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Economic Analysis of the Thermal Performance of a Novel Solar Thermal Power Generation System Considering Solar Radiation Intensity

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Studies have shown that solar thermal power generation (STPG) can partially replace conventional power generation techniques, thus solving the global problem of energy shortage. Targeting a 70kW butterfly type STPG system, this paper discusses the impacts of solar radiation intensity on the concentrator, and analyses the economic efficiency of the system against such economic indices as internal rate of return (IRR), net present value (NPV) and levelized energy cost (LEC). The research results show that: When the solar radiation intensity is greater than 400W/m2, the proposed system can operate at above 70% of the full load without using natural gas; when the solar radiation intensity is greater than or equal to 700W/㎡, the system can operate at full load. The butterfly type STPG system requires more basic investment and has a longer payback period than common power generation systems. Besides, the combined generation mode incurs a far smaller energy cost (0.75kWh) than the generation mode dominated by solar power (2.045kWh). The on-grid electricity price has the greatest impact on the IRR and NPV, followed by basic system investment and natural gas price. The research findings lay the theoretical bases and provide economic references for the development of STPG systems.

1. Introduction

Under the increasingly serious environmental pollution and shortage of petrochemical energy supply, countries around the world are competing to develop renewable energies like wind energy, tidal energy and solar energy and to build a clean and low-carbon modern energy system. Compared with other new energy sources, the solar energy enjoys a promising application prospect thanks to its ubiquity, infinite reserve, as well as clean and economic utilization.

Photothermal, photovoltaic and photochemical conversions are the main ways to utilize solar energy. As a type of photovoltaic conversion, the solar thermal power generation (STPG) marks the most important direction of solar energy utilization. By this power generation method, the solar energy is converted into thermal energy, mechanical energy and finally electrical energy (Silva et al., 2018).

There are three types of STPG systems with concentrated solar power collectors: the through type, the butterfly type and the tower type (Jafarian et al., 2013). The butterfly type STPG system stands out for its low investment, easy installation, long life and high efficiency. It has been proved as a feasible alternative to traditional power generation technologies (Cooman and Schrevens, 2007).

The foreign research on butterfly type STPG can be dated back to as early as the 19th century. However, this type of STPG system has not been widely adopted due to the high cost (Kalogirou, 2009). Later, the US, Saudi Arabia and Germany successively developed and established butterfly-type Stirling engine STPG systems and power stations. Large butterfly-type power stations were built and put into use in many countries, with the continuous maturity of technology in recent years.

By contrast, the domestic research on butterfly type STPG systems is still in its infancy. Developed in 2008, the 25kW butterfly type STPG device was basically ready for commercialization (Herazo et al., 2018). Despite some valuable experience acquired through R&D, China is still in lack of the independent R&D ability for key components and has not built any commercial STPG system.

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Based on the above analysis, this paper briefly introduces the butterfly type STPG system in light of related studies at home and abroad, and designs a 70kW butterfly type STPG system by modifying the 70kW tower type STPG station developed by Academician Zhang Yaoming. In addition, several common economic indices were described, including net present value (NPV), internal rate of return (IRR) and levelized energy cost (LEC), to evaluate the performance of power generation systems, especially the thermal performance and economic efficiency of the proposed butterfly type STPG system. Specifically, the author analysed the impact of solar radiation intensity on solar collector, discussed the economic efficiency of the system under different power generation modes, and identified the sensitive factors affecting the system's economic efficiency.

2. Theoretical Bases

2.1 Butterfly type STPG system

The butterfly types STPG system mainly consists of a thermal power generator set, a concentrator and a receiver (Leon and Kumar, 2007). Using a butterfly type parabolic collecting lens, the concentrator has either a single disc or multiple discs (Lazaar et al., 2015) (Figure 1). The receiver is the key to photothermal conversion and the driver to the heat engine. As the core component of the STPG system, the receiver is usually a cavity receiver with high efficiency and simple structure (Wang and Lior, 2011).

