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Wind Farm-based Green Hydrogen: A Virtual Power Plant Case Study

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***Abstract*—Decarbonization of the energy sector requires further wind farms for electricity generation. Green hydrogen can assist in many aspects, such as overcoming the uncertainty of wind generation. In this study, the concept of a virtual power plant (VPP), including a wind farm, electrical energy storage, power-to-hydrogen, hydrogen-to-power, and gas network, is investigated to exploit the full potential of wind farms. The gas network will play the role of virtual green hydrogen storage for the wind farm operator (WFO). The WFO interacts with two main electricity markets, namely the day-ahead electricity market, to sell the major share of production, and the balancing electricity market, to handle the deviations. The simulation results show the effectiveness of the proposed model in decreasing the deviations of WFOs to deliver the required electrical power committed to the electricity market, thus increasing their profit. Moreover, sensitivity analyses performed on the conversion ratio of the power-to-hydrogen show that the profit of WFO will increase with improvement in this parameter.**

***Index Terms*—Electricity markets, green hydrogen, gas network, linepack, virtual power plant, wind farm.**

I. Introduction

The policies to protect the environment through decreasing carbon emissions require less dependency on fossil fuels and more on renewable energy resources. Wind farms play a crucial role in the energy sector decarbonization plan, yet the volatility is a major concern to be addressed. Currently, the renewable energy and conventional producers, along with consumers, offer/bid the main quantity of electrical power they want to sell/purchase in the day-ahead electricity market. The mentioned market close typically a day before delivery of the electricity with the share of electrical power that needs to be supplied/consumed by producers/consumers. The challenge of the wind farm in this market increases when it has to offer electricity to this market, considering the uncertainty of wind power production and facing possible deviation when obliged to supply electricity.

Some works investigated the capabilities of the electricity markets to assist WFOs, integrated into the power system. An operation-planning model was proposed in [1] to assist wind farms, as a renewable energy producer, to increase the profit, while the day-ahead market was considered to offer the produced electricity. The profit of a wind company was maximized in [2] through a probabilistic method considering the volatility in the market prices and wind power generation. The authors in [3] tackled the problem of penalties related to the deviations in the renewable energy delivery to the market. A risk analysis was performed in [4] to survey the investment-operation decisions of wind producers and different assets participating in the energy markets. A stochastic method was implemented in [5] to model the uncertainties related to the wind and electricity markets, namely day-ahead and balancing, with the aim of alleviating deviations in renewable energy production. The focus of these papers was mainly on the electricity markets, and specifically, the balancing market showed as a fruitful tool to decrease the deviations of the WFO. However, the possibilities that green hydrogen brings to the picture were overlooked.

Electrical energy storage is another viable option to overcome the deviations for the WFO. The optimal battery size for a microgrid integrated with wind power in grid-connected and standalone mode was investigated in [6]. Economic dispatch was used in [7] to study the impact of the energy storage system on the operation of a power system with wind power. Authors in [8] surveyed the operation and planning problem of a system, including the combination of wind powers and storage devices. Some prediction challenges of wind power in the electricity market were resolved in [9] through a hybrid system consisting of wind power and battery. The siting and sizing of distributed batteries to improve the operation of the power system with distributed wind farms were studied in [10] while only focusing on the batteries and neglecting opportunities that green hydrogen can provide.

In this paper, we investigate the potential of green hydrogen and the available gas network to overcome the stochasticity of wind generation, aiming to reach a higher profit. In this context, a virtual power plant (VPP), including a wind farm, power-to-hydrogen (P2H), hydrogen-to-power (H2P), electrical energy storage (EES), and gas network are considered. The concept of linepack [11] in the gas grid will be used to form virtual green hydrogen storage for the WFO through a fixed price contract. The simulation consists of WFO's participation in the day-ahead electricity market. During overproduction, the WFO can store electrical energy in the EES. Moreover, it can turn the electricity into green hydrogen through P2H and store it in the gas network. For the underproduction, it can discharge electrical energy from EES. Furthermore, it can withdraw green hydrogen from the gas grid and turn it into electricity through H2P. The electricity balancing market is another option to handle the deviations. These options enable the WFO to fulfill the commitments to the day-ahead electricity market and increase the benefit. This paper investigates the abovementioned multi-options to evaluate their impact on the cost and functionality of a renewable energy producer. Moreover, the techno-economic potential of green hydrogen in assisting WFOs will be studied. The main contributions of this paper can be summarized as follows.

