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Das, Kaushik; Cossu, Alessandra; Sørensen, Poul Ejnar; Murcia Leon, Juan Pablo

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Component sizing of an utility-scale hybrid power plant

Kaushik Das, Alessandra Cossu, Juan Pablo Murcia Leon, Poul Ejnar Sørensen
Wind and Energy Systems
Technical University of Denmark
Denmark
kdas@dtu.dk, jumu@dtu.dk, posq@dtu.dk

***Abstract*—A Hybrid Power Plant combining wind and solar generators with battery energy storage system is analyzed in this paper. The objective is to determine the rated capacities of the technologies which yield the maximum revenue stream while ensuring a feasible investment. Therefore, a mathematical model to maximize the Net Present Value is implemented which is applied for a realistic case study of a peak power plant in India.**

***Index Terms*—battery, hybrid power plant, sizing, solar, storage, utility-scale, wind**

I. Introduction

Increased interests in renewable energy sources (RES) to mitigate the impact of climate changes, allowing electrification of different energy sectors, and enhanced energy security is posing stress to power systems all around the world. An hybrid power plant (HPP) comprising of wind, solar and/or storage is becoming a potential (and important) energy generation solution in the future energy mix. HPP allows for integration of larger volume of RES through single grid connection point among many other benefits [1], [2]. Two main objectives of HPP can be pursued from the plant owner point of view: develop economies of scope, namely reduce LCOE by a more efficient exploitation of resources and infrastructures, and increase profitability [3]. The coupling of solar and wind technologies is still potentially convenient in terms of power delivery strategy. For instance, with high wind penetration in the market, prices peaks occurrence can be inverse to high wind production occurrence, but revenues can still be obtained through the sell of solar production [2].The revenue stream opportunities of HPPs depend on the market structure: capacity market, energy market and ancillary services. Although all the mentioned markets are potentially suitable for HPP, they require great reliability, while the energy markets, both day-ahead and real time, are currently the dominant source of revenue. Revenues are either based on price fluctuations over time, feed-in tariffs incentives or power purchase agreement [3], as in the case study analysed in this work. In [2], examples of existing and under construction hybrid power plants are indicated, where wind-solar ratio is fairly variable, it depends mainly on the location resources.

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The sizing methodologies usually applied present different levels of complexity, according to which they are listed as follows: probabilistic, graphic, analytical, iterative, artificial intelligence and hybrid [4]. Very few examples of sizing and operation of utility-scale Wind-Solar-Battery HPP have been found in the literature barring a few examples in very recently [5]. This paper develops a simple methodology for component sizing of a wind-solar-battery based HPP which is applied for peak power generation. Detailed analysis including sensitivity studies are performed to assess the value of HPP for realistic case studies.

II. Methodology

A simple methodology is developed in this paper for component sizing of a RES based HPP for providing peak power in Indian power system based on a peak-power tender from 2019 [6]. It is assumed that the grid connection capacity is limited to 300 MW without any limitations in land availability.

A. Input data

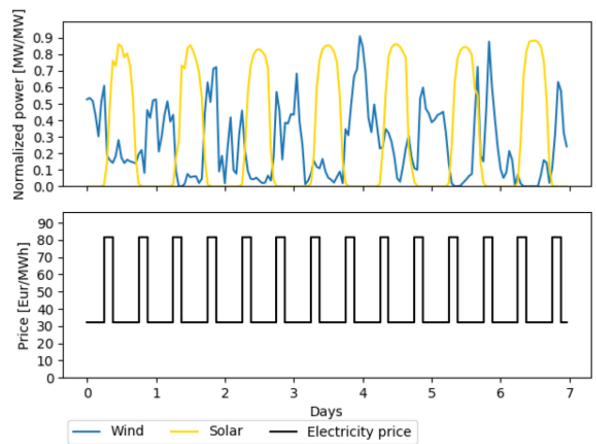

Fig. 1. Correlation between base case price profile and wind and solar power normalized time series over a week

a) Renewable Power Generation and Electricity Price Profile: The wind and solar power time series measurements are collected for two utility-scale wind and solar power plants in India placed few kms away from each other for 1 year. The capacity factors of the wind and solar power plants are calculated to be 29.5% and 23.5% respectively. For simplicity purposes, it is assumed that the load peak hours could occur in the first hour of the morning (6-9) and the first hours of the evening (18-21) as per the tender requirement in [6]. Fig. 1 depicts both price profile and wind and solar normalized time series over a sample week to demonstrate which resource is more correlated with the peak price hours and which one is expected to benefit more from an energy shift in time.

