Enhanced Features of Wind-Based Hybrid Power Plants

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***Abstract*—** The objective of this paper is to review and elaborate qualitatively and quantitatively the benefits of wind-based hybrid power plant (HPP) as compared to individual wind/PV power plant. A set of analyses are performed to assess annual energy production/capacity factor, power fluctuations and ramp rates of HPP production and to identify different operating conditions to understand the benefit of combining wind with solar and energy storage in an HPP. The analyses are performed based on spatio-temporally correlated wind power and solar power time series as well as on historical market price time series. Correlation of market price with wind-solar combined time series is exploited to assess the flexibility of having storage by moving the power production to hours where market prices are high from the hours when market prices are low.

Keywords- Hybrid power plant, wind power, solar power, energy storage

I. Introduction

The penetration rates of renewable energy sources (RES), such as wind and solar, have drastically expanded during the last years due to increased environmental concerns and market acceptance [1]. At the same time, the levelized cost of energy (LCOE) for onshore wind power and the prices for solar photovoltaics (PV) and storage are sharply reducing. Furthermore, the maturity of these technologies has resulted in severe diminution of subsidies and spot market prices, reducing revenues for renewable generations [2].

In the last few years, combining different RES, as wind and solar power with a storage system by leveraging their complementary nature and operation conditions, has become a general trend towards improvement of system efficiency and power reliability. For example, the variability and power fluctuations of individual RES can be reduced which is beneficial from the grid point of view. This facilitates the green transition by providing solutions to integrate higher penetration of renewable energy. Moreover, the presence of storage system makes power curtailment – previously an unthinkable economic burden for renewables to be a more viable scenario in the future power systems with large share of renewables in power grids.

Since the capacity factors of wind and solar power are generally low, electrical infrastructures like cables, converters, transformers remain unutilized for a large portion of time for individual wind or solar power. Combining wind and solar power provides the opportunity to optimally utilize these electrical infrastructures, increasing the annual energy production and thereby potentially reducing the LCOE. Moreover, seen from wind power plant developers' perspective, the idea to combine wind, solar and storage can enable entrance in new market for wind power [3], facilitating possible additional revenue streams, e.g. ancillary services. All these factors motivate the exploitation of potentials for combining different energy sources like wind turbine and solar PV with energy storage. Another benefit of combining wind and solar power from the system operator's point of view is better utilization of grid infrastructure and reduced congestion, thereby improving security of supply and system stability

A combination of wind and solar power for utility-scale hybrid power plants (HPP) has been getting global attention. Furthermore, a global trend is that different manufacturers are considering over-planting to increase the use of the already existing infrastructure. Recently, several industry members have been interested in developing HPPs. Vestas installed first utility scale wind-solar-battery Kennedy Energy Park Hybrid power plant in 2018 [3]. India has come out with National Wind-Solar Hybrid Policy and intends to launch 2.5 GW auction [4]. Juhl Energy leaded in 2017 a hybrid project in Red Lake Falls, Minnesota, using two 2.3-116 wind turbines from GE

Renewable Energy's Onshore Wind business supported by 1MW of solar power conversion equipment provided by GE's Current business [5]. Siemens Gamesa already provides hybrid power solutions, which allows for the integration of one or more renewable power generation assets with an energy storage system. Their first commercial On-Grid hybrid project combines a 29 MW solar system with a 50 MW wind farm and was installed 2017 in India [6]. Vattenfall has their first Hybrid Parks in operation (solar + wind & wind+ battery) in UK and NL while wind / solar + battery is under development [7].

A general movement in the industry is to develop utility-scale wind-based hybrid power plants (HPP) to maximize the profit from different markets (i.e. capacity market, energy market and ancillary services market through optimal design and operation of HPP) as compared to just minimizing the LCOE.

A plant combining wind, solar and battery energy storage is referred in this paper, as depicted in Figure 1, as utility scale co-located grid connected HPP, being characterised by:

- All the assets are owned by the same company so higher controllability
- Motivation is to maximize profit from different energy markets
- Control of electrical load is not of concern of the plant owner as compared to traditional hybrid power systems.

It operates as grid integrated power plant unit to serve the needs of the bulk power system and energy system environment.