- Proposing a virtual power plant including WFO, EES, P2H, H2P, and gas grid to increase the profit of the WFO while selling its major share of electricity production in the day-ahead electricity market. The potentials of the mentioned facilities are fully investigated under different conditions, revealing their impact on the profit of the WFO and fulfilling the commitment to the electricity market.
- The gas grid will play the role of green hydrogen storage for WFO, providing the opportunity for WFO to increase the profit further and use the potential of green hydrogen. The economic analysis illustrates the effect of green hydrogen on the performance of WFO. Moreover, the deviation of the wind farm will be studied to highlight the role of the gas network.
- The balancing electricity market is considered to assist WFO under overproduction and underproduction situations. A flexibility analysis will be conducted to reveal the impact on the deviation management.

The rest of the paper is presented as follows. The structure of the VPP and problem formulation is introduced in Section II. In Section III, various case studies are defined to assist us in further studying the problem. The simulation results and sensitivity analysis are discussed in Section IV. Section V presents the conclusion of the paper.

II. Problem Description

A. VPP Structure

The VPP structure is depicted in Fig. 1. The wind farm is paired with EES, P2H, and H2P facilities. The P2H and H2P facilities allow WFO to trade green hydrogen with the gas grid via a fixed price contract. In the overproduction condition, WFO has the chance to turn the surplus generation through the P2H facility into green hydrogen and store it in the gas grid, selling under a fixed price. In the underproduction, the WFO can buy this green hydrogen from the grid at a fixed price and turn it into electricity through an H2P facility. The capability to trade green hydrogen with the gas grid in any scenario makes the gas network act as green hydrogen storage. The WFO has the potential to store/withdraw green hydrogen to/from the gas grid. The EES plays the same role in the form of electrical energy storage. It can be charged in the overproduction and discharged in the underproduction. The interaction of the proposed model with the electricity markets would be as follows. The main platform to sell the electrical power production of wind farms is the day-ahead electricity market, while under overproduction/underproduction, it has the opportunity to sell/buy its deviation in the balancing market. Moreover, the EES may charge/discharge electrical energy under overproduction/underproduction. Moreover, the gas grid has the potential to store/withdraw energy in the form of green hydrogen in the overproduction/underproduction with the assistance of the P2H and H2P facilities.

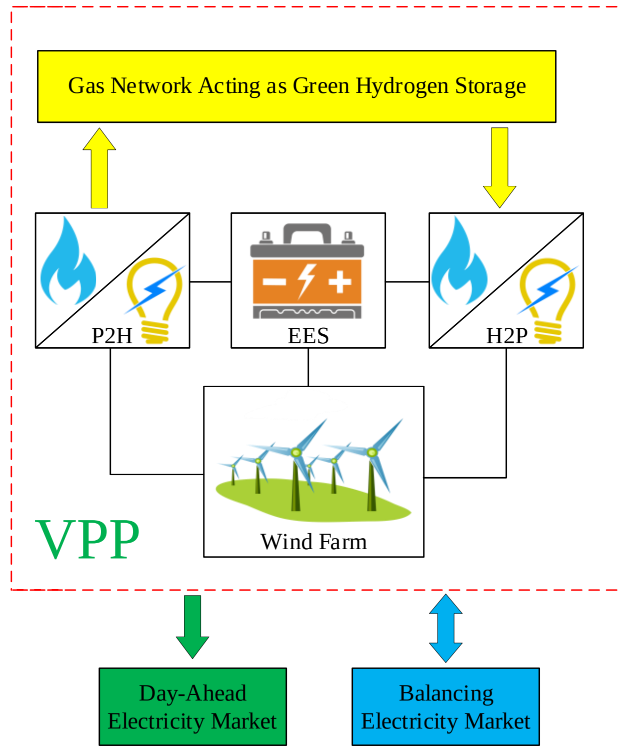

Figure 1. The structure of the VPP.

B. Problem Formulation

The objective of the optimization problem is to maximize the overall profit of the WFO when participating in the day-ahead and balancing electricity markets, as stated in (1). This includes both the investment and operation costs. The investments of WFO on the EES, P2H, and H2P facilities are limited by (2), (3), and (4), respectively. The quantity of electrical power that wind farms will commit to the day-ahead electricity market has an upper cap equal to the forecast of its generation, (5). The deviation between the real generation of the wind farm and the amount committed to the day-ahead electricity market defines the unbalance power, (6). The unbalance power could be overproduction (more generation than the commitment to the day-ahead electricity market) or underproduction (less generation than the commitment to the day-ahead electricity market), determined by (7), (8), and (9).

