

Capacity Value of Wind Powered Pumped Hydro Storage Virtual Power Plants

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Abstract— This paper aims to shed light on the capacity value (CV) of wind-powered pumped hydro storage (PHS) Virtual Power Plants (VPP). A reliability-oriented methodology to approximate VPP operation is developed and incorporated into a resource adequacy assessment model built upon the sequential Monte Carlo simulation technique. The CV of the VPP is quantified through the Equivalent Firm Capacity metric. Further, a distinction is made between the capacity value of the virtual plant and its constituents, aiming to furnish insights into the specific contribution of each component to the overall capacity-oriented performance of the VPP. Several VPP configurations with different PHS and wind farm capacities are examined, utilizing the Greek power system as a case study. Results demonstrate that such VPP establishments can effectively contribute to capacity adequacy; indicatively, a virtual plant consisting of 1 GW WF and 1 GW PHS can claim a CV of up to 90%.

Keywords—*Virtual Power Plant, capacity value, resource adequacy, pumped hydro storage, wind farms.*

I. INTRODUCTION

The inherent stochastic nature of renewable energy sources (RES) generation is a substantial obstacle to their massive integration into power systems ([1]–[3]). To address such a challenge, Virtual Power Plants (VPPs) could provide a potential solution by aggregating diverse distributed resources, including RES and energy storage systems (ESS), under a unified management entity, [4]–[7]. In principle, the VPP concept foresees the coordination of decentralized resources to operate as a single, centrally controlled entity similar to conventional power plants [8]. In this sense, as the power systems move towards decarbonization, RES-ESS-based VPPs emerge as instruments to enhance renewable penetration by providing dispatchable generation. However, a critical concern for VPPs is related to their responsibility in ensuring capacity adequacy within a RES-ESS-dominated power system ([9]), a role that traditionally undertaken by thermal generators.

The contribution to system adequacy for RES and ESS assets is evaluated employing the concept of capacity value (CV), [10]–[13]. Alternative definitions are provided in the literature regarding the capacity value estimation, each calculated by different metrics [14]. The most well-established CV metrics include the equivalent firm capacity (EFC) and the effective load carrying capability (ELCC). EFC signifies the fully reliable generation unit that yields the same adequacy results as the asset under investigation [15], while ELCC represents the additional constant load that can be

accommodated by a system integrated the asset in question, maintaining the same adequacy level as the original system [16].

The effect of the joint operation of RES and storage portfolios on system adequacy and the capacity value that such establishments might achieve is discussed in the relevant literature ([17]–[27]). Several studies highlight that the operation of RES and energy storage under a common portfolio yields a notably greater contribution to system reliability than the independent operation of each asset [20], [25]. The beneficial role of ESS in amplifying the CV of RES installations when both assets are combined as a single market entity is also demonstrated in numerous studies [17], [18], [21]–[23]. However, it's worth noting that certain studies ([17], [18], [21], [23], [24]) stress out a saturation effect in CV as ESS capacity increases.

The literature explores the contribution to resource adequacy of different RES technologies combined with storage, assessing, at the same time, the sensitivity of the obtained results against the variations of various parameters. In [17], the CV of standalone wind farms (WF) and those combined with battery ESS is estimated, exploring the impact of WF and energy storage capacity. The capacity value of PV-plus-storage is examined in [18] considering different assumptions about the interactions between PV, storage and grid, while ESS of various sizes are also considered. Authors in [19] assess the CV of numerous battery energy storage configurations incorporated into a RES-based hybrid power plant operating in a non-interconnected power system. The CV of ESS coupled with PVs is estimated in [20] for different levels of PV penetration and various storage configurations. Similarly in [21], the contribution of both WF and PV accompanied with storage systems are calculated for different RES penetration conditions and storage power capacity. The CV of battery ESS embedded into a small WF operating in an autonomous island system is assessed for various storage configurations in [22]. Authors in [23] calculate the capacity value of a concentrating solar plant with thermal storage, for various configurations and different storage energy-to-power ratios. The CV of a given WF is calculated in [24] with and without battery storage of different energy capacities. In [25], the contribution of energy storage on the CV of a WF is calculated assuming different reliability targets for the system under investigation. Alternative operating policies for batteries incorporated within wind farms are implemented in [26] and [27], applying different objectives that include addressing system inadequacies, achieving specific levels of RES integration, or simultaneously pursuing both goals,

eventually demonstrating the substantial impact of the battery storage operation strategy on the resource adequacy of the power system.

