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Analysis and Simulation of CSP and Hybridized Systems

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Design and Operation of Hybrid CSP-PV-Wind Plants Operating on the Italian Day-Ahead Electricity Market and on the Ancillary Services Market

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Abstract. Concentrating Solar Power equipped with Thermal Energy Storage (TES) allows for dispatchable power production, but the worldwide installed power is still limited due to its higher investment costs with respect to other renewable technologies. A promising option to reduce costs, while keeping a high dispatchability level, is the hybridization of CSP with Photovoltaic (PV) and wind turbine (WT) plants. Hybrid CSP-PV-Wind plants have already shown their capability to achieve higher dispatchability level and lower costs with respect to stand-alone CSP, PV and wind plants. This work investigates the techno-economic optimization of hybrid CSP-PV-Wind plants capable of operating on both the Day Ahead Market (DAM) and the Ancillary Services Market (ASM), assuming different market scenarios. The design and operation of the hybrid plant are co-optimized using the optimization framework developed by Politecnico di Milano and considering the simultaneous participation of such plant to the DAM and ASM Italian markets. Results showed that while a price multiplier of 4 should be applied to the current spot market prices to make the hybrid plant economically viable in the DAM market, a price multiplier of 2 is sufficient for a positive NPV when also the revenues from the ASM market are considered. Moreover, the CSP turn out to be an essential flexibility provider: conversely to the solution combining PV and WT with a battery storage, CSP-based configurations avoid the need for a large battery for the reserve provision, with a significant economic benefit on the plant NPV.

Keywords: CSP Hybridization, Electricity Market, Ancillary Services, MILP, Design and Dispatch Optimization

1. Introduction

Coordinated efforts to meet climate goals are driving rapidly the renewable energy development. However, as the penetration of renewable power in the electricity grid increases, the electrical infrastructure is subject to a significant stress due to the instability and intermittency of these power sources [1][2]. Therefore, the progressive growth of green electricity in the generation mix is expected to increase the demand for ancillary services, which are essential for maintaining grid stability and avoid mismatches between consumption and generation [3][4]. Currently, ancillary services are largely provided by the conventional large-scale fossil fuel thermal and hydro power plants [4], but this approach will no longer be sustainable in the future and new alternatives should be considered. For this reason, in many countries, the regulatory framework is evolving to progressively enable renewable power plants to participate in the ancillary services market, contributing to grid stability alongside traditional generation sources [4][5].Several pilot projects across Europe, including Italy's "UVAM" project, have successfully demonstrated the potential for aggregated renewable energy plants to deliver critical grid services [6]. Among the commercially available renewable technologies, Concentrated Solar Power (CSP) plants are well known for their ability to offer firm and dispatchable generation, primarily due to the possibility of relying on the thermal energy storage. Recent studies [7][8][9] have further highlighted that CSP plants, when hybridized with other renewable technologies such as photovoltaics (PV) and/or Wind Turbines (WTs), can achieve very high capacity factors, delivering reliable power under a wide range of conditions throughout the year. These factors suggest that hybridized CSP plants can represent a promising solution for providing ancillary services to the future electricity grid. This fact is even more relevant as many of the existing renewable technologies, such as PV and Wind alone, cannot provide reserve power because their intrinsic intermittent and not reliable nature.

The objective of this study is to evaluate the potential of hybridized CSP plants within the context of the Italian electricity markets. Various plant designs are explored considering the presence of multiple revenue streams from the participation to different electricity markets: the Day-Ahead Market (DAM) and Ancillary Service Market (ASM). The study also assesses the impact of market prices and demand profiles on the optimal design of hybrid CSP plants Finally, the ability of such plants to deliver flexibility services to grid operators is analyzed and discussed.

2. Methodology

2.1 Hybrid plant description

The hybrid plant combines the CSP plant with ground-mounted fixed-tilt PV panels, one or multiple on-shore WT and a lithium-ion Battery Energy Storage System (BESS) for electricity storage. The CSP section of the plant features Linear Fresnel Reflectors (LFR) technology with molten salts, a direct two-tank TES and a conventional Rankine Power Block (PB): this technological solution is the same adopted in the Partanna plant [10], the latest CSP plant built in Sicily. In addition, an Electric Heater (EH) is included in the plant layout to convert the electricity in excess generated by the PV field and WTs into thermal energy that can be stored in the TES. A simplified scheme of the hybrid plant is shown in Figure 1.

