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Optimization of a highly integrated CSP-PV plant

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ABSTRACT

The dispatchability of renewable power plants and the role of energy storage are gaining relevance and hybrid technologies, such as CSP-PV plants, constitute a promising solution that can effectively exploit different synergies, lowering the production costs and, at the same time, increasing the overall system dispatchability.

This work proposes a model aimed at optimizing the design and operation of highly integrated concentrated-solar - photovoltaic power plants. The integration level occurs not only via the energy management system but also through the introduction of electric heaters in the TES, physically linking the CSP and PV plants.

The entire system has been optimized developing an accurate Mixed Integer Linear Programming model. It was demonstrated, how compared to the respective separate configurations, hybrid solutions can achieve similar performances at a lower LCOE.

Keywords: CSP, PV, hybrid power plant, optimization, MILP.

NOMENCLATURE

Abbreviations	
BESS	Battery Energy Storage System
CSP	Concentrated Solar Power
EMS	Energy Management System
GCR	Ground Coverage Ratio
HTF	Heat Transfer Fluid
LCOE	Levelized Cost of Energy
LPSP	Loss of Power Supply Probability
MILP	Mixed-Integer Linear Programming
NOCT	Nominal Operating Cell Temperature
PB	Power Block
PV	Photovoltaic
RES	Renewable Energy System
SAM	System Advisor Model
TAC	Total Annual Cost
TES	Thermal Energy Storage
TMY	Typical Meteorological Year

1. INTRODUCTION

The decarbonization of the energy sector and the rapid deployment of power plants based on intermittent renewable energy sources will represent a key challenge in the next decades. Although PV and wind technologies have undergone rapid growth in the last years, intermittent electricity production represents a limit for their future development as stand-alone technologies. A promising alternative consists of combining existing RES, creating hybrid energy systems able to take advantage of joint synergies and provide more flexibility to the power grid. In particular, CSP-PV hybrid systems rely on the combination of low-cost thermal energy storage to extend the plant operation to not-sunny periods and on the cheap and relatively simple PV technology to reduce the overall plant LCOE.

Nevertheless, because of the number of variables and degrees of freedom resulting from the integration of different components, the management of such systems is more challenging and requires adequate EMS strategies. Thus, system optimization plays a key role in the achievement of good energy and economic performances of such complex plants.

In this work, a mixed-integer linear programming (MILP) approach was developed to tackle the optimization problem of a highly integrated hybrid CSP-PV plant. The present work is part of the collaboration between the Polytechnic University of Milan and ENEA,

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which for many years has been active in developing CSP-based projects in southern Italy [1][2] and, in general, Mediterranean regions.

2. SYSTEM DESCRIPTION

2.1 Hybrid system description

The hybrid plant considered in the study, represented in Fig. 1, is constituted by a PV field, a Battery Energy Storage System (BESS), a Solar Field (SF) with concentrating solar collectors, a Thermal Energy Storage (TES) and a Power Block (PB) section. The PV-BESS and the CSP plant are not only fully integrated via the EMS but also by means of electric heaters placed inside the TES, to generate additional heat with the excess of electricity production, physically linking the CSP and PV systems.

The electricity produced by the PV, after the inverter, can be fed directly into the grid, stored in the BESS, or used to power the TES electric heaters. The BESS power can be fed into the grid or used to power the TES electric heaters. All other energy flows and exchanges are regulated by means of energy balance constraints.

To the author's knowledge, there are currently only two commercial operating CSP-PV power plants, one located in Chile [3] and the other one developed in collaboration with ENEA in Sicily [1]. However, none of these plants features a high level of integration even if several studies published in the open literature investigated hybrid and technology-integrated CSP-PV solutions [4].

2.2 PV and BESS technologies

A multi-crystalline silicon technology with a fixed orientation was adopted for the PV field while a lithium-ion BESS has been considered for short-term electricity storage. Optimal design tilt and Ground Coverage Ratio (GCR) values have been determined by a sensitivity analysis, then the expected specific PV production profile for each hour of the reference year (2017) has been computed with the NOCT method [5], taking into account the effect of outside temperature and wind speed. The model for estimating the PV production was validated in SAM [6], using the same input data and similar results obtained regarding the estimation of the yearly energy produced.

2.3 CSP technology

Regarding the CSP field, a linear Fresnel technology working with molten salts as HTF and with a direct two tanks TES has been selected. The characteristics and performance of the mirror fields were evaluated in SAM and have been integrated with ad-hoc algorithms developed in Matlab [7].