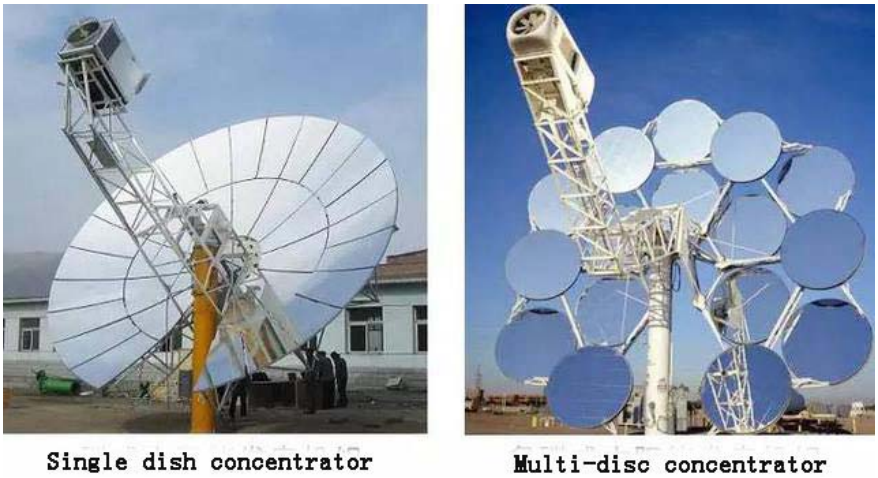

Figure 1: Single-disc and multi-disc concentrators

Here, a 70kW butterfly type STPG system is designed by modifying the 70kW tower type STPG station developed by Academician Zhang Yaoming (Montes et al., 2009). The main modifications include reducing the land occupation by replacing the original collecting lens with a butterfly type collecting lens, which is composed of ten small mirrors arranged at an interval of 40mm (Figure 2), and adopting a cylindrical cavity receiver that reduces the radiation loss rate to 0.8% (Figure 3).

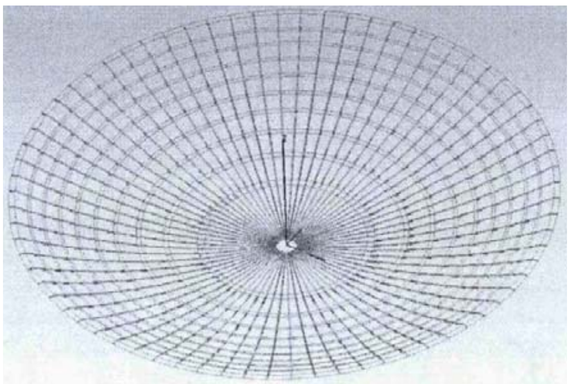

Figure 2: Structure of the new condenser

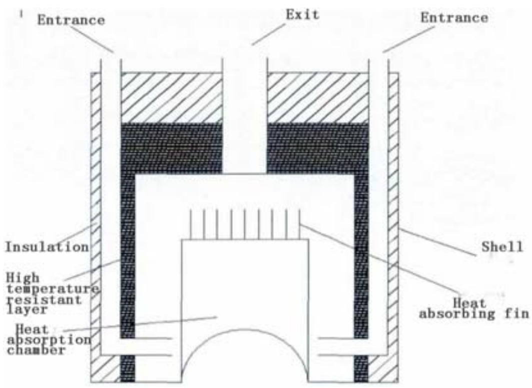

Figure 3: Structure of the new receiver

2.2 System economic indices

Considering the high R&D cost of STPG systems, the proposed system should be subjected to economic analysis in the construction and operation phases, such as to judge if the system satisfies the requirements on economic efficiency. The following economic indices can be used to determine the economic efficiency of the proposed STPG system. The NPV is the algebra sum of the future net cash inflow and future net cash outflow calculated at a pre-set discount rate. This index helps to determine the maximum limit for enterprise investment. If $NPV \geq 0$, the investment project is feasible in that it is capable of generating profit or just enough to generate the expected profit; otherwise, the investment project is not feasible in that it cannot generate the expected profit. The NPV can be expressed as follows:

$$NPV = \sum_{t=0}^{n} (CI - CO)_t (1 + i_c)^{-t} \tag{1}$$

where i_c is the basic discount rate; n is the accounting period of the project; $(CI - CO)_t$ is the cash flow of year t.

The IRR is the discount rate when the NPV equals zero. If $IRR \geq i_c$, the investment project is feasible. The greater the IRR, the better is the project. The IRR can be expressed as:

$$\sum_{t=0}^{n} (CI - CO)_t (1 + IRR)^{-t} = 0 \tag{2}$$

The P_t refers to the time needed to recover the initial investment considering the time value of the funds. Let P_c be the benchmark payback period. If $P_t \leq P_c$ and $\mathrm{NPV} \geq 0$, the investment project is feasible; otherwise, the project is not feasible. The P_t can be expressed as:

$$NPV = \sum_{t=0}^{Pt} (CI - CO)_t (1 + \mathrm{i_c})^{-t} = 0 \tag{3}$$

The WACC measures whether a project is worth investing, and represents the average capital cost of the enterprises. If it is lower than the financing rate of return, the project is feasible (Dikpati and Charbonneau, 1999). The WACC can be expressed as:

$$WACC = a \bullet i \bullet (1 - T_c) + b \bullet \mathrm{R_e} \tag{4}$$

where R_e is the return on invested capital; a and b are the proportions of debt and capital, respectively; T_c is the income tax rate; *i* is the interest rate.