This paper aims to investigate the capacity value of renewable-based VPPs comprising wind farms and pumped hydro (PHS) as a storage unit. In the examined configuration, the PHS has been designated to utilize only the wind power generated by the WFs belonging to VPP for charging, excluding the possibility of filling its upper reservoir from energy absorbed from the grid. To evaluate the contribution of VPPs to adequacy, the adopted operational strategy aligns with the principles of greedy approaches ([28]–[30]) that primarily focus on the mitigation of loss of load events, accounting for system assets' failures in real time. A heuristic algorithm is developed to simulate the operation of the VPP, suitably incorporated into a resource adequacy assessment (RAA) model. The RAA employs the sequential Monte Carlo simulation (SMCS) technique to introduce system assets' outages. The capacity value of VPP is quantified via the EFC metric. Various combinations of PHS and WF are examined to delve into the significance of RES and storage capacities in shaping the final capacity value of the VPP.

The structure of the remaining sections in the paper is as follows: Section II presents RAA model and the methodology utilized for the VPP's operation. Section III describes the case study system. The main findings of the study are provided and discussed in Section IV, while Section V summarizes the conclusions of the work.

II. METHODOLOGY

A. Monte Carlo-based resource adequacy assessment model

The RAA aims to estimate the traditional reliability index of EENS which is used as a reference for EFC calculation [13]. The SMCS method is employed for the RAA problem to introduce random failures of production assets. Multiple annual time-series of outages are constructed through this technique, representing the availability of thermal units, interconnections, and VPPs. The EENS index is calculated for numerous scenarios based on these annual availability patterns until it stabilizes around its actual value [31].

Equation (1) defines EENS by comparing the system's available conventional capacity ($ACC_{t,s}$) with the residual load ($R_{t,s}$) in each sample year of the SMCS. N_{SMCS} expresses the total number of SMCS samples executed until a high level of convergence is achieved in the SMCS process. $ACC_{t,s}$, defined in (2), includes the cumulative available net generating capacity of thermal units ($\sum_{u \in U} (a_{u,t,s} \cdot NGC_{u,t})$) and net transfer capacity of all available interconnectors to neighboring systems ($\sum_{i \in I} (a_{i,t,s} \cdot NTC_{i,t})$). The binary variables $a_{u,t,s}$ and $a_{i,t,s}$ indicate the availability status of thermal unit u and interconnection i in the SMCS sample s . Noted that the availability of VPP is included in variable $p_{t,s}^{VPP}$, which represents VPP power output. The residual load, presented in (3), is calculated by subtracting the production of RES stations ($\sum_{res} p_{res,t}^a$) and VPP from system load demand (p_t^d), which is further increased by the energy exported to neighboring systems ($\sum_{i \in I} a_{i,t,s} \cdot p_{i,t}^{exp}$).

$$EENS_{N_{SMCS}} = \frac{\sum_{s=1}^{N_{SMCS}} \sum_{t=1}^{8760} \max(0, R_{t,s} - ACC_{t,s})}{N_{SMCS}} \quad (1)$$

$$ACC_{t,s} = \sum_{u \in U} (a_{u,t,s} \cdot NGC_{u,t}) + \sum_{i \in I} (a_{i,t,s} \cdot NTC_{i,t}) \quad (2)$$

$$R_{t,s} = p_t^d - \sum_{res} p_{res,t}^a - p_{t,s}^{VPP} + \sum_{i \in I} a_{i,t,s} \cdot p_{i,t}^{exp} \quad (3)$$

B. Integrating virtual power plant operation into the RAA model

To estimate the contribution of wind-powered PHS VPPs to system adequacy, a reliability-driven operating policy is adopted. Under this strategy, PHS and WF cooperate to mitigate capacity inadequacy incidents. Specifically, PHS discharges exclusively during potential loss of load events, provided that wind generation alone is insufficient to meet the demand. Conversely, PHS is charged by the WF only when the power system's adequacy is not compromised.

