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Parametric analysis of a solar Organic Rankine Cycle trigeneration system for residential applications

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ABSTRACT

In this paper, the potential of a small scale concentrated solar Organic Rankine Cycle unit coupled with an absorption chiller for trigeneration purposes is investigated using a simulation analysis.

At the moment, only few research works encompass small-scale solar trigeneration systems and most of them do not refer to real plant. On the contrary, in this work electric, heating and cooling maximum generation of a real and experimental small scale prototype system composed of a 50 m^2 CPC solar field, a 3.5 kWe ORC plant and a 17 kWc absorption chiller is investigated by means of TRNSYS. In particular, this work relies on the evaluation of the dynamic performance of the mentioned plant varying some selected system parameters to provide proper modifications of its design configuration and operation.

More precisely, working temperature ranges, heating and intermediate fluid flow rates as well as volume of the storage tanks and size of the solar field have been varied within the simulation model. Results have shown that operating temperature ranges of the storage tanks considerably affect the overall performance of the system; by appropriately choosing these ranges the primary energy production can be increased by 6.5% compared to the baseline configuration without any additional investment costs. Moreover, setting suitably some design parameters can significantly contribute to extend the operating hours and the feasibility of a such small scale integrated system for residential applications.

1. Introduction

One of the major concerns threatening our society is the world increasing energy demand. Fossil fuels are limited and the related environmental impact has serious effects on human health, ecosystems and climate. Therefore, in the last decades renewable energy technologies such as PVs and wind turbines have been widely adopted and energy production from renewables has accounted for about 19.2% of the global final energy consumptions in 2014 [1].

Among renewable energy technologies, solar technologies are becoming more and more attractive thanks to their increasing cost-competitiveness. Also, the industrial capacity of Concentrated Solar Power (CSP) is increasing especially in developing countries. CSP, indeed, is recognized as a valuable alternative to substitute power generation from fossil-fueled plants due to its lower environmental impact [2]. Thanks to optical devices like lenses or mirrors the CSP technology is able to concentrate sunlight from a large area onto a small one and to convert it into electrical or thermal power depending on the applications. With respect to the method of capturing solar thermal energy, four main CSP technologies are available at present: Parabolic Trough Collector (PTC), Solar Power Tower (SPT), Linear Fresnel Reflector (LFR) and Parabolic Dish System (PDS) [3]. Compound Parabolic Collector (CPC) is also another suitable option due to its low cost and good thermal performance for low and medium temperature ranges [4]. It is able to collect both direct and diffuse solar radiation without a tracking system. One of its very promising applications is in combination with Organic Rankine Cycles (ORC) as already addressed by several studies [5,6]. For example, Antonelli et al. [7] already investigated the integration of small size compound parabolic collectors with ORC for electricity distributed production using the simulation tool AMESim.

An Organic Rankine Cycle plant works similarly to a Rankine steam power plant but it makes use of organic working fluids which fit low grade heat not incurring issues of water use at low temperatures presenting the advantages mentioned in [8]. Therefore, for low grade heat

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Nomenclature

A	area of the collector [m^2]
a_0	first order efficiency coefficient [$W/m^2 K$]
a_1	second order efficiency coefficient [$W/m^2 K$]
CCHP	combined cooling, heating and power
COP	coefficient of performance
CPC	compound parabolic collector
DNI	direct normal irradiation [W/m^2]
FESR	fuel energy saving ratio
G_b	direct radiation on collector plane [W/m^2]
G_d	diffuse radiation on collector plane [W/m^2]
h_{abs}	operating hours of the absorption chiller [h]
h_{ORC}	operating hours of the ORC unit [h]
HTT	high temperature storage tank
LTT	low temperature storage tank
K_θ	incident angle modifier for direct radiation
K_d	incident angle modifier for diffuse radiation
NTU	number of transfer units
P_e	electrical power [kWe]
P_c	cooling power [kWc]
P_t	thermal power [kWt]
SM	solar multiple
TES	thermal energy storage
T_a	ambient air temperature [°C]
T_{av}	average temperature [°C]
T_m	mean temperature of the fluid in the collector [°C]
PEP	primary energy production [kWh]
$\dot{m}_f$	mass flow rate of the organic fluid [kg/s]
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_h	hot period working temperature range of HTT-ORC inlet [°C]
ΔT_c	cold period working temperature range of HTT-ORC inlet [°C]
ΔT_m	mid seasons working temperature range of HTT-ORC inlet [°C]