The LEC is internationally adopted to evaluate the economic efficiency of renewable energy power generation. This index gives comprehensive consideration to the relationship between various costs and device efficiency. The LEC can be expressed as:

$$LEC = \frac{C \bullet a + C_{om} + C_f}{E} \tag{5}$$

where E is the annual power output; a is the annual coefficient; C_f is the fuel cost; C_{om} is the cost of operation and maintenance; C is the total initial investment.

3. Economic Analysis of Butterfly Type STPG System

3.1 Thermal performance analysis

The STPG system can generate power solely based on solar energy, when the weather is fine with sufficient sunlight. Figures 4 and 5 present the variation in power generation and thermal cycle efficiency with solar radiation intensities. It can be seen that, with the growth in solar radiation intensity, both power generation and thermal cycle efficiency were on the rise. When the solar radiation was greater than or equal to 700W/ m^2, the system could operate at full load without using any other fuel. The solar radiation intensity had a great impact on thermal cycle efficiency. After the solar radiation intensity reached 500W/m^2, the thermal cycle efficiency increased at a slow pace.

It is difficult to ensure the thermal cycle efficiency solely based on solar radiation in overcast and rainy days or in nighttime. In this case, the power generation should be assured by combusting natural gas. Figure 6 shows the natural gas consumption per hour at different solar radiation intensities and loads. It is clear that the solar radiation intensity directly bears on the natural gas consumption. When the solar radiation intensity was greater than 400W/m^2, the system did not need any natural gas and could operate at over 70% of the full load.

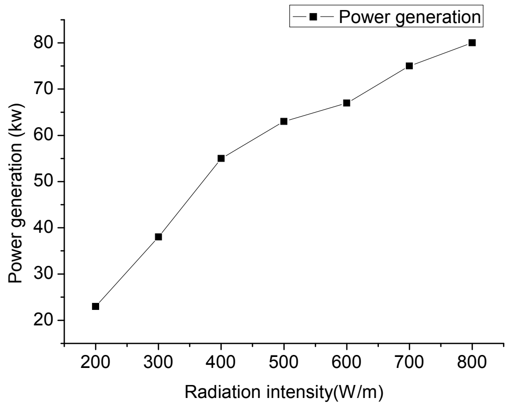

Figure 4: Relationship between solar radiation intensity and power generation

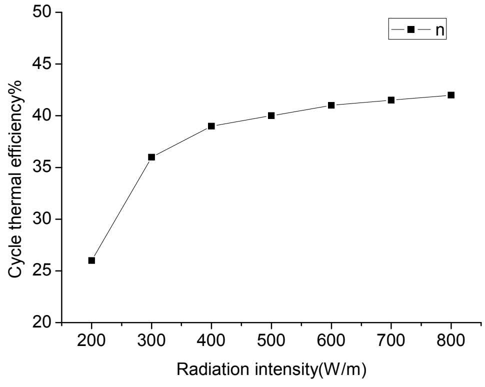

Figure 5: Relationship between solar radiation intensity and thermal cycle efficiency

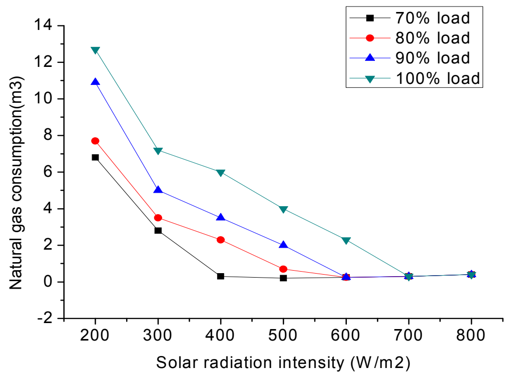

Figure 6: Relationship between solar radiation intensity and natural gas consumption

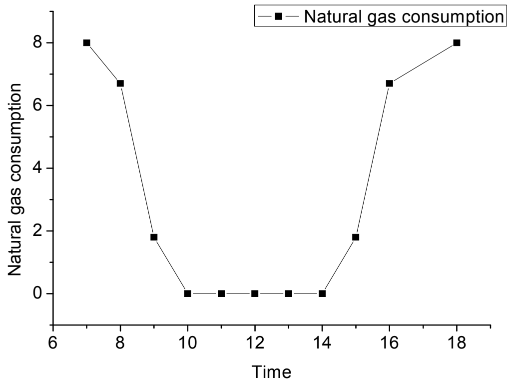

Figure 7: Natural gas consumption on summer solstice

Figure 7 displays the relationship between natural gas consumption and solar radiation intensities measured at different hours on summer solstice in Tianjin, China when the system operated under full load and the weather was fine. As shown in the Figure, the natural gas consumption gradually declined with the continuous growth in solar radiation intensity, and reached zero between 10am and 2pm. After that, the consumption gradually increased with the weakening of solar radiation intensity.

