ARTICLE IN PRESS

Applied Energy xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

A novel renewable polygeneration system for a small Mediterranean volcanic island for the combined production of energy and water: Dynamic simulation and economic assessment

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HIGHLIGHTS

- A novel fully-renewable trigeneration system is designed and simulated.
- The system uses low-enthalpy geothermal energy and solar energy.
- The system produces cool, heat, electricity and desalted water.
- The system is based on MED desalinization technology.
- The system is very promising from energetic, economic and environmental viewpoints.

ARTICLE INFO

Article history:
Received 2 December 2013
Received in revised form 28 February 2014
Accepted 22 March 2014
Available online xxxx

Keywords:
Geothermal energy
Solar heating and cooling
PVT
Solar desalination
MED

ABSTRACT

This paper investigates the integration of solar and geothermal energy in a novel polygeneration system producing simultaneously: electricity, thermal energy, cooling energy and fresh water. The polygeneration system under analysis includes concentrating photovoltaic/thermal solar collectors (CPVT), a Geothermal Well (GW) a multi-effect distillation (MED) system for seawater desalination, a single-stage LiBr–H_2O absorption chiller and additional components, such as: storage tanks, heat exchangers and balance of plant devices. The CPVT produces simultaneously electrical energy and thermal energy, at a maximum temperature of about 100 °C. The electrical energy is delivered to the grid, whereas the thermal energy can be used for different scopes. First, the thermal energy can be used for heating purposes and/or Domestic Hot Water production. As an alternative, solar thermal energy can be used to drive an absorption chiller, producing chilled water for space cooling. Finally, solar energy, in combination with the thermal energy produced by low-enthalpy (about 80 °C) geothermal wells, may be used by the MED system to convert seawater into desalinated water. Geothermal energy is also used to produce Domestic Hot Water at 45 °C. The system is dynamically simulated by means of a zero-dimensional transient simulation model. The simulation model also includes detailed control strategies, for the management of the different technologies included in such a complex system. The system is assumed to be operated in some of the several small volcanic islands in the Mediterranean Sea, assuming Pantelleria (Trapani, Italy) as main case study. Here, the availability of solar and geothermal energy is high whereas the availability of fresh water is scarce and its cost consequently high. Results show an excellent energetic performance of the system under investigation. From the economic point of view, the profitability of the system dramatically increases when user Domestic Hot Water demand is high.

1. Introduction

During the last few years, world is facing severe issues related to the increasing consumption of energy and water resources. This increase is basically due to the huge amount of energy and water demanded by the developed Countries (USA, EU, Japan, etc.). Nevertheless, a significant and increasing amount of energy and water is also demanded by the highly crowded emerging Countries (China, India, Brazil, etc.) [1]. Unfortunately, the present energy and water policies used by the majority of the Countries are based on an intensive utilization of fossil fuels and water resources. Such

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http://dx.doi.org/10.1016/j.apenergy.2014.03.064
0306-2619/

Nomenclature

A	area (m^2)
c	specific heat (kJ/kg/K)
c_p	heat capacity at constant pressure (kJ/kg/°C)
c_{ue}	electricity unit cost (€/kW h)
c_{ut}	heat unit cost (€/kW h)
c_{uwat}	water unit cost (€/kg)
e	specific energy consumption in fresh water production (€/m^3)
eff	heat exchange effectiveness
BPE	boiling point elevation (°C)
Cop	operating cost (€)
COP	coefficient of performance (–)
$COP_{EHP,rs}$	coefficient of heat pump in reference system (–)
E_{el}	electrical energy (kW h)
I_{beam}	beam radiation (kW h)
I_{tot}	total radiation (kW h)
I_0	system capital cost (€)
J	component capital cost (€)
$\dot{M}$	mass flow rate (kg/s)
m_{wat}	desalinated water mass (kg)
NTU	number of transfer units
$\dot{Q}$	thermal power (kW)
Q	thermal energy (kW h)
SPB	simple pay back period (years)
t	temperature (°C)
T	temperature (K)
U	overall heat transfer coefficient (kW/m^2 °C)
V	volume (m^3)
X	water salinity (parts per million, ppm)

