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Thermo-economic optimization of solar organic Rankine cycle based on typical solar radiation year

Shuai Li, Weiyi Li*

Key Laboratory of Efficient Utilization of Low and Medium Grade Energy, MOE, Tianjin University, Tianjin 300072, China

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ABSTRACT

The thermo-economic optimization of a solar organic Rankine cycle (SORC) should consider the features of fluctuations in solar radiation based on local historical solar radiation. However, the use of historical solar radiation is inconvenient for thermo-economic optimization because it involves considerable computational effort for simulation. To overcome this inconvenience, we propose the thermo-economic optimization of SORC by using typical solar radiation year (TSRY). TSRY is a synthesis of typical solar radiation on the basis of historical solar radiation, indicating that TSRY can reflect the typical features of fluctuations in solar radiation in a specific area. Afterward, the multi-objective genetic algorithm (GA) is selected to optimize the dynamic performance of a small-scale SORC by using the TSRY. In GA, the evaporation temperature and capacity of thermal energy storage are taken as optimization parameters, and the power output and fluctuation in power output are optimization goals. Accordingly, Pareto frontiers that optimize the SORC performance can be obtained. The effect of different parameter combinations in the Pareto frontiers and the scale of the SORC on thermo-economic are further analyzed using annual net profit as an indicator. Our analysis shows that a minimum SORC scale for profitability is set for a given location, and the profit growth rate increases as the system scale increases.

1. Introduction

Solar energy utilization systems have been widely applied due to global warming and fossil fuel shortage because solar energy is a clean energy source. Solar organic Rankine cycle (SORC) is an effective system to use solar energy [1] and has many advantages, including reliability, flexibility, and simplicity [2,3].

A constant temperature for a stable heat source is generally considered in the design and optimization of an organic Rankine cycle (ORC) system to simplify the calculations of system design and optimization [4,5]. For example, Ksayer analyzed the effect of evaporation temperature on SORC with constant hot water as a heat source instead of solar radiation [6]. Baral et al. investigated the economic and thermodynamic performance of a system under constant operating conditions with hot water at a constant temperature to represent the solar heat source[7]. He et al. utilized a steady-state model to examine the effects of working fluid, flow rate, thermal energy storage (TES) capacity, and evaporation temperature on SORC [8]. Helvaci and Khan evaluated the performance of 24 working fluids and different evaporating pressures in a small-scale SORC, which is considered a steady system [9]. Vetter et al. compared the influence of different working fluids on the performance of an ORC with fixed heat-source temperatures of 130 °C, 150 °C, and 170 °C [10]. Zhu et al. studied the exergy, entransy, and entropy of an ORC with a constant heat source [11]. Yang et al. compared the effects of six working fluids with evaporation temperatures ranging from 58 °C to 68 °C on an ORC [12]. Zare developed exergoeconomic and thermodynamic models of an ORC to compare the performance of three system configurations with a stable heat source [13]. Some researchers also assessed the dynamic performance of ORC systems because of the considerable influence of an unstable heat source on the system's performance. For example, Quoilin et al. utilized a dynamic ORC model with a waste heat source to compare the effects of different control strategies [14]. Moreover, Manente et al. analyzed the optimal design parameters of an off-design ORC model with geofluid as a heat source (130–180 °C) [15].

To investigate the energy and financial analysis of SORCs with parabolic trough collectors, Tzivanidis et al. study the thermodynamic investigation of the SORC by using various working fluids [16]. Hajabdollahi et al. [17] studied the effect of three working fluids and flow rate on the economy of the regenerative SORC system by considering one year's historical solar radiation. Conclusions in their paper show that R245fa was recommended for the more continuous power production compared with other working fluids. Considering the safety and economy, we used R245fa as the working fluid. On this basis, we

* Corresponding author.
E-mail address: liwy@tju.edu.cn (W. Li).

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Nomenclature

$\dot{I}_b$	direct solar radiation (kW/m^2)
$\dot{I}_d$	scattering solar radiation (kW/m^2)
$\dot{I}_h$	sum of direct and the scattering radiation (kW/m^2)
R_b	ratio of total solar radiation on inclined surface to horizontal surface (–)
ρ_g	reflectance from the surrounding (–)
β	collector angle (degree)
$\dot{M}$	mass flow rate (kg/s)
$\dot{H}$	rate of heat (kW)
T	temperature (°C)
$\dot{q}$	heat flux (W/m^2)
U	heat transfer coefficient (W/m^2 K)
A	heat transfer surface area (m^2)
M	mass (kg)
h	specific enthalpy J/ kg
p	pressure (MPa)
v	specific volume (m^3/kg)
w	specific work (J/kg)
W	amount of work (J)
C_{inv}	investment cost (CNY)
E_b	the amount of electricity bought (kW)
E_s	the amount of electricity sold (kW)

Greek abbreviation

η	efficiency (–)
ρ	density (kg/m^3)
$\varphi_{e,b}$	unit price of buying electricity (CNY/kW h)

Abbreviations

TES	thermal energy storage (L)
ANP	annual net profit (CNY/year)
ATE	annual total electricity
DSR	daily solar radiation

Subscripts

stor	thermal energy storage
hf	hot fluid
l	Liquid status
v	Vapor status
f	working fluid

focused on the research of thermal economic optimization of SORC with evaporation temperature, volume of TES, and solar collector area as design parameters.

