Potential of Smart Renewable Hubs including Concentrated Solar Power in the Interconnected European Power System

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Abstract

The cost of wind and solar renewable energy technologies is dropping significantly and as deployment increases, access to grid permits are likely to become scarcer and grid costs make up for a proportionally larger share of total project costs. Contextually, with a higher penetration of Variable Renewable Energy Sources (VRES) there is an increased need for dispatchable and flexible generating technologies. A logical response to this trend is the deployment of hybrid power plant, of which Gridsol and Smart Renewable Hubs (SRHs) are an example. These couple renewable technologies with back-up and storage units in loco. Gridsol integrates synchronous generators besides VRES: Concentrated Solar Power (CSP) equipped with thermal storage and a gas turbine with heat recovery. SRHs are a broader term to define all the hybrid power plants possibly including electric storage and both synchronous generators and VRES, such as wind and solar PV. This paper identifies the optimal composition in Gridsol and SRHs until 2050. The latest European long-term deep decarbonization pathways serve as a framework for the analysis and the simulations are carried out with Balmorel, a fundamental market model able to perform hourly power dispatch and optimal capacity expansion. Results show that flexibility in the generation becomes increasingly important starting from 2030 in order to capture higher market prices. The optimal hybrid power plant composition in South European countries is dominated by the combination PV+BESS. PV is overplanted in the hubs and excess energy is either stored or curtailed, with curtailment levels of up to 19% in 2050. Gridsol appears only in selected instances and with a small capacity. On the other hand, it is demonstrated that the Levelized Cost of Electricity (LCoE) of CSP, as low as 42 EUR/MWh in 2050 under the hypothesis of large cost reductions, is lower than that of PV+BESS for application beyond the daily cycle and when a great amount of energy has to be shifted in time.

Keywords: smart renewable hubs, hybrid power plants, CSP, storage, energy systems modelling, scenario analysis

1. Introduction

With the undersigning of the Paris Agreement, the 28 EU Member States agreed to put into practice policies and measures to keep global warming in this century well-below 2 degrees compared to pre-industrial levels; a further effort is made to contain the global temperature increase to 1.5 degrees (UNFCCC. Conference of the Parties (COP), 2015). The power sector is still responsible for a large part of GHG production in the EU: in 2018, the CO_2 emissions settled at 985 million tonnes, marking a 5% reduction with respect to the previous year but still accounting for 58% of all EU Emission Trading System (EU ETS) sectors (Agora Energiewende and Sandbag, 2019). The spread of renewable energy technologies is a key factor to achieve long-term decarbonization goals, but the fluctuating and variable nature of wind and solar resources requires the installation of back-up units that ensure security of supply. The combination of dispatchable and non-dispatchable technologies in hybrid power plants can be attractive not only from a private perspective (more stable and predictable generation, higher capacity factors), but also from a socio-economic point of view. Sharing the grid connection equipment potentially leads to significant total system savings and constitutes a key strength of hybrid installations as compared to single-source units. The synergy among components and the presence of electric or thermal storage increases the plant capacity factor (CF) and reduces periods of downtime, potentially leading to lower cost for balancing and back-up.

This paper investigates the potential and functioning of SRHs including CSP in five Southern European countries until 2050: France, Greece, Italy, Portugal and Spain. The research envisions four different scenarios that ground on the 2018 EU Climate Strategy (European Commission, 2018a). By using the fundamental market model Balmorel, this study analyses optimal configurations of Smart Renewable Hubs in the future European power system, under different assumptions regarding decarbonization efforts and the demand of electricity for production of hydrogen.

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2. Method

The study makes use of Balmorel[1], a bottom-up, fundamental market model particularly suited for the representation of the power and heat sectors. The model is able to calculate the optimal dispatch of generation, transmission, and consumption of power and heat on an hourly basis, as well as optimize the development of electricity, heat, and transmission capacity in the system to supply the future demand. Its geographical and temporal layers allow for a customized and flexible implementation of the physical, economic and policy constraints at different levels (Wiese *et al.*, 2018).

The entire EU28 plus Switzerland, Norway, Albania, Kosovo, Serbia, Bosnia, Montenegro and Macedonia are simulated to account for cross-national flows between countries; the model scope and interconnection lines are visible in Figure 1. The option to invest in SRHs integrating CSP is assigned only to five Southern European countries: France, Greece, Italy, Portugal and Spain. The resource profiles are taken from selected areas: Extremadura (Spain), Faro (Portugal), Marseille (France), Puglia (Italy) and the Peloponnese (Greece).

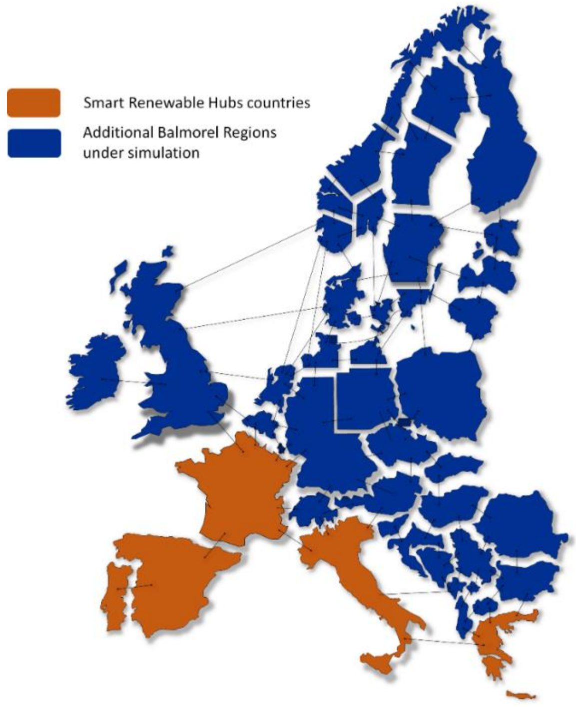

Figure 1. Simulated geography; countries in which reference Smart Renewable Hubs including Concentrated Solar Powerare highlighted in orange.

