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Multi-Alternative Operation-Planning Problem of Wind Farms Participating in Gas and Electricity Markets

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ABSTRACT By taking subsidies out of the picture, wind farm operators (WFO) face new challenges to participate in electricity markets. While conventional producers benefit from dispatchable generation, wind farms with stochastic nature have a challenging job to compete with these players in the market and need to come up with alternative solutions. To this end, energy storage devices have a great potential in managing the volatile generation and thereby increasing the profit of WFOs. On the other hand, the gas market opens new opportunities to improve the flexibilities of WFOs in addressing the incurred penalties due to deviation between prediction and generation. For the sake of practicality, this paper proposes a joint operation-planning model. The WFO bids in both the day-ahead electricity market and gas market while also invests in alternative facilities, including electrical energy storage, gas storage, power-to-gas, and gas-to-power. The proposed framework is formulated as a mixed-integer nonlinear programming (MINLP) model. To guarantee to find the global solution, the original MINLP model is recast into a mixed-integer linear programming (MILP) model. Several case studies are defined to capture the potential of the proposed framework on the profit of the WFO, scrutinizing the performance of different facilities and interactions with the aforementioned markets. The modeling provides a tool for the WFOs for considering different alternative approaches to deal with uncertainty of generation. This includes storing the surplus generation of wind farm in the form of electricity through electrical energy storage or by converting this surplus into gas via power-to-gas technology and either store it in a gas storage or sell it in the gas market. Moreover, under the lack of generation condition, the electrical energy storage can provide electricity, or the gas from gas market and gas storage can turn to electricity through gas-to-power facility to assist WFOs. Results show the effectiveness of the proposed framework in enhancing the profitability of wind farms via different alternatives while highlighting the role of the gas market as a promising solution.

INDEX TERMS Electricity market, electrical energy storage, gas storage, gas-to-power, gas market, operation and planning, power-to-gas, wind farm.

NOMENCLATURE

INDEXES

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

PARAMETERS

ρ_ω	Weighting coefficient of scenario ω [h].
λ_ω	Electricity price in the day-ahead market in scenario ω [€/MWh].
λ_g	Gas price in the gas market [€/Mm^3].
P	Capacity of offshore wind farm [MW].
IC_S	Investment cost of battery [€/MW].
IC^{P2G}	Investment cost of P2G facility [€/Mm^3/h].
IC^{G2P}	Investment cost of G2P facility [€/MW].
IC^G	Investment cost of gas storage [€/Mm^3/h].
OM_{G2P}	Operation and maintenance cost for G2P facility[€/MWh].
OM_{P2G}	Operation and maintenance cost for P2G facility [€/Mm^3].
OM_W	Operation and maintenance cost for offshore wind farm [€/MWh].

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OM_S	Operation and maintenance cost for electrical energy storage [€/MWh].
OM_G	Operation and maintenance cost for gas storage [€/Mm^3].
η_c	Charging efficiency of electrical energy storage.
η_d	Discharging efficiency of electrical energy storage.
η_{cg}	Charging efficiency of gas storage.
η_{dg}	Discharging efficiency of gas storage.
α_{P2G}	Conversion factor of P2G facility.
α_{G2P}	Conversion factor of G2P facility.
$E_{I,max}^S$	Maximum investment level of electrical energy storage [MW].
$G_{I,max}$	Maximum investment level of gas storage [Mm^3/h].
$G_{I,max}^{P2G}$	Maximum investment level of P2G facility [Mm^3/h].
$P_{I,max}^{G2P}$	Maximum investment level of G2P facility [MW].
$\alpha_{NPV,I}$	Net present value of investment costs.
$\alpha_{NPV,O}$	Net present value of operating costs.

VARIABLES

$P_\omega^{W,bid}$	Bidding power of offshore wind farm to the day-ahead market in scenario ω [MW].
$P_\omega^{W,P}$	Prediction of generation for offshore wind farm in scenario ω [MW].
$P_\omega^{W,A}$	Actual generation of the offshore wind farm in scenario ω [MW].
P_ω^{op}	Total overproduction in scenario ω [MW].
P_ω^{up}	Total underproduction in scenario ω [MW].
$P_\omega^{op,r}$	Remained overproduction in scenario ω [MW].
$P_\omega^{up,r}$	Remained underproduction in scenario ω [MW].
P_ω^{u}	Total unbalance power in scenario ω [MW].
P_ω^{ch}	Charging power of electrical energy storage in scenario ω [MW].
P_ω^{ch1}	Electrical energy storage charging power from wind farm in case of overproduction in scenario ω [MW].
$P_\omega^{G2P\_b}$	Charging power of electrical energy storage from G2P facility in scenario ω [MW].
P_ω^{dch}	Discharging power of electrical energy storage in scenario ω [MW].
P_ω^{dch1}	Discharging power of electrical energy storage to grid in case of underproduction in scenario ω [MW].
$P_\omega^{dch\_P2G}$	Discharging power of electrical energy storage to P2G facility in scenario ω [MW].
E_I^s	Capacity of electrical energy storage [MW].
G_ω^{ch}	Charging of gas storage in scenario ω [Mm^3/h].
$G_\omega^{P2G\_ch}$	Charging of gas storage from P2G facility in scenario ω [Mm^3/h].
$G_\omega^{ch\_b}$	Gas bought from the gas market to be stored in the gas storage in scenario ω [Mm^3/h].
G_ω^{dch}	Discharging gas amount of gas storage in scenario ω [Mm^3/h].
$G_\omega^{dch\_G2P}$	Discharging of gas storage to G2P facility in scenario ω [Mm^3/h].
$G_\omega^{dch\_s}$	Gas sold to the gas market from gas storage in Scenario ω [Mm^3/h].
G_I	Investing level of gas storage [Mm^3/h].
G_I^{P2G}	Investing level of P2G facility [Mm^3/h].
P_I^{G2P}	Capacity of G2P facility [MW].
G_ω^{P2G}	Gas generation of P2G facility in scenario ω [Mm^3/h].
$G_\omega^{P2G\_s}$	Gas sold to the gas market by P2G facility in scenario ω [Mm^3/h].
P_ω^{P2G}	Input power to P2G facility in scenario ω [MW].
$P_\omega^{P2G\_W}$	Input power to P2G facility from the offshore wind farm in case of overproduction in scenario ω [MW].
P_ω^{G2P}	Output power of G2P facility in scenario ω [MW].
$P_\omega^{G2P\_W}$	Output power from G2P facility to the grid in case of underproduction in scenario ω [MW].
G_ω^{G2P}	Gas input to G2P facility in scenario ω [Mm^3/h].
$G_\omega^{G2P\_b}$	Gas bought by G2P facility from the gas market in scenario ω [Mm^3/h].
G_{max}^t	The maximum gas that can be traded with the gas market facility in [Mm^3/h].
u_ω, V_ω^{cb} V_ω^{db}, V_ω^{cg}, V_ω^{dg}, e_ω	Binary variables.

I. INTRODUCTION

The share of wind farms in the generation sector is increasing as the policies strongly support moving toward a carbon-free society. Due to the decrease in the subsidies used to help the wind farm owner (WFO) to cover their expenses, they faced new challenges to compete with conventional and other renewable energy players on the available electricity markets. Besides, the random nature of wind power is another big issue for WFOs in competing with those players owning dispatchable generation. Thus, solutions to cope with such stochastic behavior are essential to increase the profitability of wind farms. Studies investigate different solutions to deal with the stochasticity of wind farm generation, resulting in multiple fruitful outcomes, e.g., increasing the share of renewable energy generation, enhancing the security of the power system, and increasing the profitability for WFOs. Some alternative solutions to guarantee the profitability of WFOs are considering interaction with electricity and gas markets, as well as pairing with facilities such as electrical energy storage (EES), gas storage, power-to-gas (P2G), and gas-to-power (G2P) devices, etc.