The binary variable d_ω assist us to have only surplus or shortage of generation. The WFO can manage the overproduction by selling to the balancing market, charging the EES, turning it into green hydrogen through P2H, or assigning a penalty to the surplus, (10). For the underproduction, the WFO can purchase from the balancing market, discharge the EES, turn green hydrogen into electricity, or assign a penalty to the deficit, (11). The amount of electrical power that WFO can trade with the balancing electricity market in overproduction and underproduction is bounded in (12) and (13), respectively. The EES unit is modeled by (14), (15), (16), (17), (18), (19), (20), (21), (22), and (23); (14) states that the total charge and discharge of the EES over the simulation should be zero; the charge of the EES is possible via the wind farm overproduction and the H2P unit, in (15), while the discharge is for wind farm underproduction situation and the P2H unit, (16); charging of the EES unit is bounded between 20%-95% of the installed capacity in (17), (18), and (19), while similarly the discharge power is presented in (20), (21), and (22); binary variables B_ω^{cb} and B_ω^{db} force the EES unit to only charge or discharge at each scenario ω through (23). The gas grid acts as green hydrogen storage for the WFO via (24), (25), (26), (27), (28), and (29); Here, the assumption is that the gas grid will act as a storage and, to simulate the same behavior as EES, (24) makes sure that the summation of charge and discharge of green hydrogen in the simulation is equal to zero; charging and discharging of the gas grid happen through P2H and H2P units in (25) and (26), and are limited to the capacity of the gas network, (27) and (28) ; binary variables V_ω^{ch} and V_ω^{dh} enforce to only have charge or discharge of green hydrogen at each scenario ω, (29). The P2H unit is modeled via (30), (31), and (32). The amount of green hydrogen that the P2H unit produces is bounded to the investment in this unit (30). The input electricity of the P2H unit will turn to green hydrogen through (31). The wind farm surplus of generation or the electricity withdrawn from EES will supply this unit presented in (32), while the output green hydrogen will store in the gas grid in (25). The H2P unit is formulated through (33), (34), and (35). The output electrical power of this unit is bounded to the investment in this unit, (33) . The input green hydrogen of this unit will turn to electrical power, as stated in (34). The output electrical power of this unit can assist WFO in underproduction or charge the EES in (35). The input green hydrogen of this unit is via the discharge of the gas network, (26).

$$\max\left\{\begin{array}{l}\underbrace{\left[\alpha_{NPV,I}\times(-E_I^S\times IC_S-H_I^{P2H}\times IC^{P2H}-P_I^{H2P}\times IC^{H2P})\right]}_{Planning\ \ costs}\\+\underbrace{\left[\begin{array}{l}\sum_{\omega=1}^{N\Omega}(\rho_\omega)\times(\lambda_\omega\times P_\omega^{W,offer}+\lambda_H\times(H_\omega^{P2H}-H_\omega^{H2P})\\-10\times\lambda_\omega\times(P_\omega^{d+,r}+P_\omega^{d-,r})+\lambda_\omega^{d+}\times P_\omega^{b,d+}\\-\lambda_\omega^{d-}\times P_\omega^{b,d-}-OM_W\times P_\omega^{W,F})\end{array}\right]}_{Wind\ \text{farm operation cost}}\\+\underbrace{\left[\begin{array}{l}\alpha_{NPV,O}\times\sum_{\omega=1}^{N\Omega}(\rho_\omega)\times(-OM_{H2P}\times P_\omega^{H2P}\\-OM_{P2H}\times H_\omega^{P2H}-OM_S\times(P_\omega^{ch}+P_\omega^{dch}))\end{array}\right]}_{Facilities\ \text{operation cost}}\end{array}\right\} \quad (1)$$

