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# Risk-averse optimal bidding strategy for a wind energy portfolio manager including EV parking lots for imbalance mitigation

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**Abstract:** In this study, an optimal bidding strategy for a wind energy portfolio manager (WEPM) including electric vehicle parking lots (EVPLs) that aims to maximize profits by trading in the day-ahead (DA) market and balancing market (BM) and through bilateral contracts, taking into account line capacities and risk management is proposed. The mentioned structure is modeled in mixed integer linear programming (MILP) framework, and the uncertainties regarding electric vehicle (EV) behavior, electricity market data, wind power generation are captured via a stochastic approach. To demonstrate the effectiveness of the model, several case studies are carried out considering Sweden and Turkey electricity market prices with different risk aversion factors and bilateral contract situations. In this manner, the important results as well as useful findings regarding the economic impacts of the proposed concept are analyzed in detail.

**Key words:** Electricity market, electric vehicle parking lots, optimal bidding, risk aversion, wind energy portfolio

## 1. Introduction

### 1.1. Motivation and background

Due to the greenhouse gas effect caused by the high level of CO2 emissions regarding fossil fuel utilization, all countries tend to use renewable energy sources which are critically important due to their environment-friendly nature [1, 2]. Wind energy as one of the most mature and important types of renewable energy technologies has the largest market share in renewable energy installations and is growing significantly worldwide [3, 4]. In many countries, wind power plants (WPPs) have to participate in the electricity market like conventional power generation facilities. However, the variability and limited predictability of wind energy may cause WPPs to be responsible for real-time balancing cost/deviation penalty [5, 6]. Therefore, it is reasonable for WPPs to participate in the electricity market in a joint structure with flexible resources to manage their unstable structures [7]. In this respect, renewable energy portfolios are interesting structures in terms of risk management in trading activities within electricity markets [8]. The portfolios facilitate the management of sources, allow them to address uncertainties, and help to balance profit, costs and risks [9].

Electric vehicles (EVs) are replacing traditional internal combustion engine vehicles [10], and in the future, transportation is expected to be dominated by EVs [11]. Since the number of EVs increases day by day, it can be stated that the inclusion of EV parking lots (EVPLs) containing EVs in their portfolios can provide advantages

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in many aspects, especially in issues such as charge management over the case where EVs are scattered, economic operation and elimination of imbalances in terms of portfolio. In general, the electricity market in which WPPs can participate consists of submarkets such as the day-ahead (DA) market, intraday market, and balancing market (BM) [7]. Except for those, bilateral contracts are carried out commonly to reduce the risk against volatility in electricity prices [12]. For energy trade in the medium term, it is recommended to distribute energy in submarkets [7]. Besides, while making decisions in the electricity markets, it is important to take into account risk management in terms of the uncertainties for the changes in profits and negative profit that may occur [13].

### 1.2. Relevant background

In recent years, many countries have turned towards renewable energy sources, especially wind, by supporting them with financial supports and various promotive policies. The management of WPPs while participating in the electricity markets within a portfolio structure attracts both investors and researchers. Besides, in terms of eliminating the imbalances that occur in real-time in the relevant literature, the inclusion of storage systems or flexible resources in the portfolio as a balancing element is one of the important issues that are studied. Fan et al. [14] proposed a medium and long-term energy trading approach for a structure with wind and solar energy sources and thermal power plants. Although this study mentioned medium and long-term trading, electricity markets, which are DA and BM, were not included. Besides EVs, risk management, portfolio structure, and line capacities were not specified. Zhan and Chen [15] developed an optimum participation model for a WPP with multienergy sources to take place in the BM. However, in this study, the DA market, bilateral contracts, EVs, risk management, and portfolio structure were not taken into account. Moghaddam et al. [16] suggested a model in which a wind farm with a battery energy storage system participates the DA market and BM. In [16], in addition to [15], the DA market was included, while line capacities for the wind farm were not mentioned.

Zhang et al. [17] proposed a two-stage dispatching strategy for an energy storage system-wind farm hybrid system. In the first stage, the use of lead-acid batteries aimed to increase the revenue obtained from the DA market, while the lithium-ion batteries participated in the BM to eliminate forecasting errors in the second stage. Besides, the energy storage system was considered to serve the ancillary service market. Zhang et al. [18] suggested a model in which wind farms and power-to-gas power plants, collaborate and participate in the DA market, BM and reserve markets, and excess energy from wind farms and DA market is converted to hydrogen. It should be stated that these two studies lack bilateral contracts, EVs, risk management, portfolio structure, and line capacities.

A bidding model for the optimum participation of a WPP and energy storage aggregator in the DA market and the BM was designed in [19] by Han and Hug. However, this study did not take into account bilateral contracts, EVs, risk management, and line capacities. Asensio and Contreras [20] suggested a joint decision making model for wind energy producers and demand response aggregators that bid on the DA market. In their results, the authors concluded that the proposed model increased the income of both sources. Zhao et al. [21] proposed a model aiming to minimize the cost by participating in the DA market and the BM of the virtual power plant consisting of distributed renewable energy sources and consumers with inelastic demands. The authors modeled their proposed method with the two-level stochastic optimization method. Nazari and Ardehali [22] presented a structure to maximize the profit of a generation company with a pumped hydro-based energy storage system and thermal resource from its participation in the DA and reserve market. In [20–22], bilateral contracts, EVs, and line capacities were not mentioned. Besides, [21] and [22] did not include risk management.