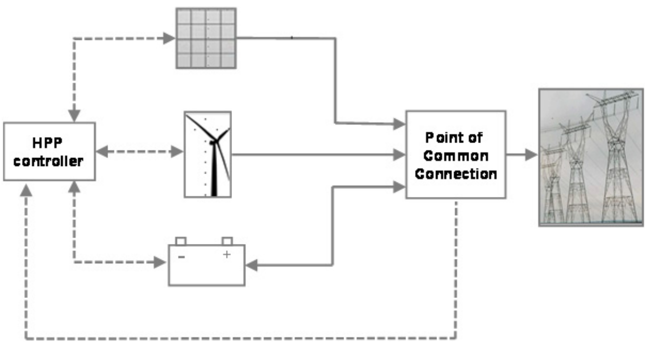

Figure 1: HPP –utility scale co-located grid connected

A utility scale HPP can have the advantages as compared to an individual technology-based power plant in terms of:

- reduction in variability
- increase in availability
- increase in capacity factor
- reduction in cost
- increase in revenue
- increase in ancillary service capability
- increase of lifetime of the wind turbine.

Furthermore, as described in [8], an HPP is also of providing power smoothing, production loss minimization, and sudden power injections to help in the frequency regulation.

However, all these capabilities and advantages are highly dependent on cost benefit analysis, and thus on grid, market and available resources at a given location.

To the best of authors' knowledge, the available literature on HPP is quite poor in different topics like assessment of the annual energy production/capacity factor, power production ramp rates, power fluctuations. Many questions like, which service to prioritize, how to ensure that the common grid connection is not overloaded in case of overcapacity, grid code compliance, which unit should be curtailed first, will be necessary to answer through thorough research to enhance the HPP capabilities as attractive sustainable energy solutions in the next few years.

II. ENHANCED VALUE OF HPP

To understand the enhanced value of HPP different studies in terms of capacity factors, variability, curtailment, value of storage etc. It should be noted that the value of HPP is enhanced when the evacuation capacity to the grid is limited. It can be interpreted that for limited grid connection, maximum weather resources should be used to generate maximum power close to the evacuation capacity to maximize revenue. However, since the capacity factor of wind power is around 30 to 40% and that of solar power is less than 20%; therefore, the electrical infrastructure remains unused most of the time. Overplanting with wind turbines and/or solar panel may be a good option to better utilize the electrical infrastructure. Three locations in Europe are chosen to simulate the weather conditions using CorRES [9] to study the value of HPP over individual wind power plant (WPP) or solar power plant (SPP). Table 1 below illustrates the capacity factors (CF) for wind and solar power as well as their correlation for three different locations in Europe, i.e. a location in Denmark with high wind/low solar resources, a location in Sweden with low wind/low solar resources and a location in France with low wind/high solar resources. Notice the negative correlation between wind power and solar power in Denmark and Sweden. The stronger the negative correlation the better regarding e.g. utilization of the grid connection & balanced energy output.

Table 1: Capacity factor (CF) and correlation of wind and solar power

Location	Wind Power CF [%]	Solar power CF [%]	Correlation
Denmark (DK)	42	12	-0.1574
Sweden (SE)	24	10	-0.1206
France (FR)	32	16	0.0097

A. *Increase in capacity factor*

Increase in capacity factor can be observed when the evacuation factor is limited, and overplanting is done. In the following studies, evacuation capacity of 500 MW is assumed. For different mix of wind and solar power installed capacity, the capacity factors are calculated.

Table 2 Energy and Capacity Factor for different locations when the HPP is overplanted with Solar Power