b) Capital cost: The capital cost is the crucial factor influencing the sizing of the HPP. It is composed by the investment cost for each technology and the Balance of System (BoS) costs related to the entire plant. The latter are deduced by looking at the cost elements for each single technology and then only addressed once for the entire system. For instance, since there is a point of common coupling, there is only one direct grid connection for the whole plant. The grid connection cost usually includes [7]: medium voltage cables and connectors, switch gears and control boards, transformers, substation and housing, meter. Costs are divided in three main categories: hardware, installation and soft cost. Hardware and installation costs except grid connection costs, are taken into account as costs singularly related to the PV panels. Indeed, those include components specifically related to the PV construction and installation, such as modules, inverter, racking and mounting for assembling the panels and DC and AC cabling. It is interesting to note that one of the plausible configurations, where battery and PV are coupled with the wind turbine inverter, would require only one DC-DC converter, eventually contributing to a cost reduction.
Soft costs include typical costs related to the installation of a renewable plant: margin, financing costs, system design, permitting, incentive application and costumer application. For instance, permitting involves all costs for permits necessary for developing, construction, operation and environmental regulations which are needed for all the HPP technologies. Therefore, in this paper, soft costs of are assumed as BOS costs shared between PV and WT.

The capital cost breakdown of onshore wind power plant is divided in four main components [7]- a) Turbine cost: rotor blades, gearbox, generator, power converter, nacelle, tower and transformer; b) Civil works: construction works for site preparation and foundations for towers; c) Grid connection costs: transformers, substations and connection to the local distribution or transmission network; d) Planning and project costs: development cost and fees, licenses, financial closing costs, feasibility and development studies, legal fees and construction management.

Based on their function, each component of BESS is categorised as Battery components, Grid connection components and components for control of the System operation. The battery components usually scale with nominal energy capacity while the grid connection components scale more with the battery power rating. For this reason, the storage capital costs are divided between the ones related to the energy capacity and the ones related to power capacity. Energy related costs [8]- Battery pack cost: Cells, modules and battery management system. Power related costs [8]- a) Power Conversion System cost: power electronics such as inverter and its packaging; b) Grid control management system cost: Control and monitoring of power electronics, thermal management of power electronics; c) Balance of Plant cost: components such as site wiring and interconnecting transformers.

c) BESS Operation and Maintenance cost: It consists of - a) Variable O&M [€/kWh-year]: battery energy related costs since is based on the annual energy discharge throughput. Costs necessary to operate the storage system throughout the duration of its economic life considering its wear and tear [8]; b) Fixed O&M [€/kW]: all costs necessary to keep the storage system operational throughout the duration of its economic life that do not fluctuate since these are not dependant on the energy usage, hence energy capacity deterioration [8]; c) Battery capacity maintenance cost [€/kWh]: refers to the battery installed capacity that represents an amortised capacity replacement cost over the years [9].

d) RES Operation and Maintenance cost: Considering that wind and solar power plants have no fuel costs, their operation and maintenance costs are quite low. In the latest years these costs have followed a downward trend thanks to improved design and manufacturing. As a result, newer technologies require fewer maintenance interventions than the older ones. For this reason, in this work the Variable O&M costs are disregarded and only fixed OM are considered [10] [11]. Indeed, according to [12], 75 % of the total yearly wind turbine O&M costs are assumed to be fixed cost (14000 €/MW/year) and 25 % are assumed to be variable cost. Variable O&M cost is equal to while Fixed O&M cost (1.5 €/MWh). While PV panels only have fixed OM costs: there are no moving parts, only the tracker systems, and no wear and tear. The replacement cost of the inverters should eventually be taken into account, which lifetime is shorter than PVs lifetime, typically 10-15 years [12].

