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Research Paper

Appropriate feed-in tariff of solar–coal hybrid power plant for China's Inner Mongolia Region

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HIGHLIGHTS

- The potential for the first 10 MWe level solar–coal hybrid power plant is estimated.
- Economic feasibility analysis is performed based on the discounted cash flow model.
- The appropriate feed-in tariff prices of different scenarios are provided.
- The results provide suggestions for the development of solar–coal hybrid technology.

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ABSTRACT

Middle-temperature solar heat can be used to preheat feed water before it enters the boiler in a coal-fired power plant. Previous studies have shown that this approach can improve the performance of coal-fired power plants. The present study estimates the first solar–coal hybrid power plant in the Inner Mongolia Region. It will have a potential net solar power output of 10 MW on the basis of the operating data of a traditional 200 MW coal-fired power plant. Economic feasibility analysis is then performed on the solar–coal hybrid power plant. The appropriate feed-in tariff prices are provided on the basis of different financing scenarios, solar field cost, collector area size, and other conditions. The results obtained in this study are expected to provide suggestions for the further development of solar–coal hybrid technology.

1. Introduction

As the most widely distributed and clean renewable energy resource, solar energy is one of the most effective solutions to mitigate environment pollution and address fossil fuel shortage. According to the technology roadmap [1] studies on solar photovoltaic (PV) energy and concentrated solar power (CSP) of the International Energy Agency (IEA), solar energy will become the world's largest source of electricity by 2050 at 27% of total global power generation. The development of CSP technology is important to China. According to the "12th Five-Year Plan", the installed CSP capacity of China should reach 1 GW in 2015 and 3 GW in 2020.

Since the 1990s, researchers have focused on hybridizing solar energy with fossil power plants to achieve the sustainable development of solar thermal power plant in the near and mid-terms [2]. By using a high-efficiency thermal cycle, the electricity production costs of a solar-coal plant can be reduced compared with a solar-only plant with the same field size. Furthermore, by using the existing infrastructure (and existing grid) of a conventional power station, the technical and economic risks for solar energy can be reduced. At present, the main approach for hybridizing solar energy with the Rankine cycle [3] involves adding solar heat to the bottoming cycle of a combined-cycle plant to evaporate steam and increasing the size of the steam turbine to produce additional electricity. This approach is called ISCC. Supported by the Global Environment Facility, ISCC projects have already been under construction in several countries [4,5], such as Algeria, Egypt, Iran, Italy, Morocco, and the United States.

However, unlike these countries, China is a country that lacks gas and oil. The domestic fossil energy resource of China is coal, and coal-fired power plants supply almost 70% of the country's electric power consumption. Hu et al. [6] and Hong et al. [7] found that the collected solar heat at approximately 300 °C matches well with the feed water back to the boiler. The use of solar heat to replace steam extractions for heating feed water can increase the work output of the steam turbine. The annual net solar-to-electricity efficiency of solar-coal power plants is expected to increase to 18% [8], which is approximately 4% higher than that

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Nomenclature

DNI	direct normal irradiance
t	temperature
p	pressure
h	enthalpy
m	mass flow
w	the net solar incremental output work of replacing 1 kg of steam extraction
H	equivalent enthalpy drop
σ	heat change in the reheater
q	heat releases
η	efficiency
Q	collected solar heat
W	nominal power output
G	net annual incremental solar work output
AA	aperture area
aa	collector aperture area per kWe
FiT	feed-in tariff
NPV	net present value
IRR	internal rate of return
CI	annual cash inflow
CO	annual cash outflow
r	discount rate
k	interest rate
n	solar field lifespan
P	collector price per square meters (including surcharge for design, construction, and installation)
I	annual interests
L	liquid capital
OM	operating and maintain cost
SA	labor cost per employee and year
NU	number of employees
RE	repair charge ratio
ST	sales tax and surcharges
T	income tax
l	load period
d	debt equity ratio

Subscript

j	steam extraction point
i	year
col	solar field collector
sol	incremental solar heat/power
c	heat-to-work conversion
γ	enthalpy drop in drain water
τ	enthalpy increase in feed water
sol-to-elec	solar-to-electricity conversion
mir	mirror

of solar-only power plants. Correspondingly, the solar field area size for the same electricity production will be reduced. Thus, solar–coal hybrid power plants can increase the efficiency of solar thermal power plants and provide a cost-effective method for middle-temperature solar heat utilization. The relation expressions for relative net solar-to-electricity improvement and saved collector area of the solar-coal hybrid systems were identified [9] compared with the solar-only power plants.

