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Mathematical modelling of operation modes and performance evaluation of an innovative small-scale concentrated solar organic Rankine cycle plant

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HIGHLIGHTS

- An innovative small scale concentrated solar ORC has been modelled using TRNSYS.
- The performance of the system have been evaluated under a given control strategy.
- Different operating modes of the systems are analysed during one year period;
- At high DNI the plant is able to achieve performance close to the design ones.
- The simulation analysis provides insights for the subsequent testing of the real plant.

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ABSTRACT

In this paper an innovative small-scale concentrated solar 2 kWe organic Rankine cycle plant coupled with a phase change material storage tank equipped with reversible heat pipes is investigated using a simulation analysis. The plant, intended for residential applications, is going to be built and tested under the European funded H2020 Innova MicroSolar project executed by the consortium of several Universities and industrial organizations, led by Northumbria University. The authors of this work used the design of the integrated system, developed by the consortium, to preliminary estimate the overall performance of the system in order to provide useful information for its forthcoming real operation. In particular, according to the varying ambient conditions, the influence of different operation modes of the prototype plant are evaluated. The dynamic simulation analysis has shown an interesting performance of the system in terms of annual operating hours, power production and conversion efficiencies. More precisely, the organic Rankine cycle unit is able to operate for more than 3100 h/year, achieving the design performance when solar power is sufficiently high, producing about 5100 kWh_e/year. For the considered operating set-point temperatures of the thermal energy storage, the plant is able to reach high conversion efficiency also when the organic Rankine cycle unit is supplied by discharging the energy stored in the storage tank, for about 800 h/year. Hence, the work has provided some useful insights into the best working conditions of such micro combined heat and power system to be integrated in residential buildings. Moreover, the analysis could serve as a general guide for the design and optimization of the mutual interactions of the different subsystems in small-scale concentrated solar organic Rankine cycle plants.

1. Introduction

In order to achieve the ambitious and challenging climate goals set by the Paris Agreement [1] that entered into force on October 2016, breakthrough energy technologies and innovation are recognized of paramount importance. Irrespective of any tangible climate change mitigation agreement, renewable sources have a key role in reducing greenhouse gas emissions, thus contributing to a sustainable development [2]. In 2015 renewable power generation increased by about 5% and it accounted for around 23% of the overall electricity generation worldwide [3]. Energy from the sun is by far the major source of renewable energy and about $1 \cdot 10^5$ TW reaches the surface of the earth. Therefore, solar energy is available in many regions and represents the most promising and clean energy for future power generation [4]. In particular, Concentrated Solar Power (CSP) technologies are foreseen as a valuable alternative to substitute thermal and electric power generation from fossil fuel. These technologies are able to concentrate sunlight from a large area onto a smaller one by means of optical devices like lenses or mirrors. The concentrated light is then collected using a solar receiver and converted into electric or thermal power

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Nomenclature

A	area of the primary collectors [m^2]
c_1	first order heat losses coefficient [kW/m C]
c_4	fourth order heat losses coefficient [kW/m C^4]
CAPEX	capital expenditure [€]
CPC	Compound Parabolic Collector
CHP	Combined Heat and Power
CSP	Concentrated Solar Power
DNI	Direct Normal Irradiation [kW/m^2]
dr	discount rate [%]
IAM	Incident Angle Modifier
h_{ORC}	operating hours of the ORC unit [h]
L_{abs}	length of the absorber tubes [m]
LCOE	Levelized Cost of Electricity [€/kWh_e]
LFR	Linear Fresnel Reflector
OM	Operation Mode
ORC	Organic Rankine Cycle
Eff_{LFR}	overall conversion efficiency of the LFR solar field [%]
Eff_{TES}	efficiency of TES [%]
$Eff_{ORC,el}$	electric efficiency of the ORC unit [%]
$Eff_{ORC,th}$	thermal efficiency of the ORC unit [%]
$Eff_{ORC,tot}$	overall efficiency of the ORC unit [%]
Eff_{TOT}	total conversion efficiency of the plant [%]
E_{gen}	electric energy generated [kWh_e]
ir	inflation rate [%]
$\dot{m}_c$	mass flow rate of the cooling water [kg/s]
$\dot{m}_f$	mass flow rate of the organic fluid [kg/s]
OPEX	operating expenditure [€]
PCM	Phase Change Material
$P_{LFR,in}$	inlet power to the LFR [kW]
$P_{LFR,out}$	outlet thermal power from the LFR [kW_t]
$P_{LFR,peak}$	peak outlet thermal power from the solar field [kW_t]
$P_{TES,in}$	inlet thermal power to the TES [kW_t]
$P_{ORC,in}$	inlet thermal power to the ORC [kW_t]
$P_{ORC,in,n}$	nominal inlet thermal power to the ORC [kW_t]
$P_{ORC,out}$	outlet thermal power from the ORC [kW_t]
$P_{ORC,el}$	electric power produced by the ORC [kW_e]
PV	Photovoltaic
PTC	Parabolic Trough Collectors
Q_{loss}	heat losses at the receiver [kW_t]
Q_{PCM}	heat exchanged by the PCM [kW_t]
SM	Solar Multiple
TES	Thermal Energy Storage
T_{abs}	average temperature of the absorber tube [°C]
$T_{LFR,out}$	outlet temperature of the diathermic oil from the LFR solar field [°C]
T_{oil}	temperature of the diathermic oil [°C]
$T_{ORC,in}$	inlet temperature of the diathermic oil to the ORC [°C]
$T_{ORC,off}$	lower bound temperature set-point of the TES [°C]
$T_{ORC,on}$	upper bound temperature set-point of the TES [°C]
$T_{TES,av}$	average temperature of the TES [°C]
$T_{TES,max}$	maximum temperature of the TES [°C]
T_{in}	inlet temperature of the cooling water at the condenser [°C]
T_{out}	outlet temperature of the cooling water at the condenser [°C]
Δh_e	actual specific enthalpy difference across the expander [kJ/(kg K)]
Δh_p	actual specific enthalpy difference across the pump [kJ/(kg K)]
ΔT_{PCM}	temperature difference between the PCM and the heat transfer medium [°C]
$\Delta t_{int\text{-}timestep}$	time interval of the internal time step [s]