SRHs are hybrid power plants whose units are coordinated by an intelligent Dynamic Output Manager of Energy (DOME); the controls minimize the revenue loss associated to balancing penalties and ensure a stable and predictable power output.

SRHs are modelled as specific regions in the model from which power can flow out to meet the national electricity demand; the model can freely choose to install a CSP block considering a tower configuration with thermal energy storage (TES), possibly integrating a gas turbine (GT) with heat recovery, solar PV, wind turbines and BESS. The capacity of each element in the hub is unconstrained, but the grid connection capacity is fixed at 200 MW (Figure 2). The size of the hub components depends on the specific location, i.e. on the quality of the natural resource available therein, on the demand profile and on the interaction with other existing generators. For each of the countries indicated in orange in Figure 1, a reference SRH is optimized to find the optimal capacity composition of the hub.

The discount rate is set to 5% for all technologies and countries in the analysis, while the economic lifetime is uniformly set to 20 years. As for specific cost assumptions, the study relies on data from technology catalogues regularly updated by the Danish Energy Agency, representing cost and performance of generation technologies in the European context (Danish Energy Agency and Energinet.dk, 2019).

[1] The Balmorel user-guide prepared by Ea Energy Analyses is available at: https://ea-energianalyse.dk/papers/Balmorel_UserGuide.pdf.

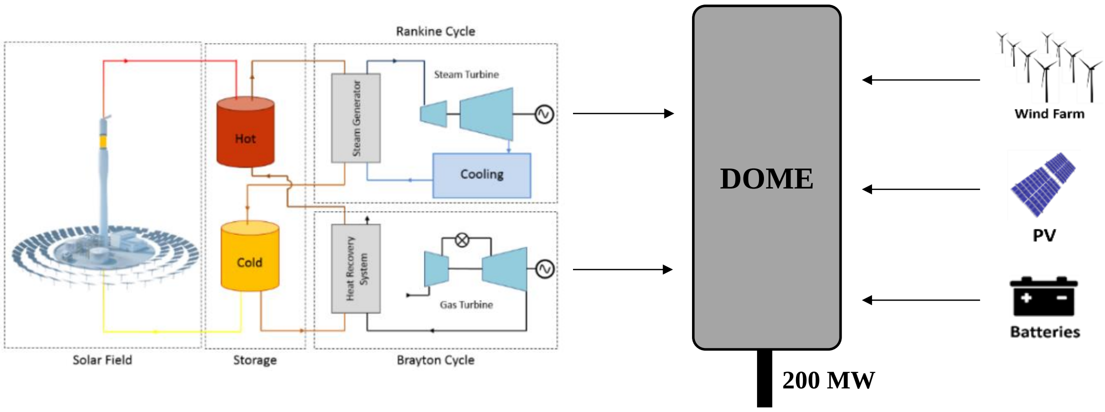

Figure 2. Smart Renewable Hub potential components including Gridsol concept (on the left), connected to the grid through a 200 MW connection.

Since only a limited number of projects based on tower configuration have been developed to date, the evolution of the cost of CSP is based on component-based learning curves approach. The resulting cost assumptions for tower-based solar field, thermal storage gas turbine and steam turbine are shown in Table 1, together with the basic cost parameters for PV, wind and BESS.

Table 1. Cost assumptions for main components of the SRH. Costs for CSP are derived from consortium partners, while PV, wind and BESS costs are from the Technology Catalogue from Danish Energy Agency. All figures are in 2018 EUR.

Component		Investment cost [MEUR/MW] [1,2]		
Year		2020	2030	2050
Gridsol - CSP	Solar field/receiver [1]	0.38	0.31	0.27
	Thermal storage [1,2]	0.020	0.015	0.012
	Steam turbine	1.45	1.22	1.09
	Gas turbine *(incl. heat recovery)*	0.63	0.54	0.49
PV		0.64	0.53	0.43
Wind		1.48	1.46	1.31
BESS [2]		0.44	0.20	0.14

[1] *Investment cost for receiver and thermal storage is expressed per thermal unit (MW or MWh).*
[2] *Investment cost for storage, both thermal and electrical is expressed per MWh rather than per MW.*

One of the potential benefits of combining different generators in a hybrid plant is the opportunity to share part of the grid connection costs for the SRHs; this leads to cost savings with respect to conventional single-source installations. The synergies relate mostly to the step-up transformer, connection, switchboard and potentially other grid related expenditures, such as grid reinforcement of the adjacent grid. No synergy in terms of sharing the power conversion equipment is considered in this study. In Europe, the legislation on grid connection costs is not uniform (Agora Energiewende, 2016): some countries adopt a shallow cost allocation principle, i.e. new installations need only to bear the expenditures for being connected to the system; others require to contribute also to the reinforcement of the grid (deep cost allocation). On the whole, these costs can range between 2 and 8% of the capital expenditures (Stennett, 2010). In this study, a connection cost of 40,000 EUR/MW is considered and the SRH components connected to the bus thus benefit from a specific investment cost discount compared to similar technologies installed outside a hybrid configuration. These include the CSP steam turbine, the gas turbine, solar PV, wind turbines and the BESS. This assumption implies that the cost savings for solar projects are in the range of 3-9%, in line with figures found in a study about co-location of solar and wind farms in Australia (AECOM Australia, 2016).