Interacting with the available markets are some of the viable options to increase the profit of WFOs. Some of the works in the literature have only considered the electricity market for trading wind power. The optimal bidding of the wind farm in the electricity markets was investigated in [1]. The authors in [2] studied the profit of wind farms when bidding separately compared with the situation in which they are bidding together. The advantage of acting strategically for wind power producers over the non-strategic ones on their profit by participating in the day-ahead market was investigated in [3]. The profit of a group of wind power producers participate in different electricity markets was surveyed in [4]. However, these studies lack to investigate the gas market and facilities like EES, gas storage, P2G, and G2P and their role on the profitability of these producers.

The EES device as a viable option to assist WFOs in tackling stochasticity of generation has been the focus of several works. The optimal location and size of energy storage were determined in [5] through a mixed-integer linear programming (MILP) formulation. The capability of EES to overcome the need for gas supply was investigated in [6] as a planning problem. Optimal siting, sizing, and operation of energy storage were considered in [7] to evaluate their performance in reducing the congestion in power systems in the presence of renewable energy resources. The size of a battery energy storage system was determined in [8] aiming at harnessing the variability of wind energy while optimizing its operation through a receding horizon control. To find the power and capacity of battery energy storage, an optimization approach was developed in [9] to minimize the cost of a joint wind farm and battery energy storage. Risk analysis for a wind farm paired with energy storage bidding in the day-ahead electricity market was performed in [10] to manage the existing risk in an uncertain environment. Participation of a wind farm coupled with battery in the frequency regulation surveyed in [11]. The bidding of a wind farm paired with storage in electricity markets was investigated in [12]. The optimal size of a battery energy storage to overcome stochasticity of wind generation plays a key role in energy systems, and this was investigated in [13] for a microgrid case and in [14] for the power system via an economic dispatch problem. Also, the capacities of battery energy storage systems were determined in [15] to assist large-scale offshore wind farms in dealing with uncertainty. On the other hand, the authors in [16] studied the planning and operation of coordinated wind turbines and energy storage systems under different market mechanisms, while the scheduling problem of a wind-battery system to participate in the day-ahead electricity market was investigated in [17]. In the area of energy storage, it is always challenging how to offer a promising future for the retired EV battery-storage system, and in [18], the authors coupled these batteries with wind energy and studied bid situations in different electricity markets. Although the aforementioned works provided strived to propose near-practical models, they only focused on EES and did not consider other facilities such as gas storage, P2G, and G2P.

As mentioned earlier, due to the increase in the share of renewable energy resources like wind energy in the generation sector, stochasticity has become a bigger challenge. The gas market has great potentials to interact with the electricity market and improve the WFOs performance by providing opportunities for WFOs and renewable energy resources to decrease their volatility of generation, which still needs to be investigated. Some studies surveyed the co-working of electricity and gas markets, including [19]–[22]. Interaction with the gas market requires its primary facilities such as P2G, G2P, and gas storage. Authors in [19] investigated the P2G technologies and their effect on electricity and gas networks. Advantages of combined bidding of natural gas generating unit and P2G conversion facilities over separate bidding were investigated in [20]. A game-based approach was implemented in [21] to maximize the total benefit of wind farms equipped with P2G facilities. Planning of P2G facilities, gas storages, wind farms, generating units, transmission lines, and gas pipelines on integrated electricity and natural gas system were investigated in [22], aiming to minimize the total investment and operation costs. However, these studies did not look into the problem from a WFO's viewpoint.

More often than not, the WFOs, due to the variability of wind power generation, face two crucial issues that result in losing profit, i.e., overproduction (producing more than the bid power, i.e., the committed power to the electricity market) and underproduction (producing less than the bid power). Assets consist of EES, gas storage, P2G, and G2P facilities have the potential to raise the profit of a WFO by overcoming the challenges mentioned above. In other words, these assets assist the WFO in reducing their overproduction and underproduction costs by decreasing the difference between the committed power to the market and the actual generated power. Historical data of electricity market price and wind farm generation enables us to have a more accurate assessment of their economic impact on wind farm performance. The literature review above summarized in Table 1, shows that although different studies have been performed in this area of research, to the best of our knowledge, considering multi-alternative asset operation-planning for WFOs while interacting with different sector markets is still a big gap to be filled. Overall, the main contributions of this study can be summarized as follows.

- Proposing a scenario-based stochastic MILP model for multi-alternative asset operation-planning problem of wind farms. For the sake of finding an appropriate

TABLE 1. **Comparison of literature studies and proposed approach in this paper.**

Approach	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Proposed
Wind farm	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓
EES	×	×	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	×	×	✓	✓	✓	✓	✓	✓	×	✓	✓
P2G	×	×	×	×	×	×	×	×	×	×	×	×	✓	✓	✓	✓	×	×	×	×	×	×	×	×	✓
G2P	×	×	×	×	×	✓	×	×	×	×	×	×	✓	✓	×	✓	×	×	×	×	×	×	×	×	✓
Gas storage	×	×	×	×	×	✓	×	×	×	×	×	×	✓	×	×	✓	×	×	×	×	×	×	×	×	✓
Operation	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Planning	×	×	×	×	✓	✓	✓	✓	✓	×	×	×	×	×	×	✓	✓	✓	✓	×	✓	✓	✓	✓	✓
Stochasticity	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	×	✓	×	✓	✓	✓	✓	✓	✓
100% Renewable	✓	✓	✓	✓	×	×	×	✓	×	✓	✓	✓	×	✓	✓	×	×	×	×	✓	✓	✓	×	✓	✓
Electricity market	✓	✓	✓	✓	×	×	×	✓	×	✓	✓	✓	×	✓	✓	×	×	×	✓	✓	✓	×	✓	✓	✓
Gas market	×	×	×	×	×	✓	×	×	×	×	×	×	✓	✓	✓	×	×	×	×	×	×	×	×	×	✓
Sensitivity analysis for level of trading with gas market	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	✓

tradeoff between computational tractability/efficiency and modeling accuracy, scenarios are generated via the duration curve method to properly consider the correlation between the random nature of wind power generation and electricity market price [23], [24]. The considered assets in the operation-planning decision-making process of this paper include EES, gas storage, P2G, and G2P facilities.

- Developing an interaction between WFOs and the gas market, which is made possible through investment in assets like gas storage, and P2G and G2P facilities. Moreover, the model jointly considers the interaction with the electricity market.
- Performing a thorough evaluation of the role of the aforementioned assets and interactions with different markets on the economic condition of a wind farm. To provide a roadmap/look-up table for WFOs, this paper investigates the contribution of the gas market on increasing the wind farm's benefit and reducing the deviation between bidding power in the electricity market and actual generation.

The remainder of this paper is organized as follows. Section II describes the problem formulation. Case studies and the data required for the simulation are presented in section III. Simulation results and discussion are provided in section IV. Section V presents concluding remarks and future work.