TABLE I
WIND AND SOLAR COMPONENTS COSTS, GRID CONNECTION COST REFERRING TO GRID CAPACITY AND SOFT COST REFERRING TO THE TOTAL SOLAR AND WIND CAPACITY. ALL COSTS ARE IN €/MW.

Wind cost	€/MW	PV cost	€/MW	Shared cost	€/MW
WT	851k	PV	219k	Soft costs	120k
Civil works	117k	Hardware, Installation	242k	Grid connection	37k
Fixed O&M	12.8k	Fixed O&M	8149		

TABLE II
BATTERY ENERGY STORAGE SYSTEM COST COMPONENTS.

Battery Energy Storage System				
Power coversion system [€/MW]	Electric BoP, installation, commissioning [€/MW]	Grid management control system [€/MW]	Battery pack, Battery management system [€/MWh]	Capacity maintenance [€/MWh]
64k	73k	18k	181.5k	10k

Table I shows the capital cost assigned to each component and installation phase. The following costs are assumed to be equal to the data extracted from IRENA 2018 database for

India [13]: wind turbine, planning, civil works, PV Hardware, installation and soft costs, grid connection. The HPP elements configuration was out of scope in this work, therefore no further assumptions on the sharing of other cost elements can be stated. For this reason, the hardware balance of system costs are related to each technology separately. Table II indicates the cost components of the BESS. The battery costs, except the capacity maintenance cost, are assumed to be the values on the lower end of the range of average costs of Lithium-Ion batteries [9]. Indeed, its cost trend is decreasing and it is projected to be significantly lower up to 2030 [14]. The capacity maintenance cost represents the amortised battery replacement cost. It indicates the yearly amount paid referring to the battery energy installed capacity. It is assumed to be equal to the highest cost found in [9].

e) Discount rate and Lifetime: A discount rate equal to 7% is assumed [15]. Maximum lifetime for Wind turbines is generally assumed to be 25-27 years for recently constructed large wind turbines on land and it is expected to reach 30 years by 2030 [10], [12]. Large scale PV utility systems have a technical lifetime that ranges between 30-35 years and is expected to reach 40 years by 2030. In this paper, total project lifetime of 25 years is assumed.

B. Optimization

The following equations define the objective function and the equality and inequality constraints of the mixed-integer linear optimization problem.

$$\begin{aligned} Max. \quad NPV = \sum_{n=1}^{N} \frac{\sum_{t=1}^{T} p_t \cdot P_t^{HPP}}{(1+r)^n} - \frac{c_{bm} \cdot E_{batt}}{(1+r)^n} \\ - \frac{c_{wm} \cdot P_{Wind} + c_{sm} \cdot P_{Solar}}{(1+r)^n} \\ -(c_w \cdot P_{Wind} + c_s \cdot P_{Solar} + c_{BoS} \cdot (P_{Wind} + P_{Solar}) \\ + c_{grid} \cdot P_{grid} + c_{b1} \cdot E_{batt} + (c_{b2} + c_{b3} + c_{b4}) \cdot P_{batt}) \end{aligned} \tag{1}$$

$$s.t. \quad P_{Wind} \geq 0 \tag{2}$$

$$P_{Solar} \geq 0 \tag{3}$$

$$E_{batt} \geq 0 \tag{4}$$

$$P_{batt} \geq 0 \tag{5}$$

$$P_c \geq 0 \tag{6}$$

$$-P_{batt} \leq P_t^B \leq P_{batt} \quad \forall t \in T \tag{7}$$

$$P_t^{HPP} = P_t^{Wind} * P_{Wind} + P_t^{Solar} * P_{Solar} + P_t^B - P_t^c \quad \forall t \in T \tag{8}$$

$$0 \leq P_t^{HPP} \leq P_{grid} \quad \forall t \in T \tag{9}$$

$$SOC_{t+1} = SOC_t - P_t^B \cdot \Delta t \quad \forall t \in T \tag{10}$$

$$E_{min} \leq SOC_t \leq E_{batt} \quad \forall t \in T \tag{11}$$

$$SOC_0 = 0.5 * E_{batt} \tag{12}$$

$$SOC_T = SOC_0 \tag{13}$$

a) Sets: Set T includes the total amount of hours in the time frame considered for power time series and prices, which is one year in this paper. Set N is the project lifetime over which the discounted cashflows are calculated.