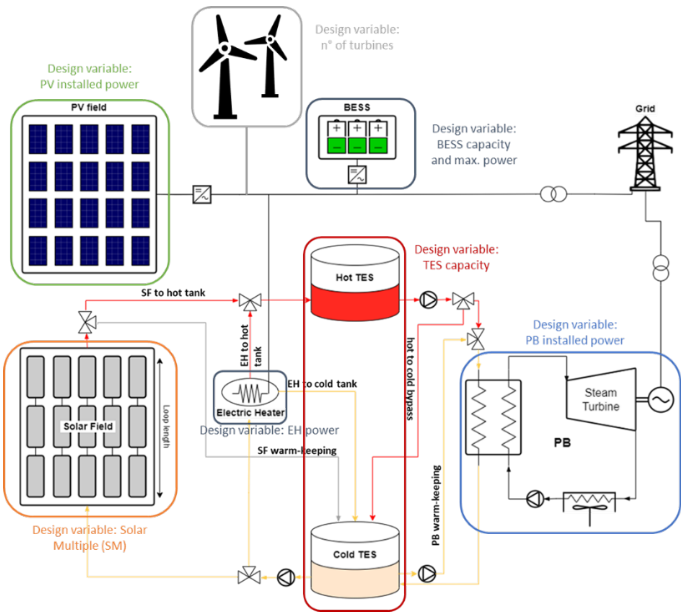

Figure 1. *Layout of the hybrid CSP+PV+Wind+BESS plant with EH*

2.2 Optimization approach

The tecno-economic optimization of the hybrid plant is carried out using the Aggregated Energy Systems Optimizer (AESOPT) [7], a Python-based optimization framework developed by Politecnico di Milano to assess the techno-economic performances of hybrid plants, characterized by the presence of multiple renewable energy sources, conversion technologies and storage units. AESOPT can identify the optimal size of each plant component while also providing the preliminary plant dispatch strategy throughout the year to properly assess the main plant KPIs. Core to the methodology is the formulation of the hybrid system design and operational problem as a single monolithic Mixed-Integer Linear Program (MILP), which can be solved in a reasonable amount of time by existing commercial linear solvers such as Gurobi [11].

In this study, the AESOPT framework is adapted to consider the presence of multiple electricity markets at the same time. This is done by adding to the AESOPT input profiles the electricity demand and the associated electricity prices characterizing each market regime, as outlined also in Figure 2, illustrating the flowchart AESOPT optimization framework. For a detailed description of the mathematical model behind AESOPT, the interested reader can refer to ref. [7].

