of techno-economic analysis for the RT system. The heat consumption decrement of the regenerative system is 46.9 kJ/kWh, and the $\Delta I_{es}$ of the RT system reach $1.06 \text{M}$. Eventually, the values of net economic benefit of the RT system are $0.57 \text{M}$. The RT system can bring considerable economic benefits by superheat utilization of extracted steam of related regenerative heaters.

### Sensitivity analysis

According to the economic evaluation (cf. Section 5.1), the fluctuations of key economic parameters will influence the economic performance of the power plant with RT. Figure 8 shows the net economic benefit of the RT system as functions of percent changes in additional ICC ($\Delta ICC$), fuel price, discounted rate and annual operation hours, respectively.

Obviously, the net economic benefit of the RT system increased as fuel price and annual operation hours increased, but showed a decrease with the increase of additional ICC and discounted rate. Besides, the net economic benefit of the RT system was highly depended on the fuel price and the annual operation hours. This is due to the fact that fuel is the sole input of the power plant and thus these two factors directly influence the income of energy saving. Quantitatively, a 20% increase in fuel price would cause the net economic benefit to increase from $0.57\text{M}$ to $0.77\text{M}$ in the RT system. By contrast, when the additional ICC of the RT system increased by 20% compared to the baseline value, the net economic benefit would decrease from $0.57\text{M}$ to $0.37\text{M}$.

#### Table 5. Basic assumptions for net economic benefit calculation.

| Investment index          | Value                  |
|---------------------------|------------------------|
| Fuel price ($P_F$)        | $4.09 \$/GJ            |
| Annual discount rate ($k$)| 0.12                   |
| Plant economic life ($n$) | 30 years               |
| Annual operation hours ($h_{eq}$) | 5500 h/year        |

1The coal price is based on Ref [10].
2Plant economic lifetime and discount rate are according to Ref. [28].

#### Table 6. Additional installed capital costs of the RT system.

| Investment index          | Values (M$) |
|---------------------------|-------------|
| Regenerative turbine      | 2.16        |
| Pipes                     | 0.72        |
| Construction and installation costs | 0.14 |
| Total additional installed capital costs | 3.02 |

#### Table 7. Annual economic performance of the RT system.

| Performance index                      | Values           |
|----------------------------------------|------------------|
| Decrement of heat consumption (kJ/kWh) | 46.9             |
| Extra economic benefit of energy saving (M$) | 1.06           |
| Annualized additional installed capital costs (M$) | 0.37          |
| Annualized operation and maintenance costs (M$) | 0.12           |
| Net economic benefit (M$)              | 0.57             |

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benefit just slightly decreased from $0.57M to $0.46M. This is because that the influence of the additional ICC of the RT system on the economic benefit is weakened by the factor of CRF.

In general, the sensitivity analysis revealed that the net economic benefit of the RT system were more sensitive to the fuel price and annual operation hours and relatively less sensitive to the additional ICC and discounted rate. More importantly, within a wide range fluctuations of power market conditions, the RT system will still performed economically as compared to the reference system without RT.

**Conclusion**

The thermodynamic and economic analyses of the regenerative steam turbine system in a 1000 MW USC power plant were conducted in this study. The RT system exhibits better performance than the reference system under design/ off design condition. The results reveal the followings.

1. The heat consumption rate of the RT system is significantly reduced by 46.9 kJ/kWh than that of the reference system under design condition, which reveals the significant energy saving effect of steam superheat utilization.

2. The RT system exhibits different energy saving effects under off-design conditions. The heat consumption rate decrement of the RT system decreases from 46.9 kJ/kWh to 20.5 kJ/kWh as the load of the power plant decreases from THA condition to 40% THA condition. However, a more obvious energy saving effect with higher isentropic efficiency of the RT can be expected no matter under design or off-design conditions.

3. Economic analysis results showed that the remarkable energy saving effect outweighed the increase in ICC, and consequently, the RT system featured considerable

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**Figure 8.** Influence of the in fuel price, discounted rate, additional ICC and annual operation hours on net economic benefit of RT system.
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Conflict of Interest

None declared.

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