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Analysis and Simulation of CSP and Hybridized Systems

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Optimization of the Design and Operation of Hybrid CSP-PV-Wind Plants

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Abstract. This work investigates potential benefits deriving from the integration of CSP plants with other renewable technologies, such as PV and Wind. An optimization tool, based on mixed-integer linear programming, is used to derive the optimal design of a hybrid plant located in the south of Italy (Sicily) with the objective of satisfying a fraction of the national-shaped, hourly variable, electrical load. A sensitivity analysis is performed to explore the Pareto front of solutions satisfying different dispatchability requirements in terms of demand coverage. As expected, increasingly oversized and expensive plant designs, characterized by high Levelized Cost of Electricity (LCOE), are necessary to satisfy larger fractions of the imposed load. Subsequently, the benefits of hybrid plants with respect to conventional standalone or partially integrated solutions are investigated: in particular, the results of this analysis clearly demonstrated that integrated CSP+PV+Wind configurations can reach the same or higher dispatchability level (i.e. 80%) at a much lower electricity cost with respect to (i) separate production (stand-alone PV, Wind and CSP) and (ii) configurations characterized by a lower level of integration (36% and 12% reduction of LCOE with respect to CSP+PV and CSP+Wind, respectively).

Keywords: Hybridization, CSP-Wind Integration, CSP-EH Integration, Optimization

1. Introduction

Concentrating Solar Power including Thermal Energy Storage (TES) allows for dispatchable power production, but its diffusion is anyhow hindered by the higher investment costs with respect to other renewable technologies [1], [2]. On the other hand, in the last decade PV and Wind have experienced amazing cost reductions and are now competitive with fossil fueled power plants [1], but provide non-dispatchable power unless expensive Battery Energy Storage systems (BESS) are used: this may become a limit for these technologies, if their fraction in the energy mix becomes significant. To overcome the drawbacks of CSP and PV technologies more and more studies are now focusing on hybrid solutions coupling PV and CSP, where an Electric Heater (EH) physically connects the two plants allowing to store excess electricity from PV in the CSP plant TES system: this solution, even if not attractive from the thermodynamic point of view, allows to obtain dispatchable electricity at lower costs. As PV panels and solar collectors located in the same area use solar radiation as energy input, their production curves are quite similar, with significant deviations only when the diffuse to direct radiation ratio becomes high. Considering a further hybridization with the inclusion of Wind Turbines (WT) in the same system can thus become very convenient, given the independence of solar and wind resources: by alternatively exploiting PV and Wind generation, complementing each other, this type of hybridization (CSP+PV+WT) has thus the potential to achieve, for the same level of dispatchability (e.g. for very high Capacity Factors) lower electricity cost. The present study expands the scope of a previous work investigating the potential of CSP and PV hybridization [3] by including the WT technology. In particular, the simultaneous optimization of the design and operation of a hybrid CSP+PV+WT plant located in Sicily is performed, showing the performances improvement that can be obtained with respect to the CSP+PV hybrid solution, both in terms of system dispatchability and electricity cost.

2. Methodology

2.1 Hybrid plant description

The system under investigation is composed of (i) a fixed-tilt PV field, (ii) a Wind farm, constituted by one or multiple WT, and (iii) a CSP plant based on Linear Fresnel Reflectors (LFR) technology with molten salts, a direct two-tank TES and a conventional Rankine Power Block (PB). The PV field and the Wind farm can store the excess electricity into the TES in form of thermal energy via an Electric Heater (EH), as shown in **Figure 1** showing a simplified representation of the hybrid plant.