In order to evaluate the production of thermal power from the mirror field, the optical and thermal losses of the collector were estimated as a function of the sun position and the irradiation conditions. The model developed uses the weather data and the sun dependent optical efficiency to estimate the thermal power losses and the specific production of thermal power; in particular, for a single SF loop, it is known (i) the loop mass flow rate, (ii) the loop outlet temperature, (iii) the loop pumping power consumption and (iv) the heat absorbed by the HTF for any hour of the year.

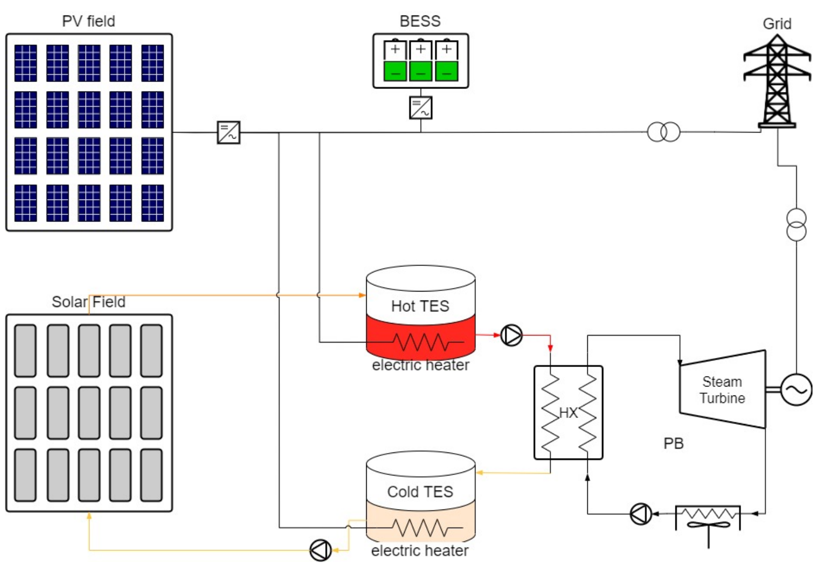


Fig. 1. CSP-PV Hybrid plant scheme

The power section of the CSP field is based on a traditional Steam Cycle, with some appropriate modifications to make this type of unit suitable to handle molten salts. A detailed model of the power block was developed inside the Thermoflex [8] simulation environment in order to estimate the power block performance in design and in off-design operating conditions. This process was repeated for different PB sizes in order to find a linear correlation between the power generated by the PB and a given load and size to be provided as operating maps to the MILP optimizer.

3. SYSTEM DESIGN AND OPERATION OPTIMIZATION

3.1 Problem statement

Given the expected hourly profiles of PV production (specific per unit of area), molten salts temperature and flow rate, the electricity demand for the whole typical year of operation, it is desired to determine the optimal values of (i) the amount of land used and its share between PV and SF technologies, (ii) the sizes of the different system components (TES, PB and BESS), (iii) the operating variables related to heat, electricity and mass flows exchanged within the plant in each hour of the expected operating year and (iv) the operational status (on/off) of the controllable units (i.e. PB). The constraints are related to total land area availability (occupied by PV and SF collectors), minimum and maximum component sizes, minimum and maximum storage levels, minimum temperature of molten salts inside the cold tank, BESS maximum charge and discharge rates, minimum and maximum PB load, part load efficiency map of the PB, start-up ramping trajectory of the PB, energy and mass balances and required levels of energy dispatch. The objective function of the problem is minimizing the Total Annual Cost (TAC) of the plant.

Due to the nonlinear part-load performance maps of the PB and the non-isothermal mixing process occurring in the TES tanks, the resulting optimization problem is a challenging Mixed-Integer Nonlinear Program (MINLP).

3.2 Problem linearization

In order to avoid solving a challenging MINLP problem, the part-load operation of the PB is represented with the convex hull formulation [9] and the strategy proposed by Yokoyama in [10] is adapted to linearize the size effects on units costs and performance. Specifically, the linearization of the size effects on PB capital cost is carried out by adopting a piecewise approximation of the investment cost as a function of the size while the input-output relationship was linearized and the power generated was expressed as a linear correlation of the PB thermal load and size.