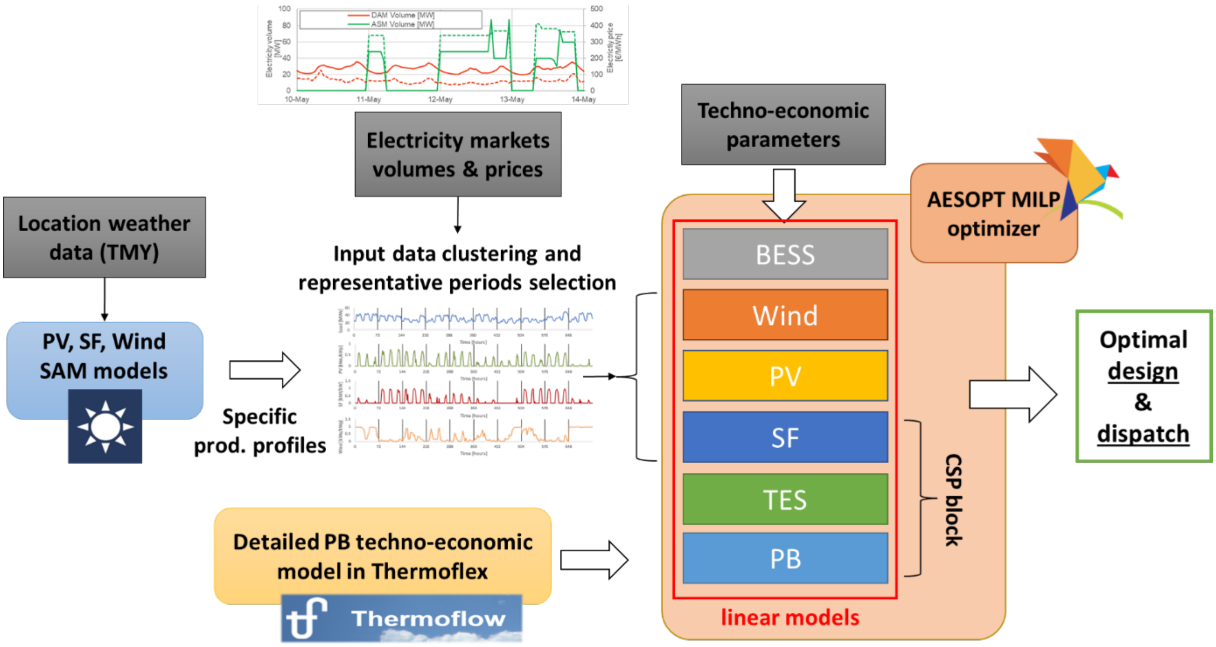

Figure 2. *AESOPT optimization framework flowchart*

The optimal design is carried out by seeking to maximize the plant profits, assuming the perspective of the plant owner or an investor who aims to maximize the return on the investment. Therefore, the maximization of the Net Present Value (NPV) is established as optimization problem objective function, defined as:

$$NPV = -CAPEX + \sum_{y=1}^{LT} \frac{REV_{DAM} + REV_{ASM} - OPEX}{(1+d)^y} \tag{1}$$

where $CAPEX$ represents the overnight capital costs while the annual cash flows are given by the difference between the revenues of the electricity sold in market (REV), derived both from the participation to the DAM (REV_{DAM}) and ASM markets (REV_{ASM}), and the operational expenditures ($OPEX$). A plant lifetime (LT) of 25 year and a discount rate (d) of 8% are assumed for the NPV calculation.

3. Case study

3.1 Case study description

The hybrid plant is located in Priolo Gargallo, a municipality in the South-East of Sicily (Italy). The weather data at the plant location for the year 2019 were provided by ENEA and the main meteorological characteristics are summarized in Table 1.

Table 1. *Meteorological data of the selected plant location (Priolo Gargallo)*

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

The plant is assumed to operate in the Italian Electricity Market ("Mercato Elettrico") as a Virtual Power Plant (VPP) [12]. According to this emerging concept, different type of distributed resources (e.g., PV, WT, CSP) dispersed in different points of electricity network can be aggregated to create a unique, larger, hybrid plant participating in the market as a single entity. Therefore the VPP represents a flexible portfolio of distributed resources characterized by a single operating profile.

The Italian Electricity Market is composed of: (i) the DAM, called "Mercato del Giorno Prima" (MGP), where electricity is traded for the following day and (ii) the Ancillary Services Market, called "Mercato dei Servizi di Dispacciamento" (MSD), in which Terna procures the resources needed to manage and control the system in order resolve intra-zone congestions, create the energy reserve and balance the system in real-time. The MGP is the wholesale electricity market where hourly blocks of electricity are negotiated for the next day: at the closure of the market prices, volumes and injections and withdrawal schedules are defined. The overall traded volume and clearing price are identified by the interception of the supply and demand curves (i.e., market equilibrium point). In the MSD market, three different types of resources are traded: Primary, Secondary and Tertiary control. Primary control uses the Frequency Containment Reserve (FCR), an automatic mechanism to suddenly compensate any variation of the grid frequency from the nominal value due to physical imbalance between generation and demand. The Secondary control uses the Frequency Restoration Reserve (FRR) mechanism to keep or restore the power balance between generation and load in each control area. The last is the Tertiary control and uses the Replacement Reserves (RR) to prepare the system for further imbalances in case FCR and FRR have already been activated up to a certain extent. These control mechanisms are activated progressively every time a mismatch between generation and consumption occurs and they act on different time scale (respectively in the range of seconds for FCR, minutes for FRR and hours for RR). In the MSD market, two kind of offers are possible: (i) upward offers, corresponding to an increase in energy production or a decrease in energy consumption and (ii) downward offers, corresponding to a decrease in energy production or an increase in energy consumption of the plant. Conversely to the MGP market, MSD offers are not remunerated at a single price but at the offered price ("pay-as-bid" remuneration mechanism). For this reason, production units which provide essential resources to the TSO can earn significant revenues streams from the operation on the MSD market.

The data relative to the MGP electricity market are publicly available at the website of the Italian Transmission System Operation (TSO) [13], where is possible to download, for each hour the year, the regional value of the load and the corresponding zonal market price ("Prezzo Unico Zonale") of the Sicilian region, which constitutes one of the seven bidding zone of the

Italian electricity market. Similarly, the relevant data on the hourly traded MSD resources can be downloaded from the Italian market operator ("Gestore dei Mercati Energetici") website [14]. In this analysis, only the possibility of providing the Tertiary control is considered, therefore only the quantities relative to the traded volumes of RR are collected from the GME website.