Overplanting by Solar [MW]	Available Energy [TWh/yr]			Energy to grid [TWh/yr]			Curtailed Energy [TWh/yr]			Capacity Factor [%]		
	DK	SE	FR	DK	SE	FR	DK	SE	FR	DK	SE	FR
0	1.844	1.073	1.409	1.844	1.073	1.409	0.000	0.000	0.000	42.1	24.5	32.2
100	1.951	1.169	1.553	1.947	1.168	1.542	0.004	0.002	0.011	44.4	26.7	35.2
200	2.058	1.266	1.697	2.042	1.259	1.660	0.016	0.007	0.037	46.6	28.7	37.9
300	2.165	1.362	1.841	2.133	1.349	1.772	0.032	0.013	0.068	48.7	30.8	40.5
400	2.272	1.458	1.985	2.220	1.438	1.881	0.052	0.021	0.104	50.7	32.8	42.9
500	2.379	1.555	2.128	2.303	1.524	1.985	0.075	0.030	0.144	52.6	34.8	45.3
600	2.486	1.651	2.272	2.382	1.609	2.083	0.103	0.042	0.190	54.4	36.7	47.5
700	2.593	1.747	2.416	2.454	1.690	2.173	0.139	0.058	0.244	56.0	38.6	49.6
800	2.700	1.844	2.560	2.515	1.761	2.247	0.184	0.083	0.313	57.4	40.2	51.3
900	2.807	1.940	2.704	2.566	1.818	2.305	0.241	0.122	0.399	58.6	41.5	52.6
1000	2.914	2.036	2.848	2.608	1.867	2.352	0.305	0.170	0.496	59.5	42.6	53.7

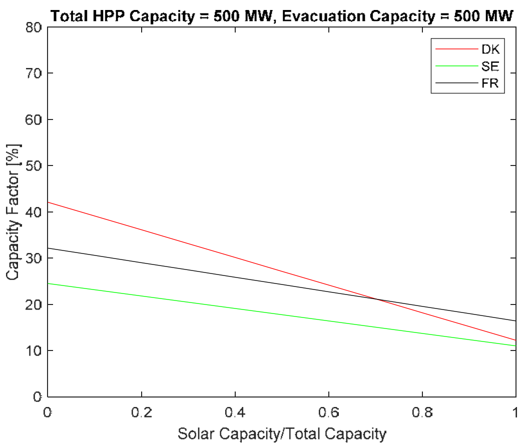

Figure 2 CF for different locations for different mix of wind and solar installation in an HPP

Figure 2 shows CF for different mix of wind/solar without overplanting. There is no advantage of mixing solar to WPP, since the CF is maximum with only wind power (although land and economic constraints not considered).

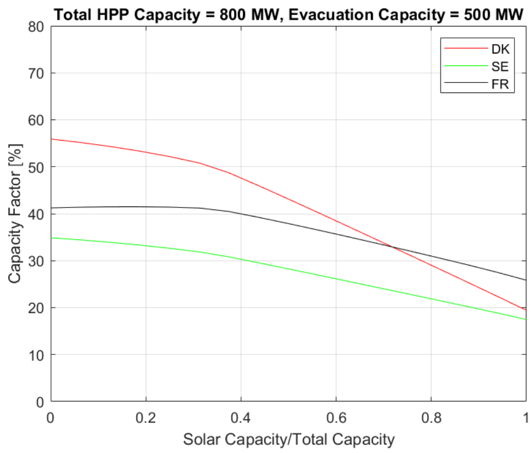

Figure 3 CF for different locations for different mix of wind and solar installation in an HPP with overplanting

Figure 3 shows CF for different mix of wind/solar with overplanting by 300 MW. It can be observed that again as expected, the value of overplanting in CF is more pronounced if overplanted with wind power. However, it can also be observed that when wind power is dominating in the mix (left part of the curves in Figure 3), the increase in CF is not linear. The reason for this is when wind installation is high, the curtailment required (due to limited evacuation capacity) is also high. This can be clearly observed in Figure 4.

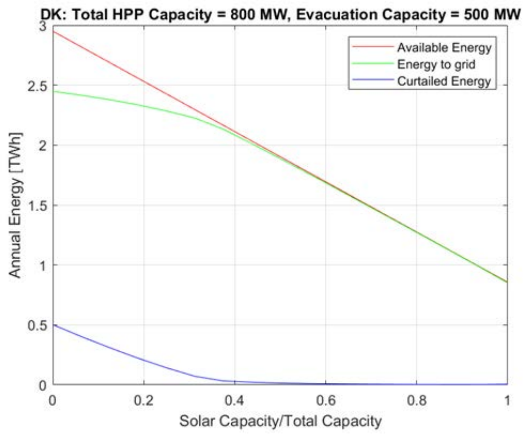

Figure 4 Available energy, curtailment and energy to grid for a simulated HPP in Denmark with overplanting

Table 2 demonstrates annual energy production, curtailed energy and capacity factor for different values of is twofold. Firstly, the CF of the solar power is low and secondly the negative correlation between wind power and solar power.