Four scenarios are considered for the simulations: two main scenarios and two sensitivities. The three main scenarios are named '*Baseline*' *'2.0 degrees'* and '*1.5 degrees*'. The former represents the evolution of the power sector in case of a weak development of alternative fuels and relatively low carbon prices, with assumptions aligned to the Reference scenario from the European Commission (European Commission, 2016); the latter follow the assumptions of the latest “Deep decarbonization” study from the European Commission (European Commission, 2018a) and aims at limiting the greenhouse gas emissions of Europe in order to be in line with a global temperature rise of no more than 2.0 and 1.5 degrees respectively.

The two sensitivities, performed using the ‘1.5 degrees’ scenario as a starting point, are ‘*Biogas+*’, in which biogas prices are capped and decoupled from the price of natural gas at very high carbon prices, and ‘*CSP+*’ which includes a further 40% cost reduction with respect to the reference projections, representing a breakthrough in the cost development of concentrated solar power.

The characteristics of each scenario are summarized in Table 2.

Table 2. Scenario characteristics.

Scenario	CO_2 price	Hydrogen demand	CSP costs
Baseline	Low (92 EUR/t in 2050)	Low (126 PJ in 2050)	Reference (Gridsol consortium)
2.0 degrees	High (250 EUR/t in 2050)	Moderate (837 PJ in 2050)	
1.5 degrees	Very high (366 EUR/t in 2050)	High (3,349 PJ in 2050)	
CSP+			- 40% with respect to the Reference
Source:	(European Commission, 2018b), *(European Commission, 2016)*	(European Commission, 2018b), *(European Commission, 2016)*	*Gridsol project*

The simulations are carried out for the years 2020, 2030, 2040 and 2050; for each year both the overall development of the system in terms of generation fleet and the optimal composition of the SRHs is computed using the Balmorel model. This means that CSP is given as an option for investment, together with the rest of generation technologies and no fixed development or installation pathway is assumed.

The composition of SRHs is therefore assessed in all of the aforementioned scenarios, which are affected by different values of the exogenous parameters: the CO_2 quota price in the European Emission Trading System (EU ETS); the natural gas/biogas price trajectories; the CSP investment cost projections; the hydrogen demand level. The CO_2 quota price is supposed to provide the appropriate price signals to invest in renewable energy: the higher the CO_2 price, the larger the share of clean technologies in the generation mix, due to the fact that conventional alternatives becomes more expensive. The Baseline scenario reaches a quota price of 92 EUR/t in 2050, whereas in the 2.0 and 1.5 degrees (including CPS+) pathways, the 2050 price is 250 EUR/t and 366 EUR/t respectively. These high prices reflect the scarcity of allowances in the long term due to the ambitious decarbonization goals of the European Union outlined in the EU Climate Strategy (European Commission, 2016, 2018b).

The biogas price impacts the attractiveness of the gas turbine with heat recovery, coupled with the CSP block. Together they form a hybrid group that constitutes the synchronous component in Gridsol. Its competitiveness is heavily influenced by the fuel costs. In the analysis, the price of biogas is assumed to be equal to that of natural gas plus carbon (i.e. perfect substitutes) until methanation and thermal gasification become a cheaper option, at a level of around 17 EUR/GJ in 2050 (Ea Energianalyse, 2017). The long-term natural gas price trajectories follow the assumptions from the *Sustainable Development* scenario contained in the latest World Energy Outlook (International Energy Agency, 2018).

In a system characterized by high penetration of VRES, whose short term marginal cost of production is very low, hydrogen is projected to play a role in substituting conventional fuels, especially in case of high carbon prices; in 2050, the European Commission projects a modest 3 Mtoe (126 PJ) demand level for the Baseline and a consistently higher need with soaring carbon prices: levels of 20 Mtoe (837 PJ) and 80 Mtoe (3,349 PJ) are chosen for the 2.0 and 1.5 degrees pathways (including CSP+) in this analysis, in line with assumptions from the Commission (European Commission, 2018b).

3. Results

3.1. Power system overview

Before looking at the specific composition of the SRHs, it is worth giving an overview of the system evolution until 2050 in Europe in the simulated scenarios (Figure 3). All scenarios indicate a large penetration of wind and solar PV in the European power system in the medium and long term, reaching between 70% and 75% of the total generation in 2050, of which around 2/3 are covered by wind and 1/3 by solar PV. In the 1.5 degrees scenario coal is completely phased out already by 2030 and the system is carbon neutral by 2050. On the other hand, in the Baseline scenario a small portion of coal remains in 2030 (~10%) and gas in 2050 (~5%).

CSP plays a relatively small role and only in the long term (after 2040, 2030 in the CSP+ scenario). In the 1.5 degrees scenario, the installed CSP capacity in 2050 is 22 GW. However, the largest impact is achieved with a marked drop in the CSP costs: in the CSP+ scenario, the installed CSP capacity tops 80 GW, enabling the technology to cover 9% of the EU generation (23% of the countries under focus).