The provision of the MSD resources to restore the frequency of the grid or to solve congestion always occurs at local level. For this reason, to estimate the demand for MSD services, the accepted RR volumes and associated awarded prices of six different existing production units located in the Siracusa province, nearby the selected plant location, has been collected and aggregated. From the resulting aggregated profile all the values above 400 MW (approximately 5.3 times the standard deviation) are identified as outliers and removed while all the other are kept as the original. By doing so, it is possible to estimate the overall RR demand profile for each hour of the year, required by the grid operator in that specific area.

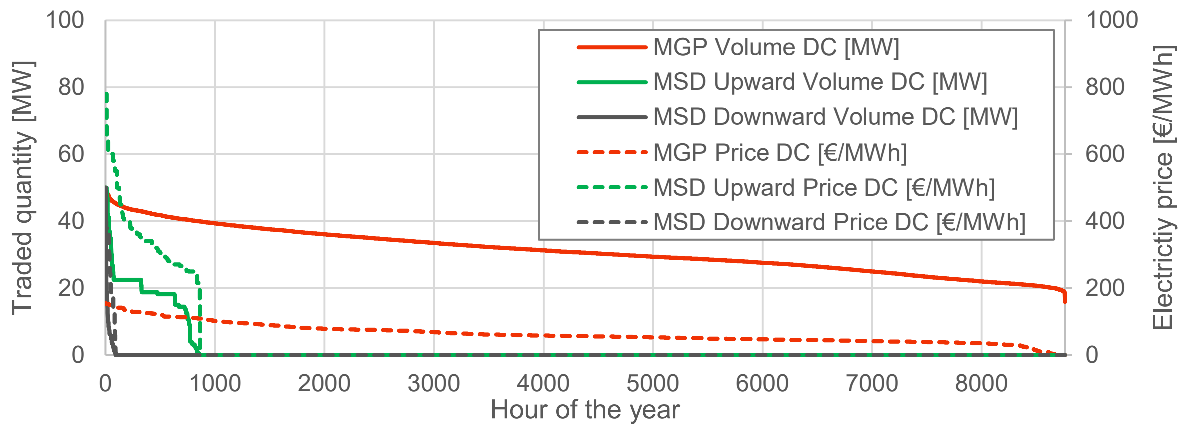

Figure 3. *Duration curves of electricity volumes and prices traded in the MGP and MSD markets scaled t0 50 MW$_e$*

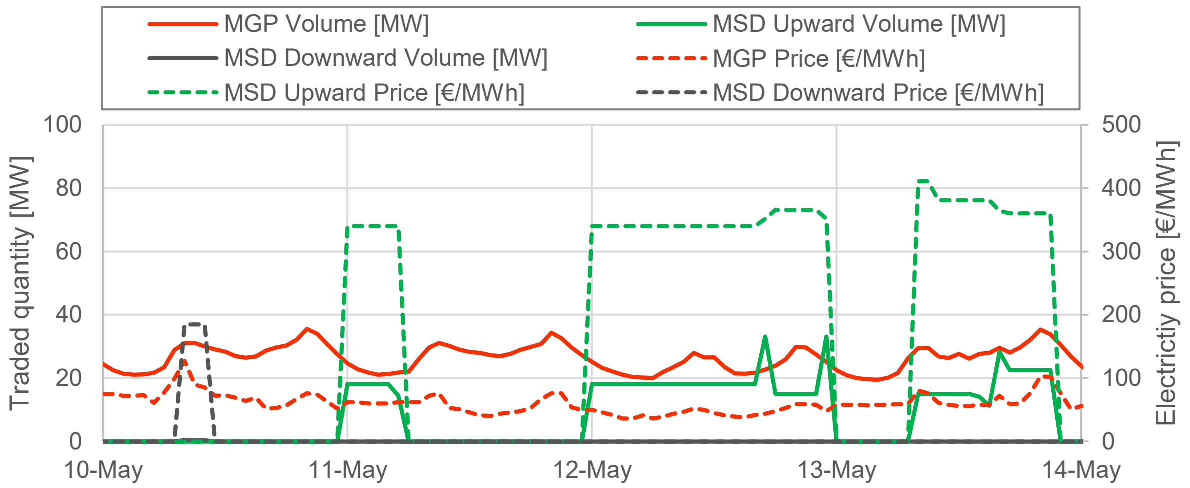

Figure 4. *Example of electricity volumes and prices traded in the MGP and MSD markets scaled to 50 MW$_e$*