Greek symbols

ρ	density (kg/m^3)
λ	latent heat of vaporization/condensation (kJ/kg)
η_t	thermal efficiency
η_{el}	electrical efficiency
$\eta_{el,RS}$	reference system electrical efficiency

Subscripts

aux	auxiliary
B	brine
bot	bottom
c	cooling/cold
d	demanded
ch	chilled/chilling
D,i	distillate by evaporation at *i*th effect
D,flash "*i*"	distillate produced by flash at brine inlet at *i*th effect
el	electrical
ext	external
f	feed water
f_t	feed-in tariff
h	heating/hot
in	inlet
motive	related to the hot water stream supplying energy to the MED plant
o	outlet
p	produced

policies scarcely take into account the sustainability of this approach, which can lead to rapid deployment of fossil fuels and water resources in few decades. In particular, in the last few years, the majority of OECD (Organisation for Economic Co-operation and Development) Governments realized that new policies must be implemented in order to promote a more sustainable use of energy resources [2]. Conversely, negligible efforts have been performed in order to promote a more careful utilization of water resources, which are becoming extremely scarce in several locations in the world. This issue was analyzed by Artistidis et al. for Crete [3], addressing the relationship between water research status and climate changes. The same relation was studied for the Southern Africa by Kusangaya et al. [4]. A similar analysis for the Mediteranean districts was analyzed by Manios et al. [5]. All these researches pointed out that in the next future the availability of water may become an issue more severe than fossil fuels accessibility. Therefore, water and energy problems must be addressed in an integrated approach aiming at promoting new technologies for a sustainable production of both water and energy.

In this framework, significant improvements have been performed in the last decades aiming at promoting renewable energy sources. In fact, although conventional energy conversion technologies, based on the utilization of fossil fuels, are the most profitable option, renewable energy sources are becoming economically competitive when they are supported by public funding. Moreover, in the last decades, the fossil fuel cost is rapidly increasing and the capital cost of Renewable Energy Sources (RES) technologies is simultaneously dramatically decreasing. Therefore, it can be expected that some of the renewable energy technologies will become economically competitive with conventional ones in the near future. Simultaneously, renewable energy sources are also an interesting option for producing potable water from seawater using electrical or thermal energy. Therefore, a mature development of renewable systems may be helpful for both energy and water issues.

It is worth noting that, in continental EU Countries these issues are mitigated by the large availability of natural water resources and fossil fuels (or nuclear power plant). Conversely, this issue is particularly severe in the islands of the Southern Mediterranean Sea, where the availability of fossil fuels and water resources is scarce or null. Nevertheless, such islands are typically rich in renewable energy (solar energy and, in case of volcanic islands, geothermal energy) and have easy access to seawater. Therefore, the scope of this paper is the design of a novel integrated process, based on the use of renewable energy sources (namely solar and geothermal), aiming at the production of energy (electricity, cool and heat) and fresh water at reasonable costs.

In particular, the study is focused on volcanic islands, due to the availability of a constant heat flow from geothermal resources, to be used in order to mitigate the oscillations of solar energy availability.

The following technologies are simultaneously included in the system: Solar Heating and Cooling (SHC), Concentrating Photovoltaic–Thermal collectors (CPVT), Multiple Effect Distillation (MED) for seawater desalination and Geothermal Wells (GW) for the utilization of low-enthalpy geothermal energy.

Solar Heating and Cooling (SHC) systems are based on conventional solar thermal collectors, producing thermal energy. During the winter, such thermal energy is used for space heating. Conversely, during the summer, solar thermal energy is converted in cooling energy by a thermally driven chiller (absorption, adsorption, etc.). In particular, SHC technology is especially attractive in summer, when the demand for cooling is often simultaneous to the large availability of solar radiation [6].