$$0\le E_I^S\le E_{I,\max}^S \quad (2)$$

$$0\le H_I^{P2H}\le H_{I,,\max}^{P2H} \quad (3)$$

$$0\le P_I^{H2P}\le P_{I,\max}^{H2P} \quad (4)$$

$$0\le P_\omega^{W,offer}\le P_\omega^{W,F} \quad (5)$$

$$P_\omega^d=P^{W,R}-P_\omega^{W,offer} \quad (6)$$

$$P_\omega^d=P_\omega^{d+}-P_\omega^{d-} \quad (7)$$

$$P_\omega^{d+}\le C\ \times(1-d_\omega) \quad (8)$$

$$P_\omega^{d-}\le C\times d_\omega \quad (9)$$

$$P_\omega^{d+}=P_\omega^{b,d+}+P_\omega^{EES,d+}+P_\omega^{P2H\_d+}+P_\omega^{d+,r} \quad (10)$$

$$P_\omega^{d-}=P_\omega^{b,d-}+P_\omega^{EES,d-}+P_\omega^{H2P\_d-}+P_\omega^{d-,r} \quad (11)$$

$$P_\omega^{b,d+}\le 0.05*P_\omega^{W,F} \quad (12)$$

$$P_\omega^{b,d-}\le 0.05*P_\omega^{W,F} \quad (13)$$

$$\sum_{td,b}\rho_\omega\times((P_\omega^{ch}\times\eta_c)-(\frac{P_\omega^{dch}}{\eta_d}))=0 \quad (14)$$

$$P_\omega^{ch}=P_\omega^{EES,d+}+P_\omega^{H2P\_EES} \quad (15)$$

$$P_\omega^{dch}=P_\omega^{EES,d-}+P_\omega^{EES\_P2H} \quad (16)$$

$$0.20\times E_I^S\times B_\omega^{cb}\le P_\omega^{ch}\le 0.95\times E_I^S\times B_\omega^{cb} \quad (17)$$

$$0.20\times E_I^S\times B_\omega^{cb}\le P_\omega^{EES,d+}\le 0.95\times E_I^S\times B_\omega^{cb} \quad (18)$$

$$0.20\times E_I^S\times d_\omega\times B_\omega^{cb}\le P_\omega^{H2P\_EES}\le 0.95\times E_I^S\times d_\omega\times B_\omega^{cb} \quad (19)$$

$$0.20\times E_I^S\times B_\omega^{db}\le P_\omega^{dch}\le 0.95\times E_I^S\times B_\omega^{db} \quad (20)$$

$$0.20\times E_I^S\times B_\omega^{db}\le P_\omega^{EES,d-}\le 0.95\times E_I^S\times B_\omega^{db} \quad (21)$$

$$0.20\times E_I^S\times(1-d_\omega)\times B_\omega^{db}\le P_\omega^{EES\_P2H}\le 0.95\times E_I^S\times(1-d_\omega)\times B_\omega^{db} \quad (22)$$

$$B_\omega^{cb}+B_\omega^{db}\le 1 \quad (23)$$

$$\sum_{td,b}\rho_\omega\times((H_\omega^{ch}\times\eta_{ch})-(\frac{H_\omega^{dch}}{\eta_{dh}}))=0 \quad (24)$$

$$H_\omega^{ch}=H_\omega^{P2H} \quad (25)$$

$$H_\omega^{dch}=H_\omega^{H2P} \quad (26)$$

$$0.2\times H_I\times V_\omega^{ch}\le H_\omega^{ch}\le 0.95\times H_I\times V_\omega^{ch} \quad (27)$$

$$0.2\times H_I\times V_\omega^{dh}\le H_\omega^{dch}\le 0.95\times H_I\times V_\omega^{dh} \quad (28)$$

$$V_\omega^{ch}+V_\omega^{dh}\le 1 \quad (29)$$

$$0\le H_\omega^{P2H}\le H_I^{P2H} \quad (30)$$

$$H_\omega^{P2H}=\alpha^{P2H}\times P_\omega^{P2H} \quad (31)$$

$$P_\omega^{P2H}=P_\omega^{P2H\_d+}+P_\omega^{EES\_P2H} \quad (32)$$

$$0\le P_\omega^{H2P}\le P_I^{H2P} \quad (33)$$

$$P_\omega^{H2P}=\alpha^{H2P}\times H_\omega^{H2P} \quad (34)$$

$$P_\omega^{H2P}=P_\omega^{H2P\_d-}+P_\omega^{H2P\_EES} \quad (35)$$

III. CASE STUDIES

a) Base Case: Wind Farm Participate in Electricity Markets

This case study survey the conditions where the EES, P2H, and H2P units are not available for investment. The generation of the wind farm will sell mainly in the day-ahead electricity market. Due to the stochasticity of wind generation, deviations in the production at the moment of delivery are possible in the forms of surplus or shortage of electrical power. The balancing market is the only option in this case to lower the deviations.

