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# Risk Analysis of Wind Farm Paired with Assets in Electricity and Gas Markets


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***Abstract*—The structure of the day-ahead electricity market obliges wind farm owners (WFOs) to make commitments hours before delivery. Due to the uncertainty of wind generation, WFOs bid in the electricity market with the prediction of its generation that, more often than not, is different from the actual generation. Therefore, WFOs experience deviations between their commitment to the electricity market and the actual generation, namely overproduction and underproduction, which are subject to penalties. This paper investigates solutions to decrease such deviation and increase the profit of the WFO. To this end, the joint planning and operation of electrical energy storage (EES) and power-to-gas (P2G) units to be paired with wind farms are evaluated while considering both the electricity and gas markets. Two case studies, with only EES and with both the EES and P2G units, are conducted to reveal the potential of the proposed approach, while risk analyses are performed to study the impact of different risk criteria on the decisions of WFO. This problem is formulated as an MINLP and then recast into MILP to obtain global solutions. Results offer the best strategies for WFOs to enhance their profit under the existing uncertain conditions.**



***Keywords—Electricity market, electrical energy storage, gas market, power-to-gas, risk analysis, wind farm.***


## NOMENCLATURE

A. Indexes

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

B. Parameters

| | |
|---|---|
| $\rho_{\omega}$ | Weighting coefficient of the scenario $\omega$ [h]. |
| $\lambda_{\omega}$ | Electricity price in the day-ahead market in scenario $\omega$ [€/MWh]. |
| $\lambda_g$ | Gas price in the gas market [€/M$m^3$]. |
| $P$ | Capacity of offshore wind farm [MW]. |
| $IC_S$ | Investment cost of electrical energy storage [€/MW]. |
| $IC^{P2G}$ | Investment cost of P2G facility [€/M$m^3$/h]. |
| $OM_{P2G}$ | Operation and maintenance costs for P2G facility [€/M$m^3$]. |
| $OM_W$ | Operation and maintenance costs for offshore wind farm [€/MWh]. |
| $OM_S$ | Operation and maintenance costs for electrical energy storage [€/MWh]. |
| $\eta_c$ | Charging efficiency of electrical energy storage. |
| $\eta_d$ | Discharging efficiency of electrical energy storage. |
| $\alpha_{P2G}$ | Conversion factor of P2G facility. |
| $E_{I,max}^{S}$ | Maximum investment level of electrical energy storage [MW]. |
| $G_{I,max}^{P2G}$ | Maximum investment level of P2G facility [M$m^3$/h]. |
| $\alpha_{NPV,I}$ | Net present value of investment costs. |
| $\alpha_{NPV,O}$ | Net present value of operation costs. |

Variables

| | |
|---|---|
| $P_{\omega}^{W,bid}$ | Bidding power of offshore wind farm to the day-ahead market in scenario $\omega$ [MW]. |
| $P_{\omega}^{W,P}$ | Prediction of generation for offshore wind farm in scenario $\omega$ [MW]. |
| $P_{\omega}^{W,A}$ | Actual generation of the offshore wind farm in scenario $\omega$ [MW]. |
| $P_{\omega}^{op}$ | Total overproduction in scenario $\omega$ [MW]. |
| $P_{\omega}^{up}$ | Total underproduction in scenario $\omega$ [MW]. |
| $P_{\omega}^{op,r}$ | Remained overproduction in scenario $\omega$ [MW]. |
| $P_{\omega}^{up,r}$ | Remained underproduction in scenario $\omega$ [MW]. |
| $P_{\omega}^{u}$ | Total unbalance power in scenario $\omega$ [MW]. |
| $P_{\omega}^{ch}$ | Charging power of electrical energy storage in scenario $\omega$ [MW]. |
| $P_{\omega}^{ch1}$ | Electrical energy storage charging power from wind farm in case of overproduction in scenario $\omega$ [MW]. |
| $P_{\omega}^{dch}$ | Discharging power of electrical energy storage in scenario $\omega$ [MW]. |

$P_{\omega}^{dch1}$ Discharging power of electrical energy storage to grid in case of underproduction in scenario $\omega$ [MW].

$P_{\omega}^{dch\_P2G}$ Discharging power of electrical energy storage to P2G facility in scenario $\omega$ [MW].

$E_{I}^{s}$ Investing level of electrical energy storage [MW].