B. Reduction in variability

Due to their variable and fluctuating nature, individual RES is typically challenging the power system as they are driven by weather conditions and not by demand. The fact that daily as well as seasonal variability are inherent to both wind and solar resources may yield to additional stress on the electrical grid, curtailment of renewable generators and low or even negative power prices.

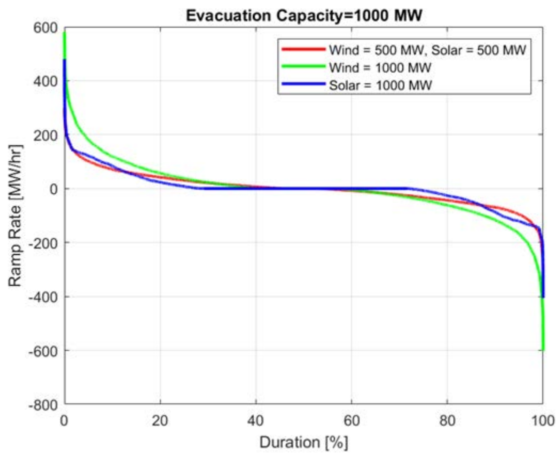

Figure 5 Ramp rate of HPP with total installed capacity = 1000 MW and evacuation capacity = 1000 MW

Figure 5 shows that the combination of wind and solar power reduces the variability (represented by ramp rates) as compared to individual WPP of same installed capacity. This is possible for less variability of solar power as compared to wind power. However, it should be noted that the cloud covering modelling in the input time series used for the simulation is rather simplistic and might have impact on the results (although cloud covering is very location specific). It can be observed, for example for 10%

From Figure 2 to Figure 4, it is clear that for the considered locations it might be beneficial to utilize wind power to generate power until evacuation capacity and henceforth, it might be useful to overplant using solar power to minimize the curtailment and maximum utilize the electrical infrastructure. It should be noted that detailed cost benefit analysis needs to be carried out to proper sizing of wind and solar power in an HPP taking many constraints into account such as land constraints, economic constraints, grid constraints etc. However, these studies presented here provides clear justification for overplanting when the evacuation capacity is limited.

overplanting with solar power. It can be observed that with increasing solar capacity, the capacity factor and annual energy production increases monotonously. However, curtailed energy is quite low. The reason for this of the time the wind power production has a ramp of 200MW/hour – this shows clearly that by mixing wind and solar photovoltaic units inside an HPP, the variability of the power is lower than the case when only wind units are present.

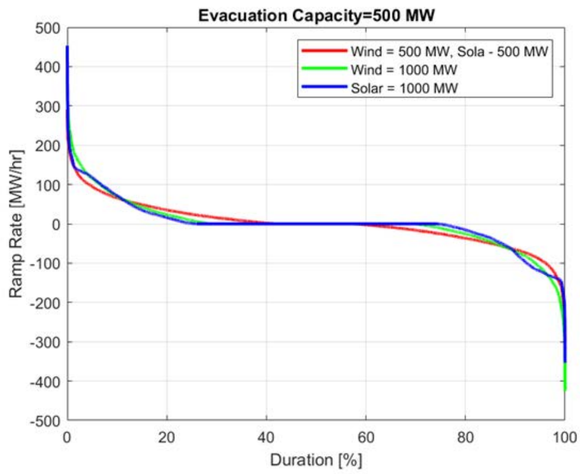

Figure 6 Ramp rate of HPP with total installed capacity = 1000 MW and evacuation capacity = 500 MW

However, this advantage of reduction of variability is diminished if there is substantial curtailment. Figure 6 shows the ramp rates when the installed capacity is 1000 MW and the evacuation capacity is 500 MW. As expected, the variability of wind power is reduced due to curtailment.

C. Increase in availability

The availability of wind and solar energy at a given location strongly depends on weather conditions. By combining the daily and seasonal complementarity in generation profiles of these technologies, a higher degree of annual energy production (AEP) and capacity factor (CF) is achievable by storing the excess energy production, which would otherwise be curtailed [3].