b) Case I: Wind Farm with Possibility to Invest in the EES Unit participate in the Electricity Market

Here, the only candidate unit for possible investment is the EES while the P2H and H2P units are not available. In case of deviation, two options are assisting wind farms. The first option is to sell/purchase electricity to/from balancing electricity market similar to the Base Case in surplus/shortage of electricity generation, respectively. Moreover, the EES unit may store/withdraw electricity in the positive and negative deviations, respectively.

c) Case II: VPP Bidding in Day-Ahead and Balancing Electricity Markets

Here, investments in the EES, P2H, and H2P units are considered. After commitment to the electricity market, the compensation of deviation is done partly through interaction with the balancing electricity market. The functions of EES, P2H, H2P, and trade with the gas network will be determined through optimization to maximize the profit. Under overproduction, EES may charge to support the WFO under wind generation surplus conditions. Moreover, WFO may sell green hydrogen to the gas grid by turning electricity into green hydrogen through the P2H facility. Under underproduction, EES may discharge to support WFO under wind generation deficit. Furthermore, WFO may buy green hydrogen from the gas grid and, with the assistance of H2P unit, produce electricity and deliver it to the day-ahead electricity market.

IV. Numerical Results And Discussion

A. Simulation Results

The overall profit for different case studies is presented in Fig. 2. The profits that WFO makes in Case I and Case II are respectively 187% and 195% bigger than the profit obtained in the Base Case study. The performance of the WFO in the scenarios where it faces overproduction is shown in Fig. 3. In the Base Case, presented in Fig. 3.a, the WFO can only sell the overproduction partly to the balancing market. Here, the P2H and EES units are not present, and the amount of overproduction not sold in the balancing market causes penalty costs. The function of the WFO in Case I is shown in Fig. 3.b, where the EES unit is present. Here, under overproduction, the WFO sells partly to the balancing market or stores it in the EES unit. Fig. 3.c displays the performance of the VPP in the overproduction, where besides the EES and balancing market, WFO can turn the electricity into green hydrogen and store it in

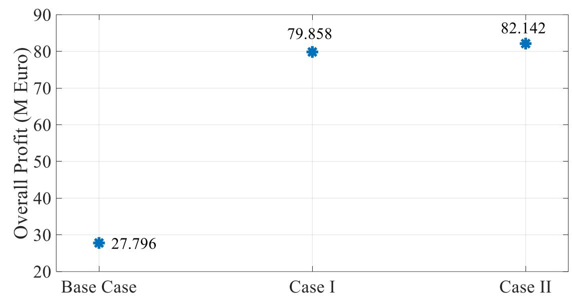

Figure 2. The overall profit of WFO in different case studies.

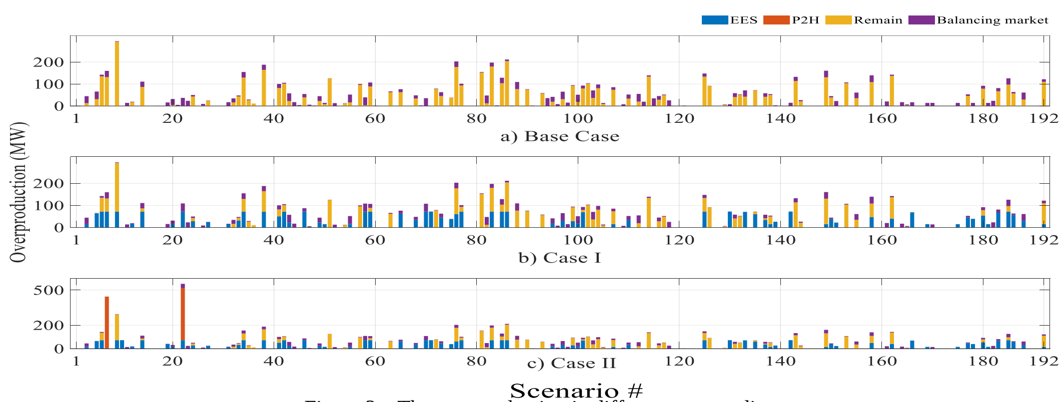

Figure 3. The overproduction in different case studies.