$G_{I}^{P2G}$ Investing level of P2G facility [M$m^3$/h].

$G_{\omega}^{P2G}$ Gas generation of P2G facility in scenario $\omega$ [M$m^3$/h].

$G_{\omega}^{P2G\_s}$ Gas amount that sold to the gas market by P2G facility in scenario $\omega$ [M$m^3$/h].

$P_{\omega}^{P2G}$ Power input of P2G facility in scenario ω [MW].

$P_{\omega}^{P2G\_W}$ Power input of P2G facility from the offshore wind farm in case of overproduction in scenario ω [MW].

$u_{\omega}$ ,$V_{\omega}^{cb}$ $V_{\omega}^{db}$ Binary variables.

# I. INTRODUCTION

The new policies toward decarbonizing the electricity generation support wind farm owners (WFO) to contribute further in the generation side. In the current electricity market, conventional producers have the advantage over WFOs due to the capability to handle their generation. Wind farm generation depends on wind speed, which has stochastic behavior. The day-ahead market is one of the platforms for trading electricity for producers and consumers, and the current structure of this market obliges participants to make commitments hours before delivery. Therefore, WFOs bid into the day-ahead market with the prediction of their future generation. They are likely to experience the difference between the actual generation and the committed capacity to the market caused, mainly due to the stochasticity of wind speed.

Some solutions to deal with the aforementioned challenge are proposed and investigated in this work. A possible answer to overcoming the variability in the generation is pairing with storage devices. It enables WFOs to store their surplus generation in times of overproduction, and in times of underproduction, these devices can discharge to assist WFOs in fulfilling their committed delivery. Power-to-Gas (P2G) units have the function of turning electricity into gas, increasing the flexibility of WFO. In times of overproduction, WFO can take advantage of P2G units to turn this additional power into gas and sell it on the gas market. Therefore, this work investigates the planning and operation of electrical energy storage (EES) and P2G units to be paired with wind farm bidding in the day-ahead electricity market and gas market under different risk criteria.

The literature review of the works done on this subject shows the importance of proposing an effective structure to handle different situations that WFOs are facing. Authors in [1] and [2] studied the problem of a wind farm producer bidding in electricity markets while disregarding the EES as a possible option to assist WFO. A risk-based bidding performance of wind farms participating in the electricity markets together and separately was surveyed in [3]. This study did not investigate the potentials of storage to couple with the wind farms. The optimum location and size of energy storages to be installed in a power system were investigated in [4], while the potential of storage to overcome the shortage of gas supply was studied in [5]. In [6], to alleviate congestion in a power system contain renewable energy resources, the optimum location, size, and operation of storage were investigated. These studies were not from the viewpoint of the wind farms participating in the electricity markets. Some works studied the availability of storage devices for wind farms aiming at enhancing their outcomes. The optimal size and operation of storage paired with a wind farm were determined in [7] while disregarding the risk associated with these decisions. Risk-based bidding of a wind farm in the day-ahead electricity market was studied in [8] where the wind farm was equipped with storage devices. The optimal size of a battery paired with a wind farm was investigated in [9] aiming at minimizing the total costs. On the other hand, considering P2G facilities can be of great help for WFOs to interact with the gas market and thereby increase the total profit. The authors in [10] surveyed the effect of P2G on the electricity and gas networks. In [11], wind power paired with battery participate in frequency regulation. In [12], the authors investigate the participation of a wind farm coupled with storage in the electricity markets.

This paper strives to fill the gaps or provide adequate information on the drawbacks of the existing works. We study the optimal sizing of storage devices as well as P2G facilities to be paired with the wind farms by proposing a joint operation-planning model aiming at maximizing their profits. The proposed model also activates the participation of WFO in the day-ahead electricity market and gas market. Risk analyses are also performed in bidding to the electricity market. Therefore, the primary contributions of this paper toward assisting the WFO to fulfill their objectives in the upcoming years, with a high percentage of contribution to the electricity generation, are as follows.

