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Performance analysis of a micro gas turbine and solar dish integrated system under different solar-only and hybrid operating conditions

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Abstract

A hybrid energy system comprising a parabolic dish solar energy concentrator (Solar Dish) and a micro gas turbine is investigated in the study. A thermodynamic model of the system is presented, able to simulate both on-design and off-design performance of the system and accounting for the main technical aspects of the concentrator, receiver and gas turbine engine. Then, simulations are performed for various system sizes and operating strategies, with and without supplementary firing and for a reference location (Seville, Spain), yielding solar-to-electric power conversion efficiencies between 16.78% and 18.35% (rated conditions), depending on size. Annual performances result in a capacity factor of about 29% (2540 full operating hours) in solar only operation and annual average efficiency at 95% of the nominal value.

The main results indicate that moderate supplementary firing is interesting for it increases the average efficiency of the system and the annual yield, whilst still keeping the carbon footprint within reasonable values. Nevertheless, as heavy fossil fuel firing is adopted, the system becomes less competitive against conventional, standard distributed generation power systems either for natural gas or diesel fuel. Whilst these trends were somehow to be expected, the interest of this paper is to provide the reader with a fundamental analysis from which a technical and economic analysis can be performed, aimed at identifying the most leveraged solar share (i.e., fuel utilisation).

Keywords: CSP technology; Solar dish; Micro gas turbine; Dish-mGT integration

1. Introduction

Solar power generators are basically divided in two categories depending on whether or not the production of electricity relies on a power cycle (such as Stirling, Rankine or Brayton cycles): photovoltaic (PV) and concentrated solar power (CSP/STE) systems. Amongst the latter, multiple solutions can be implemented to collect and concentrate solar energy. In increasing concentrating capacity, the following are mature technologies for this purpose: linear collectors employing parabolic trough or Fresnel technologies, heliostats for large central receiver systems and parabolic (dish) collectors (Pavlović et al., 2012). These technologies can also be combined with other energy sources like non-solar renewable energies and/or fossil fuel systems, yielding the so-called hybrid systems which enable the simultaneous exploitation of "green" resources in conventional high performing energy systems such as gas

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Nomenclature

α	absorptivity
$\dot{m}$	mass flow rate
η_{is}	isentropic efficiency
γ	ratio of specific heats
κ	pressure drop coefficient
μ_f	weight carbon content of fuel
ϕ	non-dimensional parameter of mass flow rate, shaft speed and pressure ratio in turbomachinery
ρ	density
σ	Stefan–Boltzman constant
τ	transmissivity
Θ	angle between receiver surface and horizon
ε	emissivity
ϱ	reflectivity
ξ_{rcp}	recuperator effectiveness
A	area
C_f	capacity factor
F_{CO_2}	specific carbon dioxide emissions
F_{fuel}	fuel share
I_b	heat flux on surface
k_{cv}	convective heat transfer coefficient
Q	heat power
q_{in}	specific radiative energy input
Q_w	incident power
r_c	compressor pressure ratio
r_e	expander pressure ratio
T_{amb}	ambient temperature
CapEx	Capital Expenditures
CSP	concentrated solar power
DNI	direct normal irradiance
E	annual energy
h	enthalpy
LHV	low heating value
$LMTD$	logarithmic mean temperature difference
mGT	micro gas turbine
N	shaft speed
O&M	operation and maintenance
OpEx	operational expenditures
P	power
p	pressure
rcv	receiver
s	entropy
STE	solar thermal electricity
T	temperature
UA	global heat transfer coefficient
W	specific work

turbines (GT) and others (e.g. gas and steam combined cycle power plants) (Franchini et al., 2013).

Gas turbines operated partly or entirely on solar energy have already been investigated in the past by several authors, both for their thermodynamic potential (Barigozzi et al., 2012) and for the technical challenges posed by the necessary modifications to enable the addition of solar power (Fisher et al., 2014). Moreover, there are practical implementations which have demonstrated the technology at a representative power level, ~5 MWe, as it is the case of the EU-funded project SOLUGAS. In this project, a Solar Mercury 50 engine is located atop a tower where it is supplied with concentrated energy from a field of 69 heliostats. This solar heat input rises the temperature of combustion air up to some 800 °C, which is further increased to 1150 °C by merely burning natural gas in a standard gas turbine combustor (Quero et al., 2014). The experience so far confirms the feasibility of the system and its capacity to operate under variable insolation.

At a smaller scale, very small (micro) gas turbines have already been explored as an alternative to Stirling engines integrated into dish-type parabolic collectors, either using turbocharger technology (Six and Elkins, 1981; Gallup and Kesseli, 1994; Kesseli and Wells, 1989) or with dedicated engines (Dickey, 2011). This is so because despite the apparent advantages of Stirling engines over gas turbines for dish applications, the truth is that dish-Stirling technologies have not been fully deployed to the market yet (Stine and Harrigan, 1985; Mancini et al., 2003) and, accordingly, gas turbines are still envisaged as an effective and cost competitive alternative to volumetric engines (Various, 2013). Nevertheless, whilst it is widely acknowledged that collector and tracking system are mature technologies, the scientific and industrial communities agree that the micro gas turbine and, most importantly, the solar receiver are not. The work by DLR (Germany) in the latter field during the nineteen nineties (Bauer et al., 1994; Buck et al., 1996; Heller et al., 1994) put forward a number of issues that still pose major engineering challenges; this is confirmed by more recent reports on the topic, for instance (Wang et al., 2015; Hischier et al., 2012).

Based on this vision, the number of research activities aimed at developing the technology has increased in recent years, putting emphasis on the development of one particular aspect of the system: optimisation of a large dish, tubular receiver and expander for compressed air applications (LLC, 2011), optimisation of a tubular receiver for dish-turbocharger integration (Le Roux et al., 2012), simulation of the performance of an heliostat field, volumetric receiver and micro gas turbine (Aichmayer et al., 2013), optimisation of a small parabolic concentrator (Lanchi et al., 2015), modelling and testing of a pressurised receiver (Hischier et al., 2012), simulation of impinging refrigeration to volumetric receiver (Wang et al., 2015), design of a micro gas turbine for solar dish applications (Ragnolo et al., 2015).

Most of the earlier work focuses on the optimisation and evaluation of single components of such systems,