b) Parameters: p is the hourly electricity price [€/MWh]. c_w,c_s [€/MW] and c_{b1} [€/MWh] represent the capital cost corresponding to the rated capacity of each HPP asset. c_{b2}, c_{b3} and c_{b4} [€/MW] are the battery costs related to its power capacity: power conversion system cost, Electric BoP cost and Grid management control system cost respectively. r is the discount rate. P_{grid} is the nominal grid connection capacity [MW]. c_{bm} [€/MWh] represents the amortised battery maintenance cost over the project lifetime. P_t^{Wind} and P_t^{Solar} are the hourly wind and solar normalized power outputs. E_{min} is the minimum SOC value expressed in [MWh]. It is based on the depth of discharge (DOD) of the battery:

$$E_{min} = (1 - DOD) * E_{max} \tag{14}$$

c) Decision variables: P_{Wind} indicates the rated wind power capacity [MW]. P_{Solar} indicates the rated solar power capacity [MW]. E_{batt} indicates the rated battery energy capacity [MWh]. P_{batt} indicates the rated battery power [MW]. P_t^{HPP} is the power flow of the HPP to the grid at each time unit t. It can be obtained by direct wind and solar energy production and additional battery supply in case of discharging or direct power reduction in case of charging or power curtailment[MW]. P_t^B is the amount of charged power into the battery when it takes negative values and discharged power for positive values [MW] at each time unit t. P_t^c represents the power curtailment when the total HPP output exceeds the grid connection power limit (P_{grid}) [MW] at each time unit t. SOC_t represents the state of charge in [MWh], namely the amount of energy stored in the battery at each time unit t.

d) Equations: Equation 1 shows the objective function to be maximized: the NPV formula. It is expressed as the summation of the ratio of discounted cash flows. Equations 2, 3, 4, 5 are bound constraints which set the minimum rated wind and solar power capacity, battery rated energy capacity and power rating respectively. Equation 6 implies that the variable indicating the amount of power curtailed can only be positive. It is equal to the difference between the sum of wind,solar and battery supply and the P_{grid}, but it corresponds to excess power only when this difference is positive. Equation 7 limits the single power discharge/charge to be within the maximum power that the battery is able to allow instantaneously. It is either negative, zero or positive when charging, idle or discharging respectively. Equation 8 sets the final power dispatch of the HPP. Equation 9 indicates the boundaries of the HPP output. Equation 10 determines how the amount of energy stored in the battery changes after either a charging, discharging or idle occurring during a time interval Δt. Δt in this case is considered to be one hour. Equation 11 ensures that the level of energy in the battery is within the battery min and max energy capacity to avoid overcharging or deep discharging of the battery. Equation 12 imposes the initial state of charge of the battery which is assumed to be half of the energy capacity allowing room for both charging and discharging. Equation 13 imposes that the final state of charge at the end of the year equals the initial one. It ensures correct performance of the battery, since the total energy charged should equal the total energy discharged at the end of the time frame considered [16].

Implementation of the methodology is carried out in python with CPLEX solver using the Python library Docplex [17].

