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Techno-economic assessment of thermal energy storage solutions for a 1 MWe CSP-ORC power plant

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ABSTRACT

Organic Rankine Cycle (ORC) have principally been used in the past couple of decades to recover medium grade heat from sources such as geothermal, biomass and the exhaust of a realm of different industrial processes (waste heat recovery). In the past few years, this power generation technology has also been proposed in concentrating solar thermal power applications, aiming to exploit its features in intermediate temperature systems (low water consumption, water-free operation, scalability). These inherent features are best exploited if coupled with thermal energy storage systems to enable good performance in spite of the intermittent energy supply and also to increase the average load factor. To achieve these objectives though, a proper storage system tailored to the heat profile captured by the solar collector and to the characteristics of the power cycle must be identified.

This paper discusses the cited design criteria and presents an analysis aimed at identifying the potential storage solutions to be implemented into a Concentrated Solar Power (CSP) plant for electricity generation operating at temperatures between (170 °C) and (300 °C). The system so developed will be integrated in the 1 MWe CSP-ORC facility based on Fresnel technology that is currently under construction at Iresen's premises in Benguerir, Morocco. Detailed transient models of performance of two-tank and thermocline storage systems are presented. The annual simulations carried out reveal that thermocline solutions are globally more attractive, since they exhibit similar thermal performance but at a much lower (30% lower) cost.

1. Introduction

A recent report released by Greenpeace in collaboration with the German Aerospace Centre (DLR) claims that "there are no major economic or technical barriers to moving towards 100% renewable energy by 2050" (Teske, 2015). The same statement was made some years ago (2011) by the World Wide Fund for Nature (WWF) in collaboration with ECOFYS and the Office for Metropolitan Architecture (OMA): "it is technically possible to achieve almost 100 per cent renewable energy sources within the next four decades, even if the transition will present significant challenges" (Singer and Denruyter, 2011). More recently (April 2016), researchers at Stanford University published a similar report in The Solutions Project's website, claiming that there are 139 countries in the world ready to become 100% renewable by 2050. According to this research, the final scenario would rely mostly on photovoltaics (54%) and wind (32%) but Concentrating Solar Power would contribute with 7.5% of the total energy production (Jacobson et al., 2016).

It is thus clear that, regardless of whether or not they will achieve 100% share, renewable energies are set to form the backbone of the power generation system in two or three decades. Nevertheless, to this end, it is mandatory that a number of technical challenges be successfully tackled, mainly in the field of energy storage and flexibility. In effect, if the cited report from Stanford is true, three quarters of the power produced in 2050 will come from non-dispatchable technologies (wind and photovoltaic), meaning technologies that are not able to secure a certain power

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Abbreviations: ϵ-NTU, Number of Transfer Units method; ACC, Air Cooled Condenser; CFD, Computational Fluid Dynamics; CSP, Concentrated Solar Power; HTF, Heat Transfer Fluid; IAM, Incidence Angle Modifiers; LCOE, Levelised Cost of Electricity; ORC, Organic Rankine Cycle; TES, Thermal Energy Storage.

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Nomenclature

C_p	specific heat [J/kg K]
$\dot{m}$	mass flow [kg/s]
$\dot{Q}_{conv}$	convective heat transfer [W]
$\dot{Q}_{rad}$	radiative heat transfer [W]
$\dot{Q}_{tot}$	two-tank net heat flux [W]
ϵ	void fraction [–]
ϵ_i	emissivity of surface i [–]
η_{ORC}	ORC solar to electricity efficiency [–]
$\eta_{SF,0}$	solar field reference optical efficiency [–]
η_{SF}	solar field efficiency [–]
μ	dynamic viscosity [N s/m^2]
ρ	density [kg/m^3]
σ	Stefan-Boltzmann constant [W/m^2 K^4]
θ_l	longitudinal incidence angle [°]
θ_t	transversal incidence angle [°]
$\vec{u}$	velocity vector [m/s]
A	area [m^2]
A_{sf}	solar field aperture area [m^2]
d_p	diameter of the filler particles [m]
DNI	direct normal radiation [W/m^2]
e	layer thickness [m]
$F_{i\to j}$	shape factor between surfaces i and j [–]
Gr	Grashof number [–]
h_r	convective heat transfer coefficient [W/m^2 K]
h_r	radiative heat transfer coefficient [W/m^2 K]
h_v	intersticial heat transfer coefficient [W/m^3 K]
k	thermal conductivity [W/m K]
k_c	choke constant [–]
k_{eff}	effective thermal conductivity [W/m K]
Nu	Nusselt number [–]
p	pressure [kPa]
Pr	Prandtl number [–]
s	turbulent-laminar transition coefficient [–]
v	specific volume [m^3/kg]
v_m	mean velocity [m/s]
E	energy [MW h]
h	enthalpy [J/kg]
U	internal energy [J]

