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Optimal design of a hybrid CSP-PV plant for achieving the full dispatchability of solar energy power plants

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ABSTRACT

With the aim of providing fully dispatchable power using only solar energy, this paper focuses on a hybrid power generation system based on Concentrating Solar Power (CSP) and Photovoltaic (PV) plants. In particular, the CSP section is based on linear Fresnel collectors using thermal oil as heat transfer fluid, a two-tank direct TES system and an Organic Rankine Cycle (ORC) power plant. In the PV section, the PV array is coupled with a battery bank for electrochemical storage.

The study evaluates the optimal design parameters (solar field area, TES capacity and ORC nominal power for the CSP section, nominal power of the PV array and battery capacity for the PV section) that minimize the energy production cost of the hybrid CSP-PV plant while the plant is constrained to follow a power output curve characterized by a constant power level. Moreover, to assess the influence of meteorological conditions, the study considers two different locations: Ottana (Italy) and Ouarzazate (Morocco).

The results demonstrate that hybridization of PV and CSP technologies becomes highly cost-effective if a constant power output is required for daily time periods longer than about 16 h, when the distinguishing feature of CSP plants of decoupling power generation from sunlight is effectively exploited, independently of the location under study. On the contrary, for production periods shorter than 8 h, the use of a PV system coupled with a proper battery bank is the most cost-effective solution for both locations evaluated. Solar energy availability and unmet load fraction remarkably influence the hybrid plant design, especially for load duration periods in the range between 8 and 16 h/day. As expected, due to the lower amount of available solar energy, the hybrid solar plant located in Ottana needs larger sizes of both CSP solar field and PV arrays than the same plant located in Ouarzazate resulting in higher energy production costs.

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1. Introduction

The contribution of Renewable Energy Sources (RES) to the global energy mix is steadily increasing. Worldwide, RES power capacity has grown by about 85% during the last 10 years with about 30% of the overall installed power capacity (IRENA, 2015). Over 1400 GW of new wind turbines (WT) and more than 1000 GW of new photovoltaic (PV) power plants is expected to be installed by 2040 (WEO, 2014).

However, owing to their intermittent and variable nature, the large penetration of PV and WT plants into electrical grids can cause oscillations in the power system's voltage and frequency (Karimi et al., 2016; Moradzadeh et al., 2015; Nguyen et al., 2016). Another important issue is represented by the frequent mismatch between PV and WT energy production and load demand. In fact, during periods of high wind and solar energy availability, the share of energy supplied by these variable sources may exceed grid limits, and a curtailment of their energy production may be required. Therefore, an economic limit on the penetration of such "intermittent" renewable energy sources occurs depending on grid flexibility (Denholm and Hand, 2011). The latter can be improved by a more intensive use of gas turbines and internal combustion engines, by the introduction of suitable energy storage systems or by the promotion of integrated demand-side management strategies (Huber et al., 2014). An important option for improving both grid flexibility and solar energy penetration is the development of Concentrating Solar Power (CSP) plants integrated with Thermal Energy Storage (TES) systems (Denholm and Mehos, 2014). In CSP systems, solar radiation is concentrated by mirrors along a receiver tube where the Heat Transfer Fluid (HTF) is heated. The HTF is subsequently involved in a thermodynamic cycle that

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Nomenclature

Symbols

A	area (m^2)
AC	annual cost (€)
E	energy (J or kW h)
GI	global irradiance (W/m^2)
IC	initial cost (€)
P	electric power (W)
SOC	state-of-charge (–)
T	temperature (°C)
V	volume (m^3)
d	degradation rate (–)
η	efficiency (–)

Subscripts

A	ambient
B	battery
BC	battery during charge phase
BD	battery during discharge phase
DEF	defocusing
EX	excess
DIR	direct
IND	indirect
NOM	nominal
SF	solar field

Abbreviations

BoP	Balance Of Plant
CSP	Concentrating Solar Power
DNI	Direct Normal Irradiance (W/m^2)
HTF	Heat Transfer Fluid
IAM	Incidence Angle Modifier
LCOE	Levelized Cost Of Energy
LFC	Linear Fresnel Collector
NOCT	Nominal Operating Cell Temperature
ORC	Organic Rankine Cycle
OUA	Ouarzazate
OTT	Ottana
PV	Photovoltaic
RES	Renewable Energy Sources
TES	Thermal Energy Storage
WT	Wind Turbine

converts thermal energy to mechanical energy and subsequently to electricity through a generator.