Once the two electricity markets have been characterized in terms of exchanged volumes and prices, these data are used by the AESOPT optimizer to assess the optimal size of an hybrid plant designed to operate as a VPP in the Italian electricity market in order to maximize the profits. The resulting demand profiles on the MGP and MSD are scaled to a maximum value of 50 MW, representing the assumed maximum feed-in capacity for the hybrid plant. Figure 3 reports the annual duration curves of the traded volumes and prices in the MGP for the Sicilian bidding zone and in the MSD for the Siracusa province while in Figure 4 is visible the hourly pattern of these profiles for a period of four consecutive days. As clearly visible from Figure 3, the request for MSD services is concentrated in a limited number of hours per year (less than 1000 and 100 hours for the upward and downward direction, respectively), however the prices of the exchange quantities are significantly higher than the MGP prices. Moreover, while the MGP demand is always non-zero and shows a periodic behavior on daily basis, the MSD demand is more randomly distributed during the day and does not follow a regular pattern. Such trend highlights how the request for MSD services is much more difficult to predict and estimate in advance.

3.2 Techno-economic parameters

In Table 2 the list of the techno-economic parameters assumed for each plant component is reported. Such parameters have been collected from previous investigations on hybrid CSP system [7].

Table 2. *List of the techno-economic parameters.*

PV	**Value**	**Units**
Tilt/Azimuth angle	24/180	[°]
Ground coverage ratio	0.5	[-]
Module nominal cell efficiency	17.14	[%]
PV/Inverter investment cost	714/50	[€/kW]
O&M costs	15	[€/kW-y]
Solar Field	**Value**	**Units**
Desing DNI	850	[W/m^2]
Number of mirrors per SF module	16	[-]
Module area	537.6	[m^2]
Solar Field/Land preparation cost	170/17.2	[€/m^2]
Power Block	**Value**	**Units**
Min/Max HTF temperature	290/550	[°C]
Steam pressure at SH/RH outlet	100/21	[bar]
Net cycle efficiency	39-41	[%]
Investment cost	1000-1780	[€/kW]
TES	**Value**	**Units**
Charge/discharge efficiency	95/95	[%]
Investment cost	27.5	[€/kWh]
O&M fix cost	0.3	[€/kWh]
Electric heater investment cost	80	[€/kW]
Wind Turbine	**Value**	**Units**
WT model	V136	[-]
Hub height/Rotor diameter	132/136	[m]
Nominal power	3.45	[MW]
Investment cost	1500	[€/kW]
O&M fix cost	10.8	[€/kW-y]
O&M var cost	3.4	[€/kWh]
BESS (lithium-ion)	**Value**	**Units**
Charge/discharge efficiency [%]	97/97	[-]
Module investment cost	257	[€/kWh]
BESS BoP investment cost	223	[€/kW]
O&M fix cost	12.0	[€/kW-y]
O&M var cost	0.1	[€/kWh]

4. Results

A techno-economic optimization is performed through the AESOPT tool, aimed at finding the optimal design of the hybrid plant operating in one or multiple electricity market. In this analysis, the Italian electricity market has been taken as reference but the study is replicable also for other European electricity markets as they exhibit a similar market structure [3]. The following market scenarios has been investigated:

(i) Hybrid plant operating as a VPP exclusively on the wholesale electricity market (MGP)
(ii) Hybrid plant operating as a VPP in the wholesale electricity market (MGP) and in the ancillary services market (MSD)

In both cases, the optimization logic is to maximize the profits or NPV of the plant. According to the dispatch strategy adopted by the optimization algorithm, the plant is able to freely determine the optimal amount of electricity to export and sell on the MGP market without exceeding the hourly cap set by the total MGP demand. Conversely, when operating on the MSD market, the plant has to satisfy the entire MSD demand, providing all the RR volumes required by the TSO in the area nearby the plant location. This assumption reflects the fact that, while the TSO has the possibility to cover the remaining fraction of the MGP demand with other power plants operating in the wholesale market, there is no other plant in the selected location that can provide MSD services to the TSO during real-time operation. Therefore the MSD resources must necessarily be provided by the hybrid plant that must guarantee the maximum level of reliability. This assumption is representative of a future scenario in which the conventional power plants currently providing MSD services to the TSO are progressively phased out and fully replaced by renewable distributed energy sources, such as the proposed hybrid plant. Moreover, it is assumed that only the components that can be considered sufficiently reliable to provide "dispatchable" power can provide ancillary services to the TSO: in the hybrid plant under study these are namely the BESS and the PB of the CSP section. Therefore the exported MSD volumes should be generated through the CSP power cycle or by discharging the BESS.