II. PROBLEM FORMULATION

Participation of WFOs in the available markets requires dealing with the stochasticity of generation. In this paper, a framework is developed to investigate the role of assets and the gas market to assist wind farms in overcoming this challenge. Different assets are available for pairing with wind farm producers to maximize their benefit by bidding in both the day-ahead electricity and gas markets. These assets consist of EES, gas storage, P2G, and G2P facilities, among all. For the sake of obtaining more practical results, this paper develops a joint planning and operation model for wind farm assets. In order to guarantee to obtain the optimal global solution, the initially proposed MINLP model (1)-(45) is recast into an equivalent MILP model.

The primary goal of the proposed model is to maximize the overall profit (1) by taking into account the net present value of the planning and operation terms. The 1st term stands for the investment costs of assets consisting of EES, P2G, G2P, and gas storage facilities. The 2nd term represents the operation cost of wind farm including incomes by selling a) electricity to the day-ahead market, and b) the produced gas (the difference between the output of P2G and gas storage facilities with the inputs of the gas storage, and G2P facilities) to the gas market; the penalty related to the deviation of committed power of wind farm to the electricity market (overproduction and underproduction); and the operation and maintenance (O&M) costs of the wind farm. The 3rd term is related to the O&M costs of assets, including production of G2P, P2G facilities, charge and discharge of EES, and gas storage.

$$\max\left\{\begin{array}{l}\underbrace{\begin{bmatrix}\alpha_{NPV,I}\times(-E_I^S\times IC_S-G_I^{P2G}\times IC^{P2G}-P_I^{G2P}\times IC^{G2P}\\ -G_I\times IC^G)\end{bmatrix}}_{\textit{Planning}\text{ costs}}\\ +\underbrace{\begin{bmatrix}\sum\limits_{\omega=1}^{N\Omega}(\rho_\omega)\times(\lambda_\omega\times P_\omega^{W,bid}+\lambda_g\times(G_\omega^{P2G\_s}+G_\omega^{dch\_s}\\ -G_\omega^{ch\_b}-G_\omega^{G2P\_b})-1.1\times\lambda_\omega\times(P_\omega^{op,r}+P_\omega^{up,r})\\ -OM_W\times P_\omega^{W,P})\end{bmatrix}}_{\textit{Wind farm operation}\text{ cost}}\\ +\underbrace{\begin{bmatrix}\alpha_{NPV,O}\times\sum\limits_{\omega=1}^{N\Omega}(\rho_\omega)\times(-OM_{G2P}\times P_\omega^{G2P}-OM_{P2G}\times G_\omega^{P2G}\\ -OM_S\times(P_\omega^{ch}+P_\omega^{dch})-OM_G\times(G_\omega^{ch}+G_\omega^{dch}))\end{bmatrix}}_{\textit{Facilities}\text{ operation cost}}\end{array}\right\} \tag{1}$$

$$0\leq E_I^S\leq E_{I,\max}^S \tag{2}$$

$$0\leq G_I^{P2G}\leq G_{I,\max}^{P2G} \tag{3}$$

$$0\leq P_I^{G2P}\leq P_{I,\max}^{G2P} \tag{4}$$

$$0\leq G_I\leq G_{I,\max} \tag{5}$$

$$0\leq P_\omega^{W,bid}\leq P_\omega^{W,P} \tag{6}$$

$$P_\omega^u=P^{W,A}-P_\omega^{W,bid} \tag{7}$$

$$P_\omega^u=P_\omega^{op}-P_\omega^{up} \tag{8}$$

$$P_\omega^{op}\leq P\times(1-u_\omega) \tag{9}$$

$$P_\omega^{up}\leq P\times u_\omega \tag{10}$$

$$P_\omega^{op}=P_\omega^{ch1}+P_\omega^{P2G\_W}+P_\omega^{op,r} \tag{11}$$

$$P_\omega^{up}=P_\omega^{dch1}+P_\omega^{G2P\_W}+P_\omega^{up,r} \tag{12}$$

$$\sum_{td,b}\rho_\omega\times((P_\omega^{ch}\times\eta_c)-(\frac{P_\omega^{dch}}{\eta_d}))=0 \tag{13}$$

$$P_\omega^{ch}=P_\omega^{ch1}+P_\omega^{G2P\_b} \tag{14}$$

$$P_\omega^{dch}=P_\omega^{dch1}+P_\omega^{dch\_P2G} \tag{15}$$

$$0.20\times E_I^S\times V_\omega^{cb}\leq P_\omega^{ch}\leq 0.95\times E_I^S\times V_\omega^{cb} \tag{16}$$

$$0.20\times E_I^S\times V_\omega^{cb}\leq P_\omega^{ch1}\leq 0.95\times E_I^S\times V_\omega^{cb} \tag{17}$$

$$\begin{aligned}&0.20\times E_I^S\times u_\omega\times V_\omega^{cb}\leq P_\omega^{G2P\_b}\\ &\quad\leq 0.95\times E_I^S\times u_\omega\times V_\omega^{cb}\end{aligned} \tag{18}$$

$$0.20\times E_I^S\times V_\omega^{db}\leq P_\omega^{dch}\leq 0.95\times E_I^S\times V_\omega^{db} \tag{19}$$

$$0.20\times E_I^S\times V_\omega^{db}\leq P_\omega^{dch1}\leq 0.95\times E_I^S\times V_\omega^{db} \tag{20}$$

$$\begin{aligned}&0.20\times E_I^S\times(1-u_\omega)\times V_\omega^{db}\leq P_\omega^{dch\_P2G}\\ &\quad\leq 0.95\times E_I^S\times(1-u_\omega)\times V_\omega^{db}\end{aligned} \tag{21}$$

$$V_\omega^{cb}+V_\omega^{db}\leq 1 \tag{22}$$

$$\sum_{td,b}\rho_\omega\times((G_\omega^{ch}\times\eta_{cg})-(\frac{G_\omega^{dch}}{\eta_{dg}}))=0 \tag{23}$$

$$G_\omega^{ch}=G_\omega^{P2G\_ch}+G_\omega^{ch\_b} \tag{24}$$

$$G_\omega^{dch}=G_\omega^{dch\_G2P}+G_\omega^{dch\_s} \tag{25}$$

$$0.20\times G_I\times V_\omega^{cg}\leq G_\omega^{ch}\leq 0.95\times G_I\times V_\omega^{cg} \tag{26}$$

$$0.20\times G_I\times V_\omega^{cg}\leq G_\omega^{P2G\_ch}\leq 0.95\times G_I\times V_\omega^{cg} \tag{27}$$

$$0.20\times G_I\times V_\omega^{cg}\leq G_\omega^{ch\_b}\leq 0.95\times G_I\times V_\omega^{cg} \tag{28}$$

$$0.20\times G_I\times V_\omega^{dg}\leq G_\omega^{dch}\leq 0.95\times G_I\times V_\omega^{dg} \tag{29}$$

$$0.20\times G_I\times V_\omega^{dg}\leq G_\omega^{dch\_G2P}\leq 0.95\times G_I\times V_\omega^{dg} \tag{30}$$

$$0.20\times G_I\times V_\omega^{dg}\leq G_\omega^{dch\_s}\leq 0.95\times G_I\times V_\omega^{dg} \tag{31}$$