D. Cost reduction and revenue increase

Combining wind and solar power provides the opportunity to optimally utilize their electrical infrastructure and thus reducing the cost developing an HPP infrastructure (CAPEX). This cost can be furthermore reduced by installing batteries and PV units in already existing wind power plants and thus by joint usage of land, electrical infrastructure (i.e. converters, substation, grid connection) and the public infrastructure (i.e. access roads). However, such overplanting by adding new generation and storage units in already existing infrastructure can overload the point of common connection. To avoid this, in the development process of HPP, it is therefore crucial to have a deep understanding of the electrical infrastructure, site conditions, grid restrictions as well as interdependencies and ratio between wind and solar capacity in the given location. Besides CAPEX, the operational expenses (OPEX) can also be reduced simultaneous maintenance.

E. Increase in ancillary services capability

The presence of the battery provides the opportunity to access new markets, facilitating thus additional revenue streams, such as ancillary services. However, as the value of the subsidies for wind and solar has strongly decreased over the years, it becomes more and more crucial for plant operators and developers to optimize the assets to make HPP able to participate on the ancillary services market.

Possibility to increase the revenue by providing ancillary services in addition to the usual energy production has become an important topic discussed in the literature [3], [8], [10]. An HPP control and dispatch architecture for testing enhanced ancillary services on the Lem Kær demonstrator [1] is discussed in [3]. In [8], control strategy for HPP is proposed to enable HPP to provide frequency support in a system with reduce inertia, a large share of renewable energy, and power electronics-interfaced generation. For example in [10], it is proposed a day ahead optimization algorithm to show that there is a potential in providing ancillary services from all generation units in a HPP.

However, the research and documentation within this area is still in a pioneer stage and therefore significant improvements in the power and revenue forecasting are needed.

F. Increased dispatchability and flexibility using storage to maximize revenue from market

As mentioned earlier, overplanting has value in terms of utilization of electrical infrastructure. However, overplanting generally will require curtailment. This curtailment can be reduced using flexible storage capabilities. Furthermore, the storage also allows to optimize the dispatch schedule to maximize revenue from the market.

For example, Figure 7 shows the curtailed power for HPP with evacuation capacity of 500 MW; installed wind power of 500 MW and overplanting by solar power of 500 MW. The peak curtailment is beyond 300 MW in this case.

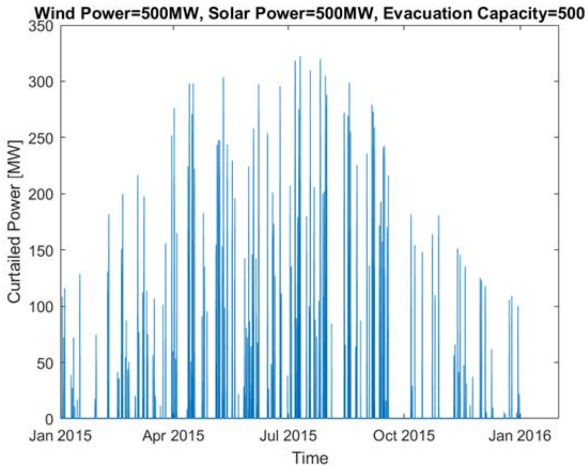

Figure 7 Curtailed power from HPP with installed wind power = 500 MW, installed solar power = 500 and evacuation capacity = 500 MW

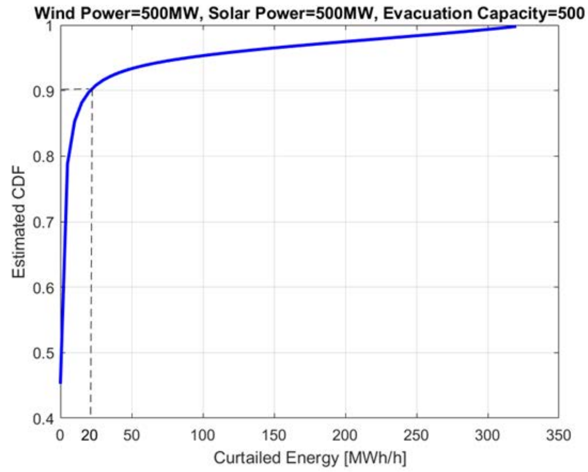

Figure 8 Estimated cumulative distribution for curtailed power

However, the cumulative distribution function shown in Figure 8 shows that 90% of the time the curtailed power is less than 20 MW in the simulated scenario. This shows that the power rating of the storage required is quite low to reduce the curtailment. Although the energy rating required for reducing the curtailment is not achievable from this curve.

