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Hybrid solar power system versus photovoltaic plant: A comparative analysis through a life cycle approach

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ABSTRACT

The sun is considered to be one of the most environmentally sound sources of clean and renewable energy. Nevertheless, new hybrid solar plants - combining solar power with another source of energy - have never been compared to traditional solar technologies. Therefore, the aim of this work is to compare the potential environmental impact of a 100 kWp photovoltaic plant (PV) with a 100 kW hybrid solar-gas turbine system (SHGT) using a life cycle assessment methodology. To the best of our knowledge, this type of comparison is the first of its kind. The analysis is performed considering three different scenarios for the SHGT. Additionally, a deep sensitivity analysis is undertaken, focusing on those parameters that mostly influence the outcomes. The results highlight that, using the currently available technology, PV resulted to be the best environmental choice, with greenhouse gas (GHG) emission of 0.043 kg CO_{2eq}/kWh. SHGT plant emissions resulted to be higher, equal to 0.236 kg CO_{2eq}/kWh when running at nominal power 12 h/day, mainly due to the fuel contribution. However, improvements in receiver technology could make it possible to reach higher receiver outlet temperatures and consequently save fuel, reducing the overall environmental impact. Moreover, replacing the natural gas used as turbine running fuel with solar radiation leads to a reduction in GHG emissions, which become comparable to PV plant gases.
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1. Introduction

The energy production sector is considered to be the main contributor to the human release of greenhouse gases (GHG), particularly CO_2, into the atmosphere, so it is clear that intervention in the energy sector must play a significant role if efforts to reduce emissions are to be successful [1,2]. A smooth energy transition needs fast development of alternative energy sources to compensate the expected deficit of fossil energy due to hydrocarbon depletion [3,4]. The utilization of renewable energy resources can make energy use clean as well as sustainable. Renewable technologies are becoming ever more cost competitive in a number of countries and conditions, but incentives are still necessary to support their deployment in many situations. Giving an overview of the different forms of renewable energy sources, solar energy is presented as an excellent candidate due to its availability [5].

The amount of energy received from the sun in just one day can theoretically satisfy the world energy demand for more than 20 years [6]. Bearing in mind this huge potential, it appears clear that, if used properly, solar radiation intercepted by Earth would be sufficient to meet global energy demand [7]. Current literature offers different studies analyzing the sustainability of photovoltaic plants [8–10]. However, other solar technologies are now mature, and their environmental impact should be assessed, along with the possibility to operate in hybrid mode because the problem of solar energy dispatchability deserves to be investigated more thoroughly.

Solar energy is usually converted in the field of energy systems in two ways:

- exploiting the photovoltaic effect, which directly converts solar energy into electric power, according to the principle of photoelectric effect;

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- exploiting solar thermal power in conventional energy systems for heating and electricity production (Rankine Cycles, Brayton cycles) with or without the auxiliary inputs of fossil boilers.

Photovoltaic panels (PV) can be installed in areas with good irradiation without specific constraint, as they exploit light for conversion into electricity. PV efficiency is related to the type of semiconductor material from which the cells are manufactured and starts from 7% for old models to a maximum of 40% for prototypes under development [11].

Concentrated Solar Power (CSP) technologies are based on the concept of concentrating solar radiation, by using mirrors or lenses, to use the sun as a heat source for electricity generation within conventional power cycles using steam turbines, gas turbines or Stirling engines. CSP systems currently exist in different forms (e.g. Parabolic trough, Linear Fresnel collector, Parabolic dish, Solar power tower), producing different peak temperatures depending on whether two- or three-dimension concentration is performed.

In addition, the power cycle portion of nearly all CSP plants can be operated with fossil fuel combustion as well as solar heat. This hybridization increases the value of CSP technology by enhancing the effective use of the power block. While still providing clean solar energy during periods of high solar radiation, the CSP plants can also provide dispatchable power at night and during periods of low solar irradiance.

A similar improvement in availability and dispatchability can be achieved using solar heat alone when CSP is integrated with thermal energy storage (TES). TES integration allows excess solar energy harnessed during the daytime to be stored and used during periods of low irradiance, e.g. cloudy periods or night time. The capability to schedule solar power production is a remarkable advantage compared to other solar and wind power technologies.

CSP can be readily integrated with any traditional combustion power cycle but is most commonly applied to steam power plants utilizing a Rankine cycle with one or two pressure levels. In such systems, thermal energy storage acts as a thermal reserve in periods with low solar irradiation.