$$V_\omega^{cg}+V_\omega^{dg}\leq 1 \tag{32}$$

$$G_\omega^{ch\_b}\leq G_{\max}^t\times(1-e_\omega) \tag{33}$$

$$G_\omega^{dch\_s}\leq G_{\max}^t\times e_\omega \tag{34}$$

$$0\leq G_\omega^{P2G}\leq G_I^{P2G} \tag{35}$$

$$G_\omega^{P2G}=\alpha^{P2G}\times P_\omega^{P2G} \tag{36}$$

$$G_\omega^{P2G}=G_\omega^{P2G\_ch}+G_\omega^{P2G\_s} \tag{37}$$

$$P_\omega^{P2G}=P_\omega^{P2G\_W}+P_\omega^{dch\_P2G} \tag{38}$$

$$G_\omega^{P2G\_s}\leq G_{\max}^t\times e_\omega \tag{39}$$

$$0\leq P_\omega^{G2P}\leq P_I^{G2P} \tag{40}$$

$$P_\omega^{G2P}=\alpha^{G2P}\times G_\omega^{G2P} \tag{41}$$

$$G_\omega^{G2P}=G_\omega^{dch\_G2P}+G_\omega^{G2P\_b} \tag{42}$$

$$P_\omega^{G2P}=P_\omega^{G2P\_W}+P_\omega^{G2P\_b} \tag{43}$$

$$G_\omega^{G2P\_b}\leq G_{\max}^t\times(1-e_\omega) \tag{44}$$

$$G_\omega^{P2G\_s}+G_\omega^{ch\_b}+G_\omega^{dch\_s}+G_\omega^{G2P\_b}\leq G_{\max}^t \tag{45}$$

The model determines the optimal size of P2G and G2P facilities, EES, and gas storage within the ranges defined in (2)-(5), respectively. The bid power in the day-ahead market is bound to the prediction of wind generation by (6). Wind farm overproduction and underproduction are subject to a penalty. Therefore, the available or candidate assets aim at assisting in decreasing these deviations, defined by (7). Deviations are distinguished in the form of overproduction, P_ω^{op}, and underproduction, P_ω^{up}, by (8), where (9) and (10) by using a binary variable u_ω specify whether there is an overproduction or underproduction at each scenario ω and also limit them to the capacity of the wind farm. The WFO tries to handle the overproduction partly by charging the EES and/or converting it to gas through the P2G facility, and the rest is considered as remained overproduction, see (11). The underproduction is compensated by discharging EES and/or converting gas to electricity using the G2P facility, and the rest is considered as remained underproduction, see (12). The residual overproduction and underproduction results in a surcharge to the wind farm, see (1). Charging and discharging of EES is modeled by (13)-(22). Constraint (13) states that the summation of charging and discharging of EES over time of day (daytime or nighttime) and defined blocks should be zero [25]. The EES is charged either through wind overproduction or via the G2P facility presented in (14), while it is discharged to compensate the wind underproduction or generate gas via the P2G facility via (15). Constraints (16)-(18) respectively determine the status of the total charging power of EES, its charging power from wind overproduction, and its charging power from the G2P facility while bounding them to the minimum and maximum nominal level. Similarly, EES discharging power, discharging power for wind underproduction, and discharging power for the P2G facility are bound to the minimum and maximum nominal level of discharging power (19)-(21), respectively, while also determining the status of these terms. Constraint (22) guarantees that charging or discharging does not occur simultaneously at each scenario ω. Gas storage is modeled via (23)-(34). The summation of charging and discharging of gas storage over time of day (daytime or night time) and the defined block is kept equal to zero via (23); the charging level of gas storage is the summation of charging from the P2G facility and charging from the gas market display by (24); (25) presents the discharging of gas storage is for G2P facility and gas market; charging level, charging from P2G facility, and charging from the gas market for gas storage is bounded to the nominal level of its charging via (26)-(28); discharging level, discharging for G2P facility, and discharging to sell to gas market is limited to gas storage nominal level of discharging through constraints (29)-(31). Constraint (32) states that at each scenario ω only charging or discharging of gas storage is possible. Constraints (33) and (34) limit the amount of gas that can be bought and sold to the gas market from gas storage to the amount of gas that can be traded with the gas market. The P2G facility is modeled with (35)-(39), where the gas level of the P2G facility is bounded to its investment value in (35); the relation between generated gas by the P2G facility and its input power is shown with (36); the generated gas can charge the gas storage or be sold to the gas market via (37). The input power of the P2G facility is either from wind overproduction or from EES, as (38). Constraint (39) limits the amount of gas that can be sold to the gas market via the P2G facility to the trading limit with the gas market. G2P facility is model by (40)-(44); the output power of the G2P facility is limited to the invested value in (40); the relation between power output and gas input of the G2P facility is shown by (41); (42) states that the input gas of the G2P facility is derived from the gas market and gas storage. The output power of the G2P facility is used for compensating the wind underproduction and/or charging of EES via (43), and (44) limits the amount of gas that the G2P facility can buy from the gas market to the trading level contracted with the gas market. The summation of the amounts of gas that can be bought/sold from/to the gas market is limited to the trading level of gas by (45). In this model, there exist several nonlinear terms that need to be linearized in order to find the optimal global solution. Constraints (16), (17), (19), (20), and (26)-(31) contain bilinear terms due to the product of binary and continuous variables, which can be linearized as follows. If A is a binary variable and B is a continuous and bounded variable, then $A \cdot B$ can be replaced by equivalent linear terms as follows.

$$\begin{aligned} &\mathit{define}\ C = A \cdot B\ \mathit{when}\ A \in \{0,1\}, \underline{B} \le B \le \overline{B} \\ &\underline{B} \cdot A \le C \le \overline{B} \cdot A \\ &C \le B - \underline{B} \cdot (1 - A) \\ &C \ge B - \overline{B} \cdot (1 - A) \end{aligned} \tag{46}$$

On the other hand, (18) and (21) include the product of two binary, L and M, with a continuous variable, Z, i.e., $L \cdot M \cdot Z$. In order to find the equivalent linear term, first, the two binary variables can be replaced with one new binary variable, K, as follows [26].

$$\begin{aligned} &K = L \times M\ \mathit{when}\ L \in \{0,1\}, M \in \{0,1\} \\ &K \le L \\ &K \le M \\ &K \ge L + M - 1 \\ &K \in \{0,1\} \end{aligned} \tag{47}$$

Then, the product of the new defined binary variable and the continuous variable can be linearized similarly to (46). The flowchart of the proposed model is displayed in Fig. 1. Simulation initiate with determining the size of the facilities (EES, P2G, G2P, and gas storage). Then the operating status of the wind farm paired with the invested facilities in electricity and gas markets will be decided as follows. In the case of overproduction, the surplus power may charge EES or can be delivered to the P2G facility and turned into gas and charges the gas storage or is sold to the gas market. In case of underproduction, the EES may discharge, or the G2P facility may buy gas or extract gas from gas storage to produce electricity in order to alleviate the shortage of production of the wind farm. In case of equality between actual generation and committed power to the electricity market, the operation of facilities and interaction with the gas market depends on the economic benefit decided in the optimization. It should be noted that the optimal operation of facilities like charging/discharging of EES and gas storage and interaction with the gas market (buy or sell) also depend on their storage availability, which will be determined through optimization.

III. DATA AND CASE STUDIES

This section presents the data required for the simulation studies as well as different case studies and model configurations to investigate multiple alternatives for WFOs to maximize their profit.