- Proposing a joint uncertainty-based operation-planning model to determine the optimal size and operation of the EES and P2G facility to be paired with WFO. The uncertainties are handled via stochastic programming approach.
- Managing the risks associated with the decisions made by WFO to participate in the day-ahead electricity and gas markets. Conditional value at risk (CVaR) is used to measure the risks pertaining to commitments of WFO to these markets. This way, the amount of variation in the profit compared to its risk is determined. This analysis enables the WFO to offer a tradeoff between the profit obtained from bidding in the electricity and gas markets and its corresponding risks.
- Investigating the role of EES in smoothing the integration of WFO in the electricity market. This includes the impact on lowering the difference between scheduled power accepted by the day-ahead market and actual production of WFO at the time of delivery. The variation on the profit of producer as a key factor regarding EES surveyed.
- Investigating the potential of P2G unit to assist WFO to increase its profit. The invested size and operation of this unit considering various risks are surveyed. Considering the P2G unit enables WFO to sell its surplus power in the gas market. This may provide opportunities for WFO to not curtailing the excess available power.

The remainder of this paper is arranged as follows. Section II provides the formulation of the problem. Case studies to investigate different possible scenarios introduced in section III. Data for simulation, results and discussion are provided in section IV. Finally, section V presents the conclusions.

## II. Problem Formulation

The risk analysis of a WFO paired with EES and P2G bidding in the gas and day-ahead electricity and markets is presented by (1)-(27). The main objective is to maximize the summation of (1-β) times profit and β times CVaR in (1). The parameter β, which varies between zero and one, assists the wind farm owner in managing the risk aversion of its decisions. The CVaR is defined in (2), while the profit is stated in (3). The profit consists of the income from bidding in the day-ahead electricity and gas markets minus the investment costs of EES and P2G units, penalty related to the overproduction and underproduction, and O&M costs of the wind farm, P2G, and EES units.

$$\max\{(1-\beta)\times \mathrm{Pr}\mathit{ofit}+\beta\times CVaR\} \tag{1}$$

$$CVaR=\zeta-\frac{1}{1-\alpha}\times\sum_{\omega=1}^{N_\Omega}\rho_\omega\times\eta_\omega \tag{2}$$

$$\mathrm{Pr}\mathit{ofit}=\left\{\begin{array}{l}[\alpha_{NPV,I}\times(-E_I^S\times IC_S-G_I^{P2G}\times IC^{P2G})]\\ +[\sum_{\omega=1}^{N\Omega}(\rho_\omega)\times(\lambda_\omega\times P_\omega^{W,bid}+\lambda_g\times G_\omega^{P2G\_s}\\ -1.1\times\lambda_\omega\times P_\omega^{op,r}-1.1\times\lambda_\omega\times P_\omega^{up,r}-OM_W\times P_\omega^{W,\mathrm{P}})]\\ +[\alpha_{NPV,O}\times\sum_{\omega=1}^{N\Omega}(-OM_{P2G}\times G_\omega^{P2G}\\ -OM_S\times(P_\omega^{ch}+P_\omega^{dch})]\end{array}\right\} \tag{3}$$

$$0\le E_I^S\le E_{I,\max}^S \tag{4}$$

$$0\le G_I^{P2G}\le G_{I,\max}^{P2G} \tag{5}$$

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

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

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

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

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

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

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

$$0.20\times E_I^S\times V_\omega^{cb}\le P_\omega^{ch}\le 0.95\times E_I^S\times V_\omega^{cb} \tag{13}$$

$$0.20\times E_I^S\times V_\omega^{cb}\le P_\omega^{ch1}\le 0.95\times E_I^S\times V_\omega^{cb} \tag{14}$$

$$0.20\times E_I^S\times V_\omega^{db}\le P_\omega^{dch}\le 0.95\times E_I^S\times V_\omega^{db} \tag{15}$$

$$0.20\times E_I^S\times V_\omega^{db}\le P_\omega^{dch1}\le 0.95\times E_I^S\times V_\omega^{db} \tag{16}$$

$$\begin{aligned}0.20\times E_I^S\times V_\omega^{db}\times(1-u_\omega)\le P_\omega^{dch\_P2G}\\ \le 0.95\times E_I^S\times V_\omega^{db}\times(1-u_\omega)\end{aligned} \tag{17}$$

$$\sum_{td,b}\rho_\omega\times[(P_\omega^{ch}\times\eta_c)-(\frac{P_\omega^{dch}}{\eta_d})]=0 \tag{18}$$