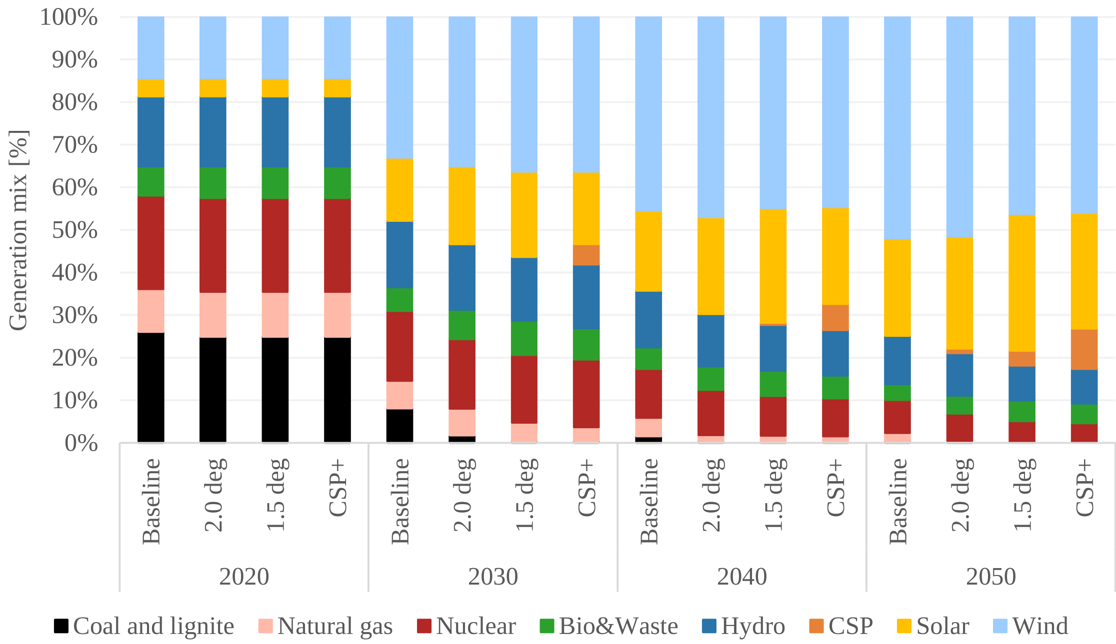

Figure 3. Development of the European power system in the scenarios analysed: CSP has a role in the long-term for the 2.0 and 1.5 degrees scenarios and most notably in the CSP+ scenario.

It should be noted that in a system with this large penetration of variable renewable energy sources (VRES), in particular PV, the price profile in the day-ahead market is largely influenced, with price valley appearing around midday and a general increase in the price volatility: increased hours with very low prices when PV (and wind) generation is abundant and higher prices when wind and PV are not operating. In the latter case, electricity prices are also driven up by a high CO_2 price and the bidding behavior of energy storage and reservoirs. In such a situation, the flexibility in the entire system becomes very important and this is reflected more broadly in the generation fleet, and more specifically in the composition of the hybrid plants.

Figure 4 shows the average daily power price in Spain and France between 2020 and 2050. The price valley in the hours of high irradiation is evident and more pronounced in Spain, due to the higher solar penetration and the reduced chance to export the excess energy to neighboring countries. From 2030, the power price in the period 13-16 drops below 20 EUR/MWh making it hard for a solar plant to be competitive without storage.

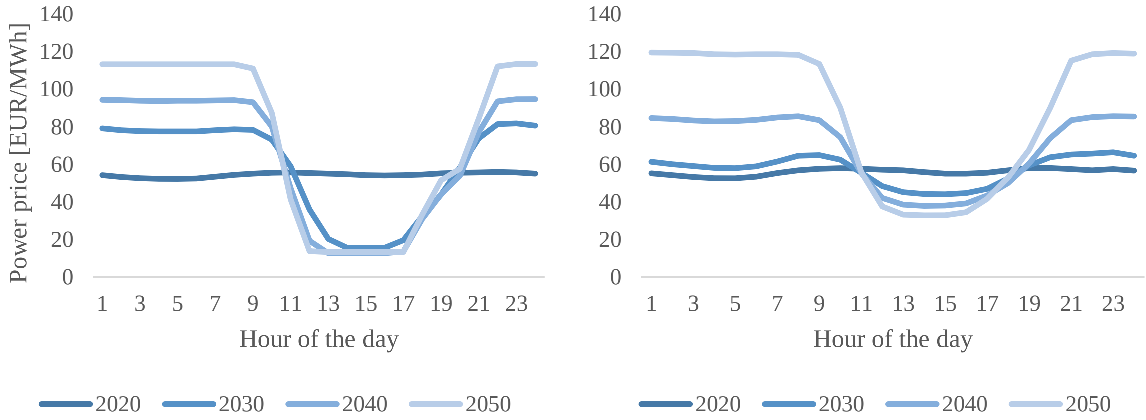

Figure 4. Average daily power prices in Spain (left) and France (right). A clear valley around midday appears from 2030.

3.2. SRH composition

Figure 5 displays the resulting composition of the SRHs for the four scenarios and the four milestone years under consideration; each box is subdivided into five slots that represent one of the SRH locations.