The algorithm presented in TABLE I provides the mathematical formulation of the proposed method. The algorithm is constructed as a sequence of orders that define how WF and PHS work together to mitigate inadequacies while adhering to their technical constraints. Specifically, in case of no risk of loss of load before the action of VPP ($ACC_{t,s} \geq R_{t,s}^{bs}$), the available WF production is utilized to replenish the PHS upper reservoir, subject to the previous state of charge ($SoC_{phs,t-1}$) and the technical constraints of the storage station (line 3 of TABLE I), while any wind generation surplus is injected directly into the grid (line 5 of

TABLE I. Algorithm of VPP operation

Input: $\bar{p}_{phs}^{ch}, \bar{p}_{phs}^{disch}, SoC_{phs}^{max}, n_{phs}, a_{phs,t,s}, wf_t^a, ACC_{t,s}, R_{t,s}^{bs}$
Output: $p_{phs,t,s}^c, p_{phs,t,s}^d, SoC_{phs,t,s}, wf_{t,s}^{direct}, p_{t,s}^{VPP}$
1: for $t=1:8760$ do
2: if $ACC_{t,s} \geq R_{t,s}^{bs}$ then
3: $p_{phs,t,s}^c \leftarrow \min \left\{ wf_t^a, \bar{p}_{phs}^{ch} \cdot a_{phs,t,s}, \frac{SoC_{phs}^{max} - SoC_{phs,t-1}}{\sqrt{n_{phs}}} \right\}$
4: $p_{phs,t,s}^d \leftarrow 0$
5: $wf_{t,s}^{direct} \leftarrow \min \left\{ wf_t^a - p_{phs,t,s}^c, \bar{p}^{VPP} \right\}$
6: else if $ACC_{t,s} < R_{t,s}^{bs}$ then
7: $wf_{t,s}^{direct} \leftarrow \min \left\{ wf_t^a, \bar{p}^{VPP}, R_{t,s}^{bs} - ACC_{t,s} \right\}$
8: if $ACC_{t,s} < R_{t,s}^{bs} - wf_{t,s}^{direct}$ then
9: $p_{phs,t,s}^c \leftarrow 0$
10: $p_{phs,t,s}^d \leftarrow \min \left\{ R_{t,s}^{bs} - wf_{t,s}^{direct} - ACC_{t,s}, \bar{p}^{VPP} - wf_{t,s}^{direct}, \bar{p}_{phs}^{disch} \cdot a_{phs,t,s}, (SoC_{phs,t-1} - SoC_{phs}^{min}) \cdot \sqrt{n_{phs}} \right\}$
11: else
12: $p_{phs,t,s}^c \leftarrow \min \left\{ wf_t^a - wf_{t,s}^{direct}, \bar{p}_{phs}^{ch} \cdot a_{phs,t,s}, \frac{SoC_{phs}^{max} - SoC_{phs,t-1}}{\sqrt{n_{phs}}} \right\}$
13: $p_{phs,t,s}^d \leftarrow 0$
14: $wf_{t,s}^{direct} \leftarrow \min \left\{ wf_t^a - p_{phs,t,s}^c, \bar{p}^{VPP} \right\}$
15: end if
16: end if
17: $SoC_{phs,t,s} \leftarrow SoC_{phs,t-1,s} + p_{phs,t,s}^c \cdot \sqrt{n_{phs}} - \frac{p_{phs,t,s}^d}{\sqrt{n_{phs}}}$
18: $p_{t,s}^{VPP} \leftarrow wf_{t,s}^{direct} + p_{phs,t,s}^d$
19: end for

TABLE I). On the other hand, when the system encounters a capacity deficit ($ACC_{t,s} < R_{t,s}^{bs}$), the following rules apply:

- The available WF generation (wf_t^a) takes precedence in direct injection into the system ($wf_{t,s}^{direct}$) to minimize the unserved load without exceeding the maximum output power of the VPP ($\bar{p}^{VPP}$) (line 7 of TABLE I).
- If capacity inadequacy remains, the PHS injects energy to contribute to the loss of load mitigation without violating its technical constraints (line 10 of TABLE I).
- If the available WF generation suffices to eliminate the risk of a load incident, any remaining wind generation charges PHS (line 12 of TABLE I).
- If any of the WF available generation still remains unutilized after points (a) and (c), it is injected into the power system, again in compliance with the maximum power output of the VPP (line 14 of TABLE I).

The final hourly VPP output is computed as the sum of PHS and WF output in line 18, while the hourly state of charge of PHS is calculated in line 17 of TABLE I. Parameters $\bar{p}_{phs}^{ch}$ and $\bar{p}_{phs}^{disch}$ represent the rated charging and discharging capacity of PHS, while SoC_{phs}^{max} and n_{phs} stand for the maximum SoC of PHS and its roundtrip efficiency.