$$P_\omega^{ch}=P_\omega^{ch1} \tag{19}$$

$$P_\omega^{dch}=P_\omega^{dch1}+P_\omega^{dch\_P2G} \tag{20}$$

$$V_\omega^{cb}+V_\omega^{db}\le 1 \tag{21}$$

$$0\le G_\omega^{P2G}\le G_I^{P2G} \tag{22}$$

$$G_\omega^{P2G}=\alpha^{P2G}\times P_\omega^{P2G} \tag{23}$$

$$G_\omega^{P2G}=G_\omega^{P2G\_s} \tag{24}$$

$$P_\omega^{P2G}=P_\omega^{P2G\_W}+P_\omega^{dch\_P2G} \tag{25}$$

$$\eta_\omega\ge 0 \tag{26}$$

$$\zeta-\left\{\begin{array}{l}[\alpha_{NPV,I}\times(-E_I^S\times IC_S-G_I^{P2G}\times IC^{P2G})]\\ +(\lambda_\omega\times P_\omega^{W,bid}+\lambda_g\times G_\omega^{P2G\_s}\\ -1.1\times\lambda_\omega\times P_\omega^{op,r}-1.1\times\lambda_\omega\times P_\omega^{up,r}-OM_W\times P_\omega^{W,\mathrm{P}})\\ +[\alpha_{NPV,O}\times(-OM_{P2G}\times G_\omega^{P2G}\\ -OM_S\times(P_\omega^{ch}+P_\omega^{dch})]\end{array}\right\}\le\eta_\omega \tag{27}$$

The maximum size of EES and P2G units is determined by (4) and (5), respectively. The amount of power that wind farm producer bid in the day-ahead market is bounded to its prediction in (6). The difference between the actual generation of the wind farm and the bidding power in the day-ahead market is equal to the unbalance power in (7). The unbalance power is either overproduction or underproduction defined in (8). The amount of overproduction and underproduction is limit to the capacity of the wind farm in (9) and (10), respectively; $u_\omega$ is a binary variable which enable us to have only overproduction or underproduction at each scenario $\omega$. The overproduction power can charge the EES and turn into gas through the P2G unit to sell to the gas market, while the remainder is subject to a penalty, see (11). The underproduction power can be compensated partly by discharging EES, and the remainder is subject to penalty as (12). The EES operation is modeled through (13)-(21). Total charging, charging from wind farm overproduction, total discharging, discharging to compensate the underproduction, and discharging to P2G unit power of EES is bound via (13), (14), (15), (16), and (17), respectively. The summation of charging and discharging of EES over time of day and block bound to zero in (18). The charging of EES is through storing surplus power of wind farm in the overproduction stated in (19). The discharging of EES is used to compensate WFO underproduction or to deliver to the P2G unit as (20). (21) makes sure that charging and discharging do not occur simultaneously. The P2G unit is modeled with (22)-(25). The amount of gas that the P2G unit can produce is limited to the invested size by (22). The relationship between input power and output gas production of P2G unit is stated by (23). The output gas of this unit will sell to the gas market completely via (24). The input power of this unit is from wind farm overproduction and EES unit in (25). (26) and (27) are related to the risk evaluation in our problem. This nature of this problem is an MINLP and needs to be recast into MILP in order to reach global solutions; (13), (14), (15), and (16) include the product of continuous and binary variable that can be linearized as (28); (17) contain the product of two binary variables and a continuous one. First, the two binary variables can be replaced with one new binary variable as stated in (29) and then the product of it and continuous variable can be linearized with (28).

$$\begin{aligned}&define\ \mathrm{c}=a\times b\ when\ \mathrm{a}\in\{0,1\},\underline{b}\le b\le\overline{b}\\ &\underline{b}\times a\le c\le\overline{b}\times a\\ &c\le b-\underline{b}\times(1-a)\\ &c\ge b-\overline{b}\times(1-a)\end{aligned} \tag{28}$$

$$\begin{aligned}&k=l\times m\ when\ \mathrm{l}\in\{0,1\},m\in\{0,1\}\\ &k\le l\\ &k\le m\\ &k\ge l+m-1\\ &k\in\{0,1\}\end{aligned} \tag{29}$$

## III. Case Studies

The investment and operation problems of WFO paired with EES and P2G units are investigated through the following case studies. The purpose of these cases is to determine the size of these units and capture their impact on the profit of WFO under different risk criteria.

