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Research Paper

Coupling a small-scale concentrated solar power plant with a single effect thermal desalination system: Analysis of the performance

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HIGHLIGHTS

- A small-scale CSP system previously tested has been re-engineered and modelled.
- A model of the CSP system coupled with a compact desalination plant has been developed.
- Performance of the system have been evaluated with different operating conditions.
- The fresh water production reached a maximum of about 75 L/day in Crendi (Malta).
- The integrated system has an interesting potential especially in remote and arid areas.

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ABSTRACT

In this paper, the potential of coupling a small-scale non-imaging focusing heliostat CSP plant with a compact single effect thermal desalination plant is presented and an analytical model for assessing the overall performance is described.

The main novelty of this work relies on the study of two small-scale prototype units designed and tested by the authors. More precisely, the system consists of 25 hexagonal non-imaging heliostats for a total reflective area of 9.5 m^2 with a peak power output of 6 kWt and of a single stage thermal desalination plant for fresh water production of few hundred liters per day.

In order to better evaluate the potential of such a coupling, three different locations in the Mediterranean area have been considered: Palma de Mallorca, Pantelleria and Crendi.

The simulation analysis proved interesting results. Compared to electrically driven desalination plant, the performance of the proposed plant is only slightly affected by the salt content of the treated water. In terms of fresh water production, the yearly fresh water production in Crendi is about 60% higher than in Pantelleria because of the higher DNI throughout the year. On the contrary, the maximum daily fresh water production differs to a smaller extent: it reaches a peak of about 70.5 L/day in Pantelleria and 75.0 L/day in Crendi whilst it is always < 60 L in Palma.

Despite further improvements are needed to reduce the cost of the fresh water produced by similar small-scale CSP desalination plant to overcome the market uptake, the results of the analysis have shown that such a coupling could have a very interesting potential especially for small-scale applications in rural and remote areas where the fresh water demand ranges between 30 L and 60 L per day.

1. Introduction

Nowadays, the rapid growth of the population, the improper wastewater management and the contamination of the soil considerably threaten the access to fresh water of almost half of the population worldwide. Sustainable access to safe drinking water represents one of the Millennium Development Goals set by the World Health Organization [1]. According to UNESCO [2] around 748 million people today still rely on scarce drinking water sources and water demand for sustainable businesses is expected to increase by 400 per cent between 2000 and 2050 globally. Considering that salt water is largely abundant on Earth, water desalination is a recognized viable solution to tackle the challenges related to fresh water scarcity [3]. However, in order to desalt seawater important amounts of energy are required.

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Nomenclature

A	area of the evaporator heat exchanger, m^2
h_{vap}	enthalpy of vaporization of the salt water, J/kg
i	number of the rows
ir	inflation rate
j	number of the columns
$\dot{m}_{fw}$	mass flow rate of the fresh water, L/s
M_{fw}	mass of the fresh water, L
$M_{fw,tot}$	present value of the total fresh water generated over plant life L
n	bisector unit vector
$Q_{receiver}$	thermal power collected at the solar collector, W
Q_{solar}	thermal power input to the desalination plant, W
Q_{loss}	thermal power losses at the evaporation vessel, W
Q_{ev}	thermal power available at the vaporization coil, W
Q_{vap}	thermal power for the salt water vaporization, W
r	receiver pointing unit vector
R_{cond}	conductive resistance of the evaporator, $W/m^2{\cdot}K$
$R_{conv,e}$	external convective resistance at the evaporator, $W/m^2{\cdot}K$
$R_{conv,I}$	internal convective resistance at the evaporator, $W/m^2{\cdot}K$
$R_{fouling,sw}$	fouling resistance of the seawater at the evaporator, $W/m^2{\cdot}K$
$R_{fouling,wg}$	fouling resistance of the water-glycol solution at the evaporator, $W/m^2{\cdot}K$
R_{tot}	overall thermal resistance of the evaporator, $W/m^2{\cdot}K$
s	sun ray unit vector
S_{tot}	overall active area of the heliostats, m^2
$S_{tot,ref}$	total reflective area of the heliostats, m^2
S_u	area of the heliostat corresponding to each simulated solar ray, m^2
U	overall heat transfer coefficient at the evaporator, $W/m^2{\cdot}K$
ΔT_{ML}	logarithmic mean temperature difference at the evaporator, K

