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Working fluid selection and electrical performance optimisation of a domestic solar-ORC combined heat and power system for year-round operation in the UK

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HIGHLIGHTS

- A domestic solar combined heat & power (S-CHP) system is optimised for maximum electrical output in the UK.
- The S-CHP system comprises a solar collector array, an ORC engine and a working fluid buffer vessel.
- A working fluid and evaporation temperature optimisation are performed for an annual operation period.
- A single-stage and a two-stage collector array configuration are compared.
- An optimum annual-average electrical power of 122 W for the two-stage configuration is reported.

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ABSTRACT

In this paper, we examine the electrical power-generation potential of a domestic-scale solar combined heating and power (S-CHP) system featuring an organic Rankine cycle (ORC) engine and a 15-m^2 non-concentrated solar-thermal collector array. The system is simulated with a range of organic working fluids and its performance is optimised for operation in the UK climate. The findings are applicable to similar geographical locations with significant cloud coverage, a low solar resource and limited installation areas. A key feature of the system's design is the implementation of fixed fluid flow-rates during operation in order to avoid penalties in the performance of components suffered at part-load. Steady operation under varying solar irradiance conditions is provided by way of a working-fluid buffer vessel at the evaporator outlet, which is maintained at the evaporation temperature and pressure of the ORC. By incorporating a two-stage solar collector/evaporator configuration, a maximum net annual electrical work output of 1070 $kW\,h\,yr^{-1}$ (continuous average power of 122 W) and a solar-to-electrical efficiency of 6.3% is reported with HFC-245ca as the working fluid at an optimal evaporation saturation temperature of 126 °C (corresponding to an evaporation pressure of 16.2 bar). This is equivalent to ~32% of the electricity demand of a typical/average UK home, and represents an improvement of more than 50% over a recent effort by the same authors based on an earlier S-CHP system configuration and HFC-245fa as the working fluid [1], thus highlighting the gains possible when using optimal system configurations and fluids and suggesting that significant further improvements may be possible. A performance and simple cost comparison with stand-alone, side-by-side PV and solar-thermal heating systems is presented.

1. Introduction

Solar energy has the potential to meet a significant proportion of household demands for heating and electricity in the UK, despite its comparatively low annual yield of incident solar radiation (~1000 $kW\,h\,m^{-2}\,yr^{-1}$ for southern UK compared to ~1800 $kW\,h\,m^{-2}\,yr^{-1}$ for parts of southern Europe) [2]. Distributed domestic solar-power provision is conventionally a choice of either electricity generation via photovoltaic (PV) devices, or water heating via solar-thermal collectors. The feasibility of installing these as side-by-side systems for provision of both heating and power is limited by cost and space availability. At present, the only available technologies that can provide both heating and power from the same area of solar collector array are hybrid PV-thermal (PVT) systems, which are expensive and have a limited ability to meet time-varying demand ratios for heating and power [3–5].

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Nomenclature

Symbols

A	area, m^2
c_1	collector heat loss coefficient, $W/(m^2\,K)$
c_2	temperature dependence of the heat loss coefficient, $W/(m^2\,K^2)$
c_3	wind speed dependence of the heat loss coefficient, $J/(m^3\,K)$
c_4	sky temperature dependence of the heat loss coefficient, $W/(m^2\,K)$
c_5	solar collector effective thermal capacity, $J/(m^2\,K)$
c_6	wind-dependence of the collector optical (zero-loss) efficiency, s/m
h	specific enthalpy, J/kg
h_c	convective heat transfer coefficient, $W/(m^2\,K)$
F'	collector efficiency factor, –
G	solar irradiance, W/m^2
K_θ	solar collector incident angle modifier, –
$\dot{m}$	mass flow-rate, kg/s
P	pressure, bar
s	specific entropy, J/kg
T	temperature, K
t	time, s
U	overall heat transfer coefficient, $W/(m^2\,K)$
W	work, W
X	exergy, J
x	vapour quality, –
ε	heat exchanger effectiveness parameter, –
η	efficiency, –
η_0	solar collector optical (zero-loss) efficiency, –
$(\tau\alpha)$	effective transmittance-absorptance product, –