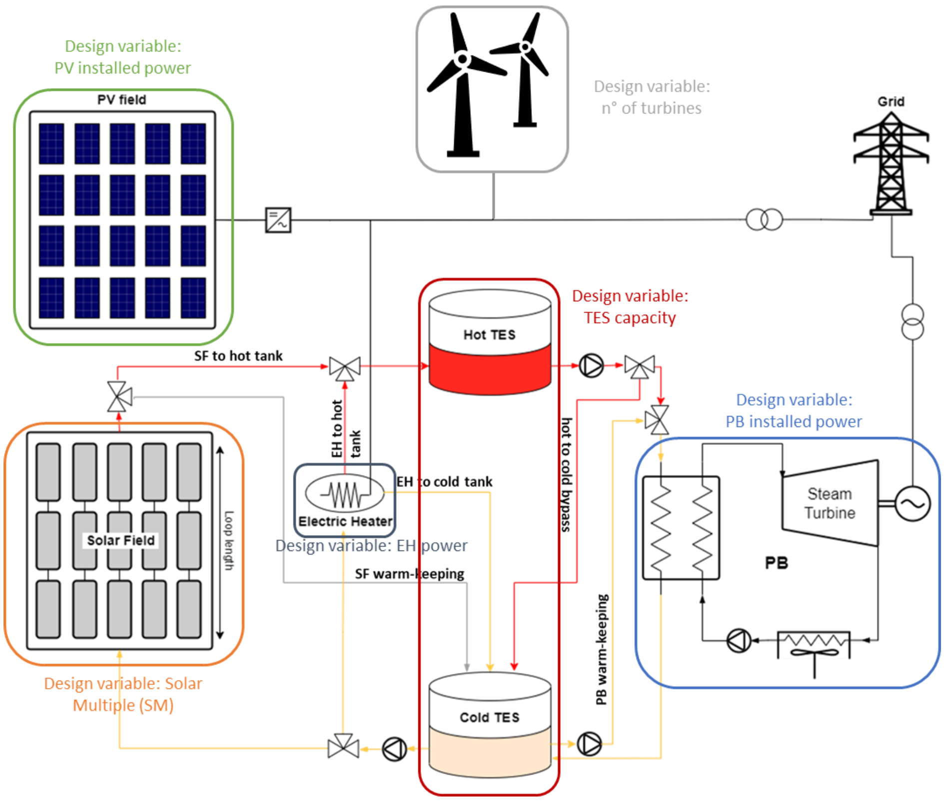

Figure 1. *Layout of the hybrid CSP+PV+Wind plant with EH*

2.2 Hybrid plant modelling

The plant design has been optimized in order to follow a variable electricity load with a peak of 50 MW and characterized by the same hourly profile of the Italian national demand curve, based on the pre-pandemic historical trend (2019 taken as reference year) [4]. Priolo Gargallo (Sicily) is selected as the ideal hybrid plant location, given its good potential in term of solar and wind energy (see Table 1). A maximum of 150 hectares of continuous land has been considered available for CSP installation. The methodological approach adopted is schematically represented in **Figure 2**.

Table 1. *Meteorological characterization of the selected case study*

Case Study	**Value**	**Units**
Location	37.13°N, 15.21°E	-
Average Ambient Temperature	17.6	°C
Annual DNI	1730	kWh/m^2-y
Annual GHI	1847	kWh/m^2-y
Average Wind Speed @ 30 m	4.5	m/s

Starting from the weather data provided by ENEA, the hourly specific electricity production of a PV field (kWh$_{el}$/m^2), the hourly specific thermal energy production of a single loop of solar collectors (kWh$_{th}$/loop) and the hourly specific electricity production per single WT generator (kWh$_{el}$/generator) have been estimated through the use of the System Advisor Model (SAM) [5], where non-linear models of the PV field, WT generator and solar field have been separately implemented. Similarly, a detailed thermodynamic model of the PB has been simulated in Thermoflex [6] to gather the operative maps describing the PB performances under different operating conditions (off-design, variable ambient temperature, etc.). Subsequently, all the time-varying profiles (i.e. ambient temperature, hourly electricity load and specific production profiles from renewables) are clustered through a clustering algorithm [7] and reduced to a set of typical operating periods used for the design optimization. Finally, the aggregated timeseries together with the techno-economic characterization of plant components (i.e. efficiencies, capital and operative cost), are fed to the Design and Operation Optimization Tool (DOOT) in order to determine the optimal hybrid plant size and performances.