*a) Case I: Wind Farm Paired with EES Bidding in Day-Ahead Electricity Market*

This case study investigates the situation when the wind farm is coupled with EES. The EES assists the WFO in overproduction by storing surplus power. Moreover, it can be discharged when the WFO faces underproduction conditions. The problem formulation for this case includes (1)-(4), (6)-(21), (26), and (27) while applying the linearization techniques in (28) and (29). The objective function, in this case, includes investment cost of EES, income from the day-ahead electricity market, penalties caused by the difference between actual generation and commitment to the day-ahead market, and O&M costs of the wind farm and EES. Risk analysis is performed to study the effect of different risk criteria on the size of EES and profit of WFO, which will be discussed in the result section.

*b) Case II: Wind Farm Paired with EES and P2G Bidding in Day-Ahead Electricity and Gas Markets*

In this case study, the WFO is paired with EES and P2G and participates in the day-ahead electricity and gas markets. Here, under overproduction condition, the WFO can charge EES or turn it into gas through the P2G facility and sell it to the gas market. Moreover, under underproduction, the EES can be discharged to decrease the deficit of power. The EES has the ability to deliver electricity to P2G units in order to sell it in the gas market. The problem formulation consists of (1)-(29). Risk analysis is performed on the risk parameter β to survey the impact on the size of EES, and P2G units and the profit of WFO.

## IV. Simulation and Results

### A. Data

The uncertainties that pertained to our problem formulation are electricity market prices and wind farm generation. Historical data of day-ahead electricity market price is first organized based on season, weekday, weekend, daytime, and nighttime and then sorted from highest to lowest for each of them. These prices are arranged into four sections, including peak, high medium, low medium, and off-peak, and each section is represented by three levels. These levels are the average of the prices of the corresponding hours of each section [13]. Wind farm generations at these sections are arranged decreasingly. Three levels are considered to represent wind farm generation at these hours by averaging them. There are 192 scenarios with pair of day-ahead electricity market price and wind farm generation. Other parameters related to the simulation, EES, and P2G units are presented in Table I. $\alpha_{NPV,O}$ is the net present value for operation cost of units which is daily and equal to $m(1+m)^n/[((1+m)^n-1)D]$ where m the annual discount rate is 5%, the lifetime of units, $n$, is 10 years and D is the number of days in one year planning of our problem; $\alpha_{NPV,I}$ is the net present value coefficient for the investment of units which is yearly and can be obtained by multiplying $\alpha_{NPV,O}$ and D.

TABLE I
DATA FOR SIMULATION

| Symbol | Value | Symbol | Value |
|---|---|---|---|
| P (MW) | 760 | $\alpha_{PtG}$ | 0.0045 |
| $OM_W$ (€/MWh) | 0.13 | $E^S_{I,max}$ (MW) | 400 |
| $OM_S$ (€/MWh) | 0.13 | $G^{PtG}_{I,max}$ ($Mm^3/h$) | 1.8 |
| $OM_{PtG}$ (€/$Mm^3$) | 2 | $\eta_c$ | 0.95 |
| $IC_S$ (€/MW) | 83000 | $\eta_d$ | 0.95 |
| $IC^{PtG}$ (€/$Mm^3/h$) | 1230000 | α | 0.90 |

### B. Results and Analyses

The implementations of the aforementioned case studies are carried out in GAMS software [14] and solved via the Cplex solver [15]. In the first Case, the WFO is only paired with EES. Fig.1 depicts the amount of profit of WFO bidding in the day-ahead electricity market versus CVaR. This figure is obtained by considering different values for $\beta$ (risk aversion) where α (confidence level) is set to 0.90. In the simulation, $\beta$ change with steps of 0.1 but here profit and CVaR displayed when there is difference in them with variation of $\beta$. As $\beta$ increases, the problem becomes more risk-averse and the WFO takes a lower risk on its decisions. It can be observed from this figure that as $\beta$ got bigger, the value of CVaR increases while the profit decreases. Therefore, the highest profit and lowest CVaR occur when $\beta$ is equal to zero. On the other hand, the highest CVaR and lowest profit are obtained when $\beta$ is equal to 1. The sizes of EES corresponding to different values of $\beta$ are presented in Table II. The biggest investment for EES is 179.14 MW that occurs when $\beta$ is equal to zero, and the WFO makes a decision with the highest risk. As $\beta$ increases, the WFO invests lower in the EES, and when $\beta$ is equal to 1, the WFO does not invest in the EES to take the slightest risk measured decision.