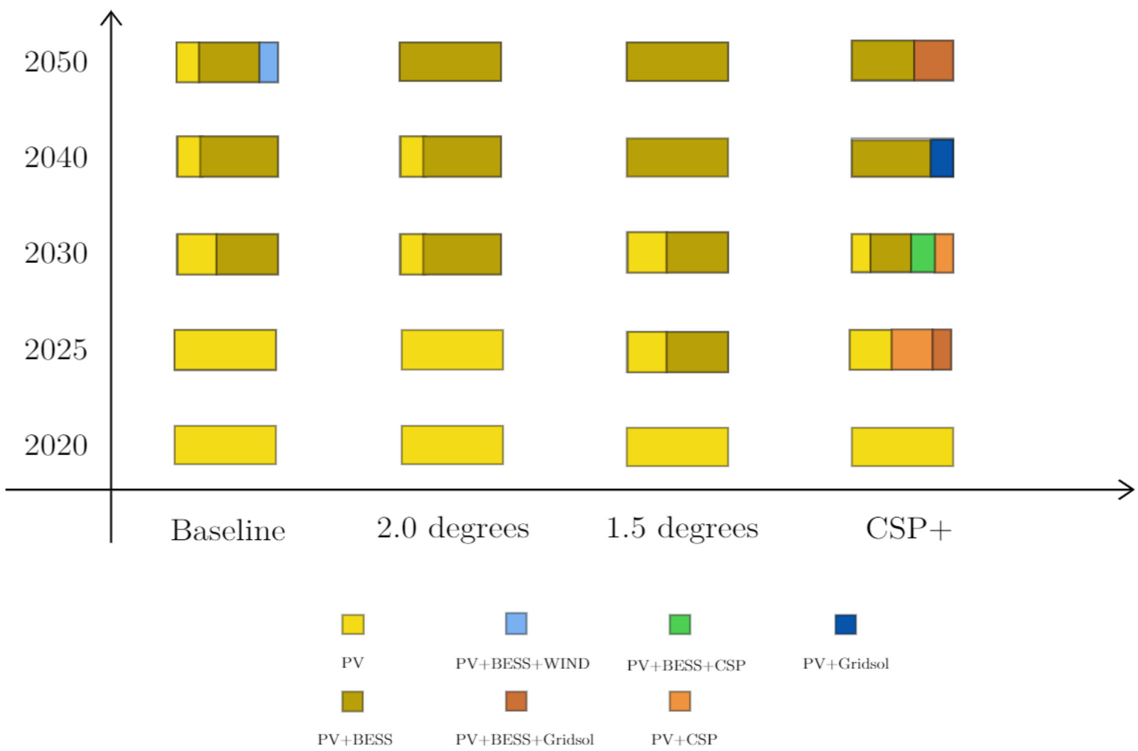

Figure 5. Overview of Smart Renewable Hubs composition for the four scenarios and the five milestone years in the five Gridsol locations. Each slot in the boxes represents one of the five Gridsol locations.

The figure shows that solar PV is the only hub component in 2020, regardless of the scenario. As the European system approaches 2050, across the different locations SRHs are primarily composed of the semi-dispatchable group PV + batteries (BESS), with selected instances in which other components are added. In France, SRHs integrate also wind turbines, which increase the hybrid power plant yield during wintertime. Only in the CSP+ scenario, CSP and GT appear already from 2025. It is worth noting that hybridization with CSP is present in 3 out of 5 locations in 2025, but in the very long term the further reduction of PV, wind and BESS costs favors these compared to CSP.

Solar PV is present in all configurations across years and scenarios, while in few configurations after 2030 the hub lacks electric storage. Even when CSP is chosen, PV is still dominating the total output of the hybrid plant. When thermal storage is installed along with CSP (Italy), less battery storage is present.

Besides the already low investment cost, PV further benefits from deployment in hybrid configurations. Indeed, being a capital-intensive technology, the reduction of the cost of connection to the grid has a higher impact on the cost of PV generation compared to other technological options in the SRH. For example, the steam turbine which is part of the CSP block, has relatively high O&M costs and a higher specific investment cost per MW, therefore the cost reduction when placing it in a hybrid plant is less impacting on the overall generation cost.

To further understand the dominance of PV in the configurations, Figure 6 depicts the composition of hubs in the CSP+ scenario for various locations.

