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A hybrid CSP–CPV system for improving the dispatchability of solar power plants

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ABSTRACT

The paper aims to demonstrate the improvement of power dispatchability that can be achieved with a suitable integration of Concentrating Solar Power (CSP) and Concentrating Photovoltaic (CPV) plants to mitigate the effects of the variability and intermittency of solar energy. In particular, the CSP–CPV plant analyzed here refers to the design data of the Ottana Solar Facility, which is currently under construction in the industrial district of Ottana (Sardinia, Italy). Since it is very difficult to know the power curves that are going to be required during the operation phases of the hybrid CSP–CPV plant, the present study has been carried out by assuming a reference daily power output curve, which is simply represented by a constant power output. Moreover, two different energy management strategies, fully integrated (F-INT) and partially integrated (P-INT), are analyzed and compared. The results of this study show the advantages of using an integrated management strategy to satisfy a constant power output curve. Optimization of the CSP and CPV power share leads to an effective use of the dispatch capabilities of the CSP plant owing to the TES section, while the CPV plant is fully exploited, especially during the hours of high solar radiation. Comparison of the results achieved with the F-INT and P-INT control strategies demonstrates that the F-INT one leads to better performance both in terms of annual energy production and hours of potential time duration.

1. Introduction

Nowadays, the share of electricity produced by Renewable Energy Sources (RES) is rapidly growing, especially in OECD countries, where RES contribute to about 37% of electricity production and, among RES production, wind power accounts for 34% and solar technologies for 18% of the total [1]. However, a further expansion of wind and solar power plants is going to become more and more challenging, as one of the main drawbacks of solar and wind sources is their intermittent and variable nature, which can cause frequency misbalances and serious problems in grid management. Up to now, the fluctuations in electricity production introduced by unpredictable RES plants have been compensated by fossil power plants. In the future, different strategies will have to be deployed to increase the security and quality of power supply, such as the use of more flexible thermal power plants, the introduction of suitable energy storage systems [2] and the adoption of integrated demand-side management strategies [3].

The integration of different renewable power plants and energy storage systems is an interesting option to mitigate the effects of the variability and intermittency of RES. These integrated systems, known as Hybrid Renewable Energy Systems (HRES), are widely studied in literature [4]. Numerous studies [5–7] have pointed out the improvement in performance induced by the integration of different generation sources, especially in the case of intermittent RES generators. Moreover, HRES is a common solution for stand-alone power generation based on renewable energy technologies [8], especially where grid extensions or use of fossil fuels are too expensive [9]. Owing to the complementary nature of solar and wind sources, the most studied HRES is the solar–wind-based system [10], mainly composed by a photovoltaic array, a wind turbine and a battery bank. However, several authors have pointed out the issue of life time and cost of battery bank, since in a typical plant life cycle the batteries have to be replaced at least 3–4 times and they also require a very frequent maintenance [11].

A promising option for sustainable power generation is the integration of different solar power plants, such as photovoltaic systems (PV) and concentrating solar power (CSP) plants. To the authors' knowledge this configuration has not yet been investigated in depth and only one work has been carried out to evaluate the dispatch features of a combined CSP–PV plants [12]. On the

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Nomenclature

Symbols
- P electric power (W)
- Q thermal power (W)
- SOC state-of-charge
- T temperature (°C)
- t time (s)
- v wind speed (m/s)
- η efficiency
- τ time duration (h)

Subscripts
- AMB ambient
- B battery
- BC battery during charge phase
- BD battery during discharge phase
- C cell
- Cln cleanliness factor
- DEF defocusing
- End end loss
- IN inlet
- LOSS losses
- MAX maximum level
- MIN minimum level
- MPP maximum power point
- Opt optical
- OUT output
- P peak
- Pipe piping
- REF reference
- SF solar field
- Tube receiver tube