III. CASE STUDY

The Greek power system serves as case study, with its development outlined in [13]. The basic components of the generation system are also summed up in TABLE II. Additionally, the system includes an HVDC link to Italy and 4 HVAC interconnectors with Albania, Bulgaria, North Macedonia, and Turkey, with a combined net transfer capacity of 2.45 GW for imports and 1.5 GW for exports. The annual energy demand totals approximately 61.8 TWh, with a peak load of around 11 GW.

The assumptions about the availability of thermal stations have been retrieved by the ENTSO-e database [32]. A 5% and 8% forced outage rate (FOR) is adopted for the new and the

TABLE II. System generation assets (excluding VPP).

Technology	Capacity [GW]
Thermal (13 Combined Cycle Gas Turbines (CCGT) fueled by natural gas)	7
Hydroelectric power plants	3.5
Wind farms	7.5
PV	10
Other dispatchable RES (biomass/biogas, small hydro, geothermal, and concentrating solar thermal stations)	1

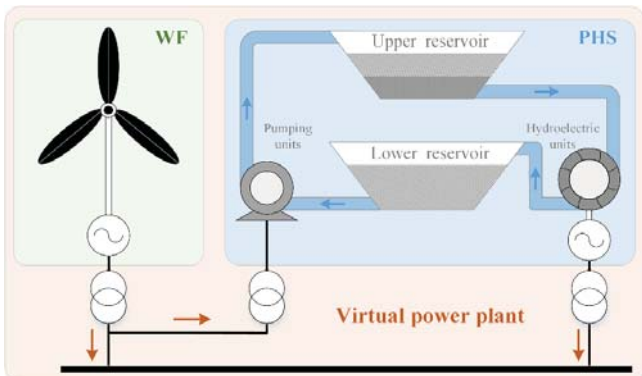


Fig. 1. Conceptual representation of a wind powered PHS VPP.

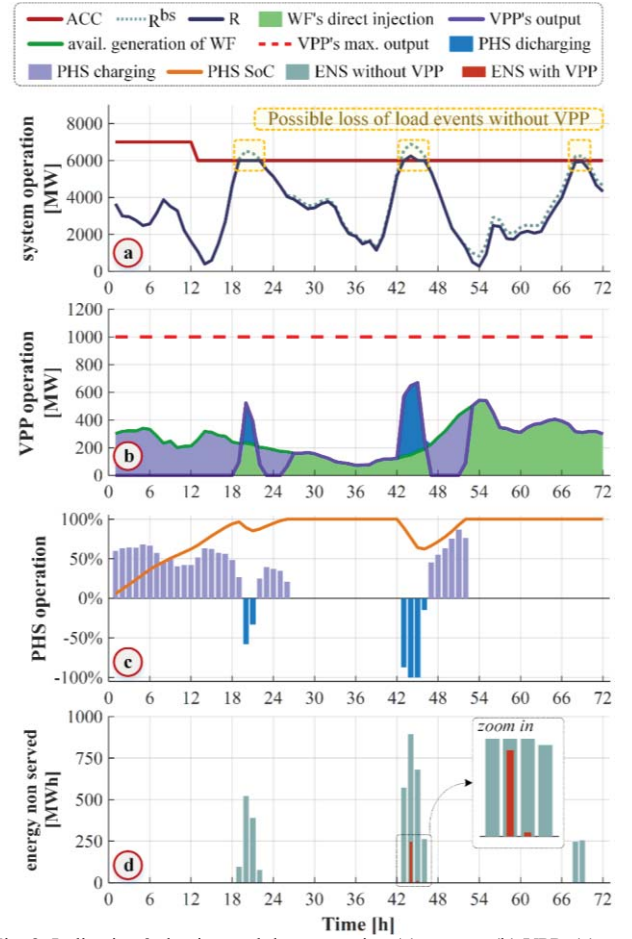


Fig. 2. Indicative 3-day interval demonstrating (a) system, (b) VPP, (c) PHS operation and (d) the unserved energy, for a VPP consisting of 1 GW WF and 500 MW / 8-h PHS.

old CCGTs, respectively, while a 24-hour mean time to repair (MTTR) is used for all units. Regarding interconnectors, a 5% FOR is considered for the AC links. In comparison, the higher FOR value of 25% is adopted for the DC link, a much older and relatively unreliable asset, being historically out-of-service for several months over the year. The MTTR of all interconnections is set to 168 hours.