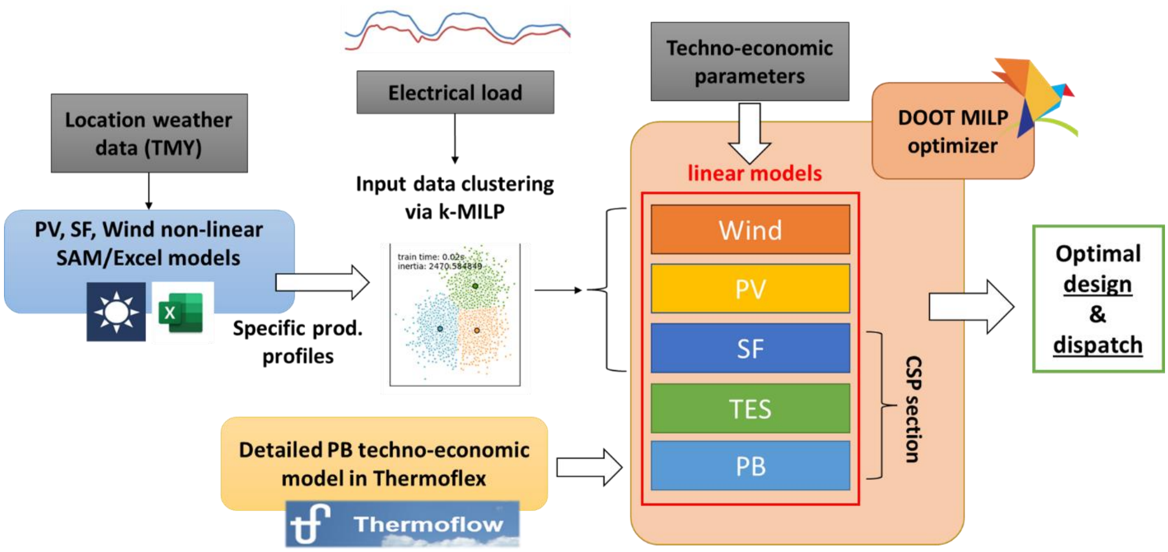

Figure 2. *Flowchart of the methodology adopted*

The optimization tool is based on a Mixed-Integer Linear Programming (MILP) algorithm, able to simultaneously optimize the design (i.e. number of SF collectors, WT, PV field and PB rated power, TES storage hours, etc.) and the operation (i.e. selecting the best dispatch strategy) of the hybrid plant taking into account a set of constraints (e.g. maximum land available, PB minimum load and part-load performances, start-up and shut-down operations, etc.) with the objective of minimizing the Total Annual Cost (TAC), computed as the sum of the annualized investment and operation costs. In addition, it is possible to specify the minimum Dispatchability Level (DL) required for the system, defined as the percentage of yearly demand covered by the plant (e.g. 60%, 70%, 80%). In the following sections, the techno-economic models of the plant components are described in detail.

2.2.1 PV model

The technology adopted for the PV field modelling is a multi-crystallin silicon module, whose specifications are reported in Table 2. Tilt and Azimuth angles have been optimized according to the selected location, together with the ground coverage ratio to maximize the PV field annual yield. Once all the tecno-economic parameters are defined, a detailed PV model is setup in SAM [5] and the expected PV production for each hour of the year ($\hat{P}_{DC,t}^{PV,spec.}$) is estimated from the weather data related to the case study location, taking into account the effect of outside temperature, wind speed, shading and all the system losses.

Table 2. *PV techno-economic characterization*

PV	Value	Units
Tilt/Azimuth angle	24/180	[°]
Ground coverage ratio	0.5	[-]
Module nominal cell efficiency	17.14	[%]
Module power temperature coefficient	-0.415	[%]
Total system losses (mismatch, electrical, wiring, nameplate)	5.5	[%]
Soiling losses	5	[%]
DC to AC power ratio	1.25	[-]
Inverter efficiency	96	[%]
PV/Inverter investment cost	714/50	[€/kW]
O&M costs	15	[€/kW-y]

From the SAM model the vector of normalized PV production per unit of installed power is obtained and this time-varying profile is used subsequently in the characterization of the PV model within the optimization algorithm. In particular, as expressed by Eq. (1), in each timestep t of the optimization horizon, the sum of the PV AC power output ($P_{out,t}^{PV}$) and the curtailed power ($P_{curt,t}^{PV}$) should be equal to the normalized PV production multiplied by the installed PV power (P_{DC}^{PV}).

$$P_{out,t}^{PV} + P_{curt,t}^{PV} = P_{DC}^{PV} \cdot \hat{P}_{DC,t}^{PV,spec.} \qquad \forall t \in T \qquad (1)$$

2.2.2 CSP model

The technology adopted in this study for the CSP modelling is based on LFR collectors with solar salts as Heat Transfer Fluid (HTF), a direct TES storage and a steam cycle for the power production section. Table 3 reports the main tecno-economic parameters assumed for the CSP plant. A procedure similar to the one adopted for the PV field has been implemented to incorporate the model of the Solar Field (SF) within the optimization problem. Starting from the weather data file, the model of SF receiver and collectors have been selected and a simplified layout of the SF has been defined in SAM. At this point it was possible to estimate the thermal power absorbed by the HTF in each hour of the year for a single loop of SF collectors at design conditions ($\hat{\dot{Q}}^{SF,spec.}_{loop,t}$).