A. DATA

In this paper, the historical data of electricity market price and the falsified generation data of a real wind farm located in the North Sea area is used to generate scenarios representing the random nature of uncertain parameters. In order to guarantee the tractability of the model while not underestimating its accuracy, the duration curve method is used to generate an adequate number of scenarios [24]. To do so, first, the seasonal electricity market price is divided based on week, weekend, and daytime and nighttime. Then, these prices are arranged decreasingly for each division. Four levels are considered for prices, including peak, high-medium, low-medium, and off-peak periods. After that, each level is divided into three equal parts, and these parts are represented with values obtained by getting the average of the prices at

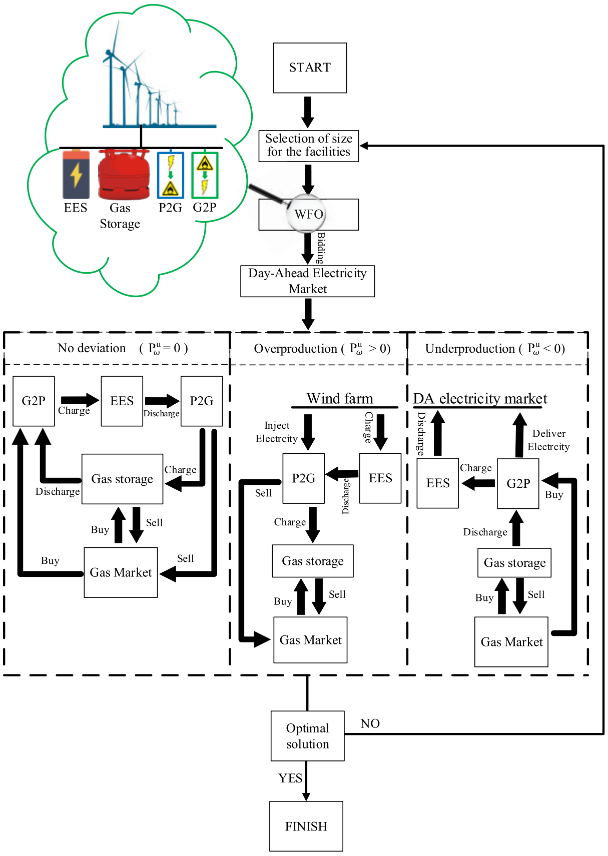

FIGURE 1. Flowchart of the proposed model.

these hours. Similarly, the wind generations corresponding with these prices are sorted decreasingly for each level. These levels are divided into three equal parts, and wind powers in each part are represented by the average of its values over the related hours. As an instance, Fig.2 displays the electricity market price and wind farm generation for winter during the week and in the daytime. Overall, there are 192 scenarios that have a pair of electricity market price and wind farm generation. The net present value coefficient for operation costs is hourly and can be calculated as $\alpha_{NPV,O} = m(1+m)^n/[((1+m)^n-1) \times D \times H]$ where m is the annual discount rate considered 5%, n is the lifetime of the facility assumed to be 10 years, D is the number of days in the one year of planning, and H is the number of hours in a day. $\alpha_{NPV,I}$ is the net present value coefficient for investment costs and considered yearly obtained by multiplying $\alpha_{NPV,O}$, D, and H. Table 2 present parameters of the wind farm, EES, gas storage, P2G and G2P facilities [27], [28].

B. CASE STUDIES

To investigate the performance of different facilities and markets on the profit of the WFO, several operation-planning-based case studies are conducted.

TABLE 2. Data for simulation.

Symbol	Value	Symbol	Value
P (MW)	760	α_{P2G}	0.0045
OM_W (€/MWh)	0.13	α_{G2P}	0.005
OM_S (€/MWh)	0.13	$E^S_{I,max}$ (MW)	400
OM_G (€/Mm^3)	0.13	$G_{I,max}$ (Mm^3/h)	10
OM_{P2G} (€/Mm^3)	2	$G^{P2G}_{I,max}$ (Mm^3/h)	5
OM_{G2P} (€/MWh)	2	$P^{G2P}_{I,max}$ (MW)	1000
IC_S (€/MW)	83000	η_c	0.95
IC^{P2G} (€/Mm^3/h)	1230000	η_d	0.95
IC^{G2P} (€/MW)	6232	η_{cg}	0.95
IC^G (€/Mm^3/h)	500000	η_{dg}	0.95
λ_g (€/Mm^3)	1.3005		

1) BASE CASE: WIND FARM ONLY INTERACTS WITH ELECTRICITY MARKET

In this case, the wind farm only participates in the electricity market. Therefore, the results of this case are used as the benchmark for comparison purposes. The problem formulation, in this case, consists of (6)-(10). The overall profit will be the summation of selling power to the electricity market minus wind farm O&M costs and penalties related to the deviation between actual generation and the bid power to the electricity market.

2) CASE I: CONSIDERING ELECTRICITY MARKET AND EES

This case aims at finding the optimal size of EES to be paired with the wind farm in order to maximize the profit of the WFO by bidding in the electricity market. Other facilities include gas storage, P2G, and G2P, and gas market are not considered in this case study; therefore, problem formulation includes (1), (2), and (6)-(22). Nonlinear terms in (16), (17), (19), and (20) are linearized through (46), while the bilinear terms in (18), and (21) are recast via (46), and (47). This results in a MILP planning problem to find the optimal size and operation of storage over the planning period. Here, the overall profit is the summation of the cost of planning for EES, selling power to the electricity market, O&M costs related to the EES and wind farm, and penalties associated with the deviation.

3) CASE II: CONSIDERING ELECTRICITY MARKET, GAS STORAGE, P2G, AND G2P FACILITIES

This case considers the planning and operation of some facilities to be paired with the wind farm. The available facilities for investment in this case study are gas storage, P2G and G2P, while the EES and gas market are not considered. The formulation of this problem is through (1), (3)-(12), (23)-(32), (35)-(38), and (40)-(43). The linearization of nonlinear terms in (26)-(31) is handled via (46). In this case, the overall profit consists of the planning costs of candidate facilities, income from selling electricity to the day-ahead market, penalties related to the deviation in bidding power, and O&M costs of gas storage, and P2G and G2P facilities. That is the planning, operation, and O&M costs of EES, as well as interaction with the gas market is ignored.