III. Results

A. Optimal Solution

The optimal wind and solar capacity, battery energy and battery power capacity to be installed in order to obtain the maximum NPV has been found to be 171 MW of Wind, 378 MW of Solar and 83 MW /271 MWh of BESS. The battery integration allowing energy shifting and the solar investment cost lower than the wind investment cost [€/MW], are the potentially influencing factors determining a solar installed capacity greater than the wind capacity. The contracted capacity is 300 MW, but over-planting of 83% is enforced for optimal leverage of wind and solar anti-correlation. Since the battery power rating (i.e. the inverter rating) is the nominal power which can be instantaneously delivered, its maximum threshold is almost equal to the power grid limit. Fig. 2 illustrates how hourly power charge/discharge occurs over one day and modifies the potential power output given by the sum of solar and wind production for each hour. Both power curtailment avoidance and energy arbitrage effects can be observed. Power is discharged during the time ranges between 6-9 and 18-21, which correspond to peak price intervals. Whereas, the power output at off-peak hours, is reduced by storing a certain amount in the battery and then dispatching it over the peak hours. In this case, during morning peak hours, the grid limit between 8 and 9 is almost reached by the solar and wind production. During that time the battery only dispatches 26 MWh. Hence, before the first morning peak hour (6-7), the battery is not required to be fully charged. The total energy required is 174 MWh, which the battery is able to provide with its SOC equal to 219 MWh at 6. Indeed, it only needs to continuously discharge power for two hours while its maximum duration is 3 hours at a nominal power output equal to 83 MW. Between 9 and 14, excess power generation occurs and power is recharged into the battery in order to avoid curtailment. At 14, the battery is fully charged. The full charge is only needed after 14, when the potential wind and solar power drops below the nominal grid capacity (300 MW). Subsequently, the battery SOC is again maximum at 18, able to supply additional electricity for the next three peak hours. The SOC curve then declines to the minimum SOC level that is equal to 27.1 MWh (calculated as in Eq. 14). It can be observed, however, that the nominal grid power is not reached during the evening peaks, due to the limited energy size and power rating of the battery.

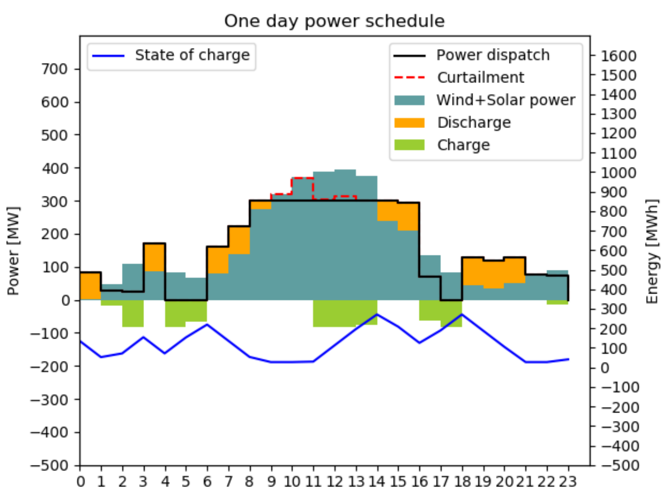

Fig. 2. Battery behaviour and final HPP power dispatch over a day

The CAPEX for this optimal solution is calculated to be 488 Mill.€, IRR to be 9%, LCOE to be 39 €/MWh and NPV to be 82 Mill.€. The observed LCOE is comparable to LCOE values for the single solar technology (29-53 €/MWh) and wind technology (35 €/MWh) found in [10]. Precisely, it is slightly lower than the values found for India: the weighted-average LCOE amounts to 44 €/MWh for onshore wind farms and 40 €/MWh for utility scale PV. It is reasonable to obtain a similar LCOE for the three combined technologies, considering that to a surge in total investment cost can correspond a higher annual energy production and more imporatantly high NPV and IRR through energy arbitrage. Summaries of annual production and capacity factors are provided in Table III.

TABLE III
YEARLY ENERGY GENERATION AND CAPACITY FACTORS FOR OPTIMAL HPP SOLUTION.

Potential wind-solar energy at nominal capacity	1219	GWh
Maximum potential energy at contracted capacity	2628	GWh
HPP Annual energy production	1199	GWh
Total energy discharge	227	GWh
Capacity factor	46	%
Full load hours	3997	Hours
Total curtailment	20	GWh
Potential wind and solar energy curtailed	2	%
Capacity factor during peak hours	54	%
Capacity factor during off-peak hours	43	%

B. Comparison of different technology mix

Table IV shows a comparison between the optimal HPP case (as discussed in previous subsection), optimized wind and solar configuration (without BESS), single solar plant and single wind plant with a fixed capacity equal to the grid limit (contracted capacity). The purpose of this comparison is to highlight some of the benefits determined by hybridization. It can be observed that Solar Power Plant (SPP) is cheapest source but does provide enough revenue as a peak power plant as can be seen with respect to low NPV (37 M€)as opposed to optimal HPP (82 M€). Wind Power Plant (WPP) is

TABLE IV
COMPARISON AMONG SINGLE PV PLANT AT FIXED CAPACITY, SINGLE WIND PLANT AT FIXED CAPACITY, WIND AND PV PLANT OPTIMIZATION AND WIND, SOLAR AND BATTERY OPTIMIZATION.