The mixing of non-isothermal flows occurring in the TES could not be properly linearized, as the enthalpy involves the product of the continuous variables mass flow and temperature. Thus, the TES temperature cannot be tracked instant by instant but is still possible to adopt an approach based on McCormick envelopes [11] to limit the upper bound and the lower bound temperature inside the TES, with the advantage of keeping the model linear.

To decrease further the complexity of the MILP, the k-MILP clustering technique [12] was employed to reduce the expected operational year into a set of eight 72-hours periods, 6 typical and 2 extremes (periods characterized by high and low radiation, respectively).

4. RESULTS

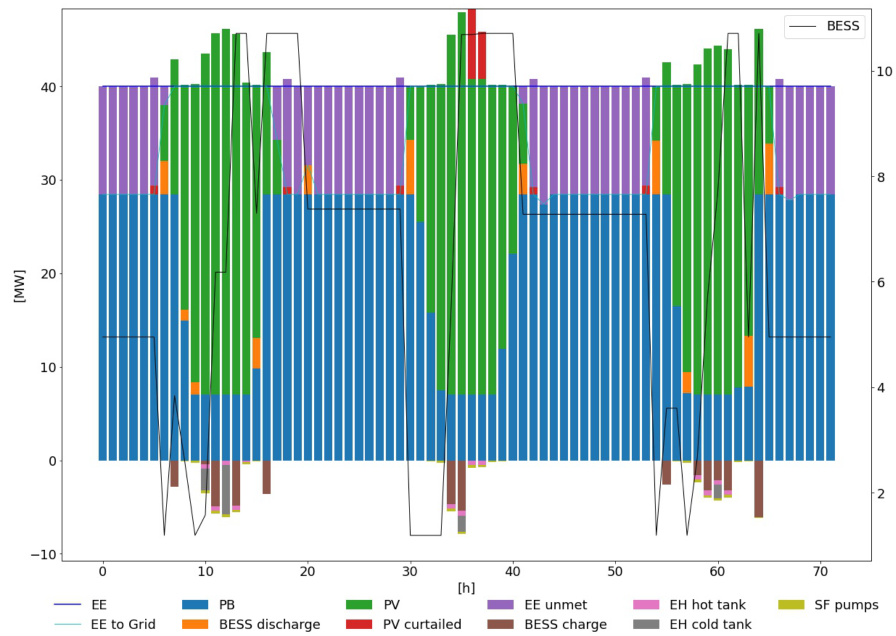
4.1 Results

Priolo (Sicily) was selected as a suitable location for the hybrid plant object of the study. The TMY file containing the weather data was provided by ENEA. It was assumed that plant has to supply a constant power demand of 40 MW, acting as a baseload.

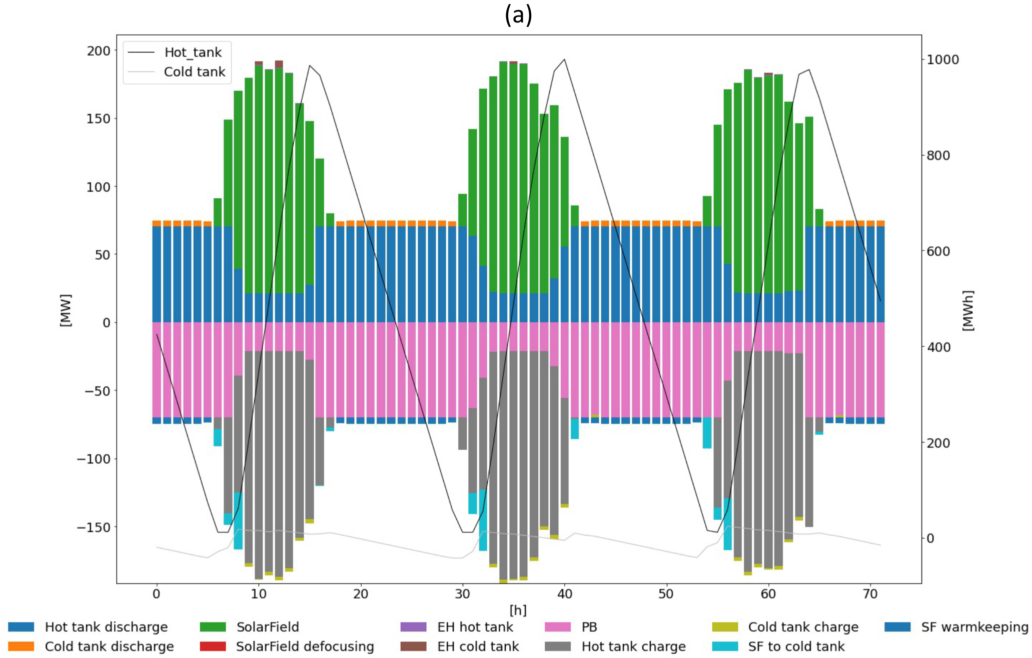
BESS size [MWh]	11.9
PB size [MW]	28.8
TES size [h]	16.8
PV size [MW]	59.3
Total surface [ha]	150.0
PV surface share [%]	47.6%
SF surface share [%]	52.4%
SF loops [#]	41
CSP solar multiple [-]	2.6