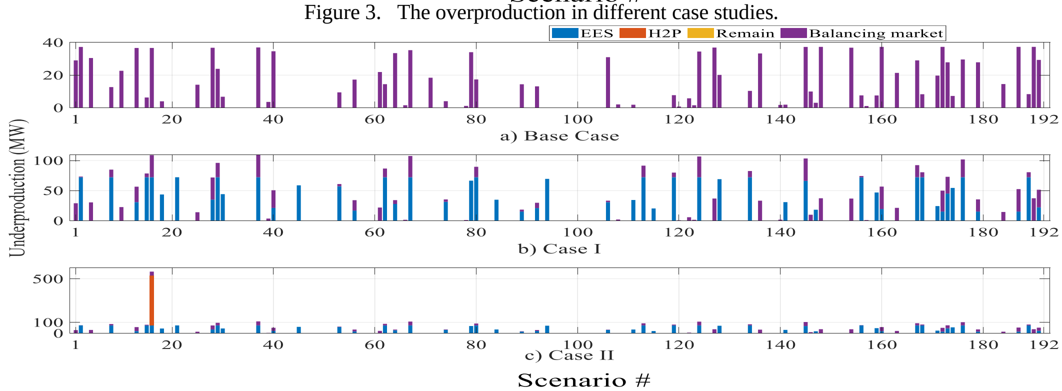

Figure 4. The underproduction in different case studies.

TABLE I. AMOUNT OF VARIABLES IN CASE II FOR SOME SCENARIOS.

Scenario #	P_ω^{d+} (MW)	$P_\omega^{b,d+}$ (MW)	$P_\omega^{EES,d+}$ (MW)	$P_\omega^{P2H\_d+}$ (MW)	$P_\omega^{d+,r}$ (MW)	P_ω^{d-} (MW)	$P_\omega^{b,d-}$ (MW)	$P_\omega^{EES,d-}$ (MW)	$P_\omega^{H2P\_d-}$ (MW)	$P_\omega^{d-,r}$ (MW)
3	44.49	29.29	15.2	0	0	0	0	0	0	0
6	142.35	7.49	72.2	0	62.66	0	0	0	0	0
22	553.36	36.72	72.2	444.44	0	0	0	0	0	0
15	0	0	0	0	0	78.49	6.29	72.2	0	0
16	0	0	0	0	0	566.32	36.62	72.2	457.50	0
67	0	0	0	0	0	107.47	35.27	72.2	0	0

the gas grid. The total remained overproduction in Case II over scenarios is 3337.8 MW which is 1.73% and 41.81% lower than Case I and Base Case, respectively.

The performance of the case studies under underproduction conditions is depicted in Fig. 4. Fig. 4.a presents the Base Case study where the WFO can partly buy the shortage of electricity from the balancing market, and the rest causes penalty costs. In Case I, Fig. 4. b, the WFO can also withdraw electricity from the EES unit. In Case II, WFO is equipped with an H2P unit and can withdraw green hydrogen from the gas grid to turn it into electricity and take advantage of the EES unit and the balancing market. The performance of the VPP when it has a shortage of electricity is depicted in Fig. 4.c. The deficit of electricity in Base Case, Case I, and Case II is completely overcome and the total remained underproduction (the last term in (11)) is zero over all scenarios. The optimal size of the EES unit in Case I is 76 MW. The size of EES, P2H, and H2P units in Case II are 76 MW, 2 Mm^3/h, and 457.505 MW, respectively. The values of some variables in Case II for some sample scenarios, are presented in Table I. In this Table, Scenarios 3, 6, and 22 represent overproduction conditions, while Scenarios 15, 16, and 67 are underproduction. In Scenario 3, there exists 44.49 MW surplus of wind farm generation, out of which 29.29 MW is sold to the balancing market, and the rest charged the EES. In Scenario 22, the 553.36 MW of overproduction is partly sold to the balancing market (36.72 MW), partly charged to the EES (72.2 MW), and the rest (444.44 MW) delivered to the P2H facility to turn to green hydrogen. Scenario 16 showed that the underproduction (566.32 MW) is partly compensated by purchasing electricity from the balancing market (36.62 MW), partly by discharging the EES (72.2 MW), and the rest of the deficit provided by the H2P facility (457.50 MW) by turning green hydrogen to electricity.