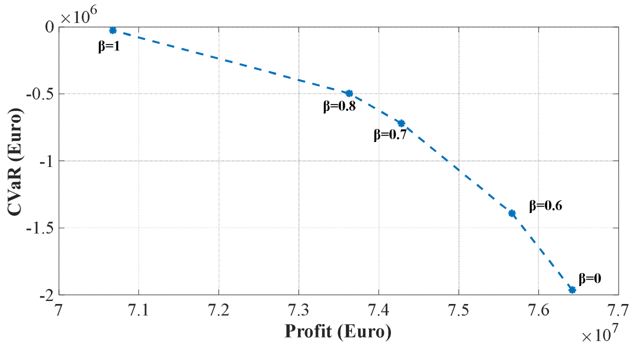


Fig. 1. Efficient frontier (CVaR versus profit) in Case *I*

TABLE II
SIZE OF EES FOR CASE I

| β | 0 | 0.6 | 0.7 | 0.8 | 1 |
|---|---|---|---|---|---|
| EES (MW) | 179.14 | 126.14 | 64.15 | 43.47 | 0 |

The second Case considers the possibility of investing in both the EES and P2G, and bids in both the day-ahead electricity and gas markets. The amount of profit of WFO and CVaR for different values of $\beta$ is depicted in Fig. 2. In the simulation, $\beta$ change with steps of 0.1 but here profit and CVaR displayed when there is difference in them with variation of $\beta$. Similar to Case I, the profit decreases as $\beta$ increases and CVaR increases. Therefore, the highest profit and lowest CVaR occur when $\beta$ is equal to zero, while the lowest profit and highest CVaR happen when $\beta$ is equal to 1. The sizes of EES and P2G units in MW for different levels of $\beta$ (risk aversion) are presented in Table III. The biggest investment for these units happens when $\beta$ is zero where the sizes of EES and P2G units are 304.74 MW and 386 MW,

TABLE IV
RESULTS OF SIMULATION FOR CASE II

| Scenario # | $P_{\omega}^{op}$ (MW) | $P_{\omega}^{op,r}$ (MW) | $P_{\omega}^{P2G\_W}$ (MW) | $P_{\omega}^{ch1}$ (MW) | $P_{\omega}^{up}$ (MW) | $P_{\omega}^{up,r}$ (MW) | $P_{\omega}^{dch1}$ (MW) | $P_{\omega}^{dch\_P2G}$ (MW) | $P_{\omega}^{dch}$ (MW) | $P_{\omega}^{P2G}$ (MW) | $G_{\omega}^{P2G}$ (Mm$^3$/h) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 6 | 280.42 | 0 | 280.42 | 0 | 0 | 0 | 0 | 0 | 0 | 280.42 | 1.262 |
| 7 | 199.162 | 0 | 0 | 199.162 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 24 | 299.823 | 0 | 146.362 | 153.461 | 0 | 0 | 0 | 0 | 0 | 146.362 | 0.659 |
| 25 | 0 | 0 | 0 | 0 | 151.096 | 0 | 151.096 | 0 | 151.096 | 0 | 0 |
| 28 | 0 | 0 | 0 | 0 | 171.71 | 0 | 171.71 | 0 | 171.71 | 0 | 0 |
| 29 | 0 | 0 | 0 | 0 | 117.369 | 0 | 117.369 | 0 | 117.369 | 0 | 0 |

respectively. It can be observed that as $\beta$ increases and the WFO takes lower risks, the size of these units decreases.