Table 3. *CSP tecno-economic characterization*

Solar Field		**Power block**	
Desing DNI [W/m^2]	850	Net power [MW$_e$]	50
Number of mirrors per SF module	16	Maximum HTF temperature [°C]	550
Module area [m^2]	537.6	Minimum HTF temperature [°C]	290
Module width [m]	12	Steam pressure at SH/RH outlet [bar]	100/21
Optical efficiency at design conditions [%]	64.7	Condensing pressure [bar]	0.145
Receiver thermal loss at design conditions [W/m^2]	255 @ 400 °C, 730 @ 550 °C	Net cycle efficiency [%]	39-41
Solar Field/Land preparation cost [€/m^2] [2]	170/17.2	Investment cost [€/kW]	1000-1780
TES		O&M fix cost [€/kW-y]	10.8
Charge/discharge efficiency [%]	95/95	O&M var cost [€/kWh]	3.4
Investment cost [€/kWh]	27.5		
O&M fix cost [€/kWh]	0.3		
Electric heater investment cost [€/kW]	80		

Then, the thermal power produced by the SF section of the CSP plant in the optimization model can be expressed as the product between the specific power produced by the single loop and the number of loops of SF collectors (N^{SF}_{loops}), which constitutes the sizing variable related to the SF section. In Eq. (2), the overall thermal power produced by the SF is divided into actual thermal power available to charge the TES or power the PB ($\dot{Q}^{SF}_{out,t}$) and a second term which represents the thermal power wasted through SF collectors defocusing ($\dot{Q}^{SF}_{defoc,t}$).

$$\dot{Q}^{SF}_{out,t} + \dot{Q}^{SF}_{defoc,t} = N^{SF}_{loops} \cdot \hat{\dot{Q}}^{SF,spec.}_{loop,t} \qquad \forall t \in T \qquad (2)$$

The mathematical formulation describing the TES sizing and management is constituted by the standard equations widely adopted in literature for energy storage modelling and it has been already described in details in a previous work [3]. The PB model has also been taken from [3], where a detailed thermodynamic characterization of the PB steam cycle has been obtained with the help of the Thermoflex software [6]: in particular, the PB design and off-design performance under different operating conditions have been estimated (i.e. variable solar salts flow rate and ambient temperature) and they have been subsequently linearized to fit the MILP optimization problem. Here the same linearization procedure for the PB performances has been adopted.

2.2.3 WT model

For the WT generator model, a Vesta V136 [8] was considered, characterized by a rotor diameter of 136 m and a nominal capacity of 3.45 MW. This particular model was selected because its suitable for a site with medium wind conditions (i.e. wind class IECIIIA) and its rated power is comparable with the average size of wind generators in Italy [9].

Table 4. *WT generator tecno-economic characterization*

Wind turbine generator	**Value**	**Units**
WT model	V136	[-]
Hub height	132	[m]
Rotor diameter	136	[m]
Cut-in wind speed	3	[m/s]
Cut-out wind speed	22.5	[m/s]
Nominal power	3.45	[MW]
Share coefficient	0.2	[-]
Investment cost	1500	[€/kW]
O&M fix cost	10.8	[€/kW-y]
O&M var cost	3.4	[€/kWh]

The WT model, whose characteristics are reported in Table 4, has been implemented in SAM and the actual electricity production for single WT generator has been derived. Once the specific production per single generator is known ($\hat{P}_t^{WT,spec.}$), the overall production from the entire wind farm in the optimization model is computed as the number of WT installed (N^{WT}) multiplied by the hourly specific production. As done for the PV, also in this case two separate variable are necessary to distinguish the overall production into actual ($P_{out,t}^{WT}$) and curtailed quantities ($P_{curt,t}^{WT}$), as visible in Eq. (3).

$$P_{out,t}^{WT} + P_{curt,t}^{WT} = N^{WT} \cdot \hat{P}_t^{WT,spec.} \qquad \forall t \in T \qquad (3)$$

2.2.4 Problem statement and objective function

After establishing a linear model for each component involved in the plant design, the associated optimization problem can be formulated, as follows. Given:

- the normalized production of (i) thermal power from the SF and electricity production from the (ii) PV field and (iii) WT generator, (iv) the value of the ambient temperature and (v) electricity load for each hour of the year
- the tecno-economic characterization of each plant component (nominal and part-load performance, efficiencies, technical limitations, operative and investment cost, etc.)

the optimization problem aims at determining the optimal values of (i) SF Solar Multiple (SM) and (ii) PB size, (iii) the PV rated power, (iv) the number of WT and (v) the capacity of the thermal energy storage system while taking into account the optimal operating strategy of the plant along the year.

