Energy Conversion and Management 166 (2018) 132–145

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Off-design performance modelling of a solar organic Rankine cycle integrated with pressurized hot water storage unit for community level application

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ARTICLE INFO

Keywords:
Solar ORC
Off-design analysis
Heat storage unit
Control strategy
Power output

ABSTRACT

Solar organic Rankine cycle (ORC) has advantages over common PV systems in view of the flexible operation even if solar radiation is unavailable. However, at present the dynamic performance of solar ORC with respect to the off-design behaviour of storage unit, expander, pump and heat exchanger is rarely reported. This paper investigates a medium-temperature solar ORC system characterized by evacuated flat-plate collectors and pressurised water storage unit. The main aim of the study is to investigate the performance of the system with consideration of transient behaviour of the thermal storage unit which results in off-design operation of other components. The other aim is adjusting the power output according to electricity demand throughout a day. The heat storage unit is analysed using one-dimensional temperature distribution model. A transient simulation model is developed including pump and expander models. To meet the electrical demands of different periods, the mass flow rate of heat source is adjusted for controlling the evaporation temperature. Moreover, sliding pressure operation control strategy of the ORC is implemented to meet variable heat source temperature. A 550 m^2 solar collector area and a 4 m diameter and 7 m height pressurized water cylinder are used in simulation. Produced work is controlled and the results are matched with the demands. Produced work from the expander under the given conditions are 47.11 kWh in day time, 70.97 kWh in peak period and 31.59 kWh after midnight.

1. Introduction

Renewable energy technologies have received specific worldwide attention, especially in developed countries. Although fossil fuels will undoubtedly remain the most dominant energy source over the next decades, special attention must be given to the provision of cleaner, more secure and sustainable energy sources, as strongly supported by public opinion. This trend has established renewable technologies as a necessary participant in energy production with an exponential growth in recent years in this sector. Solar energy has been defined as one of the most promising type of renewable energy sources. Solar-based energy systems are not only used for electricity generation but also applicable in various energy demanding systems such as refrigeration, desalination, hydrogen production and improvement of indoor environmental conditions [1].

In most parts of the world, electricity is the most important, sought after energy source for residential consumers. Electricity can be easily converted to other energies and household appliances need it in order to work. These factors make electricity the most demanded energy. Electricity suppliers provide the demand but their supply is not stable during the day. Previous studies have been conducted to specify and model the hourly demands [2,3]. The magnitude of this demand may differ from country to country but the general trend is quite similar for all houses [4,5]. Fig. 1 shows as an example of the 24 h domestic electricity demand of a dwelling in the UK [6]. To find a sustainable solution, PV cells have been used for years and expected to have a significant share in the upcoming electric generation systems [7]. However, as it is nature, electricity generation is intermitted with environmental factors and it needs solar irradiance absolutely. As seen from Fig. 1, peak demand occurs in the evening when there is no or significantly less residual solar irradiance. As a solution, the electricity can be stored in Lithium batteries but these come at a substantial cost and difficulty in quantifying its operational benefits for the grid [6,8]. Therefore, storing the heat in a medium which is collected by solar collectors, then using it as a heat source for the ORC is appropriate given that ORC technology has in recent years become a promising technology for converting heat into electricity [9].

Many works have been done on solar ORC, generally parabolic

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https://doi.org/10.1016/j.enconman.2018.04.024
Received 18 December 2017; Received in revised form 4 April 2018; Accepted 7 April 2018
Available online 03 May 2018
0196-8904/

Nomenclature

A	area, m^2
c_1	heat loss term, $W\,m^{-2}\,K^{-1}$
c_2	heat loss term, $W\,m^{-2}\,K^{-2}$
c_p	specific heat, $J\,kg^{-1}$
d_{st}	water tank diameter, m
Δk	de-stratification conductivity, $W\,m^{-1}\,K^{-1}$
G	solar irradiance, $W\,m^{-2}$
h	heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
k	thermal conductivity, $W\,m^{-1}\,K^{-1}$
K_θ	incident angle modifier
L	water tank height, m
$\dot{m}$	mass flow rate, $kg\,s^{-1}$
M	mass, kg
N	total node number
Pr	Prandtl number
Re	Reynolds number
r_p	pressure ratio
T	mean temperature, °C
T	temperature, °C
U	overall heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
$\dot{V}_s$	Swept volume, $m^3\,s^{-1}$
x	vapour quality
X_p	pump capacity fraction