In an alternative configuration, a hybrid gas turbine-CSP system, the solar input pre-heats pressurized air prior to the gas turbine combustion chamber, Fig. 1.

Ideally, a gas turbine cycle would operate with only thermal energy captured from the sun. However, since state of the art large thermal capacity solar collectors can provide heat at maximum 800 °C, significantly lower than the 1400 °C typical of modern gas turbines, an additional heat source is needed. The improved gas turbine cycle efficiency at these higher operating temperatures actually allows additional solar energy to be converted into electricity.

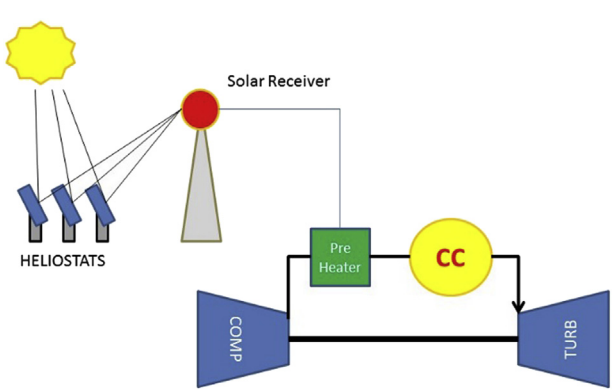

Fig. 1. Graphic representation of a Hybrid gas turbine-CSP system.

Power towers can potentially achieve very high operating temperatures, over 1000 °C, producing hot air for gas turbine operation. A Solar Hybrid Gas Turbine (SHGT) can enhance the conversion efficiency of the solar thermal cycle to over 40% exploiting Brayton cycle efficiency and gas turbine polytropic efficiency, which is higher than that of steam turbines. This conversion efficiency value, remarkable for solar energy conversion, can also strongly reduce water consumption compared to the CSP Rankine cycle. This reduction is further enhanced by the use of air as working fluid, instead of water.

The proposed technology is compatible with the solar tower CSP power plant.

A benchmark analysis highlights that this kind of hybridized gas turbine enables the production of dispatchable energy by the solar plant thanks to assistance by natural gas and the integration of high-temperature thermal storage.

Nevertheless, thanks to its specific characteristics and to the high CAPEX (Capital Expenditures) of heliostats, solar tower, and receiver, CSP technology is usually considered suitable for large-scale applications [12]. Moreover, there is an increasing interest in the field of distributed generation due to their capacity to become polygenerative hubs thanks to the potential exploitation of mGT waste heat for thermal application.

In power range <1 MW, actual ORC, and steam CSP plant are currently the most common solutions (both with very low turbomachinery efficiency). Besides, CSP systems hardly could reach success in the 20 kW–100 kW electrical output power range, except for micro-size energy units like Stirling engines (1–20 kW).

Anyway, the demand for this type of power generation is still high due to its small footprint per kW of energy produced, its extended lifetime if compared with the PV plant, its ability to be distributed in small kW increments to meet site demand and space, its relatively high electrical efficiency and its projected low cost per kW of generated electricity [13]. SHGT technology could fill this gap as hybrid plants can be a promising alternative also on a small scale [14–16]. The first commercially available SHGT of this type has been provided by the Israelian AORA Solar company, while the TES integrated cycle is provided by the US 24/7 Solar company.

In order to compare different technologies from an environmental point of view, a comprehensive approach is needed in order to determine whether reducing environmental impact in one area may result in an increase in another. In order to do so, scientific tools such as life cycle assessment (LCA) could be used. LCA, a well-known methodology to evaluate the environmental burdens directly or indirectly created by-products, goods, and services, is widely used also to evaluate the environmental impacts caused by power generation systems [17]. Solar technologies such as CSP [18–20] and PV [21–23] have been widely investigated through LCA studies, providing crucial information for a better understanding of how these technologies may reduce their environmental footprint. Literature shows better environmental performances of PV, if compared to CSP technology, in particular for small plant applications [24]. On the contrary, there is a lack of knowledge about SHGT environmental burdens and emissions. Therefore, the goal of the paper is to compare small-scale PV with small-scale SHGT technology through a life cycle assessment, in order to determine the potential environmental impacts of different solar power technologies. This paper, being the first of its kind, aims to provide useful information on SHGT technology reliability, field of use and improvement potential.

2. Methodology

Life cycle assessment (LCA) is a quantitative tool that can help to implement a life cycle thinking approach. An LCA facilitates the

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