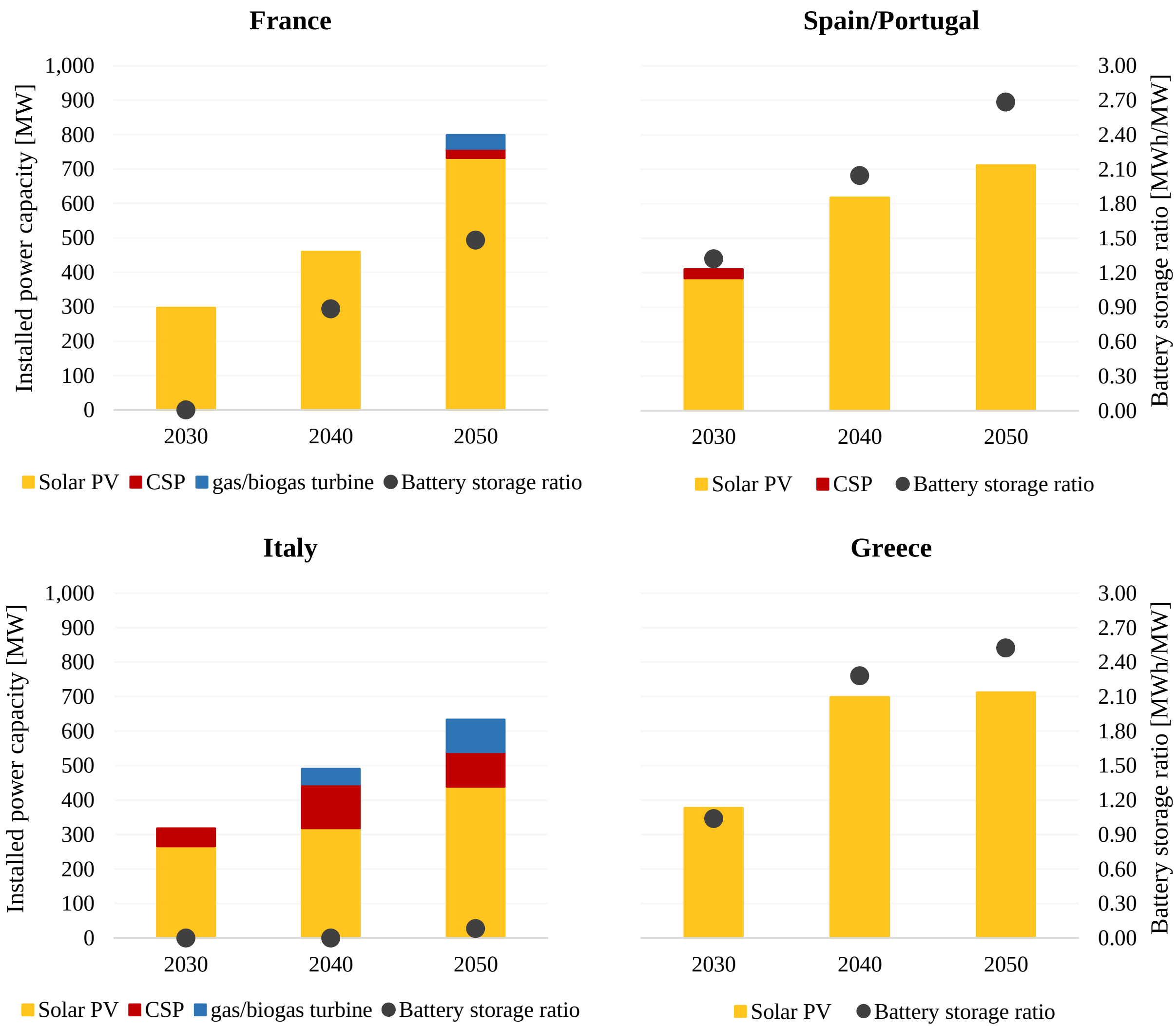

Figure 6. Composition of hubs overtime in the different locations for the CSP+ scenario.
Battery storage capacity is indicated in MWh for each MW of solar on the right axis.

It is interesting to evaluate the amount of BESS (lithium-ion batteries) installed with respect to the PV capacity in the hub. In the hybrid plants, energy storage is providing energy shifting service, allowing to charge during hours of high irradiation and discharge later in the day when power prices are higher. On average, across locations, the amount of MWh of storage needed for every MW of PV, which we refer to as Storage Ratio (SR), increases over time due to the aforementioned growing need for flexibility. Where batteries are installed, the SRs are around 1.5 in 2030, growing to over 2.5 in 2050. This means, for example, that on the Iberian Peninsula, it would be optimal to combine a 100 MW solar plant with 140 MWh of lithium-ion batteries in 2030 and 270 MWh in 2050.

It is also worth noting that in more outlying regions of the European power system, such as the Iberian Peninsula and Greece, the amount of storage capacity needed for each MW of PV installed is larger than that found in more interconnected countries such as France and Italy. Contextually, the higher solar penetration reached in the Iberian Peninsula and Greece, due to the abundant solar resource, contributes to a higher need for flexibility.

3.3. Hub functioning

Figure 7 shows the functioning of a five-piece hub including electric storage (Scenario CSP+, Italy, 2050). The total hub output, as well as the output of each component, is displayed as a duration curve, i.e., showing for how many hours during the year (x-axis) the power output was above a certain value (y-axis). As a consequence, the maximum power output (installed capacity) of a technology can be read at the intercept to the y-axis. The coordination among units within a SRH leads to very limited periods of inactivity with technologies at a standstill for less than 700 hours a year. This behavior boosts the capacity factor at the point of connection, which for the configuration presented reaches 68%. This is a relevant boost if compared to the CF of stand-alone PV (20-25%) and wind (40%).

For nearly 2,000 hours per year the PV production exceeds the capacity of the grid connection (200 MW); the largest part of this energy is curtailed and only a small quota is stored in batteries (dashed area). The power plant flexibility is rather provided by the thermal energy storage. The CSP block (Gridsol ST) runs at nominal power for more than 4,500 hours: the coupling with thermal energy storage and the design of field capacity with respect to turbine capacity (high solar multiples) makes it an intermediate load-supplying technology even in a country where the direct normal irradiation is lower than 2,000 kWh/m^2. The gas turbine (Gridsol GT) supplies power in hours of high demand, limitedly to 1,800 hours a year. The relative advantage with respect to a conventional gas turbine peaker is that heat is recovered and contributes to the output of the steam turbine. Both synchronous technologies tend to run at nominal power, minimizing the partial-load functioning. The overall hub output is constant and maximum for more than 2,500 hours per year; the production is variable for the remaining hours and follows the behavior of the other components. The shape is smooth, and the supply is dynamic, as the hybrid power plant reacts to the zonal market prices to maximize revenues.