B. Sensitivity Analysis

This section will perform a sensitivity analysis on the conversion ratio of the P2H unit. The effect on the overall profit and size of the candidate units surveyed is based on the results of the operation-planning problem. The overall profit of the WFO versus the conversion ratio of the P2H unit (while increasing with the step of 5%), is displayed in Fig. 5. It can be noticed that the improvement in this parameter will increase the overall profit. Moreover, the optimal size of the candidate units (EES, P2H, and H2P) in Case II with different values of the conversion ratio of the P2H unit, is presented in Table. II.

V. CONCLUSION

This paper studied the performance of a VPP in different electricity markets. The VPP includes the WFO, EES, P2H, H2P, and gas network as virtual green hydrogen storage. Three case studies were considered to demonstrate the function of the VPP. The Base Case has considered only WFO alone participating in the electricity markets. Case I has provided the possibility for the WFO to invest in the EES unit to implement its capability to store and withdraw electrical energy in situations of overproduction and underproduction, respectively. Finally, Case II surveyed the performance of the VPP, including the investment-operation planning of the VPP in the day-ahead and balancing electricity markets. Results of the simulation have proved that by using the concept of VPP, the overall profit of the WFO has increased while the deviation has decreased. Moreover, considering the possibility of storing/withdrawing green hydrogen to/from the gas grid has increased the WFO's profit. As a result, the energy generated by the wind farm can be further utilized through green hydrogen. A sensitivity analysis performed on the conversion

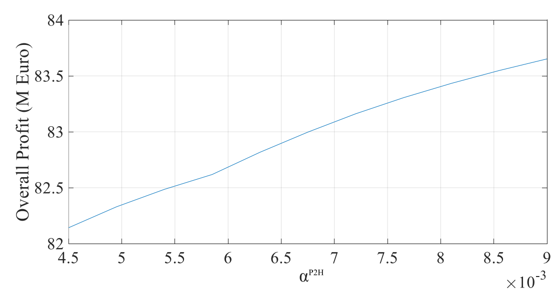

Figure 5. The overall profit of WFO with different P2H conversion ratio.

TABLE II. THE OPTIMAL SIZE OF UNITS WITH DIFFERENT P2H CONVERSION RATIO.

α^{P2H}	E_I^S (MW)	H_I^{P2H}(Mm^3/h)	P_I^{H2P} (MW)
0.0045	76	2	457.505
0.00495	76	2	457.505
0.0054	76	2	457.505
0.00585	76	2.027	463.654
0.0063	76	2.027	463.654
0.00675	76	2	568.307
0.0072	76	2	568.307
0.00765	76	2	568.307
0.0081	76	2	568.307
0.00855	76	2	568.307
0.009	76	2	568.307

ratio of the P2H unit has proved an increase in the profit of WFO, which shows a great opportunity for WFO in the near future as technology enhances.

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APPENDIX

NOMENCLATURE

A. Indexes

ω Index of scenarios, $\omega \in 1..N_{\omega}$.

B. Parameters

C Capacity of offshore wind farm [MW].

$E_{I,max}^{S}$ Maximum investment level of EES [MW].

$H_{I,max}^{P2H}$ Maximum investment level of P2H facility [Mm^3/h].

H_I The trading limit of green hydrogen between WFO and gas network [Mm^3/h].

IC_S The cost of investment in the EES [€/MW].

IC^{P2H} The cost of investment in the P2H [€/Mm^3/h].

IC^{H2P} The cost of investment in the H2P [€/MW].

OM_{P2H} The O&M costs for P2H [€/Mm^3].

OM_{H2P} The O&M costs for H2P [€/MWh].

OM_W The O&M costs for wind farm [€/MWh].

OM_S The O&M costs for EES [€/MWh].

$P_{\omega}^{W,R}$ Generation of the wind farm at the moment of delivery in scenario ω [MW].

$P_{\omega}^{W,F}$ Forecast of generation for wind farm in scenario ω [MW].

$P_{I,max}^{H2P}$ Maximum investment level of H2P facility [MW].

$\alpha_{NPV,I}$ Net present value of investment costs.

$\alpha_{NPV,O}$ Net present value of operation costs.

ρ_{ω} Weighting coefficient of the scenario ω [h].

λ_{ω}^{d+} Electricity price in the balancing market in case of overproduction in scenario ω [€/MWh].