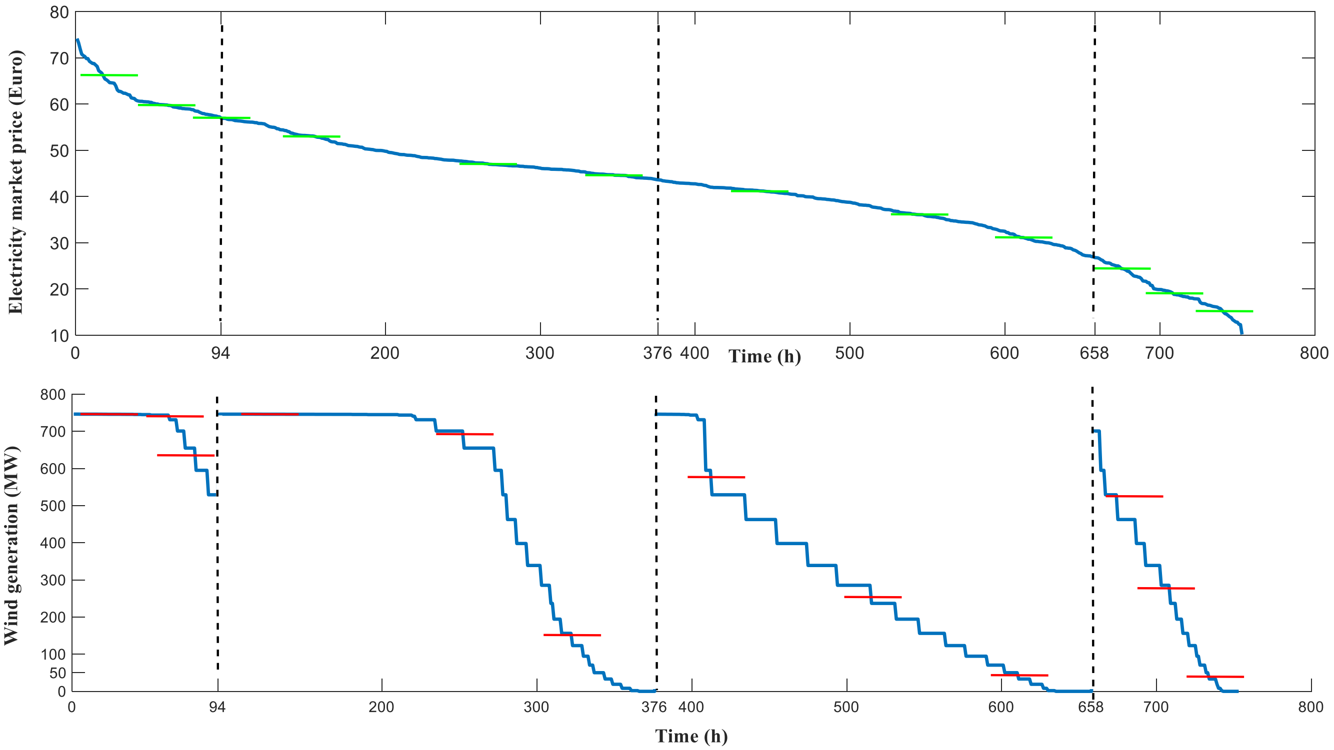

FIGURE 2. Electricity market price and wind farm generation in winter, weekday, and daytime.

4) CASE III: CONSIDERING EES, GAS STORAGE, AND P2G AND G2P FACILITIES, AND ONLY INTERACTION WITH THE ELECTRICITY MARKET

In this case study, investment on all the mentioned facilities, including EES, gas storage, P2G and G2P is considered, while the WFO interacts only with the electricity market. The problem formulation consists (1)-(45), while the trading with the gas market is set to zero. The approach presented in (46) is used to linearize the nonlinearities in (16), (17), (19), (20), and (26)-(31), while to linearize the bilinear terms in (18), and (21), techniques in (46), and (47) are applied. Here, the overall profit is the summation of income from the electricity market minus the planning costs of facilities, O&M costs for facilities and wind farm, and penalties related to the deviation in the bid power and actual generation.

5) CASE IV: ALL THE ALTERNATIVE FACILITIES AND BOTH THE ELECTRICITY AND GAS MARKETS ARE AVAILABLE

In this case study, the planning and operation of all the alternative facilities are considered and the wind farm owner can simultaneously bid in both the electricity and gas markets. Sensitivity analysis is carried out on this case study to evaluate the effect of limitation on the trading with the gas market on the investment decisions and the profit of the wind farm. The formulation of this case includes (1)-(45), and similar to Case III, (46) and (47) are used to recast the nonlinear terms into equivalent linear terms. The profit in this case study includes income from the electricity and gas market minus buying costs from these markets, planning costs of facilities, operation and maintenance costs of facilities and wind farm, and penalties related to the deviation of actual generation from bidding power.

IV. NUMERICAL RESULTS AND DISCUSSION

A. *SIMULATION RESULTS*

Simulation results perform a deep analysis of the outcomes of the proposed model under different conditions. Such analysis aims at helping the WFO in facilitating the planning-operation-based decision-making procedure. The investment actions include the planning decisions on the optimal size of EES, gas storage, P2G, and G2P facilities. The potential and performance of these units on increasing the profit of the wind farm are investigated via different aforementioned case studies. Moreover, the role of the gas market as a viable option in contributing to the profit of WFOs is studied in more details.

A thorough analysis of different case studies provides us an in-depth understanding of the effects of facilities and markets on the profit and performance of the wind farm. The simulations are carried out in GAMS [29], and the commercial solver Cplex is used to handle the model [30].

In the base case study, we only have the wind farm participating in the electricity market and not taking advantage of any other facilities. This provides us the basic information to be used for comparison purposes with other cases and learn about the effects of facilities and markets

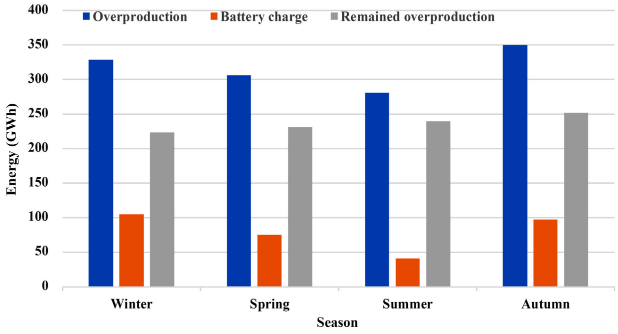

FIGURE 3. Overproduction, remained overproduction and EES charge in Case *I* for different seasons.

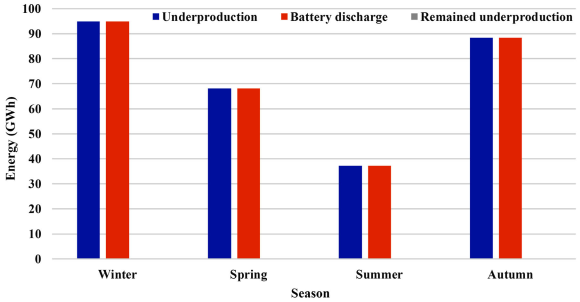

FIGURE 4. Underproduction, remained underproduction and EES discharge in Case *I* for different seasons.

on the profit and performance of the wind farm. In this case, the profit of the WFO is about 70.675 M€. Over a year, the total energy of overproduction has been 1000.679 GWh with 258.397, 244.257, 242.400, and 255.623 GWh for winter, spring, summer, and autumn, respectively, while no underproduction is observed for this case study.

In Case I, we pair an EES with the wind farm to bid in the electricity market. By solving the equivalent MILP model, the optimum capacity of EES is obtained as 179.142 MW. In this case, the total profit of the wind farm resulted from participating in the electricity market is 76.340 M€ which is 8.01% higher than the base case. Here, for those scenarios with overproduction, EES will store energy to reduce the deviation between bid power and actual generation. As an instance, in a sample scenario, i.e., Scenario 8, there exists about 170.185 MW overproduction, and the whole amount is stored in the EES. Fig. 3 displays the total overproduced energy, EES charge, and the remained overproduction in different seasons of the year. In this case, the remained overproduction over the year that causes the penalty is 5.38% lower than the base case study. Moreover, the stored energy will discharge in scenarios with underproduction in order to decrease the deviation related to generating less than committed. For instance, in the sample Scenario 4, there is about 163.191 MW underproduction compensated by discharging the EES. The total energy of underproduction, EES discharge, and the remained underproduction is depicted in Fig. 4. Here, similar to the base case, no underproduction remains to cause a penalty for WFO.

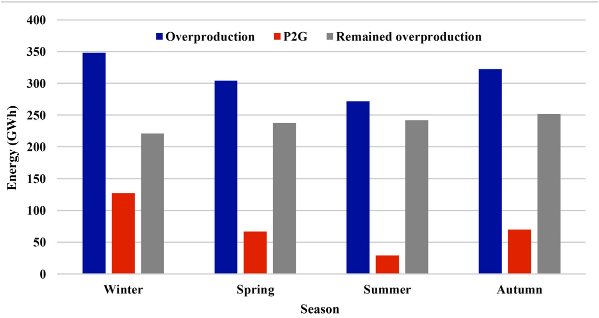

FIGURE 5. Overproduction, remained overproduction and P2G in Case *II* for different seasons.

