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Techno-economic analysis of a solar photovoltaic/thermal (PV/T) concentrator for building application in Sweden using Monte Carlo method

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ABSTRACT

The solar energy share in Sweden will grow up significantly in next a few decades. Such transition offers not only great opportunity but also uncertainties for the emerging solar photovoltaic/thermal (PV/T) technologies. This paper therefore aims to conduct a techno-economic evaluation of a reference solar PV/T concentrator in Sweden for building application. An analytical model is developed based on the combinations of Monte Carlo simulation techniques and multi energy-balance/financial equations, which takes into account of the integrated uncertainties and risks of various variables. In the model, 11 essential input variables, i.e. average daily solar irradiance, electrical/thermal efficiency, prices of electricity/heating, operation & management (OM) cost, PV/T capital cost, debt to equity ratio, interest rate, discount rate, and inflation rate, are considered, while the economic evaluation metrics, such as levelized cost of energy (LCOE), net present value (NPV), and payback period (PP), are primarily assessed. According to the analytical results, the mean values of LCOE, NPV and PP of the reference PV/T connector are observed at 1.27 SEK/kW h (0.127 €/kW h), 18,812.55 SEK (1881.255 €) and 10 years during its 25 years lifespan, given the project size at 10.37 m^2 and capital cost at 4482–5378 SEK/m^2 (448.2–537.8 €/m^2). The positive NPV indicates that the investment on the selected PV/T concentrator will be profitable as the projected earnings exceeds the anticipated costs, depending on the NPV decision rule. The sensitivity analysis and the parametric study illustrate that the economic performance of the reference PV/T concentrator in Sweden is mostly proportional to solar irradiance, debt to equity ratio and heating price, but disproportionate to capital cost and discount rate. Together with additional market analysis of PV/T technologies in Sweden, it is expected that this paper could clarify the economic situation of PV/T technologies in Sweden and provide a useful model for their further investment decisions, in order to achieve sustainable and low-carbon economics, with an expanded quantitative discussion of the real economic or policy scenarios that may lead to those outcomes.

1. Introduction

1.1. Solar photovoltaic/thermal (PV/T) technology

Over the past 26 years, energy consumption in Sweden was almost stable within the range of 46–53 Mtoe (Million Tonnes of Oil Equivalent) in comparison to the global energy consumption [1]. This is mainly owing to the fall in fossil fuel use, offset by slight increase in renewables. The renewable shares grew up gently at approximately 3.58%/year, ranging from 38% to 64% during the period from 1990 to 2016. When looking further ahead, it is projected that the renewables will be the continuous-growing sources of energy generation over the period of 2015 to 2040, rising by an average rate of 2.8%/year, in which solar and wind will dominate growth in renewables [2]. In Sweden, it has set up a goal of 100% renewable electricity in 2040 and solar energy is planned to contribute 5–10% electricity generation, comparing to today's marginal level of less than 0.1% [3]. Along with potential technological improvements, the Swedish government has also published several strategies to support their future increased applications in solar field. For instance, the government introduces a 'SOLROT' deduction instead of investment support for individuals to facilitate the development of small and medium-sized solar plants in the electricity market [3]. Such adjustment allows homeowners to receive the corresponding compensation level faster. Other measures include

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Nomenclature

A	area, m^2
C	cost, SEK
C_0	capital cost, SEK
CF	cash flow, SEK
dg	degradation rate,%
DE	debt to equity ratio,%
E	energy, kW h/year
EP	electricity price, SEK/kW h
G	daily solar irradiance per unit area, kW h/m^2-day
G_w	solar irradiance per unit area, W/m^2
HP	heating price, SEK/kW h
Ifr	inflation rate,%
Itr	interest rate,%
I_0	initial investment, SEK
j	number of simulation trials
L	loan cost, SEK
$LCOE$	levelized cost of energy, SEK/kW h
n	number of life span
NPV	net present value, SEK
OM	operation & maintenance cost, SEK
PP	payback period, year
r	discount rate,%
S	savings in year t, SEK
t_a	temperature of surrounding air, °C
t_m	mean temperature, °C
T	time, year
Ta	tax, SEK
TR	tax rate per kW h, SEK/kW h

Greek

η	efficiency, %

Subscripts

e	electricity
et	electricity in year t
t	time in the unit of year
th	thermal
tht	thermal energy in year t

the possibility of reducing tax rates for medium-sized plants, adjusting energy taxes per plant instead of legal personality, and expanding efficiency by reviewing building permit processes, waste management and spatial planning as well as support for electricity certificates for micro-production [3].