4.1 Hybrid plant operating on the MGP market

As the MGP market prices for the 2019 in Sicily were particularly low (average annual MGP price of 62.8 €/MWh), the MGP remuneration is not sufficient to justify the construction of the plant. This means that even the installation of the two technologies with lowest cost of the electricity among the ones considered (i.e., PV and Wind) would have been resulted in a negative value for the NPV. Therefore, without any incentive mechanism, the trivial solution is to not install anything. For this reason a price multiplier has been applied to rescale the MGP price profiles as an incentive for the plant construction. The results reported in Table 3 show that the hybrid plant featuring also the CSP section is installed when a price multiplier of 4 is considered, while, for price multipliers below 4 a solution coupling PV and Wind generation with a battery energy storage system (BESS) is preferred. The impact on the price multiplier is twofold: increases (i) the size of the plant components and consequently (ii) the amount of energy produced and sold in the MGP.

Table 3. *Optimization results for MGP at different values of the MGP price multiplier.*

MGP price multiplier	**x 1**	**x 2**	**x 4**
Average MGP price [€/MWh]	**62.8**	**125.6**	**251.2**
Design PB Power [MW]	-	-	28.52
Solar Multiple [-]	-	-	2.67
TES Size [h]	-	-	11.22
Design power EH [MW]	-	-	11.18
Design AC Power - PV [MW]	-	12.00	31.00
Total Design Power - WT [MW]	-	37.95	37.95
BESS Size [MWh]	-	15.10	23.72
Annual Energy Yield [GWh]	-	111.42	221.82
Fraction of MGP demand covered [-]	-	42.1	83.8
MGP Revenues [M€/y]	-	15.01	59.53
NPV [M€]	-	50.30	309.65

4.2 Hybrid plant operating on the MGP and MSD markets

Table 4 shows the optimization results obtained considering the simultaneous presence of MGP and MSD markets. In this analysis, three different configurations that can potentially provide the required flexibility on the MSD are considered and compared each other: (i) the CSP with an EH, (ii) PV and WTs coupled with a BESS and (iii) the full hybrid plant obtained as combination of the previous configurations. For each configuration the NPV is maximized with the constraint of fully covering the upward and downward MSD volumes.

Table 4. *Optimization results for the MGP and MSD scenario for different plant configurations.*

	CSP+EH	**PV+WT +BESS**	**PV+WT+BESS+ CSP+EH**
Design PB power [MW]	26.20	-	33.91
Solar Multiple [-]	2.96	-	1.40
TES hours [h]	9.11	-	6.78
Design power EH [MW]	41.25	-	31.59
Design AC Power - PV [MW]	-	112.00	41.00
Total Design Power - WT [MW]	-	3.45	-
BESS size [MWh]	-	673.57	33.51
Annual Energy Yield [GWh]	95.23	181.34	121.85
Annual Energy exported to MGP [GWh]	79.63	164.39	104.90
Fraction of MGP demand covered [-]	29.24	60.35	38.51
Annual Energy exported to MSD [GWh]	15.60	16.95	16.95
Fraction of MSD demand covered [-]	**92.00**	**100.00**	**100.00**
MGP Revenues [M€/y]	3.22	7.39	4.41
MSD Upward Revenues [M€/y]	5.02	5.46	5.46
MSD Downward Revenues [M€/y]	0.69	0.76	0.75
NPV [M€]	**-99.88**	**-333.36**	**-110.41**
Price multiplier for NPV breakeven [-]	**2.05**	**3.30**	**1.97**