This is done taking into account several constraints characterizing the plant object of the optimization, such as minimum and maximum component sizes, energy storage evolution dynamics, PB minimum technical load, off-design performance and startup trajectories, energy balances and a minimum fraction of annual demand coverage. In particular, the constraint on the dispatchability target defines the minimum amount of energy that should be produced by the plant to cover a share of the annual electricity demand and it can be mathematically formulated as follows (Eq. (4)):

$$\sum_{t \in T} E^{el}_{unmet,t} \leq \left(1 - \widehat{DL}\right) \cdot \sum_{t \in T} \hat{E}^{el}_{load,t} \qquad (4)$$

where $E^{el}_{unmet,t}$ is a variable quantifying the amount of electricity unmet in each hour of the year, while $\widehat{DL}$ and $\hat{E}^{el}_{load,t}$ are parameters, respectively defining the DL and the hourly electricity demand. It must be noted that dispatchability requirement is not defined on a hourly basis (i.e. for each hour of the year) but the constraint it is written on yearly basis, considering integral values.

The optimization function consists of minimizing the plant TAC, expressed in Eq. (5) as the sum of annualized plant investment and operative costs.

$$OBJ = CAPEX \cdot CRF + OPEX \qquad (5)$$

where:

- CAPEX (CAPital Expenditures): the total investment cost of the system. It is given by the sum of the installation cost of the plant (Eq. (6)).
- OPEX (OPerational Expenditures): the total cost associated with the system operation. It accounts for the fix and variable O&M costs of each plant component (Eq. (7)).
- CRF (Capital Recovery Factor): a factor that estimates the annual charge for the capital recovery, as a fraction of the investment cost, computed starting from the investment interest rate and lifetime (see Eq. (8)). Assuming an interest rate of 8% and a lifetime equal to 25 year, the resulting CRF is about 10%.

$$CAPEX = C^{SF}_{inv} + C^{TES}_{inv} + C^{PB}_{inv} + C^{PV}_{inv} + C^{WT}_{inv} + C^{BESS}_{inv} \qquad (6)$$

$$OPEX = C^{SF}_{OM} + C^{TES}_{OM} + C^{PB}_{OM} + C^{PV}_{OM} + C^{WT}_{OM} + C^{BESS}_{OM} \qquad (7)$$

$$CRF = \frac{\mathrm{r}}{1 - (1 - \mathrm{r})^{-\mathrm{lifetime}}} \qquad (8)$$

2.3 Clustering

Given the complexity of the design optimization problem, which involves a large number of variables and constraints, considering the entire year as optimization horizon would require an excessive computational effort for today available commercial solvers, as the solution time increases exponentially with the number of time steps considered within the optimization problem. To reduce the timesteps included within the optimization horizon, hence the optimization problem is not formulated directly on the original profiles spanning an entire year of data but on a “typical” year representation built upon a few and wisely selected periods. For the construction of the typical year representation several methods are available in literature

[10] and most of them are based on automatic clustering techniques that allows to preserve many information contained in the original data: in particular, we adopted the k-MILP clustering algorithm [7] for the selection of the most representative periods of the year together with the ones characterized by extreme/atypical conditions (e.g. min/max PV or wind production). Each period represents a set of original periods with similar features in terms of irradiance, wind conditions, etc. and therefore the typical year can be constructed replacing the original data with those from the selected periods following the pattern provided by the clustering algorithm. A scheme of the clustering procedure is illustrated in Figure 3.

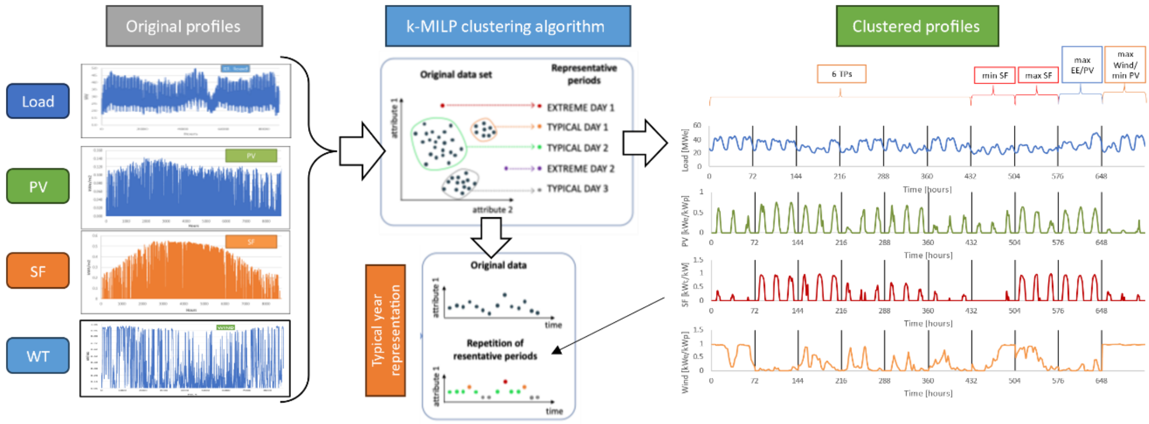

Figure 3. *Flowchart of the clustering procedure adopted*

To accurately represent the original year were necessary 6 typical periods and 4 extreme/atypical periods. Each period is constituted of 72 hours (i.e. three days length). On the right side of Figure 3 are visible the clustered profiles employed in the optimization. In particular, the extreme profiles selected include: minimum and the maximum of SF and PV production, maximum wind generation and peak of electricity demand.