Greek symbols

β	absorptance coefficient
ε	emittance coefficient
η_{el}	electrical efficiency
$\eta_{e,ORC}$	ORC unit electrical efficiency
η_m	meccanical efficiency
η_o	maximum optical efficiency
$\eta_{t,ORC}$	ORC unit thermal efficiency
$\eta_{glob,CCHP}$	CCHP global efficiency

organic Rankine fluids perform better than water. Moreover, such system exhibits great flexibility, high safety and low maintenance requirements in recovering low temperature heat even at small scale [9]. Recently, many researchers are focusing on this field: Li et al. [10], for example, evaluated the influence of heat source temperature and ORC pump speed on the performance of a small-scale ORC system using R245fa as working fluid. Al Jubori et al. [11] instead focused on the influence of several turbine design features on turbine performance in ORC systems with five working fluids. Pei et al. [12] experimentally investigated the performance of a specially designed radial-axial turbine using R123 as working fluid. The test has shown that a turbine isentropic efficiency of 65% and an ORC efficiency of 6.8% can be obtained with a temperature difference of about 70 °C between the hot and the cold sides. The same authors [13] evaluated the energetic and exergetic performance of the updated ORC system and the related thermal efficiency at different heat source temperatures. On the contrary, Quoilin et al. [14] evaluated the thermodynamic performance of low cost solar Organic Rankine Cycles considering different working fluids, expansion machines and system configurations.

However, in order to achieve higher conversion efficiencies and annual performance of ORC systems even at small scale the modeling of the different subsystem and their integration are of fundamental importance. For example, He et al. [15] developed a transient simulation model of a typical PTC system coupled with an ORC focusing on the effects of several key parameters. In particular, the authors evaluated the incidence of different size of the thermal storage tank on the performance of the system with seasonality. Instead, Borunda et al. [16] evaluated the potential of PTC-ORC system as cogeneration unit in a textile industrial process using TRNSYS to emulate the real operating conditions of the user. Furthermore, very important, as a reference for the present study, is the contribution of Calise et al. [17] who developed a dynamic simulation model of a 6 kWe ORC coupled with 73.5 m^2 of innovative flat-plate evacuated solar collectors whose heat input to the evaporator is integrated by an auxiliary heater fed with natural gas. Authors performed also a sensitivity analysis to evaluate the combination of different design parameters which maximize the thermo-economic performance of the system. This work, even though examining a CHP, differently than our CCHP configuration, allows an effective comparison with our system.

In general, micro cogeneration and trigeneration have a very interesting potential in households [18] both grid connected and stand alone and several studies have addressed the dynamic performance of such systems in TRNSYS [19,20]. For example, Angrisani et al. [21] investigated the techno-economic feasibility of a micro-trigeneration system starting from previous experimental tests of the prime mover. The integrated system used to provide air conditioning to a lecture room and domestic hot water to a nearby household has shown interesting performance, synthesized by an 82.1% overall efficiency in terms of primary energy ratio, and reduced energy consumptions compared to the reference system. They specifically developed a mathematical model of a micro-trigeneration system with the final aim to determine the primary energy saving by means of the Fuel Energy Saving Ratio (FESR). They implemented also a sensitivity analysis of primary energy saving, net saving and CHP generation bonus with respect to the electric surplus factor from the CCHP unit. However, attention has not been paid on the influence of design and adjustment parameters on plant performance. Considering the works edited until now on the topic of solar ORC as Combined Cooling Heating and Power (CCHP) system, Chang et al. [22] referred to a CCHP system consisting of a hybrid Proton Exchange Membrane fuel cell and a solar ORC. In particular, they evaluated the effects of solar radiation, current density and operating temperature of the fuel cell and ambient temperature on the performance of the trigeneration system. However, in this study the electric power is provided only by the fuel cell thus mitigating the energy dependence on the solar source because the solar powered ORC expander is coupled with the vapor compressor cycle compressor. Boyaghchi et al. [23], instead, carried out a thermodynamic and thermoeconomic optimization of a solar ORC trigeneration plant for domestic applications by varying some thermodynamic variables. The heat coming from solar collectors is integrated by a natural gas boiler when requested. They focused the attention on the following CCHP key parameters: turbine inlet temperature and pressure, turbine back pressure, evaporator temperature and heater outlet temperature. The considered objective functions were the thermal efficiency, the exergy efficiency and the total product cost rate.

In this paper an integrated pilot system installed near Orte [24,25]