Greek symbols

α	solar elevation angle
ε	emittance coefficient
η_{el}	electric efficiency
η_m	mechanical efficiency
η_{opt}	optical efficiency
$\eta_{opt,max}$	maximum optical efficiency
η_{rec}	efficiency receiver factor
σ	solar azimuthal angle
θ	solar incident angle

depending on the temperature level and the plant scale. Among the different CSP technologies, Linear Fresnel Reflectors (LFRs) proved to be a very promising solution as solar concentrator for medium and high temperature thermal applications thanks to their potential to overcome techno-economic constraints associated with conventional reflector based CSP [5]. Compared to Parabolic Trough Collectors (PTC) indeed LFRs show a great potential for cost reduction, thanks to a lighter structure and a fixed receiver, which can be designed for optimum integrated thermal performance [6]. At present, for an installed power lower than few hundreds of kW, the specific cost of a LFR solar field is about 200 €/m^2 of collector area [7], but it can be reduced up to 150 €/m^2 in case of system improvements and large scale production [8]. Although the benefits of their usage in building-façade for power generation have been proven [9], their adoption in buildings has been limited so far. In fact, at residential level evacuated tubes are preferred, because of their ease of installation and absence of tracking mechanisms. However, the use of medium and high temperature solar technologies in buildings can be economical and feasible if the systems are designed reasonably [10], because of the high potential of cogeneration at residential scale [9] where both thermal and electric energy are requested. To efficiently convert solar energy into generated power, Organic Rankine Cycle (ORC) systems are considered as one of the most common and competitive technologies [11]. An Organic Rankine Cycle plant works similarly to a Rankine steam power plant, but it makes use of organic working fluids which are able to condense and evaporate at acceptable temperatures [12]. On large scale, several manufacturing companies for ORC exist and their products are already into the market [13]. However, different factors are boosting the interest for small ORC units, such as the need of power in developing countries, the request of polygeneration systems for grid connected applications in developed countries as well as the deregulation and privatization of the electric generation sector worldwide [12]. There are still several challenges for the exploitation of low grade thermal energy resources by means of ORC systems [14], therefore, also academic research is paying a lot of attention on them. For example, Bouvier et al. [15] experimentally investigated the performance of a micro Combined Heat and Power (CHP) system composed of a solar PTC coupled to a steam Rankine cycle expander for direct steam generation. Although low output electric power and solar-to-electricity efficiency are achieved, the analysis showed the feasibility of adopting such a system for hot water or heating production into a building. Taccani et al. [16] tested a small-scale micro solar CHP (< 10 kWe) powered by parabolic trough solar collectors with a collector surface area of 100 m^2. They indicated that the system can achieve 8% as gross electricity efficiency. Instead, Xu et al. [17] evaluated the performance of a LFR-ORC system through a theoretical and simulation study. Results showed that the supercritical ORC system is better than the subcritical one independently from the considered working fluid. Antonelli et al. [18] carried out a dynamic modelling of a low concentration solar plant consisting of static compound parabolic collectors coupled with an ORC unit in AMEsim. The