λ_H Price of green hydrogen in the gas market [€/Mm^3].

λ_{ω} Price of electricity in the day-ahead market in scenario ω [€/MWh].

λ_{ω}^{d-} Price of electricity in the balancing market in case of underproduction in scenario ω [€/MWh].

η_c Charging efficiency of EES.

α^{P2H} Conversion factor of P2H facility.

α^{H2P} Conversion factor of H2P facility.

η_d Discharging efficiency of EES.

C. Variables

E_I^S Investing level of EES [MW].

H_{ω}^{ch} Charging amount of green hydrogen to the gas network in scenario ω [Mm^3/h].

H_{ω}^{dch} Discharging amount of green hydrogen from the gas network in scenario ω [Mm^3/h].

H_I^{P2H} Investing level of P2H facility [Mm^3/h].

H_{ω}^{P2H} Hydrogen generation of P2H facility in scenario ω [Mm^3/h].

H_{ω}^{H2P} Green hydrogen from gas network as input to the H2P facility in scenario ω [Mm^3/h].

$P_{\omega}^{W,offer}$ Offer power of wind farm to the day-ahead electricity market in scenario ω [MW].

P_{ω}^{d+} Total overproduction in scenario ω [MW].

P_{ω}^{d-} Total underproduction in scenario ω [MW].

$P_{\omega}^{d+,r}$ Remained overproduction in scenario ω [MW].

$P_{\omega}^{d-,r}$ Remained underproduction in scenario ω [MW].

P_{ω}^{d} Total unbalance power in scenario ω [MW].

$P_{\omega}^{b,d+}$ Bidding of WFO facing overproduction in the balancing market in scenario ω [MW].

$P_{\omega}^{b,d-}$ Bidding of WFO facing underproduction in the balancing market in scenario ω [MW].

P_{ω}^{ch} Charging power of EES in scenario ω [MW].

$P_{\omega}^{EES,d+}$ EES charging power from wind farm in case of overproduction in scenario ω [MW].

P_{ω}^{dch} Discharging power of EES in scenario ω [MW].

$P_{\omega}^{EES,d-}$ Discharging power of EES to grid in case of underproduction in scenario ω [MW].
$P_{\omega}^{EES\_P2H}$ Discharging power of EES to P2H facility in scenario ω [MW].
$P_{\omega}^{H2P\_EES}$ Charging power of EES from H2P facility in scenario ω [MW].
P_{ω}^{P2H} The input electrical power of the P2H facility in scenario ω [MW].
$P_{\omega}^{P2H\_d+}$ Power input of P2H facility from the wind farm in case of overproduction in scenario ω [MW].
P_{ω}^{H2P} Power output of H2P facility in scenario ω [MW].
P_{I}^{H2P} Investing level of H2P facility [MW].
$P_{\omega}^{H2P\_d-}$ Power output of H2P facility to the wind farm in case of underproduction in scenario ω [MW].
d_{ω} ,B_{ω}^{cb} B_{ω}^{db}, V_{ω}^{ch} V_{ω}^{dh} Binary variables.

DATA

The prices of electricity in the markets and generation of the wind farm are considered the primary sources of stochasticity in our problem. In this paper, the duration curve method is used [12], allowing to have the required accuracy for the solution while keeping the problem tractable. The full description of the duration curve method implemented in this paper can be found in [1]. The parameters related to the wind farm, EES, P2H, H2P, and the price of green hydrogen are provided in Table III. The net present value coefficient for investment and operation costs is explained in [1].

TABLE III. DATA FOR SIMULATION

Symbol	Value	Symbol	Value
C (MW)	760	α^{P2H}	0.0045
OM_W (€/MWh)	0.13	α^{H2P}	0.005
OM_S (€/MWh)	0.13	$E_{I,max}^{S}$ (MW)	76
OM_{P2H} (€/Mm^3)	2	$H_{I,max}^{P2H}$ (Mm^3/h)	10
OM_{H2P} (€/MWh)	2	$P_{I,max}^{H2P}$ (MW)	800
IC_S (€/MW)	83000	η_c	0.95
IC^{P2H} (€/Mm^3/h)	1230000	η_d	0.95
IC^{H2P} (€/MW)	6232	η_{ch}	0.95
λ_H (€/Mm^3)	1.3	η_{dh}	0.95
H_I (Mm^3)	20		