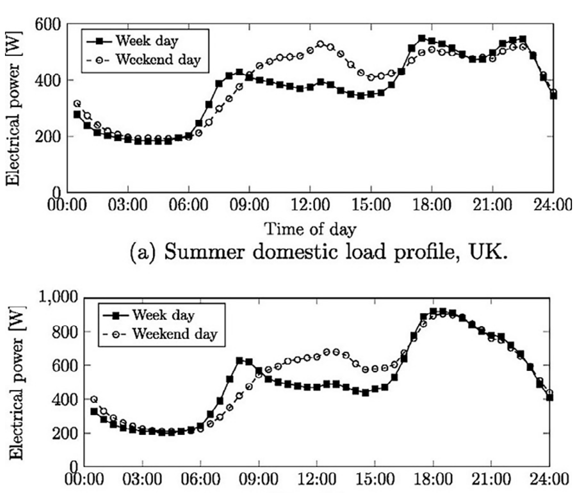
Subscripts

am	ambient
b	boiling
col	collector
cw	water in collector
e	evaporating
ex	exhaust
e_1	evaporating region
e_2	single phase region
me	mechanical
r	refrigerant
st	storage
stN	last node
v	vapour
w	water
wo	water out from evaporator
su	supply
t	tank

Greek letters

η	efficiency
ϕ	filling factor
ρ	density, $kg\,m^{-3}$

through collectors have been preferred: Wang et al. [10] examined the off-design behaviour of the solar ORC under variation of the environment temperature and thermal oil mass flow rates of vapour generator. They concluded lower environment temperature could improve the performance. Chacartegui et al. [11] analysed a 5 MW parabolic trough plant with ORC power block and thermal storage. They presented off-design and cost analysis and findings indicate that the investment cost for direct thermal energy storage systems is a 17% lower than the investment cost for indirect storage system. Tzivanidis et al. [12] conducted a parametric analysis of a solar ORC plant by using parabolic trough collectors to be optimize the system according to energy and financial considerations. Their results suggest that increasing the total collecting area reduces the solar thermal efficiency. Also flat plate collectors have been used in solar ORC systems. Wang et al. [13] prepared an experimental rig to compare two collector types and they found overall power generation efficiency was 4.2% for evacuated solar collectors and about 3.2% for flat plate solar collectors. Wang et al. [14]



(a) Summer domestic load profile, UK.

(b) Winter domestic load profile, UK.

Fig. 1. Domestic load profile in UK [6]

studied a solar-driven regenerative solar ORC with flat plate collector to compare working fluids. Their results show that R245fa and R123 are the most suitable working fluids due to higher system performance at low operation pressure. Freeman et al. [6] examined an integrated thermal energy storage for a domestic-scale solar combined heat and power system to match to the end-user demands by using evacuated flat plate collectors. They concluded that Phase Change Materials for latent thermal-energy storage were shown to provide a greater power-output from the system for a smaller equivalent storage volume than water.

Studies on the dynamic performance of solar ORC system are rare but in a fast rising trend [15–17]. However, transient performance of solar ORC in comprehensive consideration of the off-design behaviour of thermal storage unit, expander, pump and heat exchangers has not been reported yet. It is still needed to clarify how flexible a solar ORC system can operate and how it can fulfil the consumers' peak demand.

The objective of this paper is to provide a comprehensive model of the off-design analysis based on fulfilment of end user demand during the day by controlling the operation parameters. Several sub-models are included in the analysis:

- The ORC is modelled with consideration of the expander and pump behaviour alongside variations in operating conditions, such as isentropic efficiencies and working fluid mass flow rate.
- Sliding pressure operation strategy is implemented to allow and control the electricity production under varying heat source temperature.
- Transient heat storage unit is modelled with considering the thermocline behaviour. It is analysed using a one-dimensional temperature distribution model.
- To satisfy the electricity demand and conserve the heat in the storage, mass flow rate of water is controlled at different periods. Therefore, the system operates and is analysed at off-design conditions.

2. System description

The examined system in this study is shown in Fig. 2. The system is comprised of three sub-systems, namely, the collectors, water storage