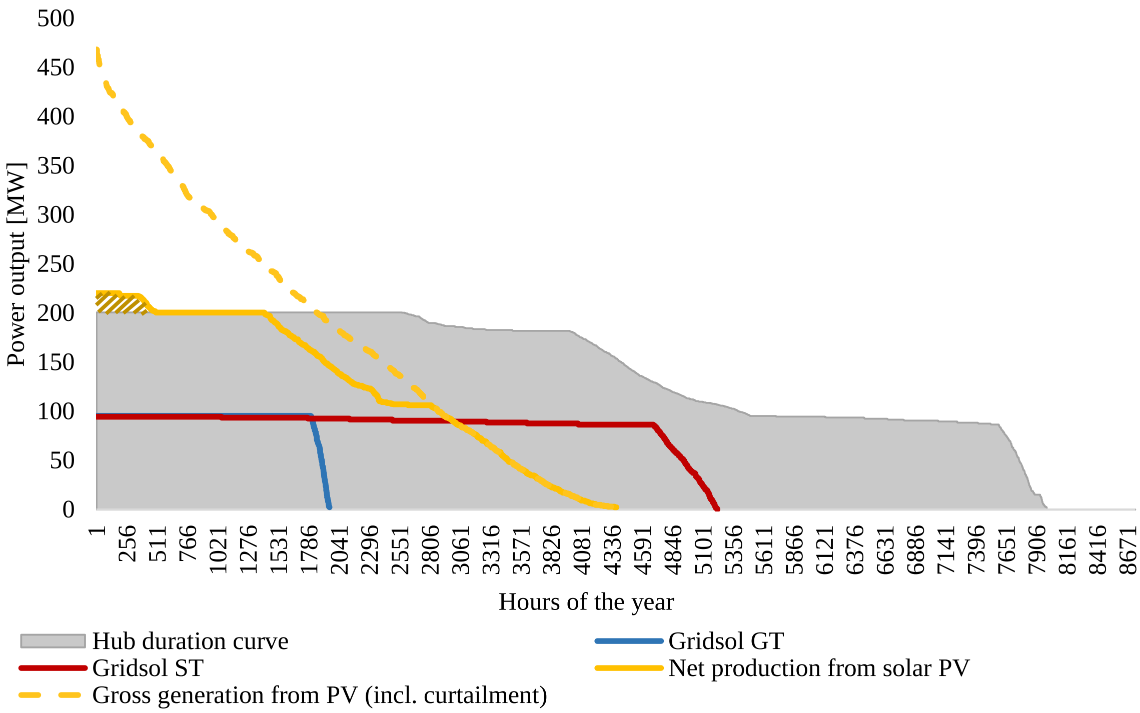

Figure 7. Generation duration curve for the Smart Renewable Hub and its components.

As can be noted in the graph, capacity of solar PV installed in the hub largely exceeds the capacity at the point of grid connection (200 MW), meaning that at no point in time the full rated PV capacity is dispatched to the grid, but a large part of it is curtailed (or stored).

When looking at CFs for all SRHs configurations (Figure 8), it can be noted that it is increasing overtime going from an average of 22% in 2020 to an average of 70% in 2050 across scenarios and locations. The level reached between 2040 and 2050 is comparable to those achieved by dispatchable conventional power plants in today's power system. The main driver for increased CF is the access to progressively cheaper energy storage capacity in the form of batteries or thermal storage. Indeed, countries like Spain, Portugal and Greece have consistently higher CF, that proportionally increase more through the years and can be motivated with the higher amount of MWh of storage per MW of PV, as shown above.

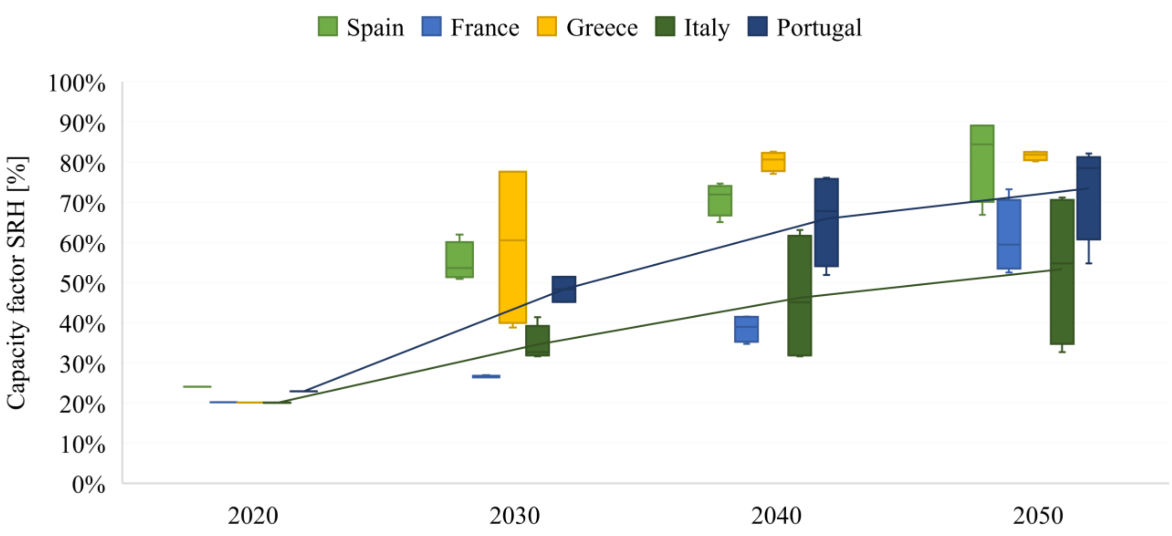

Figure 8. Evolution of capacity factor of Smart Renewable Hubs in different locations across scenarios (CSP+ scenario).

3.4. Storage flexibility

Under the cost and performance assumptions considered in this paper, the semi-dispatchable group PV+BESS demonstrated to be overall more competitive compared to the CSP block constituted by solar field, thermal storage and steam turbine, due to the very low projected price for PV and lithium-ion battery storage. However, when looking at the cost composition of such plants, it is clear that thermal energy storage has the potential to be a cheaper form of storage when shifting large share of the production for longer period of time.

As seen above, the model finds that it is optimal to install around 1 MWh of storage every MW of solar in the medium term and 2 MWh in the longer term. To assess the cost of providing more flexibility to the SRH, the Levelized Cost of Electricity (LCoE)[2] of the two groups PV+BESS and CSP is evaluated under different values of the storage ratio, using cost data for the year 2050 (Figure 9). The increased storage ratio indicates the capability for the system to store more energy during hours of high irradiation (supposedly lower price) and shift it to evening/night-hours (higher price). As a reference, a high value of the SR (e.g., above 6) allows to store the entire solar daily solar production and shift it to night-hours (full daily cycle) for most of the days in the year.