3. Results

3.1 Hybrid plant optimal design assessment

The optimal plant design is largely affected by the DL required to the plant. The DL has been defined as the fraction of the annual electrical load the plant is able to satisfy (see Eq. (4)). Hence, higher dispatchability requirements result in more conservative design, as the plant must be able to meet the imposed variable load even in the most adverse conditions of the year. This trend is clearly visible in **Figure 4**, where the optimal plant design for the hybrid plant configuration and the associated LCOE value is reported for each dispatchability level. In particular, for dispatchability levels (DL) below 65% the CSP section is not even installed and only PV and Wind technologies are present in the optimal configuration: in particular, the use of the cheaper technology option, such PV, is preferred to cover the load for very low DL (15-25%) but the coupling the PV with the more capital expensive WT technology become necessary in the range 30-60%, resulting in a overall increase of the cost of electricity produced by the plant. To further meet higher dispatchability requirements, the CSP section is included in the optimal design, given its capability of storing thermal energy in the TES (both via direct SF generation and use of EH) that could be converted back to electricity when both PV and Wind generation are absent. Moreover, the PV and Wind curtailment can be strongly reduced by the addition of the TES equipped with EH, as visible in **Figure 4**. The number of TES hours and the design SF capacity (i.e. SM) increases linearly until the fraction of yearly demand met reaches the 80%. After that point, the increase of TES size does not produce any additional benefit. Instead, in the range of 85%-95% of dispatchability level, the optimal choice is to further increase the size of the PB and the capacity of the PV and Wind generation. This is done also because the hybrid plant has the possibility to exploit the EH to convert the excess

PV and Wind production into available thermal power for the TES, reducing thus renewable power wasted. This trend is confirmed by the significant increase in the EH rated power visible in **Figure 4** in the dispatchability range 85%-95%. A remarkable result is that almost all the yearly load (95%) can be covered by adopting the most conservative hybrid plant design, which achieves a LCOE of 179 €/MWh. The steep increase in the LCOE in the right side of **Figure 4**, especially above 80% of the DL, highlights how much dispatchability targets and the ability to meet a given load can affect the economic performances of the plant.