Although solar hybrid systems have apparent improvements in system thermo-economic performance, their competitiveness compared with traditional fossil-fired power systems still need to be promoted by energy policies. For the investors, the project risks are depending on the cost under real operational conditions [10–12] and relative policies and regulations. Countries around the world usually issue different feed-in tariff (*FiT*) mechanisms [13] for the utilization of solar thermal power and other renewable energy source. In China, a CSP project was started at the end of 2010 for a 50 MWe parabolic trough solar plant in Erdos, Inner Mongolia. The lowest expected *FiT* of 0.94 RMB/kW h for an operation period of 25 years won the bidding process. However, this project cannot be started because its *FiT* price is sub-marginal. In 2014, the real first commercially operational CSP plant in China, namely, Supcon's Delingha tower power plant, won the *FiT* of 1.2 RMB/KW h authorized by the National Development and Reform Commission (NDRC) for its phase I project (10 MWe). As the first officially permitted *FiT* for CSP plants in China, Supcon's Delingha tower power plant serves as a milestone in the advancement of the Chinese CSP market. According to the National High-Tech R&D Program ("863" Program) of China, the first demonstrated solar–coal hybrid fired power plant in China is expected to be built with a previously existing coal-fired power plant and 10 MWe-level parabolic troughs. A solar hybrid power plant is more cost-effective than a solar-only power plant. Thus, a solar hybrid power plant is expected to be competitive in the Chinese market. However, the *FiT* of 1.2 RMB/KW h is not fixed for all CSP projects in China. The Chinese government implements the policy of "specific *FiT* for specific solar thermal plants," i.e., solar power plants have to apply for incentives depending on economic performance and financing conditions. The type of incentives that the government should provide for solar–coal hybrid power plants is an important issue for consideration.

In order to determine a reasonable bench-mark price for electricity of solar-coal hybrid power plant based on current feed-in tariff mechanism, this paper evaluates the economic performances of hybridizing solar heat at approximately 300 °C with a 200 MW coal-fired power plant, and establishes three different kinds of financing circumstances in China to provide a theoretical reference for the feed-in tariff of the solar-coal hybrid power plant.

2. Site selection and scheme description of the solar–coal hybrid power plant

Local direct solar irradiation is important in identifying the efficient sites for solar electricity generation. According to the solar radiation map of China with satellite-based solar irradiation data from NREL [14], China has a high potential for CSP because it experiences solar radiation of more than 5 kW h/m^2/day in its northwestern region. According to the Chinese Standard Weather Data [15,16], Zhuozi City (40.92°N/112.64°E) in Inner Mongolia has extensive semi-arid regions that receives direct normal solar radiation of 6 kW h/m^2/day and annual solar direct radiation of 1550 kW h/m^2. Furthermore, this area has relatively low annual average wind speeds of 1.7 m/s. On the basis of the good meteorological conditions of Zhuozi City, the 200 MW air-cooling coal-fired power plants in this area are selected for solar heat hybridization.

Furthermore, 200 MW coal-fired power plants are selected because of its localization near Hohhot City, the capital of Inner Mongolia (40.82°N/111.65°E). The satellite picture shows that a convenient land route exists between the coal-fired power plant and Hohhot City (93 km), thus allowing for the transport of equipment of a solar thermal power plant. The land route is shown in blue lines in Fig. 1. This figure also shows a full view of previous existing coal-fired power plants. The area inside the red solid line