For the analysis, several PHS and WF configurations are examined. In the case of PHS, we assume that the capacity examined consists of individual PHS units, each rated at 250 MW, with a FOR of 2% and an MTTR of 24-hours. The PHS roundtrip efficiency is set at 75%. A schematic representation of the VPP is given in Fig. 1.

IV. RESULTS

A. System and VPP operation under the proposed method

A three-day period is selected as an example to demonstrate the operation of the system, VPP, and PHS, as well as the non-served demand load after implementing the proposed method (Fig. 2). For this paradigm illustration, a VPP composed of a 1 GW WF and a 500 MW / 8-hour PHS is considered, with a maximum VPP output ($\bar{p}^{VPP}$) set at 1 GW. The red line of Fig. 2(a) represents the available conventional capacity (ACC), the light blue dashed line indicates the residual load without accounting for the VPP's output (R^{bs}), and the blue line shows the residual load after the VPP's intervention (R). The yellow frames in Fig. 2(a) indicate possible loss of load events before the action of VPP.

Before the first possible loss of load event interval (1-18h in Fig. 2), all the available wind power is provided to charge PHS, which is supposed to be empty at the beginning of the presented period, and there is no risk of capacity deficit. When the first potential loss of load appears (19-22h in Fig. 2), all the available wind production is injected into the grid, while PHS also discharges for two consecutive hours when wind power does not suffice to meet inadequacies. When the threat of a loss of load diminishes, the wind production is initially used to charge the PHS and then is injected into the grid (23-42h in Fig. 2). During the second possible loss of load event (43-46h in Fig. 2), VPP operates similarly to the first case. However, now, the available wind production, combined with PHS discharging at full power (Fig. 2(c)), is not enough to totally prevent inadequacy, thus load curtailments inevitably occur (Fig. 2(d)). Finally, during the third incident that could lead to a loss of load event (68-69h in Fig. 2), wind generation suffices to meet the capacity deficit without the aid of PHS.

The example demonstrates that the WF and PHS work together to mitigate loss of load events. In this sense, the improvement in capacity adequacy due to VPP's action is attributed cumulatively to both of its constituents. However, the individual contribution of each asset can also be of potential interest. Since priority is given to direct WF injection during the possible loss of load events, the CV of the WF can be derived from the capacity adequacy enhancement attributed solely to the available wind generation (green line in Fig. 2 (b)) during these events, i.e. assuming that PHS operation is neglected. Following, the capacity value of PHS can be calculated as the difference between the CV of VPP and the CV of WF. In the next two sections both the aggregated capacity value of the VPP and the individual CVs of WF and PHS are estimated.

B. Variations in VPP capacity value based on the size of the PHS

In this Section, the effect of PHS size, in terms of both energy and power capacity, on VPP's contribution to adequacy is investigated. A VPP including a 1GW WF is examined across various PHS configurations. The maximum output power of the VPP ($\bar{p}^{VPP}$) is set equivalent to the installed capacity of WF, i.e. 1 GW, while pumped storage configurations of rated power from 250 MW up to 1 GW with energy-to-power ratios of 6-h, 8-h, 10-h, and 12-h are demonstrated.

Fig. 3 shows the CV of the VPP in MWs (Fig. 3(a)) and normalized on its maximum output (Fig. 3(b)). Notably, Fig. 3(a) reveals a linear increase in CV with PHS power. The energy capacity of storage appears to yield less impact on the VPP's CV when dealing with PHS configurations of power capacities below 500 MW. Indicatively, the capacity value of a VPP with a 250 MW PHS ranges from 30.9% to 33.6% while, for a 1 GW PHS, the capacity value of the VPP reaches its highest value and fluctuating between 78.3% and 91.1%, depending on the energy-to-power ratio.

The individual capacity value of the 1 GW WF is estimated at approximately 11.2% (Fig. 3(b)). Taking this into account, in Fig. 4 the individual CV of the PHS is presented both in MWs (Fig. 4(a)) and normalized on the rated power of PHS (Fig. 4(b)). The CV of PHS, measured in MW, apparently increases as the PHS size escalates, presenting the same trend as VPP's CV. However, the normalized CV of PHS exhibits a decreasing trend as PHS capacity increases