3.2 Economic analysis of the proposed system

The butterfly type system mainly relies on solar energy to generate power. In this mode, the system only operates during the day and relies on natural gas for afterburning. Table 1 shows the basic investment estimate for the proposed system. It can be seen that the initial investment amounts to RMB 1.85 million yuan, over 50% of which goes to the concentrator.

According to the investment and financing situation in Table 2, the return rate of the WACC is 5.98%, indicating the proposed butterfly type STPG system is worthy of investment.

Assuming that the natural gas price is RMB 3 yuan/m^3, the annual operating hours of the system are 2,000, and the system life lasts 25 years, the LEC of the proposed system can be calculated as 2.045kWh. Compared with coal-fired power unit, the proposed system has a very high LEC, and extremely low IRR and NPV. The system can operate 24/7 if natural gas is supplemented for the combined generation mode. Table 3 shows the values of the economic indices at the electricity price of RMB 0.85yuan/kWh, the annual operating hours of 6,000, and the discount rate of 8%. It can be seen that the proposed system achieved a better rate of return than the expected level.

Table 1: Basic investment estimation for the proposed system

Name	Numerical value	Unit
Power generation module	3670	¥/kw
Receiver	990	¥/kw
Concentrator	2360	¥/m^2
Infrastructure fee	450	¥/m^2
Project costs	800	¥/m^2
Other	300	¥/kw

Table 2: Investment and financing situation of the proposed system

Index	Numerical value
Debt ratio	70%
Capital ratio	30%
Lending rates	7%
Loan term	16 years
Return on capital	8%
WACC	5.98%

Table 3: The values of economic indices

Index	Numerical value
NPV/ ten thousand yuan	18.44
IRR%	9.25
Pt/a	18
LEC/¥•(kw•h)$^{-1}$	0.75

From Tables 1 and 2, it is learned that the proposed butterfly type STPG system requires a high basic investment in the initial phase, which cannot be recovered in the short term due to the limited power output. The combined generation mode incurs a far smaller LEC than the generation mode dominated by solar power, and therefore can effectively reduce the cost and achieve continuous, stable power supply.

Based on the above deterministic analyses, the author carried out a sensitivity analysis to further disclose the impacts of certain factors on the final economic effect of the investment project. The sensitivities of the IRR and NPV to three uncertain factors (i.e. natural gas price, on-grid electricity price and basic system investment) are respectively displayed in Figures 8 and 9.