Autocorrelation of the curtailment is shown in Figure 9.

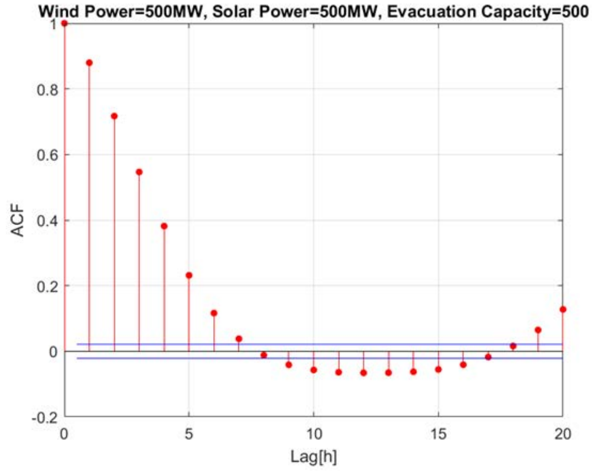

Figure 9 Autocorrelation function (ACF) for curtailed power

The ACF shows that the curtailed power has high autocorrelation for 2-3 hours. This signifies that higher the energy capacity, more curtailed energy can be captured.

Another important and interesting fact is the correlation of the curtailed power with energy price. In this regard, the historical market price from Nordpool market is correlated with the simulation using historical wind and solar data simulation. Figure 10 shows the scatterhist plot between curtailed energy and energy price. It can be observed that the price is low when high curtailment is done and vice-versa.

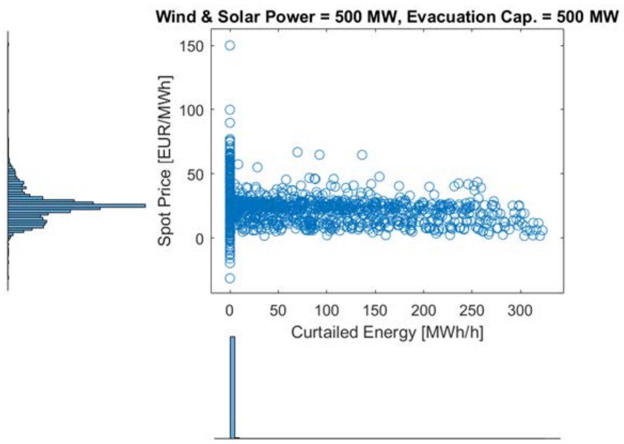

Figure 10 Scatter plot between Curtailed Energy and Energy price for a considered HPP location in DK

This information is very valuable for the HPP owner because the revenue can be increased by storing energy when the spot price is low and discharging the storage at times of high energy prices.

G. Increase of lifetime of the wind turbine

The lifetime of the wind turbine inside an HPP might be a relevant research area in the near future. A similar control approach to that described in [11], could be developed targeting to increase wind turbine lifetime by minimizing their loads by using PV and battery whenever it is feasible. For example, the production responsibility can be taken by the solar and storage whenever wind turbine loads are high and weather conditions are permitting this.

III. CONCLUSIONS

HPPs are sustainable energy solutions in which wind energy is complemented by solar energy and/or energy storage. There are multitude of feature enhancements as compared to individual wind or solar power plants. The values become more and more pertinent with reduction of prices for wind and solar technology. The values of HPP not only lies in the cost reduction and revenue maximization for HPP owner but also in providing system services and congestion reduction for power system. However, the research in utility scale grid connected VRE based HPP is still in nascent phase and the more flexibility and benefits need to be explored further.

ACKNOWLEDGMENT

The authors acknowledge support from the Indo-Danish HYBRIDize project for this work. This work has been supported by Danish Innovationsfonden.

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