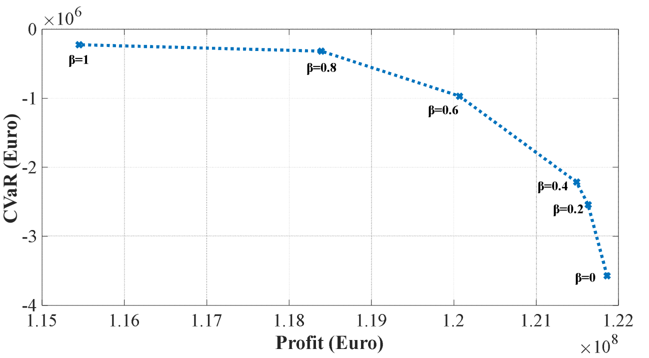


Fig. 2. Efficient frontier (CVaR versus profit) in Case *II*

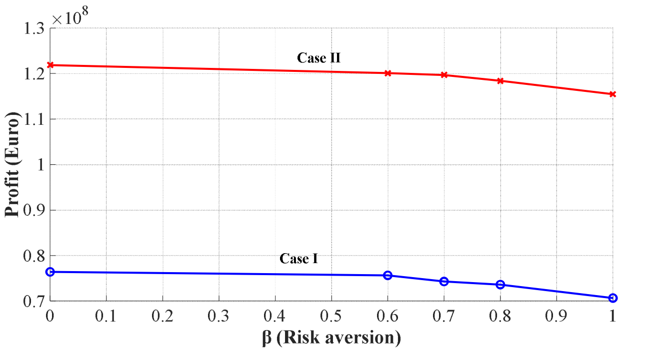


Fig. 3. Comparison of profit in Case *I* and Case *II*

When $\beta$ is equal to 1, which is the lowest risk taken for decisions, the WFO does not invest in EES. However, it installs a P2G unit with a size of 309.11 MW, which is a bit lower than the capacity obtained for $\beta$ equal to zero.

The profits of WFO for different values of $\beta$ in Case I and Case II are presented in Fig. 3. It can be observed that in Case II, where the wind farm is paired with both EES and P2G units, higher profits are obtained compared to Case I where the wind farm only paired with EES. Profits in Case II when $\beta$ is equal to zero is 59.46% higher than the profit in Case I. Profit in Case I and Case II when $\beta$ is zero is about 8.12%, and 72.42% higher than when WFO participates in only day-ahead electricity market without these units.

Results of Case II when β is equal to 0.2 are presented in Table IV for some scenarios. Scenarios 6, 7, and 24 are scenarios in which the WFO experiences overproduction. In scenario 6, 280.42 MW overproduction exists that is completely compensated by turning to gas through the P2G unit. In scenario 7, the EES stores 199.162 MW of overproduction, while in scenario 24, from the total overproduction (299.823 MW), a part of that is used to charge the EES unit (153.461 MW) and the rest is turned into gas through P2G unit (146.362 MW). Scenarios 25, 28, and 29 represent conditions where WFO experiences

TABLE III
SIZE OF EES AND P2G FOR CASE II

| β | 0 | 0.2 | 0.4 | 0.6 | 0.8 | 1 |
|---|---|---|---|---|---|---|
| EES (MW) | 304.74 | 209.64 | 179.14 | 64.15 | 3.71 | 0 |
| P2G (MW) | 386 | 386 | 386 | 386 | 385.11 | 309.11 |

underproduction. In these scenarios, there are 151.096 MW, 171.71 MW, and 117.369 MW of underproduction, respectively, which are completely compensated by discharging the EES unit.

## V. CONCLUSION

This paper proposed a joint planning-operation model for a wind farm to make optimal investment and operation decisions for the electrical energy storage and power-to-gas units while bidding in both the gas and day-ahead electricity markets. The uncertainty of electricity market price and wind farm generation has been taken into account. Two case studies have been conducted, namely considering wind farm paired only with electrical energy storage and when paired with both electrical energy storage and power-to-gas. Risk analyses have been performed in these two case studies under different risk aversion criteria. Results displayed the variation of profit versus conditional value-at-risk (CvaR) as a risk measure over different risk aversion factors ($\beta$). It has been observed that as $\beta$ increases, the profit decreases while CVaR increases in Case I and Case II. Therefore, in these two cases, the highest profit and lowest CVaR occurred when $\beta$ was set to zero. On the other hand, the lowest profit and highest CVaR happened by setting $\beta$ to 1. Moreover, the size of the electrical energy storage decreased in Case I as $\beta$ increased, meaning that wind farm owner was not interested in investing in this unit for making a decision with lower risks. The same behavior happened in Case II for this unit for higher values of $\beta$. The size of the power-to-gas unit also decreased similarly. However, for the most risk-averse decision, the wind farm owner was still interested in investing in this unit. Furthermore, the amount of profit in Case II was noticeably higher than Case I. Therefore, equipping the wind farm with both the electrical energy storage and power-to-gas facility provides higher flexibility and therefore results in better outcomes for the wind farm owner.

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