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ORIGINAL RESEARCH ARTICLE

Analysis and evaluation of thermal efficiency and environmental impact of the trough and tower solar thermal power generation

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ABSTRACT

Two kinds of solar thermal power generation systems (trough and tower) are selected as the research objects. The life cycle assessment (LCA) method is used to make a systematic and com-prehensive environmental impact assessment on the trough and tower solar thermal power generation. This paper mainly analyzes the three stages of materials, production and transportation of two kinds of solar thermal power generation, calculates the unit energy consumption and environ-mental impact of the three stages respectively, and compares the analysis results of the two systems. At the same time, Rankine cycle is used to com-pare the thermal efficiency of the two systems.

Keywords: Life Cycle Analysis; Solar Thermal Power Generation; Environmental Impact; Heat Efficiency

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1. Introduction

Solar thermal power generation technology uses optical system to gather solar radiation energy, which is used to heat working medium to generate steam and drive steam turbine generator set to generate electricity[1]. Solar thermal power generation can be divided into tower solar thermal power generation, trough solar thermal power generation and disk parabolic solar thermal power generation according to different concentrating modes.

At present, most solar thermal power generation projects are in the experimental and demonstration stage, and have not yet been put into commercial operation. Analyzing the environmental impact and thermal efficiency of solar thermal power generation system by life cycle assessment method can provide the basis for quantitatively evaluating the environmental benefits of renewable energy power generation, and can also be used for technical optimization of solar thermal power generation. And provide the basis for judgment for promotion. Zou[2] and others in China evaluated tower solar thermal power generation and compared it with coal power generation, and considered that tower solar thermal power generation has obvious energy saving and environmental protection effects compared with coal power generation. However, the life cycle evaluation of solar thermal power generation systems with different concentrating modes is still relatively few.

On the basis of systematically collecting domestic product data and environmental data, this paper uses AGP (as Session for Green Products), which is suitable for China, to evaluate and compare the whole life cycle of trough solar thermal power generation and tower solar thermal power generation.

At the same time, Rankine cycle is used to analyze the thermal efficiency of the two systems from the perspective of energy conversion efficiency, in order to provide reference opinions for developing solar thermal power generation in China from the perspective of environmental impact and thermal efficiency.

2. Evaluation object and evaluation method

2.1 Research object

In this paper, SEGS VI trough solar thermal power generation of Luz company and SOLAR ONE tower solar thermal power generation of the United States are selected as the research objects, respectively[1]. The data of the system are shown in **Table 1**, taking 10 kWh as the functional unit of life cycle assessment, assuming two the exhaust pressure of the power generation system is 0.06 bar.

Table 1. Overview of two types of solar thermal power generation

Power station name	SOLAR ONE	SEGS VI
Plant forms	Tower-type	Trough-type
Site location	California, USA	California, USA
Plant forms	10	30
Annual running hours/h	2,700	3,019
Annual net power generation/106 kWh	27	90.6
Concentrating mode	Plane mirror	Cylindrical paraboloid reflection
Number of mirrors	1,818	960,000
Cylindrical paraboloid reflection/m^2	72,540	188,000
Steam turbine inlet parameters/°C bar^{-1}	510/104	371/100
Total investment/USD 100 million	1.4	1.16
Investment ratio/kW^{-1}	14,000	3,870
Service life/a	30	30

2.2 Selection of impact assessment model and determination of system boundary

The AGP model used in this paper evaluates the product life cycle through five modules: user control interface, inventory data input, inventory result interpretation, weight determination and impact evaluation module[3].

In this paper, the solar power generation system is divided into five unit stages: raw material acquisition stage (including consumables needed for power plant equipment manufacturing), power plant construction stage (including factory buildings, cooling towers and pipelines), transportation stage (including raw materials and equipment transportation), power plant operation stage and waste treatment. Due to the complexity of solid waste treatment and many uncertain factors, this paper has not considered the energy consumption and environmental impact of waste treatment in the scrapping stage of power station. In addition, in operation, the solar thermal power generation system does not need external energy except converting solar power generation, so the energy consumption and emissions in the use stage are not considered.