	Solar Contracted capacity	Wind Contracted capacity	Wind Solar Optimized	Optimal	Unit
Wind	-	300	129	171	MW
Solar	300	-	347	378	MW
Battery energy	-	-	-	271	MWh
Battery power	-	-	-	83	MW
Potential wind-solar energy at nominal capacity	617	775	1047	1219	GWh
HPP Annual energy production	617	775	1026	1199	GWh
Capacity factor	23	29	39	46	%
Full load hours	2057	2584	3421	3997	Hours
Total curtailment	0	0	21	20	GWh
Potential wind-solar energy curtailed	0	0	2	2	%
LCOE	29	38	32	39	€/MWh
NPV	37	36	72	82	M€

neither cheaper than SPP in the considered weather condition although it has higher CF than SPP. Wind-Solar HPP can still provide much higher profit as a peak power plant as compared to individual technology power plants. Wind-solar HPP has a curtailment of 21 GWh. Interestingly, optimal HPP only reduces this curtailment by 1 GWh with the help pf BESS. This indicates that the BESS has the main role for energy arbitrage and not reduction of curtailment for the considered peak-power plant case study.

C. Comparison with different price profile inputs

TABLE V
RESULTS COMPARISON FOR DIFFERENT PRICE PROFILE INPUTS.

	Optimal	Market Prices	Evening peaks	Unit
Wind rated capacity	171	0	316	MW
Solar rated capacity	378	377	210	MW
Battery energy capacity	271	0	0	MWh
Battery power rating	83	0	0	MW
Potential wind-solar energy at nominal capacity	1219	775	1248	GWh
HPP Annual energy production	1199	761	1225	GWh
Capacity factor	46%	29%	47%	%
Full load hours	3997	2536	4084	Hours
Total curtailment	20	14	23	GWh
Potential wind and solar energy curtailed	2%	2%	2%	%
CAPEX	488	233	485	€
IRR	9%	11%	8%	%
LCOE	39	29	36	€/MWh
NPV	82	95	51	M€

Table V compares the optimal results to the results obtained with different price profile inputs: the market price profile and the PPA price based profile with only evening peaks. The first remarkable observation is that the battery installation is feasible only in the optimal case. There is always a trade off between the value added by the battery energy shifting and its investment cost. In the market price scenario, only PV plant is installed. This implies that the value of HPPs are limited without additional financial benefits in the considered location/condition. The case with the evening peaks price profile, confirms that a wind-solar HPP is an optimal solution. The solar rated capacity is lower than the other two cases while the wind rated capacity is higher. The Market price scenario determines the highest NPV despite the installation of only solar capacity and 29% capacity factor.

D. Sensitivity Analysis

Sensitivity analysis is carried out in order to assess the robustness of the results. Indeed, several risks are involved in this project. Technical risks include the reliability of generation due to dependence on weather, efficiency and maturity of the technologies, unforeseen costs of operation, due to battery degradation for instance. Economic risks include obtaining access to financing sources as equity and debt and reasonable interest rates, market risks due to uncertain and partially controllable volume production and market prices volatility in case of direct participation to spot or balancing market.