The inclusion of a TES system allows decoupling solar energy availability from electrical production (Stekli et al., 2013). Depending on its capacity, a TES system is able to mitigate short load fluctuations and shift or extend the energy supply period (Liu et al., 2016). The operability of a CSP plant integrated with a TES system could therefore be compared to conventional and dispatchable power plants: it can deliver power on demand, adapt its output to the actual energy market situation through generation shifting (Casati et al., 2015; Vasallo and Bravo, 2016) and even continuously produce electricity during 24-h operation cycles (Dinter and Gonzalez, 2013). Furthermore, owing to the use of a conventional synchronous generator, several ancillary services for secondary frequency control or for supporting power quality in the local grid can be provided by the CSP plant (Forrester, 2013). Therefore, owing to its dispatchability features, CSP is considered a very interesting technology for future sustainable energy generation (Wagner and Rubin, 2014). Moreover, a further increase in current PV power generation capacity greatly benefits from a substantial rise in power generation from CSP plants (Pietzcker et al., 2014).

One of the main barriers to the commercial development of CSP technology is its high capital cost and therefore its high electricity production cost, especially at high and middle latitudes. Owing to the use of reflecting mirrors, CSP systems require high values of direct normal irradiance (DNI) to be cost-effective. This contrasts with solar photovoltaic technologies, which can operate even with diffuse or scattered irradiance. As stated by Desideri et al. (2013), although CSP with TES is able to deliver power 24 h per day, PV technology shows better performance in terms of both energy production and land area requirement in Italy, while it is the reverse in Egypt. However, CSP technologies are at the beginning of their commercial development and therefore their costs are expected to decrease and their performance is expected to improve as the industry scales up and operating experience improves (Hernández-Moro and Martínez-Duart, 2013).

In this framework, the integration of PV systems with CSP plants can be a very interesting option in dealing with the intermittency and variability features of solar energy and reducing energy production costs (Crespo, 2015). Several advantages have also been demonstrated in the integration of wind farms and CSP plants. Chen et al. (2015) have proposed to reduce the uncertainty of wind power generation by combining CSP plants with wind farms. Vick and Moss (2013) investigated the optimal ratio between wind farm and CSP plant rated capacities to match the utility electrical load in Texas. Pousinho et al. (2016) have proposed a day-ahead schedule harmonization between wind power plants and CSP plants with TES, demonstrating an enhancement of profit. Recently, the concept of hybrid CSP-PV power plants has gained interest by offering fully dispatchable power and achieving low energy production costs. A proper integration of photovoltaic systems, characterized by lower capital costs, and CSP systems, which are able to deliver firm and stable power during periods of low insolation, provides several advantages. With these hybrid systems, PV panels supply the required electricity mainly during sunny hours while the CSP section contributes to the demanded load primarily during evening peaks and/or for early morning requirements thanks to its storage capabilities. Therefore, hybrid CSP-PV power plants may provide more economical power generation than CSP or PV alone (Green et al., 2015). This interest has been driven by solar energy companies such as SolarReserve, and currently a hybrid PV-CSP is under development in Copiapó, (Atacama Desert, Chile) (Parrado et al., 2016). Another pilot solar power plant is under construction in Ottana (Sardinia, Italy) based on a 600 kWe CSP plant with thermal energy storage, and a 400 kWe concentrating photovoltaic (CPV) power plant (Camerada et al., 2015). Cocco et al. (2016) have demonstrated the benefits of this hybrid CSP-CPV in terms of annual energy production. In particular, the optimization of the CSP and CPV rated power leads to an effective use of the dispatch capabilities of the CSP plant while the CPV plant is fully exploited, especially during the central hours of the day. In this framework, the aim of this paper is to assess the benefits and drawbacks of a hybrid power plant based on a PV and a CSP section and designed to provide fully dispatchable electricity using only solar energy. In particular, the study of the hybrid CSP-PV solar power plant was carried out to investigate the ability of the hybrid plant to produce programmable power output curves. Obviously, the performance is strongly affected by the specific power output curve considered, which depends on many variables such as electricity demand, forecasted RES production, electricity prices, and national regulations.

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