Acronyms
- CPV Concentration Photo Voltaic
- CSP Concentrating Solar Power
- DNI Direct Normal Irradiance (W/m^2)
- F-INT full integration strategy
- F-INT partial integration strategy
- HTF Heat Transfer Fluid
- HCPV High Concentration Photo Voltaic
- HRES Hybrid Renewable Energy Sources
- IAM Incidence Angle Modifier
- MPPT Maximum Power Point Tracking
- ORC Organic Rankine Cycle
- PV Photo Voltaic
- RES Renewable Energy Sources
- TES Thermal Energy Storage

contrary, it is instructive that some CSP companies have begun marketing hybrid projects associating PV and CSP to offer fully dispatchable power at lower costs [13]. As stated by [14], hybrid PV–CSP plant will probably operate with higher energy production costs than those of PV and CSP plants, but the hybrid combination could enable 24/7 electricity generation reaching higher capacity factors than the sole CSP and PV plants.

Generally, PV is more appropriate to high latitudes, especially in locations characterized by frequent cloudy weather, while CSP develops its highest potential in arid or semi-arid areas like those located in the Earth's "sun-belt" (latitudes 20–40°). Concentration Photovoltaic (CPV) is currently the solar technology with the highest conversion efficiency (46%) owing to the use of high concentrating optics and multi-junction solar cells [15]. In particular, High Concentration Photovoltaic (HCPV) represents the most advanced CPV concept. CPV systems are characterized by very fast response to solar radiation fluctuations and therefore, to enhance their dispatchability, CPV systems greatly benefit from coupling with electrical storage devices [16] and the preferred option is represented by batteries [17]. On the other hand, CSP systems have conversion efficiencies (ranging from 8.5% [18] to 17% [19] depending on the technology) lower than those of CPV systems and a slower dynamic response to Direct Normal Irradiation (DNI) fluctuations. Moreover, CSP systems are usually provided with a thermal energy storage (TES) section with a storage capacity of several hours at full load [20]. In this way, CSP plants are able to achieve an important time-shifting of the energy produced by the solar field, allowing electricity generation even during the evening and night hours. Another very important feature of CSP plants is represented by the use of rotating machines (turbines) in their power blocks, which provide easier frequency control. The combination of CPV and CSP could therefore be a very interesting option for reducing the intermittent and variable features of solar energy. In particular, due to the use of a combined thermal/electrical energy storage section, these hybrid CSP–CPV power plants have the ability to realize both a short-term energy storage and a massive energy time-shifting, with a significant advantage in comparison to HRES based only on electrical storage (e.g. PV–wind).

In this paper, the performance of a hybrid CSP–CPV system is investigated with reference to the design data of the Ottana Solar Facility, which is currently under construction in the industrial district of Ottana (Sardinia, Italy). The study aims to evaluate the capability of these small-scale concentrating solar power technologies to produce power with programmable and controllable power curves. Two different control strategies, characterized by a different degree of integration, are proposed and tested by varying the desired output power curves.

A daily analysis based on two typical days, one in summer and the other in winter, is first carried out to compare the dispatch capabilities adopting the two strategies. Subsequently, the analysis is extended to an annual simulation to estimate the expected plant performance.

2. System configuration

The Ottana Solar Facility is located in the center of Sardinia, Italy (40°14′44″N, 9°00′04″E) and its conceptual scheme is represented in Fig. 1.

The experimental facility has a nominal power output of 1 MWe and consists of a 600 kWe CSP plant based on Linear Fresnel Collectors using thermal oil as heat transfer fluid (HTF), a two-tank TES system (capacity of about 15 MW h), an ORC (Organic Rankine Cycle) power plant, a 400 kWe CPV power plant and an electrochemical storage system with a capacity of 430 kW h. A more detailed description of the plant can be found in [21].

Fig. 2 shows the simplified scheme of the CSP section, which includes three main sub-sections: the solar field, the TES section and the power block. The solar field is based on six lines of linear Fresnel collectors connected in parallel. The collector lines are aligned along the North–South direction and are equipped with a single-axis tracking system to follow the sun path. Depending on