All the three configurations are able to provide the required MSD services in both directions, covering the entire MSD demand except for the CSP standalone configuration (only 92% of MSD demand covered). The optimal design of the standalone CSP configuration exhibits a large SM (around 3), a limited TES and a medium-size PB. Compared to a standard CSP design, these values of the CSP sizing parameters derives from an operating regime that combines baseload power to sell electricity in the MGP with peaking operation to cover periods of high MSD demands. The PV+Wind+BESS configuration is characterized by a BESS with a large capacity, installed to cover the MSD requirements: this lead to a solution not attractive from the economical standpoint, with a highly negative value of NPV. The hybrid plant configuration combines the BESS and CSP presence to provide ancillary services. Compared to the configuration with only battery storage, the required BESS size is strongly reduced and also the capacity of aggregated PV and Wind renewable generation is significantly lower. Compared to the CSP standalone configuration, the optimal size of both the SM and the TES decreases while the optimal PB capacity increases. In both the configurations including the CSP plant, an EH is installed to take advantage of the request of MSD volumes in the downward direction, where the plant is paid for reducing its energy export or, alternatively, increasing its consumption. Thus, this service is provided by the EH by storing the excess power in the TES. This behavior is also illustrated in Figure 5, which shows the optimal dispatch of the hybrid plant during a three-day period. When downward MSD volumes are requested by the grid operation (i.e., lower the generation or increase the consumption), the electricity is purchased from the grid to charge the BESS or power the EH. Instead, the electricity needed to cover the MSD upward demand is generated with the PB or by discharging the BESS. The electricity exported to the MGP market mainly derives from the PV plant or from the BESS, which is discharged during evening hours where spikes in the MGP price occur.

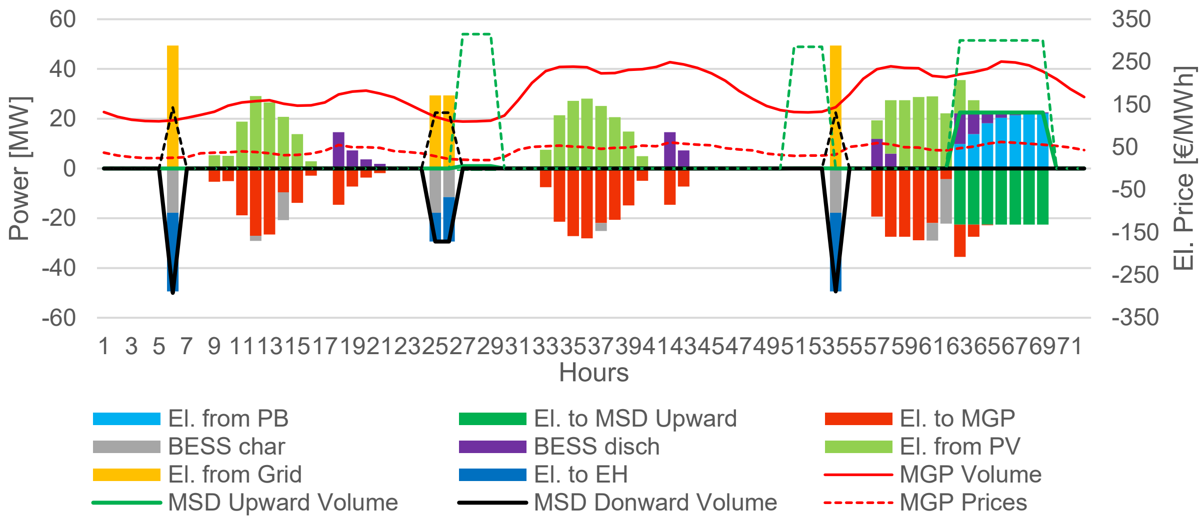

Figure 5. *Example of hybrid plant operation during a three-day period*

All the three configurations results in a negative NPV meaning that the current remuneration in MGP and MSD markets is not sufficient to payback the investment. By computing the NPV breakeven price multiplier, defined as the multiplier leading the NPV of the plant equal to zero, it is possible to understand how far each configuration is from the economic breakeven point. Among the configurations tested, the hybrid plant is able to reach the lowest price multiplier (1.97), meaning that is the most cost-effective configuration to provide ancillary service to the grid with a fully renewable plant. Therefore, if average electricity price on the MGP and MSD market will increase in the future (as expected, because the increasing penetration of renewable and demand for ancillary services) the investment in such kind of plant will become profitable without any incentives.

4.3 Sensitivity on the hybrid plant MSD dispatchability level

A sensitivity analysis on the fraction of covered MSD demand – or Dispatchability Level (DL) – has been carried out to understand how the economical performances of the hybrid plant and its optimal design change by relaxing the constraint requiring the full satisfaction of the MSD demand. By progressively reducing the fraction of MSD demand coverage (from 100% down to 75%, 50% and 25%), three different plant configurations have been obtained, as reported in Table 5. The 100% DL case is the same already presented in Table 4.