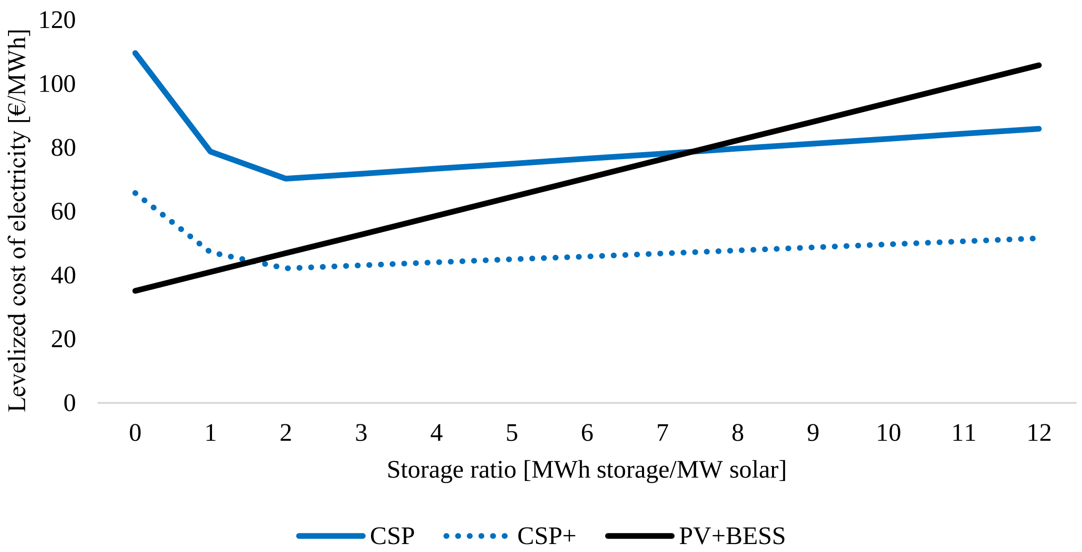

Figure 9. Levelized Cost of Electricity for different values of Storage Ratio. Comparison between CSP and PV+BESS.

[2] LCoE expresses the cost of the MWh generated over the lifetime of the plant and represents the life cycle cost. The assumed discount rate is 5% and the economic lifetime 20 years. For solar PV, FLH considered are 1,400, while for CSP 4,500, in line with values from the model.

The LCoE of CSP is not increasing significantly compared to that of PV+BESS when adding more flexibility in the form of additional MWh of storage, due to the lower cost of thermal storage compared to batteries. With reference assumption on the cost of CSP, the LCoE of PV+BESS is lower in every situation up to approximately a storage ratio of 7. This means that for daily cycles, using BESS in combination with PV is the cheapest solution. With the cost assumptions in the CSP+ scenario (cost reduction of 40%), CSP becomes the best solution for storage ratios above 1.6. This testifies the potentially diverse role of CSP compared to PV+BESS, i.e., providing a good alternative for storage cycles longer than one day and applications in which large amount of energy has to be shifted and stored for longer time horizons.

4. Conclusion

Following the pledge of decarbonization made by the European Union and the dramatic cost decline of renewable energy, the power sector in Europe is transitioning towards a future in which VRES will be dominant, covering above 70% of the total power demand. For CSP to play a sizable role in this transformation, strong cost reductions are needed to make it competitive with more mature technologies such as wind and PV, which still hold a potential for further cost decline. In this analysis it is anticipated that given a further cost reduction of 40% compared to the reference projection, CSP can meet 9% of the European demand and 23% in the five Southern European countries under focus. In a system in which the majority of power plants are non-dispatchable and have variable production patterns, flexibility will be the key to access higher market prices and make additional renewable projects profitable.

SRHs provide more stable generation due to the combination of various forms of generation and storage technologies, and thus are a potential solution to the need for flexibility at the generation side. In this study SRHs are characterized by a reduction in the installation cost due to synergies in the cost of connection to the grid.

The optimization of the composition of SRH in France, Italy, Spain, Portugal and Greece – countries for which CSP is a viable alternative – shows that the semi-dispatchable hybrid PV+BESS dominates the configurations between 2030 and 2050. Other technologies are added with limited capacity and only under specific resource and market conditions.

One of the main reasons is that organizing technologies in a hub reduces capital cost (lower cost of connection) and this favors capital-intensive technologies with relatively low investment cost per MW, such as PV and BESS. For these technologies, connection to the grid represents a higher share of total cost. Moreover, with availability of large storage capacity, PV is “overplanted” in the hubs: more capacity is installed compared to the rated capacity at the point of connection. This, in combination with smart management of storage and the diverse profiles of generating technologies can boost the CF of the SRH, which can reach values comparable to today’s conventional power plants. The average CF of the SRH simulated increases from 22% in 2020 to 70% in 2050.

The need for flexibility increases the storage capacity of the SRH, that tops 2.5 MWh for every MW of PV installed in countries with high solar irradiation in 2050. Moreover, this need for flexibility is influenced by the general solar penetration level in the country and the level of interconnection. The study also demonstrates that while PV+BESS is the best choice for daily cycles and to shift low amount of energy for short terms, CSP has a niche in situations in which all solar generation has to be shifted and stored for longer timeframes. This is due to the fact that thermal storage has a lower cost per MWh of stored energy.

To conclude, when looking at a pure cost perspective and focusing on the day-ahead market, the potential of CSP inside hybrid plants appears limited due to the very competitive nature of the alternatives such as PV+BESS and the reduced system need for energy shift beyond the daily cycles. A more aggressive CSP cost decline coupled with a lower decline in lithium-ion batteries cost could change the picture and favor CSP deployment. Moreover, other potential benefits not analyzed here could make CSP more attractive, for example the provision of ancillary services or the reduction of balancing cost due to the higher CF and more stable output of the CSP compared to PV.

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