3. List analysis

3.1 Inventory data

Foreign countries have worked out detailed procedures for clearing and analyzing orders[4], but there is no complete LCA database in China. Most of this article. Partial data comes from literature retrieval, and a small part is obtained through enterprise research. Considering the characteristics of environmental impact caused by solar thermal power generation system, this paper analyzes and evaluates several kinds of environmental potential values such as nonrenewable resource depletion (NRDP), global warming potential (GWP) and acid potential (AP).

3.2 Inventory analysis of energy consumption and emissions in each stage of solar thermal power generation

In this paper, 10 kwh power generation is selected as the functional unit. There are many kinds of materials for power station construction involved in the life cycle assessment of solar power generation. In this assessment, materials that account for less than 5% of the total consumables are ignored.

In the raw material acquisition stage, the energy consumption and emissions required for mining and processing various materials are considered[5,14]. In the production stage, the energy consumption and emissions of power plant equipment and workshop construction are considered[15]. In the transportation stage, the energy consumption and emissions of two parts are considered: one part is the manufacturing of equipment needed for transporting raw materials to power stations; The other part is that the power station construction materials are transported to the power station[16]. The total consumables in the life cycle of two kinds of solar thermal power generation are shown in **Table 2**, and the input and output results of inventory analysis are shown in **Tables 3** and **4**.

Table 2. Main consumables in the life cycle of two solar thermal power generation system

Methods of generating electricity	Rolled steel	Glass	Concrete	Raw coal	Diesel oil
30 MW Trouth-type	15,220.8	1,804.6	34,926.3	54.36	4.1
10 MW Tower-type	9,478.0	872.6	18,062.2	40.50	1.3

Table 3. Main input and input of life cycle of trough solar thermal power generation

	Name	Raw material acquisition stage	Construction phase	Transportation stage	Total
Input	Streel	1.06	4.54	0	5.60
	Coal	0	0	0.02	0.02
	Diesel oil	0	0	1.5×10^{-3}	1.5×10^{-3}
	Sandstone	0.49	-	-	0.49
	Dolomite	0.12	-	-	0.12
	Soda ash	0.15	-	-	0.15
	Limestone	-	1.12	-	1.12
	Aggregate	-	7.67	-	7.67
Output	Smoke	0.03	0.09	5.0×10^{-4}	0.12
	SO_2	0.05	0.20	6.4×10^{-4}	0.25
	NO_2	0.01	0.04	2.4×10^{-4}	0.05
	CO_2	3.68	23.29	0.10	26.97

Output list (Function Unit: 1,000 kWh)/kg

Table 4. Main input and input of life cycle of tower solar thermal power generation

	Name	Raw material acquisition stage	Construction phase	Transportation stage	Total
Input	Streel	3.36	8.34	0	11.7
	Coal	0	0	0.05	0.05
	Diesel oil	0	0	1.6×10^{-3}	1.6×10^{-3}
	Sandstone	0.80	-	-	0.80
	Dolomite	0.19	-	-	0.19
	Soda ash	0.24	-	-	0.24
	Limestone	-	2.52	-	2.52
	Aggregate	-	13.31	-	13.31
Output	Smoke	0.08	0.24	5.0×10^{-4}	0.32
	SO_2	0.15	0.41	6.9×10^{-4}	0.56
	NO_2	0.03	0.10	2.6×10^{-4}	0.13
	CO_2	10.90	34.51	0.11	45.52

Output list (Function Unit: 1,000 kWh)/kg

The data in **Tables 3** and **4** shows that the transportation phase produces environmental impacts throughout the life cycle is a small percentage of the population in the two types of solar thermal power generation. Power generation tower system construction consumes a large number of building materials, thus various consumables in the construction stage and the corresponding pollutant emissions are higher than those of trough power generation. In the raw materials acquisition phase, the main difference between tower and trough inventory analysis is for collector part. The trough type adopts curved mirror as heat collector element, while the tower type adopts the flat mirror. Because that the heat collecting effect of curved mirror fruit better than flat mirror, so in the same power generation under the circumstances of tower the required heat collection area is larger than the trough type, thus increasing the glass consumption the amount.