Table 5. *Optimization results for the hybrid plant and different MSD dispatchability levels.*

Dispatchability Level (DL) [-]	**100%**	**75%**	**50%**	**25%**
Design PB power [MW]	33.91	21.15	-	-
Solar Multiple [-]	1.40	1.19	-	-
TES hours [h]	6.78	7.67	-	-
Design power EH [MW]	31.59	40.09	-	-
Design AC Power - PV [MW]	41.00	14.00	30.00	8.68
Total Design Power - WT [MW]	-	-	-	-
BESS size [MWh]	33.51	6.58	50.98	29.19
Annual Energy Yield [GWh]	121.85	50.93	52.81	15.83
Annual Energy exported to MGP [GWh]	104.90	38.22	45.48	12.17
Fraction of MGP demand covered [-]	38.51	14.03	13.64	3.65
Annual Energy exported to MSD [GWh]	16.95	12.71	7.33	3.66
Fraction of MSD demand covered [-]	**100.00**	**75.00**	**50.00**	**25.00**
MGP Revenues [M€/y]	4.41	1.65	1.81	0.50
MSD Upward Revenues [M€/y]	5.46	4.16	3.17	1.58
MSD Downward Revenues [M€/y]	0.75	0.70	0.30	0.17
NPV [M€]	**-110.41**	**-51.70**	**-13.05**	**-4.39**
Price multiplier for NPV breakeven [-]	**1.97**	**1.74**	**1.23**	**1.18**
Mean MGP selling price [€/MWh]	42.00	43.22	39.79	41.49
Mean MSD upward price [€/MWh]	322.08	327.22	433.31	432.12
Mean MSD downward price [€/MWh]	89.86	89.86	89.86	89.86

As visible from Table 5, the optimal design is strongly affected by the DL required on the MSD. For small served MSD volumes (up to 50% of the total demand), the optimal configuration is to install a PV plant with battery storage. For higher DL, increasing further the BESS capacity is not convenient, but it is preferable to install the CSP to rely also on a thermal storage. Going from 75% to 100% DL, the size of the SM is increased as well as the nominal capacity of the PB, the PV field size and the BESS capacity. Wind turbines are never installed because the mismatch between the Wind generation profile and MSD demand patterns (Wind generation is prominent in the morning hours or during the night while the MSD demand is mainly concentrated during the day or in the evening hours). As the minimum DL requirement on MSD increases, also the energy sold on MGP increases, to boost the plant equivalent operating hours and maximize the revenues from the two markets. However, as mentioned above, as the remuneration of the energy sold on the Italian electricity markets is not enough to make the investment profitable, the increase of DL is not beneficial for the plant NPV. To incentivize such plant to bid in the MSD market the mean price of accepted offers should be higher or larger volumes of flexibility resources should be traded in the MSD market, as expected in the future.

5. Conclusions

This work evaluates the potential of hybrid CSP plant to participate in the Italian electricity markets as a VPP, analyzing different market scenarios for a plant located in the Sicily region. First the benefits of operating the plant exclusively in the Italian DAM market (i.e., MGP) are investigated and then the simultaneous operation in the DAM and ASM markets is assessed, assuming that the plant should provide the required Tertiary reserve volumes for the nearby market area. A previously developed optimization framework has been used to optimize the design of the hybrid plant component in order to maximize the market profits and the plant NPV.

Results demonstrated that current remuneration in the Italian MGP market is not sufficient to payback the initial investment, making the installation of a hybrid plant not convenient.

However, by applying a multiplier to the MGP price profiles to increase the annual average value, different configurations become economically viable: in particular, a solution employing PV and WT with a battery storage is preferred for a two-fold price increase (125.6 €/MWh) while the hybrid plant is more convenient for a four time increase in the average market price (251.2 €/MWh). When also the MSD market is considered, the optimal plant design shifts towards configurations which are able to guarantee the provision of flexibility services. In this context, CSP becomes an essential technology and its inclusion in the hybrid plant can avoid the need for a large BESS to provide the same level of ancillary services. Even in this case all plant configurations led to a negative value of the NPV, however in this case to make the investment on the hybrid plant profitable is sufficient a price multiplier of 2 because of the additional remuneration deriving from the MSD market.

Future studies should further investigate the ability of hybrid CSP plant in providing dispatchable power for flexibility services by expanding the analysis to the other type of ancillary services and products traded in the ASM market (e.g., Primary and Secondary reserve), considering also future market scenarios characterized by a high renewable penetration and its impact on the market traded volumes and prices.

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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