production one-day ahead of the demand curve nor are they able to produce power at a time when the renewable resource is not available. In this scenario, Concentrating Solar Power can play a much more relevant role than deduced from its 7.5% share, thanks to its demonstrated capability to produce dispatchable solar electricity round the clock (Relloso and García, 2015).

Despite the previous statement though, the truth is that the price of renewable electricity is strongly dependent upon the technology employed to produce it. Whilst wind power and photovoltaics are cost-effective in direct competition against standard fossil fuel technologies (7.5 c€/kWh and 10 c€/kWh for wind and PV vs. 4–10 c€/kWh for fossil fuels) (Kost et al., 2013), Solar Thermal Electricity still remains at a very high production cost (in the order of 20 c€/kWh) (Salvatore, 2013). Moreover, for the former, the quoted prices increase by some 25–50% when applied to small installations for which no economies of scale apply (Kost et al., 2013).

This sensitivity to size and dispatchability in the 1–10 MW range has been envisaged by some researcher as a critical market niche where there is room for cost-effective solar thermal technologies with low installation costs and incorporating thermal energy storage. In fact, this new concept of ‘getting bigger by going smaller’ could help to achieve the aforecited 100% renewable target and, in a shorter term, solve the problems stemming from poor infrastructures in developing countries (Skumanich, 2011).

Amongst the different alternatives to generate electricity in this output range, Organic Rankine Cycles (ORC) are considered a very good candidate thanks to their capability to achieve high efficiencies at fairly low temperatures. ORC power systems make use of an organic working fluid with high molar weight, flowing in a cycle whose peak temperatures range between 250 and 350 °C. These low operating temperatures make the technology suitable for other applications like geothermal, biomass or waste heat recovery facilities (Drescher and Brüggemann, 2007) and, for the case of CSP, they enable a substantial cost reduction in the solar field which is, by large, the dominant cost driver (Casati et al., 2013). This cost reduction comes from the lower temperature heat transfer fluids ($T_{max} < 300$ °C), as opposed to those employed in state-of-the-art steam turbine power plants ($T_{max} \approx 400$ °C), and from the possibility to use linear Frenel collectors in lieu of the more expensive parabolic troughs or tower-heliostat technologies (Cocco and Serra, 2015; Cau and Cocco, 2014). For the cited reasons, Organic Rankine Cycles are preferred to steam cycles in small scale solar thermal applications (Casati et al., 2013).

The Research Institute for Solar Energy and New Energies (IRESEN) is currently supervising the construction of a 1 MWe CSP plant for power generation (Solar Thermal Electricity) based on linear Fresnel collectors in the solar field and Organic Rankine Cycle technology in the power block. The construction site, near Benguerir (Morocco), has a very high availability of solar energy thanks to which the plant is expected to produce about 1.5 GWh of electricity. The original design does not incorporate Thermal Energy Storage (TES) but IRESEN is currently evaluating different technologies to identify the most cost-effective solution. This research work presents such analysis where several candidate technologies and integration layouts are modelled in order to assess the dynamic performance of the overall plant including solar field, power block and thermal energy storage system. Some preliminary results were already presented in Sánchez et al. (2015) for four different TES options with either one (thermocline) or two (hot/cold) tanks and with direct or indirect integration. An extension of it is presented in this paper where upgraded models are described in detail and daily simulations are performed. Moreover, in order to better assess which the most interesting technology is, annual simulations with real meteorological data have also been performed. This feature allows to better describe the TES performance and to carry out a more accurate economic assessment.

2. Model description

2.1. Power block

The core subsystem in charge of the heat to work conversion is a 1 MWe Organic Rankine Cycle (ORC) operating on superheated cyclopentane (C_4H_{10}). Given that cyclopentane is a dry fluid (i.e., the saturated vapour line in an h-s diagram has positive slope), the exhaust vapour from the turbine is also in the superheated region, enabling the adoption of a recuperative layout to increase the overall efficiency of the cycle. The turbine is of the radial