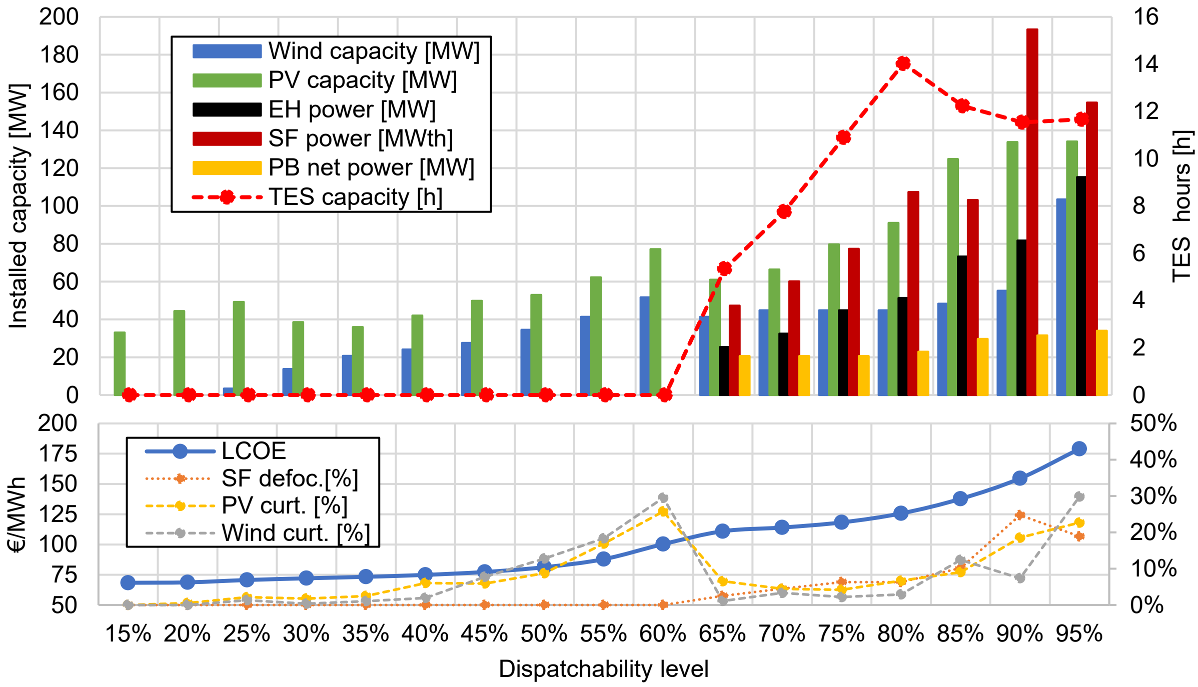

Figure 4. *Optimal hybrid plant (CSP + PV + Wind) design and corresponding value of LCOE achieved at each dispatchability level together with renewable electricity wasted by SF, PV and Wind*

The difference is considerable also in terms of plant design: the overall electricity generation capacity installed (PV+Wind+CSP) is more than three and five times, respectively for the 80% and 95% of DL, than the peak of the electrical load (50 MW) the plant is designed to cover: hence, a fully-renewable plant is considerably oversized with respect the electricity demand it will be able to provide in a dispatchable manner.

3.2 Benefits of EH physical integration

To evaluate the impact of physical EH integration, the same analysis was replicated also for a hybrid configuration without EH. In this case, the PV and Wind technology are still present in the optimal solutions but their sizes are more contained due to the absence of the possibility of converting excess electricity into thermal power via the EH. Instead, the optimal plant design generally shows larger SF sizes, specially for high DL (> 80%), with SM hitting the value of 4. However, such design also implies a large quantity of SF defocusing that could be avoided in the configuration equipped with EH. The benefits of EH integration are not only appreciable in terms of reduction of renewable energy wasted (either from the SF, Wind and PV) but looking at the plant economic performances: in correspondence of 80% DL, a LCOE reduction of 12% is achieved, with the hybrid plant with and without EH achieving a LCOE of 125.7 €/MWh and 142.6 €/MWh, respectively (see also later Figure 6).

Figure 5 shows the optimal hybrid plant scheduling during a period of three consecutive days of the year for the configuration designed according to a 80% dispatchability target. In absence of EH (Figure 5a), the renewable generation exceeding the demand is entirely lost. Conversely, the PV and Wind curtailment is significantly reduced when the EH is exploited to provide additional thermal power to the TES of the CSP system (Figure 5b). This mostly happens in the central hours of the day and the EH are mainly powered by excess of PV production. In both cases, some unmet demand (light-red bars in Figure 5) is present at the end of the third day.

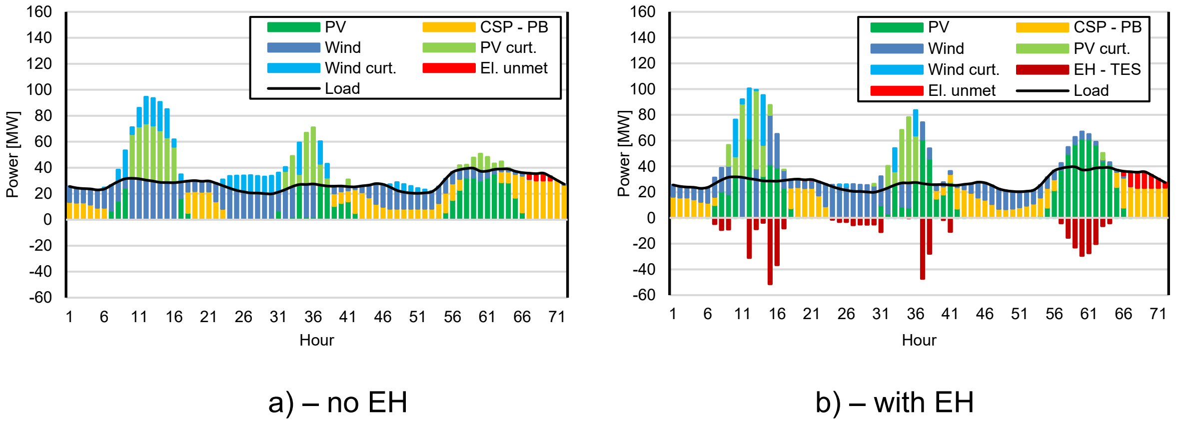

Figure 5. *Example of optimal hybrid plant operation for 3 consecutive days of the year. The dark-red bars on the negative y-axis represents the electricity powering the EH of the TES*

3.3 Configurations comparison

To assess the benefits of the hybridization, a further analysis has been performed comparing the hybrid plant performance with respect to standalone (PV, Wind, CSP) and other hybrid plant configurations (CSP+PV, CSP+Wind): Figure 6 reports the LCOE versus the fraction of the annual satisfied demand for different plant configurations.