Table. 1. Hyrbid plant optimal design.

In Fig. 2, the typical plant operation in a sunny period is shown. Looking at the electricity balance in Fig. 2 (a), the electricity demand is almost entirely covered by the PV and PB. The PV in excess is mainly employed to charge the BESS, whose size is limited by the availability of extra power coming from the PV field. During the night as well, the storage level of the TES is reduced at a constant rate - see Fig. 2 (b) - to run the PB at full load and, at the same time, to keep the SF warm. During the day, the SF is used to recharge the TES and partly power the PB whose is always on and runs at reduced output during the peaks



(a)



(b)

Fig. 2. Electricity (a) and heat (b) balances in a typical period operation characterized by high solar radiation.

of production of the PV field. Tab. 1 reports the optimal design of the hybrid plant.

Then, a comparison between the performances of the hybrid plant and the respective non-hybrid solutions (i.e. stand-alone CSP and stand-alone PV-BESS) operated separately has been made. As Tab. 2 shows, in both cases, the hybrid solution achieves better performances, with the lowest LCOE. In particular, comparing the hybrid with the CSP stand-alone plant it could be possible to

Plant performances	**Hybrid**	**CSP**	**PV-BESS**
Energy produced [GWh/y]	142.4	143.5	159.5
LPSP [%]	59.3%	59.0%	54.4%
LCOE [€/MWh]	167.3	199.4	195.2

Table. 2. Techno-economic performance comparison between hybrid and non-hybrid solutions

achieve a LCOE reduction of 17% with the same levels of energy injected into the grid. The PV-BESS solution, instead, turned out to be more flexible with higher LPSP values, however, this benefit is obtained at a higher (+ 15% increase) LCOE compared to the hybrid plant.

In order to assess the benefit of physical PV-CSP integration, the optimization was repeated with and without the possibility of exchanging energy via the electric heaters considering a LPSP of 40%. The results indicate that the electric resistance allows decreasing the LCOE of approx. 2% by reducing the curtailed PV and the size of the BESS. This economic advantage is expected to increase at lower LPSP values.

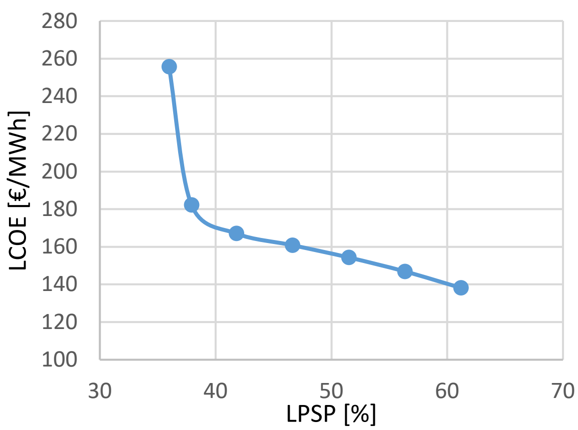


Fig. 3. LCOE vs LPSP trade-off

Finally, Fig. 3 highlights the trade-off between the plant LCOE and the yearly unmet demand fraction of electricity demand (i.e. LPSP). As more dispatchability is required by the plant (low unmet percentages), an increase in the plant component sizes will be experienced and will increase the overall cost of energy produced. The other way around, if a low dispatchability rate is tolerated, smaller values of LCOE can be reached.

4.2 Conclusions

This work investigated the design optimization of hybrid CSP-PV power plants. The optimization outcomes showed that there is no unique optimal hybrid plant solution but rather a range of interesting solutions should be explored depending on investor requirements, inventive scheme and regulatory framework. Even though the hybrid solutions offer lower LCOE and higher flexibility compared to non-hybrid CSP plants, and lower LCOE compared to PV-BESS, however a trade-off between these values should be considered.

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