In recent years, the innovative hybrid solar photovoltaic/thermal (PV/T) technology has emerged on the solar market, which can generate both electrical and thermal energy simultaneously. Solar PV modules usually can only output low energy per unit area at the efficiency up to 22.5%, whereas the majority range from 14% to 16% efficiency in practice [4]. On the other hand, standalone solar thermal collectors, consisting of heat exchangers, transform solar radiation to internal thermal energy of the transport medium. They usually generate higher energy quantity per unit area at the energy efficiencies from 40% to 85% depending on types of collectors (evacuate tube, glazed or unglazed flat plate), but they have much lower energy quality at exergy efficiencies from 2% to 3.9% [5]. To overcome these two inherent barriers, solar PV/T could become a potential solution since it combines both electrical and thermal components in a single unit area to produce electricity and heat simultaneously, leading a higher overall solar-energy conversion up to 94% than those standalone ones [6]. Moreover, PV cells drop in energy efficiency with the rise in its operating temperature. Harvesting the superfluous heat from PV cells in a compromised way, depending on local operating conditions [7], can therefore increase the overall operating efficiency of PV cells and lead to the best performance of PV/T module [8]. For instance, thermal efficiency of PV/T is improved by adding glazing layer, while the PV efficiency decreases in this case. A compromise in PV and thermal yields must be considered to achieve the best operational performance of PV/T in practice. Other major benefits of PV/T modules include: (1) more effective usage of the entire solar spectrum with PV and thermal components in one unit; (2) reduced installation cost and space, (3) decreasing the thermal load of whole building, and (4) better aesthetic architectural integration than using two individual PV and thermal collectors [9].

PV/T technologies can be categorized into flat-plate and concentrated types, for different application purposes. The flat-plate PV/T modules are the mostly common ones, dominating current PV/T market worldwide. Although they are relatively affordable, there is very limited application or research in Sweden [10]. This could be due to many reasons, but one of them could possibly be that in the circumstance of the extremely poor weather/operating conditions in Nordic area, heat is usually considered as a by-product in these PV/T types, and they must be coupled with heat pumps or boilers to upgrade temperature for applications – this increases the overall system cost and limits the application feasibility. On the other hand, PV/T concentrators have been applied in Sweden for nearly 20 years [10,11] that can generate heat at temperature of up to 75 °C [11] and yearly-mean temperature of 40 °C in Sweden scenario, which are suitable for most building applications (such as hot water), through installation on ground, or integration with roof, wall, balcony or even windows in either new or existing buildings [11,12], as shown in Fig. 1. Moreover, PV/T concentrators are able of connecting with complex heating and mechanical systems, such as district heating system [13], desalting [14], industrial processing [15], waste heat recovery [16], solar cooling [17] and solar power generation [18] etc. These studies demonstrate that PV/T concentrators are more capable to cope with complex systems and poor external operation conditions. This paper thus decided to select an existing PV/T concentrator in Sweden as the research objective for further investigation.

1.2. Techno-economic evaluation techniques

Owing to these advantages of PV/T technology, there are many researches now working on the techno-economic evaluations of various PV/T types within different scenarios. Most of them firstly assessed the energy performances of dedicated PV/T in different climate regions, and then estimated the economic benefits by inputting the values of local economic factors, based on different modelling methods [15,19–23]. There are many economic performance indicators used by investment professionals, such as LCOE (Levelized Cost of Energy) [15,19,23], NPV (Net Present Value) [24,25], EPBT (Energy Pay Back Time) [26], ROI (Return on Investment) [25], BCR (Benefit to Cost ratio) [27], IRR (Internal Rate of Return) [25], TCC (tolerable capital costs) [28], UCE (Unit Cost of Energy) [27], and simple /discounted PP (Payback Period) [24,25,29,30]. Among these indicators, LCOE, NPV, and PP are found the most popular. By comparing the research results of different authors, it can be summarized for the PV/T technologies that: (1) LCOE varies in the range of 0.06–0.12 €/kW h; (2) NPV is nearly €20,000 over a 25-year period; and (3) PP reaches about 11 years in general. In addition to the variety of economic indicators, there is often a notable discrepancy in the economic impact factors, including tax, incentives, discount rate, inflation rate, fuel cost, electricity tariff, loan interest, time, location etc., which can cause considerable differences in the main economic performance and the