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A novel solar-geothermal trigeneration system integrating water desalination: Design, dynamic simulation and economic assessment

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ABSTRACT

In this paper, an innovative solar-geothermal polygeneration system is investigated. The system supplies a small community with electricity, desalinated water and space heating and cooling through a district network. The hybrid multi-purpose plant, based on an Organic Rankine Cycle (ORC) supplied by medium-enthalpy geothermal energy and by solar energy; this latter is provided by Parabolic Trough Collectors (PTC). The geothermal brine is first used to drive the ORC loop, then to provide space heating at around 85÷90 °C (in the winter), or cooling (in the summer, by means of a single-effect absorption chiller). Finally, the geothermal brine drives a Multi-Effect Distillation (MED) system, where seawater is converted into freshwater. For such a system, a dynamic simulation model was developed in TRNSYS environment. In particular, the ORC model, developed in Engineering Equation Solver (EES), was based on zero-dimensional energy and mass balances and includes specific algorithms to evaluate the off-design performance. Similarly, a novel model of the MED unit was developed in EES. Suitable control strategies were implemented for the optimal management of system. The energy and economic performance of the system under analysis was investigated, using different time bases (day, week, month, year). Finally, a sensitivity analysis was performed to determine the set of system, design/control parameters able to minimize the simple payback period. The results showed that the novel system is highly flexible and efficient. On the other hand, a significant capital cost must be taken into account, so that the system is economically profitable only when the majority of the energy available for heating and cooling purposes is actually used.

1. Introduction

In recent years, the world demand for energy and freshwater has seriously increased, mostly because of the huge growth of Developing Countries. The energy demand is typically matched by non-renewable fossil fuels, since they are still the most economical option, in spite of the environmental issues related to their utilization [3]. In the present energy market, the majority of the renewable energy sources are considered profitable only in case of suitable public funding policies. However, recently, a dramatic decrease of the capital cost of renewables was also achieved as a consequence of liberalization policies and of promotion of distributed generation: consequently, some renewable technologies are becoming more and more competitive with respect to the conventional ones.

Similarly, the worldwide demand for freshwater represents a very serious issue in terms of sustainability. In fact, the scientific community agrees that the availability of freshwater will become in the next future a challenge even harder than energy-related issues [3].

In this framework, a sustainable and efficient development must be also based on the design of high-efficiency energy conversion facilities. This paper attempts to pursue this goal, presenting an energy and economic analysis of an innovative polygeneration system powered by solar and geothermal sources, which can provide simultaneously electricity, space heating and cooling and desalinized water.

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Nomenclature

A	area [m^2]
ACH	absorption chiller
AH	auxiliary heater
BOP	balance of plant
c_{fresh}	unit cost of freshwater [€/m^3]
c_p	specific heat [kJ/kg K]
CPVT	concentration photovoltaic/thermal system
CW	chilled water
DVG	direct vapor generating
E	energy [kWh]
F	energy fraction
FFM	falling film evaporator
GF	geothermal fluid
GHE	geothermal heat exchanger
HD	hydro distillation
HTF	heat transfer fluid
HW	hot water
J	capital cost [€]
m	mass rate
MED	multi-effect distillation
MedHE	multi-effect distillation heat exchanger
MSF	multi-stage flash system
ORC	Organic Rankine Cycle
P	power [kW]
p	pressure [bar]
PTC	parabolic trough collector
Q	thermal/cooling energy [kWh]
$\dot{Q}$	thermal/cooling flow rate [kW]
R	revenue [€/year]
RecHE	recovery heat exchanger
RPS	Renewable Polygeneration System
SecHE	secondary heat exchanger
SCF	solar collector fluid
SPB	simple payback period [years]
TK	thermal storage
TRS	thermal recovery subsystem
VMD	vacuum membrane distillation
X	molar concentration
z	depth of well [m]

Subscript

a	ambient
cond	condensation
el	electricity
eva	evaporation
feed	feeding
fresh	freshwater
geo	geothermal
w	water

This work is a continuation of an ongoing research project developed by some of the authors, aiming at designing new efficient polygeneration systems. In fact, a dynamic simulation [4] and an exergo-economic analysis [5] of a hybrid solar-geothermal power plant have been already performed. Moreover, two renewable polygeneration plants have been investigated by thermoeconomic [6] and exergo-economic viewpoints [7]. In particular, a hybrid renewable system is considered in this work, in which an Organic Rankine Cycle (ORC), powered by solar and geothermal sources, is coupled with a Thermal Recovery Subsystem (TRS) for winter heating and summer cooling and with a Multiple-Effect Distillation system (MED) for freshwater production. The solar energy is collected by means of Parabolic Through Collectors (PTC). A preliminary analysis regarding this arrangement has been presented in Refs. [8], where the system is analyzed from both exergy and exergoeconomic viewpoints. Such arrangement is much more complex and efficient than the one proposed in Refs. [5], including two more subsystems (MED and TRS) that enable the plant to supply district heating and cooling and freshwater. MED and ORC technologies have been widely analyzed in literature. However, their integration in a unique polygeneration system has never been investigated. The ORC technology represents one of the most efficient technologies to exploit renewable energies and low-medium temperature thermal cascades. In such systems, an organic fluid is used as a working fluid, instead of water. Such fluids show some disadvantages, such as high cost, toxicity and flammability. On the other hand, the same fluids also present a number of attractive properties, such as low critical temperature, low latent heat of evaporation and high molecular weight. Therefore, the ORC systems are considered the best option in the exploitation of low-medium temperature thermal cascades and energy sources.

A typical scheme of an ORC system includes an evaporator, a condenser, a pump and a turboexpander; the use of a superheater and a recuperator can also be considered, as in Refs. [4] and [5].

ORC systems have been widely investigated in literature in many different applications, as suggested in Refs. [9] and [10], including waste heat recovery from gas turbines [11] and internal combustion engines [12]. The investigation has covered many issues, such as the selection of the most appropriate working fluid: examples can be found in Refs. [13] and [14], or in Refs. [15], where the working fluids analysis is accompanied with the selection of the expander This latter can be carried out depending on the thermal source, as investigated in Refs. [16] and [17], on the particular application [18] or on the plant layout [19]. Other investigated topics are the optimum design criteria [20] and the parametric optimization of such technology, as presented in Refs. [21] and [22]. Finally, several interesting proposals for ORC design and testing can be found in literature. In particular, two ORC prototypes using R245fa with radial and axial turboexpander have been tested in Refs. [23] and [24], respectively. Moreover, small scale prototypes have been designed and tested [25]; in particular, in Ref. [26] the authors analyzed a 1.5 kW domestic-scale prototype with a global electric efficiency of 8.00%. Moreover, different combinations of geothermal and/or solar systems equipped with ORC module have been investigated, as one can read in Ref. [27]. Another interesting example is given by Astolfi et al., who performed a thermodynamic optimization [28] and a techno-economic optimization [29] of many configurations of a binary ORC power plant fueled by medium-low enthalpy geothermal source, using different working fluids. The configurations analyzed in literature include super critical Rankine cycles, as investigated in Astolfi et al. [30] and in Zhou et al. [31], and small-scale CHP [32]. These works put in evidence a few advantages in terms of efficiency and economical profits, with respect to plants powered by a single source. However, the majority of such works are based on assumptions incompatible with an accurate dynamic simulation, such as steady-state conditions and constant isentropic efficiencies of turbomachinery. In particular, in previous papers, Calise et al. [2] presented a dynamic