Greek letters

α	azimuth angle
β	cosine angle effect
θ	elevation angle
η_{CSP}	global efficiency of the solar field
η_{des}	overall conversion efficiency of the desalination unit
η_{opt}	optical efficiency of the solar field
ρ	reflectivity of the mirror coating
ρ_{fw}	density of the fresh water, kg/m^3

On large scale, Multi Stage Flash (MSF), Multiple-Effect Distillation (MED), Mechanical Vapor Compression (MVC), Thermal Vapor Compression (TVC) and Reverse Osmosis (RO) are the main desalination technologies adopted with the latter accounting for about 63% [4]. Despite the higher energy consumption, in case of high saline water or strongly varying feed water quality (salinity, silt or organic compounds content), distillation proves to be one of the best and the most economical method for fresh water production [5].

With respect to the small scale, research and development activities on thermal desalination plant are rather limited. Sen et al. reported in three successive papers [6–8] the design, the fabrication and the performance analysis of a MED plant with a fresh water production of few cubic meters per day. Similarly, Salimi and Amidpour [9] numerically investigated the benefit of recovering the thermal output of an internal combustion engine with a MED plant. The model proved a very interesting potential with a daily fresh water production ranging from 4.38 m^3 to 26.78 m^3 increasing the engine load from 40% to 100%. However, all these plants can treat cubic meters of water per day. At lower scale, He et al. [10] investigated the potential of waste heat recovery for fresh water production using humidification dehumidification technology at low top temperatures. The same authors [11] conducted a parametric analysis to evaluate the effect of different operation pressures in terms of heat capacity ratio and gain output ratio of the system. With respect to this technology, Zubair et al. [12] firstly designed and then optimized a model of a solar energy driven humidification-dehumidification (HDH) desalination system in order to evaluate the performance of such a system at different locations in Saudi Arabia. In addition, Chen et al. [13] experimentally and numerically investigated the feasibility of a spray-assisted low-temperature desalination system able to operate under low-pressure conditions compared to HDH. The system was coupled with a 7.6 m^2 flat plate solar collector and was able to provide fresh water supply of 30 L per day under Singapore's climatic conditions.

Using solar energy for seawater desalination purposes indeed is considered one of the prospective solutions [14]. Regions with stress or lack of water are usually regions with high solar radiation; therefore, these locations are promising for the production of drinking water with solar desalination technologies at affordable costs. Most of the research activities on small-scale solar desalination plants focused on solar stills [15]. For example, Al-harahsheh et al. [16] experimentally tested the performance of a solar still having phase change material (PCM) and connected to an external solar collector finding that the improved solar still is capable of producing 4.3 L/day·m^2, of which about 40% produced after sunset. El-Sebaii and El-Naggar [17] experimentally and numerically analysed the performance of a finned basin solar still made of different materials and carried out the related cost analysis of the fresh water produced. On the contrary, Mahkamov et al. [18] developed and tested a small-scale water desalination plant consisting in a combination of a heat pipe evacuated tube solar collector and a fluid piston converter. The experimental analysis found that the dynamic plant productivity was 1–4% higher than the static one and the liquid piston was able to provide lifting of saline water.

However, in order to achieve higher power generation concentrated solar power (CSP) technologies are adopted. The CSP technology allows to concentrate sunlight from a large area onto a small area using optical devices like lenses or mirrors. The concentrated light is then collected using a solar receiver and converted 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) [19].

Nowadays CSP plants are usually large scale solar farms having a total thermal power ranging from few MWs to over 250 MW [20]. However, an increasing interest exists in medium- and small-scale plants due to their higher flexibility and lower capital costs. In addition, the optical efficiency of a compact concentrator can be kept high thanks to the small ratio of the focal point's height to the distance of the heliostat. However, in scaling down tracking devices need special efforts to be low cost and reliable.

With the current development of commercial CSP technologies, their coupling with desalination plants can tackle the problems of power and water demand and reduce the cost against the independent production. To this purpose, Palenzuela et al. [21] evaluated different CSP + MED configurations using steam from the power plant as thermal energy source for the desalination process and compared them with a CSP + RO plant. The results of the analysis have shown that, under certain operating conditions, i.e. when dry cooling or once-through are used as cooling system of the power plant, low temperature MED or low temperature MED + TVC systems can be more efficient than CSP + RO. In another work, the same authors [22] carried out a