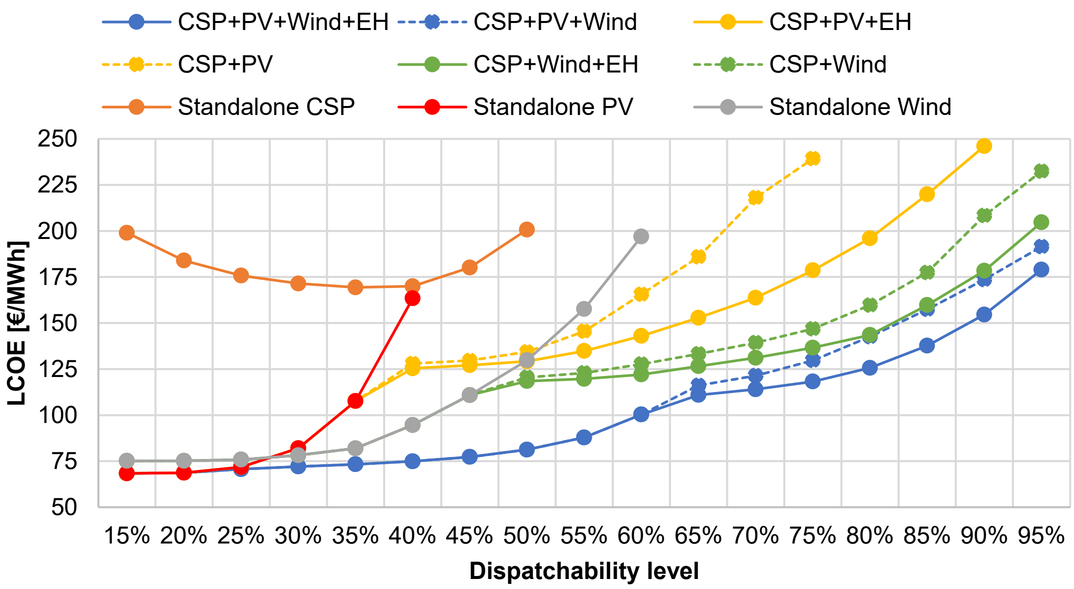

Figure 6. *LCOE versus DL for standalone and hybrid plant configurations*

The results show that standalone solutions, despite the simple design and relatively low cost of energy, are not suitable for achieving high dispatchability targets. Indeed, hybrid solutions become more attractive when medium-high DL (> 50%) are targeted: in particular, the CSP+PV configuration is always dominated by the CSP+Wind hybridization, as the production from solar and wind sources is not simultaneous and their coupling results in a smoother and more evenly distributed production profile along the year. Finally, a further LCOE reduction can be obtained, for the same DL, by the combination of the three technologies: the hybrid CSP+PV+Wind configuration is the only solution able to achieve very high DL (e.g. 95%) while limiting the LCOE increase. In all the hybrid configurations, the EH integration is always beneficial and can lead to a further LCOE reduction, particularly for high range of DL.

4. Conclusions

This work explores potential benefits deriving from the CSP hybridization with the PV and Wind technologies in a site located in southern Italy with favorable solar irradiance and average wind speed. The production specific hourly production from renewable sources has been obtained with exogenous models implemented in SAM and subsequently used in a MILP optimizer developed for hybrid plant design optimization.

The results demonstrated that CSP can greatly benefit from the integration with wind turbines, as solar and wind generation can complement each other. Thanks to this hybridization, very high dispatchability levels (> 80%) can be achieved at a relatively low cost of electricity produced. From the comparison with standalone solutions, hybrid plants appear more economically attractive than any standalone solution, specially for medium-high dispatchability targets. The results indicate also that integrating an electric heater (to convert the excess renewable electricity into high temperature heat for charging the thermal energy storage) allows decreasing the curtailment of intermittent renewable and lowering the cost of electricity of the hybrid CSP plant.

Data availability statement

Data will be made available on request.

Author contributions

L. Pilotti: Methodology, Data curation, Software, Writing – original draft, Visualization. **G. Manzolini**: Conceptualization, Methodology, Writing – review & editing, Supervision, Resources. **M. Binotti**: Conceptualization, Methodology, Writing – review & editing, Supervision, Resources, Funding acquisition. **A. Guglielmo**: Methodology, Writing – review & editing, Resources. **W. Gaggioli**: Methodology, Writing – review & editing, Resources. **E. Martelli**: Conceptualization, Methodology, Software, Supervision, Writing – review & editing, Resources, Funding acquisition.

Competing interests

The authors declare that they have no competing interests.

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