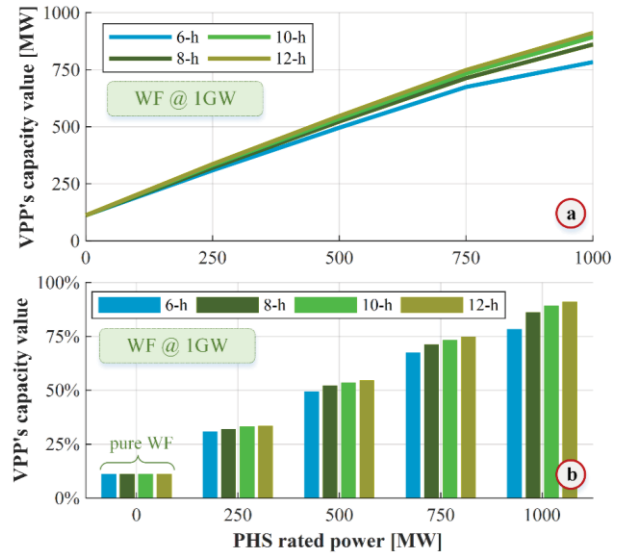


Fig. 3: Capacity value of a 1 GW VPP including 1 GW WF for different PHS configurations: (a) in MWs and (b) normalized in % of the VPP maximum output.

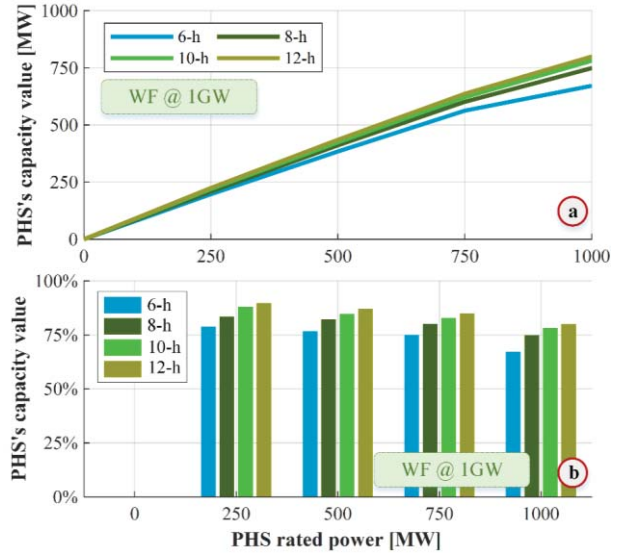


Fig. 4: Capacity value of different PHS configurations integrated into a 1GW VPP including 1 GW WF: (a) in MWs and (b) normalized in % of the PHS total rated power.

(Fig. 4(b)), implying that greater WF capacities are needed for PHS stations of higher capacities to attain elevated CV levels. For example, the 250 MW PHS yields capacity values ranging from 78.8% to 89.7%, while the respective values for a 1 GW PHS are estimated at 54.4% to 58.5%.

C. Variations in VPP capacity value based on WF capacity

To investigate how the installed capacity of WF affects the capacity value of the VPP, different VPPs are considered, each featuring a 1 GW PHS with varying energy-to-power ratios, while WF installed capacities vary from 0.5 GW to 5 GW. In this scenario, the maximum power output of the VPP aligns with the rated power of the PHS, signifying that the VPP's maximum output is determined according to the capacity of its dispatchable component.

Fig. 5 illustrates the CV of the VPP against the capacity of WFs, normalized at the 1 GW of PHS capacity. The observed trend reveals an increase in the CV of the VPP when the WF capacity increases up to 2500 MW for all the energy-to-power ratios of PHS under consideration. This improvement in the

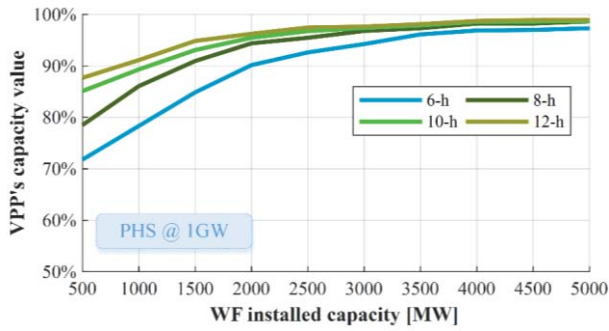


Fig. 5. Capacity value of 1 GW VPPs including 1 GW PHS of different energy-to-power ratios for different WF installed capacities.