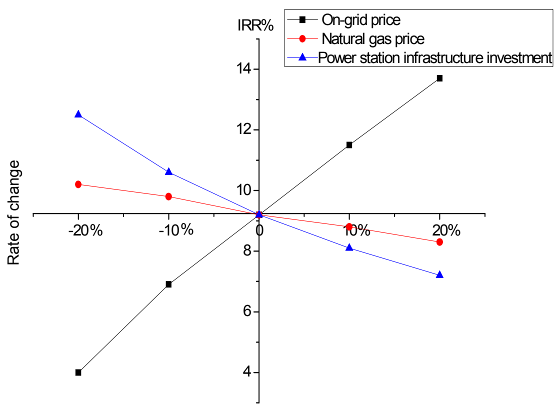

Figure 8: Sensitivity of the IRR to the three factors

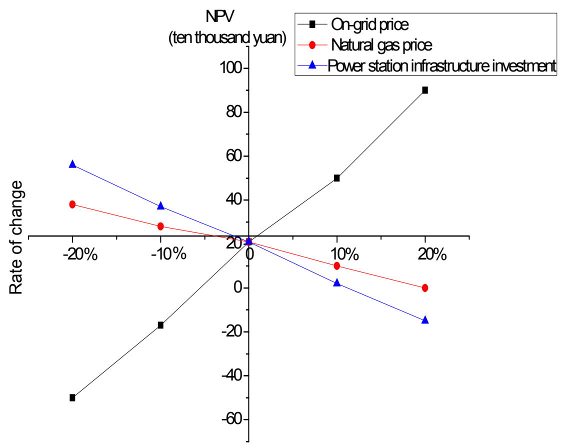

Figure 9: Sensitivity of the NPV to the three factors

The following things can be inferred from the two figures:
(1) The economic efficiency of the proposed system was severely affected when the basic system investment fluctuates by 20%, while the other two factors remained unchanged. The IRR varied from 12.22% to 7.08%, and the NPV changed from RMB 524,700 yuan to RMB -156,500 yuan. Thus, technical measures should be adopted to lower the basic system investment.
(2) When the on-grid electricity price fluctuated by 20% and the other two factors remained unchanged, the IRR shifted from 4.14% to 13.60% and the NPV changed from RMB -502,100 yuan to RMB 889,700 yuan. The proposed system made a considerable profit at the on-grid electricity price of RMB 1.02 yuan/kWh, but failed to achieve the expected profit (NPV<0) when the price fell by 10%. Therefore, a rational on-gird electricity price is the key to the profit of the proposed system.
(3) When the natural gas price fluctuated by 20% and the other two factors remained unchanged, the IRR dropped from 10.53% to 8.03% and the NPV changed from RMB 383,500 yuan to RMB 5,000 yuan, indicating that natural gas price is not a dominant influencing factor of the system's economic efficiency.
(4) To sum up, the three factors are ranked as on-grid electricity price> basic system investment> natural gas price in descending order of their impacts on the IRR and NPV of the system.

Conclusions

Considering solar radiation intensity, this paper carries out an economic analysis on the thermal performance of a novel 70kW butterfly-type STPG system, and arrives at the following conclusions.
(1) When the solar radiation intensity is greater than 400W/m^2, the proposed system can operate at above 70% of the full load without using natural gas; when the solar radiation intensity is greater than or equal to 700W/㎡, the system can operate at full load.
(2) The economic analysis reveals that the butterfly type STPG system requires more basic investment and has a longer payback period than common power generation systems. Besides, the combined generation mode incurs a far smaller energy cost than the generation mode dominated by solar power.
(3) According to sensitivity analysis, the influencing factors of the proposed system are ranked as on-grid electricity price> basic system investment> natural gas price in descending order of their impacts on the IRR and NPV of the system.

References

Cooman A., Schrevens E., 2007, Sensitivity of the tomgro model to solar radiation intensity, air temperature and carbon dioxide concentration, Biosystems Engineering, 96(2), 249-255, DOI: 10.1016/j.biosystemseng.2006.10.011

Dikpati M., Charbonneau P., 1999, A babcock-leighton flux transport dynamo with solar-like differential rotation, Astrophysical Journal, 518(518), 508, DOI:10.1086/307269

Herazo R.E.D., Ochoa G.E.V., Peralta Y., 2018, Exergoeconomic analysis of a syngas micro turbine cogeneration system, Chemical Engineering Transactions, 65.

Jafarian M., Arjomandi M., Nathan G.J., 2013, The influence of high intensity solar radiation on the temperature and reduction of an oxygen carrier particle in hybrid chemical looping combustion, Chemical Engineering Science, 95(95), 331-342, DOI: 10.1016/j.ces.2013.03.007

Kalogirou S., 2009, Thermal performance, economic and environmental life cycle analysis of thermosiphon solar water heaters, Solar Energy, 83(1), 39-48, DOI: 10.1016/j.solener.2008.06.005

Lazaar M., Bouadila S., Kooli S., Farhat A., 2015, Comparative study of conventional and solar heating systems under tunnel tunisian greenhouses: thermal performance and economic analysis, Solar Energy, 120(12), 620-635, DOI: 10.1016/j.solener.2015.08.014

Leon M.A., Kumar S., 2007, Mathematical modeling and thermal performance analysis of unglazed transpired solar collectors, Solar Energy, 81(1), 62-75, DOI: 10.1016/j.solener.2006.06.017

Montes M.J., Abánades A., Martínez-Val J.M., 2009, Performance of a direct steam generation solar thermal power plant for electricity production as a function of the solar multiple, Solar Energy, 83(5), 679-689, DOI: 10.1016/j.solener.2008.10.015

Silva E.J., Chaprão M.J., Silva I.A., Brasileiro P.P.F., Almeida D.G., Luna J.M.D., 2018, Biosurfactant application as alternative collectors in dissolved air flotation system, Chemical Engineering Transactions, 64, DOI: 10.3303/CET1864092

Wang Y., Lior N., 2011, Thermoeconomic analysis of a low-temperature multi-effect thermal desalination system coupled with an absorption heat pump, Energy, 36(6), 3878-3887, DOI: 10.1016/j.solener.2015.08.014