4. Impact assessment

This paper adopts equivalent coefficient method, and classifies the results of inventory analysis according to the depletion resource consumption (NRDP), global warming potential (GWP), acidification potential (AP), etc. Then multiply the values of various pollutants with equivalent factors, and finally add the same kind to obtain the overall effect potential result. Because the equivalent factors of sandstone, dolomite and other materials have not been determined yet, and the weight of consumed materials is small, this paper does not record their influence when evaluating the consumption potential of exhausted resources.

Table 5 and **Table 6** summarize the LCA environmental impact assessment results of trough solar thermal power generation and tower solar thermal power generation, among which the equivalent factor comes from the research of international organizations and research institutions such as IPCC results[3]. It can be seen from **Table 5** and **Table 6** that the tower-type NRDP, GWP and AP are about twice of the trough-type solar thermal power generation for every 1,000 kWh of electricity.

Table 5. Evaluation results of trough solar thermal power generation (Functional unit: 1,000 kWh)

Type of influence	Item	Mass/kg	Equivalent factor/kg·kg^{-1}	Impact potential/kg	Total
Natural Resources Depletion Potential (NRDP)	Steel	5.60	1	5.60	5.60
	Raw coal	0.02	0.031	6.00×10^{-4}	
	Oil	1.5×10^{-3}	1.33	2.00×10^{-3}	
Global Warming Potential (GWP)	CO_2	26.97	1	26.97	49.46
	CH_4	0.22	25	5.50	
	NO_2	0.05	320	16.00	
	N_2O	3.00×10^{-3}	290	0.87	
	CO	0.06	2	0.12	
Acidizing potential	SO_2	0.25	1	0.25	0.29
	NO_2	0.05	0.70	0.04	
	NH_3	7.00×10^{-4}	1.88	1.30×10^{-3}	
	H_2S	3.20×10^{-3}	1.88	6.00×10^{-3}	

Table 6. Evaluation results of tower solar thermal power generation (Functional unit: 1,000 kWh)

Type of influence	Item	Mass/kg	Equivalent factor/kg·kg^{-1}	Impact potential/kg	Total
Natural Resources Depletion Potential (NRDP)	Steel	11.70	1	11.70	11.70
	Raw coal	0.05	0.031	1.50×10^{-3}	
	Oil	1.60×10^{-3}	1.33	2.10×10^{-3}	
Global Warming Potential (GWP)	CO_2	45.52	1	45.52	94.80
	CH_4	0.26	25	6.50	
	NO_2	0.13	320	41.60	
	N_2O	3.60×10^{-3}	290	1.04	
	CO	0.07	2	0.14	
Acidizing potential	SO_2	0.56	1	0.56	0.66
	NO_2	0.13	0.70	0.09	
	NH_3	6.10×10^{-4}	1.88	0.01	
	H_2S	5.10×10^{-3}	1.88	9.50×10^{-3}	

5. Environmental impact and thermal efficiency analysis

5.1 Environmental impact analysis

The comparison of energy consumption and emissions of coal-fired steam turbine generator set and solar thermal power generation is shown in **Table 7**.

Table 7. Comparison of energy consumption and emissions for coal and solar thermal power generation

Power generation mode	Energy consumption/t·kg^{-1}	Ash/kg	CO_2/kg	SO_2/kg	NO_2/kg
Coal power[2]	400	50	1,000	8	5
Trough solar thermal power generation	12	0.12	26.97	0.25	0.05
Tower solar thermal power generation	14	0.32	45.52	0.56	0.13

(Generating capacity: 1,000 kWh)

China's main steam turbine generator set is 300 MW, and it consumes 400 kg standard coal per 1,000 kWh of power generation. The energy consumption of the whole life cycle of solar thermal power generation is converted into standard coal. For every 1,000 kWh of power generation, the energy consumed by two kinds of solar thermal power generation is more than ten kilograms of standard coal, which greatly reduces the consumption of fossil energy. The resulting emissions of pollutants and greenhouse gases are also significantly reduced. In addition, the results show that trough solar thermal power generation is better than tower solar thermal power generation in energy consumption and pollutant emission.