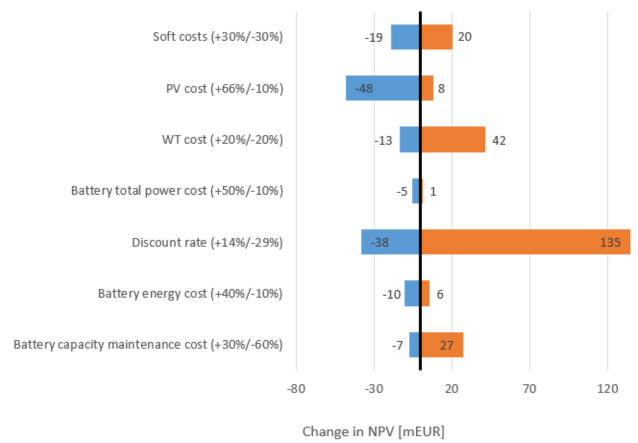

Fig. 3. Input parameters variation range and corresponding change in NPV

The tornado diagram in Figure 3 proves how the NPV is particularly responsive to a change in the discount rate. The lower bound of the range deviate by 29%, corresponding to a discount rate of 5%. Since renewable energy projects are typically characterized by a considerably elevated risk of investment, it would be quite optimistic to reckon a further lower value. The chosen upper deviation corresponds to a discount rate of 8%, since a higher value would be equal to the IRR. Its impact is quite significant, but still allowing a total NPV of 44 M€. Since the discount rate really depends on the type of investors and its trust in the reliability and feasibility of the project, it is reasonable to believe that there could be an improvement of 134.66 M€in the NPV, leading to a total estimate of the NPV approximately equal to 217 M€. Hence, from an economic point of view, this single parameter decrease would probably lead to one of the best project models. The WT cost reduction would also benefit the profitability of the project, in fact it is the most expensive technology considered. Other parameters have rather limited impact on the NPV.

Figure 4 shows the variation in battery energy capacity installed in response to a change of the aforementioned parameters and corresponding ranges. The PV cost or WT cost increase determines a lower battery energy capacity installed since the total CAPEX has to be kept within a certain threshold to ensure positive NPV. It is interesting to discover that both upper and lower values of WT cost lead to a decrease in

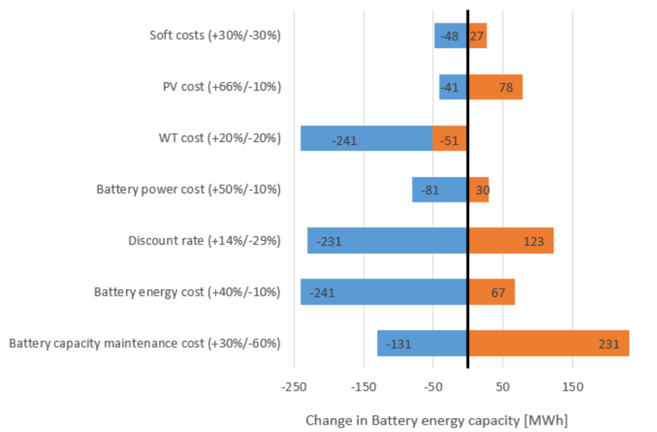

Fig. 4. Input parameters variation range and corresponding change in battery sizing

battery rated energy. The lower deviation scenario is intuitively explained by the fact that wind has a relevant average level of production distributed over all the hours of the day, therefore it is always convenient to prioritize its installation instead of the battery. As expected, battery energy and capacity maintenance costs have a greater impact than the total battery power cost. Looking at the discount rate, it can be noticed that its increase has a great impact on the battery energy rated capacity as well.

IV. Conclusion

The investment on a HPP combining wind, solar and battery technologies turns out to be profitable for the case study considered. Particularly, the PPA conditions are currently required to guarantee the viability of the project, considering that hybridization is not an optimal solution in the market price scenario. In the optimal case, the three assets synergies enhance reliability and efficiency of the plant. Overplanting of wind and solar capacities is the optimal outcome to leverage the complementary nature of the two sources. A common grid connection point and the recent lower costs of renewable generators and battery, guarantee a feasible initial investment. The PPA peak/off-peak conditions induce the battery to operate energy arbitrage, yielding higher revenues than the single technology plants or the sole combination of wind and solar. The increase in capacity factor enhances the reliability of the plant, lowering the uncertainty and risk on the business model.

In general, the developed sizing optimization model serves for an initial screening of the characteristics of the HPP that determine a viable project. However, advanced methodologies need to be developed considering different aspects such as battery degradation, selection of turbine technologies, uncertainties, different market participation, etc. Many of these issues and features are considered in detailed analysis in [18] and are implemented in DTU's HyDesign tool.

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