Subscripts

a	ambient air
cr	critical
bv	working fluid buffer vessel
bubble	bubble-point (saturated liquid condition)
exp	expander
gen	electricity generation
i, o	inner, outer
in, out	inlet, outlet
liq	liquid
n	normal incidence
r	regenerator
s	isentropic process
sat	saturation
sc	solar collector
sf	solar circulating fluid
wf	ORC working fluid
1,2,3,...	cycle state points

An alternative to PV-based technologies for electrical power generation from solar energy are solar-thermal technologies that convert heat to power via a suitable thermodynamic (heat) engine. Organic Rankine cycle (ORC) systems are one such technology that has been of recent considerable interest for low-grade heat conversion to useful power, including in waste-heat and renewable (i.e. solar, geothermal) energy research [6]. An attractive feature of solar-ORC systems is their ability to operate efficiently and affordably at lower temperatures and on smaller scales than solar-power systems based on steam-Rankine cycle technology. This opens up the possibility of developing the technology for geographical regions with a low solar resource and for distributed-level applications [7]. Despite this, a significant amount of experimental and modelling research on these systems have focused on application to regions with abundant solar resource and collector array areas beyond the size of what could be easily accommodated on the roof of a domestic property. Quoilin et al., [8] described a 3 kW_e ORC system for electricity-generation in a rural, off-grid community in Lesotho, southern Africa. The system was indirectly heated by a 75-m^2 concentrating parabolic trough collector (PTC) array with an automated tracking system and also included a 2-m^3 quartzite packed bed thermal store, while the power block featured a two-stage scroll expander configuration. Manolakos et al., [9] designed and tested an ORC reverse osmosis (RO) desalination system in Athens, Greece, indirectly heated by an evacuated tube solar collector array of gross area 216 m^2. The system incorporated a 2.5 kW reverse-operated scroll compressor as the expansion device, and was connected to the RO system via a belt and pulley arrangement. Wang et al., [10] investigated the performance of a 1.73 kW_e experimental ORC system in Tianjin, China, featuring a rolling-piston expander and powered by a 24 m^2 array of flat-plate collectors and a 20 m^2 array of evacuated tube collectors arranged in a parallel configuration. A key feature of this system was that the working fluid was directly evaporated in the solar collectors.

An important design-challenge for the successful operation of solar-thermal power systems is the ability to deal with time-varying incident radiation intensity. Thermal energy storage (TES) solutions can provide buffering for stable operation on a timescale of minutes (using small fluid buffer vessels) to hours (using large tanks of molten salts or packed beds of solid materials). Casati et al. [11] presented a range of a TES concepts for use in solar ORC systems. The authors noted that the ability to use working fluids with a "dry" (positive-gradient) vapour-saturation curve in these systems was highly favourable for solutions that consider thermal storage via direct storage of the working fluid. If the working fluid is stored under pressure as a saturated liquid, vapour can be generated by allowing the fluid to expand isenthalpically (known as flashing), and then fed to the expander. For very dry fluids, expansion from a saturated liquid to a saturated or superheated vapour state can be achieved with a relatively small drop in pressure. Working fluid storage for steam generation been used historically for various process applications. Steinmann and Eck [12] reviewed a number of configurations for steam accumulators as TES in steam-Rankine concentrating solar power (CSP) plants. A noted limitation of basic *sliding-pressure* steam accumulators in which the water working fluid is stored in two-phase (liquid–vapour) thermodynamic equilibrium is the associated drop in pressure of fluid in the vessel as steam is discharged. The aforementioned authors presented a concept for *constant-pressure* storage using encapsulated phase change materials (PCM). PCMs make use of solid–liquid phase change in order to achieve high energy storage densities (~100 kW h m^{-3}, compared to ~10 kW h m^{-3} for sensible liquid storage) under isothermal conditions. Thus temperature (and hence pressure) of the saturated steam or vapour supply can be maintained. This concept has been recently employed with success in prototype steam generator systems [13], and has been proposed for use in a refrigerant-based solar-ORC system by Jing et al., [14]. Other energy storage solutions considered for use in solar-thermal systems are thermo-chemical