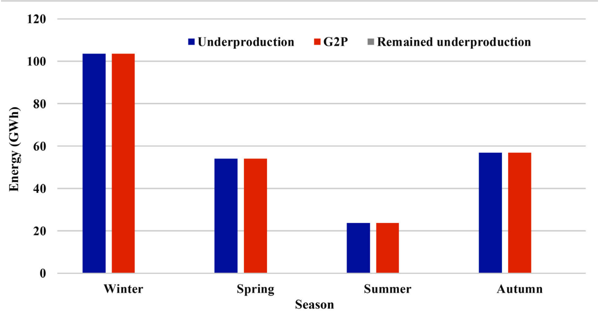

FIGURE 6. Underproduction, remained underproduction, and G2P in Case *II* for different seasons.

Case II investigates the investment in the gas storage, P2G, and G2P facilities when the wind farm is bidding in the electricity market. Simulation results show that the optimum size of these facilities are 1.524 Mm^3/h, 1.448 Mm^3/h, and 289.503 MW, respectively. The profit in this case study is 76.815 M€ which is 8.68% higher than the profit in the base case and a little higher than Case I, about 0.62%. Here, during the overproduction, the surplus power can turn into gas through the P2G facility and charge the gas storage. The total energy of overproduction, P2G input power, and remained overproduction are displayed in Fig. 5. Here, the remained overproduction over the year that results in a penalty is 4.73% lower than the base case. On the underproduction, the discharged gas of gas storage will turn into power through the G2P facility in order to decrease the deviation between generated power and committed power to the electricity market. Fig. 6 depicts the total energy of underproduction, G2P output, and the remained underproduction. In this case, similar to the base case study, no penalty will cause by underproduction.

The third case considers the planning of EES, gas storage, P2G, and G2P facilities to pair with the wind farm. The optimum values for the EES and gas storage, gas production of P2G, and power production of G2P facilities are 64.156 MW, 1.820 Mm^3/h, 1.729 Mm^3/h, and 254.915 MW, respectively. The electricity market is the only available market for participation, and it assumes that there is no connection/bilateral contract with the gas market. Simulation results show that the profit increased by 11.03%, 2.79%,

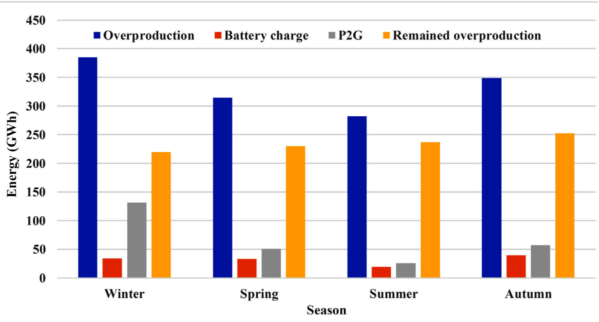

FIGURE 7. Overproduction, remained overproduction, EES charge and P2G in Case *III* for different seasons.

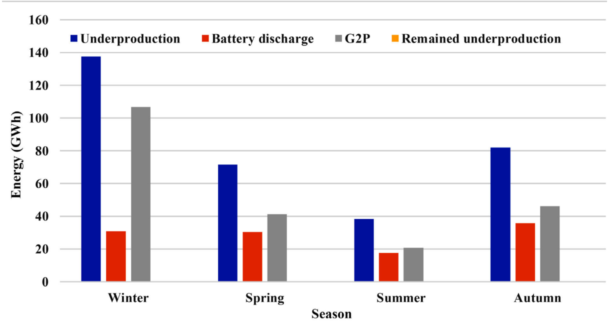

FIGURE 8. Underproduction, remained underproduction, EES discharge, and G2P in Case *III* for different seasons.

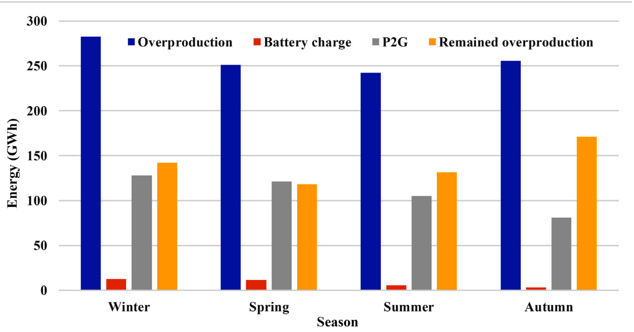

FIGURE 9. Overproduction, remained overproduction, EES charge, and P2G in Case *IV* for different seasons.

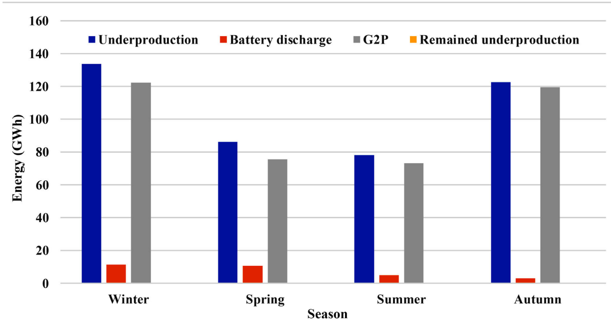

FIGURE 10. Underproduction, remained underproduction, EES discharge and G2P in Case *IV* for different seasons.

and 2.16% to the amount of 78.477 M€, compared to the base Case, Case I, and Case II, respectively. Here, in case of overproduction, the surplus power can be stored in the EES or turned into gas through the P2G facility and then stored in the gas storage. Fig. 7 shows the total energy over scenarios during the overproduction, EES charge, P2G, and remained overproduction for different seasons. In this case, and compared to the base case, there is a 6.23% decrease in overproduction over a year compare. In the case of underproduction, EES can discharge power to decrease the deviation between the actual generation and committed power to the market. Moreover, gas storage can discharge to transform gas to power by G2P facility. Fig. 8 displays the summation of energy over scenarios for underproduction, EES discharge, G2P for different seasons of the year. Similar to the base case, the underproduction will not cause any penalty to the WFO.

The last case study consists of all the facilities (EES, gas storage, P2G and G2P), and the wind farm interacts with both the electricity and gas markets in the simulation. First, the simulation for this case carried out when the amount of gas that can be traded with the gas market is limited to 0.5 Mm^3/h. Under this condition, the profit is about 110.94 M€ which is considerably higher than the other cases, i.e., 57.12%, 45.32%, 44.42%, and 41.36% higher than the base case, Case I, Case II, and Case III, respectively.