As an unstable heat source, solar radiation is affected by clouds, which are dependent on weather and seasonal changes. In practical applications of SORC, historical solar radiation should be considered to further design and optimize the system. Some studies have shown that the instability of solar radiation have an important effect on system performance of SORC. The fluctuation characteristics of solar radiation, TES capacity and evaporation temperature are important parameters affecting the dynamic performance of SORC [18]. Zhao et al. also found that the output power of SORC shows a high sensitivity to the instability of solar radiation [19]. This SORC design that considers heat source fluctuations can be called dynamic input-based optimization. Compared to constant input-based optimization, the advantages of the dynamic input-based optimization are as follows: 1) can be used to design control systems and thermal storage system; 2) the deviation of the optimization results will be relatively small compared to constant input-based optimization for scenarios with large heat source fluctuations. The disadvantages as follows:1) Dynamic model is needed, and model complexity is high; 2) The amount of simulation calculation will be very large due to the complexity of the model and the amount of input data.

The local fluctuation characteristic of solar radiation restricts the energy conversion efficiency and thermal performance of SORC [20,21]. Therefore, the fluctuation characteristics of real solar radiation should be analyzed, and this feature should be applied to the thermo-

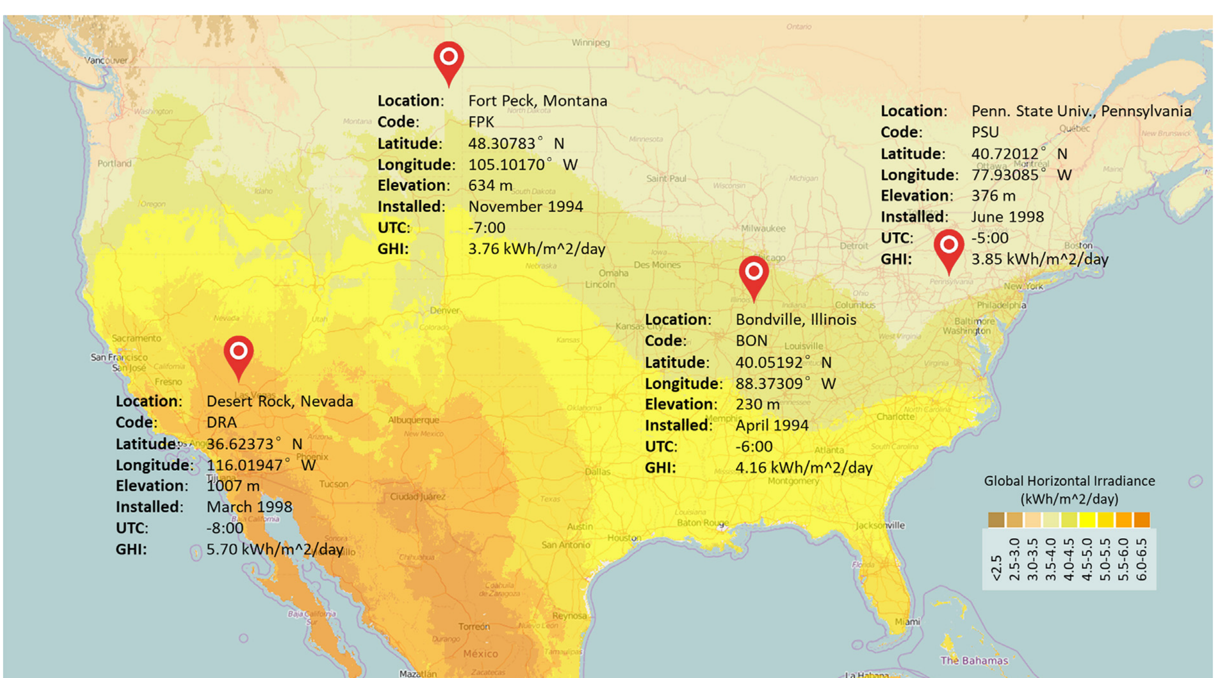

Fig. 1. Locations and information of selected four sites in SURFRAD database.