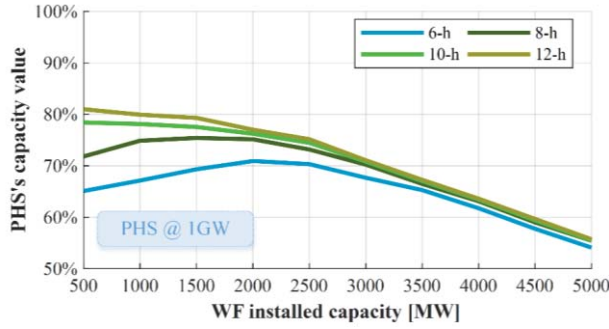


Fig. 6. Capacity value of 1 GW PHS of different energy-to-power ratios integrated into 1GW VPPs for different WFs' installed capacities.

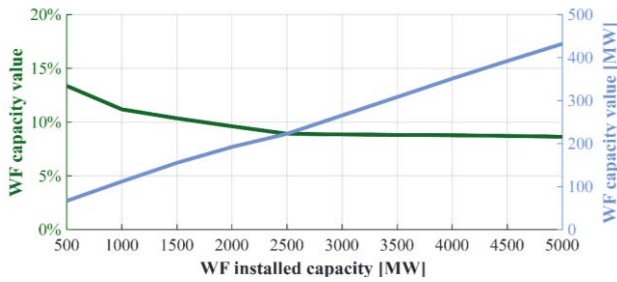


Fig. 7. Capacity value of different WF integrated into 1GW VPPs in MWs and normalized in % of the WF capacity.

CV of VPP can be attributed to two factors: first, greater WF capacity means that more wind power can be directly injected into the grid in times of capacity shortage; second, increased WF elevates the charging capabilities of the PHS, thus enhancing its ability to mitigate loss of load events through discharging.

To quantify the effect of these two factors in VPP's CV, Fig. 6 displays the normalized CV of the 1 GW PHS, while in Fig. 7 presents the CV of WF in MWs and normalized as a percentage of their capacity. Fig. 6 indicates that for PHS configurations with energy-to-power ratios exceeding 8 hours, the increase in WF capacity does not correspond to a simultaneous increase in their CV; conversely their contribution decreases, meaning that the WFs substitute storage in supporting system's adequacy. This is because the 10-h or 12-h configurations can charge substantial amounts of wind energy when system adequacy is not compromised and inject them when there is a risk of loss of load without requiring excessive additional charging. On the other hand, PHS configurations with durations below 8-h benefit from increasing WF capacities since their upper reservoir depletes more rapidly due to limited energy capacity, necessitating more frequent charging. However, beyond a certain level of installed WF capacity, a decrease in their CV is also evident (Fig. 6). Specifically, 8-hour PHS attains its maximum CV

with 1500 MW of WFs, while 6-hour PHS achieves its highest CV with 2000 MW of WF.

This substitution of PHS by WFs in terms of contributing to adequacy is attributed to the prioritization of wind generation for direct injection into the grid in cases of inadequacy. As Fig. 7 illustrates, the CV of WFs steadily rises as their installed capacity increases in terms of MW (blue line in Fig. 7), even though their contribution as a percentage of their installed capacity decreases (green line in Fig. 7).

V. CONCLUSIONS

This paper estimates the capacity value of virtual power plants that combine pumped hydro storage and wind farms. A resource adequacy assessment model based on the Monte Carlo simulation method is developed, and an adequacy-oriented operational strategy is proposed for the VPP aiming at loss of load mitigation. The Greek power system is used as a case study to explore various VPP configurations, considering numerous PHS sizes and WF capacities. In addition, the individual capacity values of VPP's components are evaluated to provide insights into their separate performances within the VPP context. Our study demonstrates that the contribution of VPP to capacity adequacy is substantial, albeit it varies significantly depending on the WF capacity and PHS size.

For a given WF capacity, a clear correlation is observed between the VPP's CV and the PHS power capacity, with the CV peaking when the PHS power capacity matches that of the WF. Notably, the impact of energy storage capacity on the VPP's CV is less pronounced, particularly for PHS configurations with lower power capacities. The individual CV of PHS in terms of MWs exhibits a corresponding increase with the VPP, but its normalized value reduces with the increase of its power capacity. The analysis also reveals that increasing WF capacity can enhance the overall CV of the VPP. However, an excessive increase in WF capacity may lead to a reduction in the individual capacity value of PHS, because WFs start to substitute PHS in supporting system adequacy, potentially resulting in the underutilization of PHS assets.

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