Since Case IV considers all the multiple alternatives, the model validation is performed via this case by providing detailed information. Table 3 displays the value of the variables in some of the scenarios in Case IV. Here, in case of overproduction, the surplus power can be stored in the EES, or it can turn into the gas by the P2G facility, which either can be stored in the gas storage or sold to the gas market. As an example, in sample scenario 8, there is 177.03 MW overproduction completely compensated where about 30.11 MW is stored in the EES and 146.92 MW is turned into gas through P2G, resulting in 0.66 Mm^3/h gas that charged the gas storage. In scenario 9, there is 382.55 MW overproduction that 111.11 MW of it compensated by turning into gas through P2G facility and the produced gas, 0.5 Mm^3/h, was sold to the gas market. The remained 271.44 MW caused a penalty to the WFO. Fig. 9 displays the total energy over scenarios for overproduction, EES charge, P2G, and remained overproduction. The remained overproduction that causes penalty for WFO decreases considerably by 43.75% compared to the base case. In case of underproduction, to help the wind farm compensating for the deviation, the EES can be discharged, or the G2P facility can generate more power. Under this condition, the gas of the G2P facility can be bought from the gas market or drain from the gas storage. As an instance, in scenario 1, there is 141.3 MW underproduction that completely compensated. The EES provided about 41.3 MW of it, and the rest 100 MW was covered from the G2P facility by buying 0.5 Mm^3/h from the gas market. In scenario 3, there was 204.72 MW underproduction that was entirely compensated, 39.60 MW discharge power from EES and the rest, 165.12 MW, was

TABLE 3. Sensitivity analysis for case *IV*.

Sc #	$P^{op}_{t,\omega}$ (MW)	$P^{op,r}_{t,\omega}$ (MW)	$P^{P2G\_W}_{t,\omega}$ (MW)	$P^{ch1}_{t,\omega}$ (MW)	$G^{P2G\_ch}_{t,\omega}$ (Mm^3/h)	$G^{P2G\_s}_{t,\omega}$ (Mm^3/h)	$P^{up}_{t,\omega}$ (MW)	$P^{up,r}_{t,\omega}$ (MW)	$P^{G2P\_W}_{t,\omega}$ (MW)	$P^{dch1}_{t,\omega}$ (MW)	$P^{dch\_P2G}_{t,\omega}$ (MW)	$P^{G2P\_b}_{t,\omega}$ (MW)	$G^{ch\_b}_{t,\omega}$ (Mm^3/h)	$G^{dch\_s}_{t,\omega}$ (Mm^3/h)	$G^{dch\_G2P}_{t,\omega}$ (Mm^3/h)	$G^{G2P\_b}_{t,\omega}$ (Mm^3/h)
1	0	0	0	0	0	0	141.3	0	100	41.3	0	0	0	0	0	0.5
2	0	0	0	0	0	0	301.69	0	260.39	41.3	0	0	0	0.34	1.3	0
3	0	0	0	0	0	0	204.72	0	165.12	39.60	0	0	0	0.5	0.82	0
8	177.03	0	146.92	30.11	0.66	0	0	0	0	0	0	0	0.5	0	0	0
9	382.55	271.44	111.11	0	0	0.5	0	0	0	0	0	0	0	0	0	0
10	118.45	0	77.15	41.3	0.34	0	0	0	0	0	0	0	0.5	0	0	0
11	249.63	0	230.05	19.58	1.03	0	0	0	0	0	0	0	0.5	0	0	0
12	388.08	276.97	111.11	0	0	0.5	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	117.36	0	91.58	25.78	0	0	0	0.46	0.45	0
59	0	0	0	0	0	0	51.18	0	9.88	41.3	0	0	0	0	0	0.049

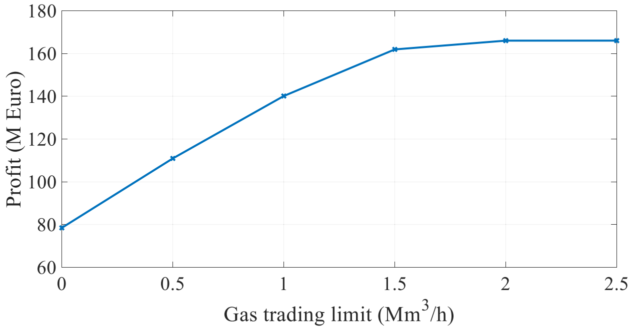

FIGURE 11. Profit of WFO based on the sensitivity analysis performed on the gas trading limit, Case *IV*.

TABLE 4. Sensitivity analysis over the amount of gas to trade with gas market for case *IV*.

GAS TRADING LIMIT (Mm^3/ h)	E_l^S (MW)	G_l^{P2G} (Mm^3/ h)	P_l^{G2P} (MW)	G_l (Mm^3/ h)
0	64.156	1.729	254.915	1.820
0.5	43.474	1.035	260.396	1.736
1	0	1.406	314.769	2.098
1.5	0	1.5	300	0
2	0	1.737	400	0
2.5	0	1.737	411.720	0

supplied by the G2P facility by using 0.82 Mm^3/h gas from the gas storage. Moreover, the gas storage sold about 0.5 Mm^3/h to the gas market. Fig. 10 shows the total energy over scenarios for underproduction, EES discharge, G2P and remained underproduction. Similar to the base case, there is no penalty related to the underproduction in this case study.

B. SENSITIVITY ANALYSIS

A sensitivity analysis is performed on the volume of gas that can be traded with the gas market. To this end, Case IV, as the most beneficial and practical case is considered, and thereby the optimal sizes of multi-alternative facilities are investigated. Table 4 displays the optimal sizes of the facilities, including the EES, P2G, G2P, and gas storage when the amount of gas that can be traded with the gas market increase with steps of 0.5 Mm^3/h. After 2.5 Mm^3/h the size of the mentioned facilities stayed the same and increasing the amount of trading gas with gas market did not affect the results. Fig. 11 depicts the total profit for the sensitivity analysis over the volume of gas to be traded with the gas market with the step of 0.5 Mm^3/h. It is noteworthy to mention that the profit of the WFO did not vary after 2.5 Mm^3/h exchange limit.

V. CONCLUSION

This paper has studied a joint operation-planning problem of multiple alternative facilities paired with wind farms aiming to enhance their flexibility in addressing challenging situations, i.e., overproduction and underproduction. The model is further developed to make a proper interaction with both the gas and day-ahead electricity markets. The resulted framework has been modeled as a mixed-integer nonlinear programming problem and has been then recast into an equivalent mixed-integer linear programming problem. Four different case studies have been proposed to capture the performance of wind farms in the presence of multi-alternative facilities and different markets. Simulation results showed increases in the profit of wind farm operators (WFOs) when they had the opportunity to pair with different facilities. Moreover, the degree of deviations between bidding power to the electricity market and the actual generation has also decreased. The study of these case studies has illustrated the capability of alternative facilities to increase the profit of WFO and to decrease the deviation costs. The optimal size of the aforementioned facilities, determined in different case studies, provides a benchmark for WFOs in performing planning. Furthermore, it has been observed that the gas market has great potentials in assisting the WFOs to overcome the existing challenges (mainly the stochasticity in generation) and thereby enhance their profits. The linking of WFOs and the gas market, which became possible through investment in P2G and G2P facilities, can further increase the share of wind generation in the electricity markets. A sensitivity analysis, performed on the volume of gas that can be traded with the gas market, reveals that at the presence of P2G and G2P facilities, when free trading with the gas market is available, considering electrical energy storage and gas storage is not beneficial, and thus, not required. However, when there was a limit to trade with the gas market, the investment occurred for electrical energy storage and gas storage. The model that has been developed in this paper provides a promising tool for WFOs planning problems to invest in any of the mentioned facilities. Moreover, analyzing their profit when trading with different limits on the gas market will give them useful insight into how they want to interact with this market.

Future works will develop a bilevel programming model to simulate the competition between renewable energy owners and conventional producers, and other large players.

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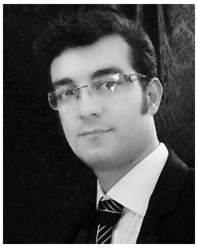

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