5.2 Efficiency analysis

This section introduces the thermal efficiency of the two solar thermal power generation modes. Line analysis and comparison show that the total efficiency of the ideal solar thermal power generation system η_S is the product of Carnot efficiency η and solar collector efficiency η_C[1], namely: $\eta_S = \eta \times \eta_C$.

The total solar radiation absorbed by the receiver of solar thermal power generation system is affected by many factors such as the direct incident solar radiation, the percentage of mirror field area covered by the mirror, and the utilization coefficient of the mirror. In this evaluation, it is assumed that the solar collector efficiency η_C of the two solar thermal power generation systems is the same. In the same temperature range, the thermal efficiency of Carnot cycle is the highest, but it is unrealistic to directly adopt Carnot cycle in actual thermal devices. In this paper, Rankine cycle (see **Figure 1**) is used to analyze solar thermal power generation, and relevant parameters are shown in **Table 8**.

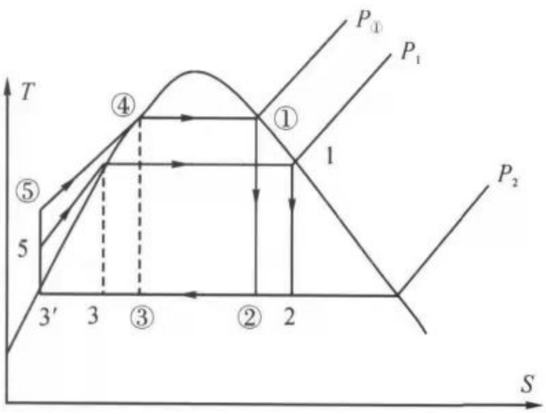

Figure 1. Schematic diagram of Rankine cycle in thermal power generation system.

Table 8. Gas parameters used in calculation of cycle efficiency

Pressure/bar	Saturation temperature T_s/K	h'/kJ·kg^{-1}	h"/kJ·kg^{-1}	s'/kJ·kg^{-1}	s"/kJ·kg^{-1}
$P_2 = P_3 = 0.06$	309.17	151.47	2,566.48	0.5208	8.3283
$P_1 = P_4 = 104$	589.08	1,424.40	2,717.01	3.3874	5.5892
$P_1 = P_4 = 100$	584.19	1,407.20	2,724.46	3.3591	5.6139

Figure 1 is a schematic diagram of Rankine cycle of thermal power generation system. 1233'54 is a trough system, and ①②③⑤④ is a tower system. The calculation results show that when the steam parameters of tower solar thermal power generation and trough solar thermal power generation are 510 ℃, 104 bar and 371 ℃, 100 bar, the cycle efficiency is 41.2% and 38.8%, respectively, and the cycle efficiency of tower solar thermal power generation is 2.4% higher than that of trough solar thermal power generation.

6. Conclusion

(1) In the case of the same system boundary, the depletion potential (NRDP), global warming potential (GWP) and acidification potential (AP) of tower solar thermal power generation are about twice that of trough solar thermal power generation, and trough solar thermal power generation has less impact on the environment.

(2) When the power generation capacity is 1,000 kWh, solar thermal power generation con-

sumes less than 5% of the fossil energy of coal power generation. Meanwhile, compared with coal power generation, solar thermal power generation significantly reduces the emission of soot, CO_2, SO_2 and NO_x.

(3) When the exhaust parameters are the same and the steam parameters are 510 ℃, 104 bar and 371 ℃, 100 bar, the cycle efficiency is 41.2% and 38.8%, respectively. The higher inlet gas parameters of tower thermal power generation increase the cycle efficiency by 2.4% compared with trough thermal power generation.

Conflict of interest

No conflict of interest was declared by the authors.

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