Liu et al. [23] proposed a model for wind energy companies to participate in the nodal market. Dai and Qiao [24] presented a stochastic optimization model for a WPP to participate in the DA market and BM. Bilateral contracts, EVs, and portfolio structure were not included in [24]. Besides, [23] did not include the BM and risk management in addition to [24]. Nieta et al. [25] suggested a strategy for the wind-pumped hydro-based energy storage hybrid system to make optimum bidding decisions in the DA market also considering bilateral contracts. However, it should be stated that EVs, risk management, and line capacities were not involved in the mentioned study.

Gong et al. [26] developed the optimum bidding model in which the thermal-wind hybrid system signs bilateral contracts with the battery swapping station and participates in the DA market. Xu et al. [27] proposed a structure in which the aggregator of the rooftop photovoltaic generation and plug-in EVs participates in the DA market and BM. Koraki and Strunz [28] presented a structure in which a virtual power plant, composed of WPPs, photovoltaic power plants, combined heat and power, pumped hydro-based energy storage system, EVs, thermal load, thermal storage, and electrical storage, participated in the DA market and intra-day market. Wu et al. [29] developed a stochastic bidding model for the optimum participation of the EV aggregator with wind power generators in the DA market and ancillary services market. Hajebrahimi et al. [30] presented a collaborative and noncollaborative bidding strategy for wind farms, solar power plants, hydroelectric power plants, and plug-in EV aggregators. Gao et al. [31] suggested a two-level optimization model for a WPP and EV aggregator hybrid system to participate in the DA market and BM as a price-maker. It should be underlined that although EVs are included in [26–30], EVPLs and line capacities are not considered in these studies. Also, bilateral contracts were not included in studies other than [26]. While risk management is covered only in [27, 29], portfolio structure is only considered in [27, 28, 30]

Aliasghari et al. [32] proposed a structure where the renewable microgrid in the presence of plug-in EVs participates in the power market minimizing the operating cost. Aghajani and Kalantar [33] presented a bidding strategy for the DA market and reserve market participation, in the joint operation of WPP, EVPL, and load retailer. Besides, in that proposed strategy, a two-level approach was applied to the interaction between the distribution system and EVPL. However, [32, 33] did not include BM, bilateral contracts, risk management, portfolio structure, and line capacities. Alahyari et al. [34] suggested an approach for virtual power plants with a WPP and EVPL to participate in the DA market and reserve market. Moreover, it should be noted that BM, bilateral contracts, and line capacities were not considered in the mentioned study.

There are also different studies on the DA market and BM participation of portfolios indirectly including renewable power production units and energy storage systems. As an example in this manner, the study in [35] including the aggregation of residential end-users including solar power and battery units to enable demand side flexibility provision can be given as an example. Besides, there are also some studies including the artificial intelligence based assessment of market participants such as in [36] and [37]. However, even the mentioned last two groups of studies have also relevance to the portfolio aggregation and bidding approaches, no more emphasis on further literature presentation for these groups is given as they are not fully parallel to the concept of this study.

### 1.3. Contribution and paper organization

This study considers a portfolio manager of a group of WPPs in which EVPLs are included in portfolio structure to eliminate power imbalances. An optimum bidding strategy is proposed in which the portfolio manager performs various transactions for the power generated from WPPs and for charging EVs in EVPLs. While wind energy portfolio manager (WEPM) can participate in the DA market and BM, it can sell power produced from WPPs through bilateral contracts. The main objective of the proposed bidding model is to maximize the profit that can be obtained by taking into account the line capacities determined by the independent system operator and the risk against uncertainties with conditional value-at-risk (CVaR). A detailed comparison of this study with the existing studies in the literature discussed in the previous subsection is given in Table 1, and accordingly the novelties of this study are twofold:

- The portfolio manager that has WPPs and a group of EVPLs to compensate for imbalances in the portfolio can make bilateral contracts and evaluate the remaining energy in the DA market and BM.
- WEPM submits various bids/offers to the market operator and/or independent system operator, taking into account maximum line capacities, risk in case of loss or missing profit due to uncertainties, and considering the charging processes of EVs.

**Table 1**. Taxonomy of the proposed methodology compared to representative literature studies.

| Ref. | Energy market | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | DA market | BM | Bilateral contracts | EV | EVPL | Risk management | Portfolio structure | Line capacities |
| [14] | – | – | – | – | – | – | – | – |
| [15] | – | ✓ | – | – | – | – | – | – |
| [16] | ✓ | ✓ | – | – | – | – | – | – |
| [17] | ✓ | ✓ | – | – | – | – | – | – |
| [18] | ✓ | ✓ | – | – | – | – | – | – |
| [19] | ✓ | ✓ | – | – | – | – | ✓ | – |
| [20] | ✓ | – | – | – | – | ✓ | ✓ | – |
| [21] | ✓ | ✓ | – | – | – | – | ✓ | – |
| [22] | ✓ | – | – | – | – | – | ✓ | – |
| [23] | ✓ | – | – | – | – | – | – | – |
| [24] | ✓ | ✓ | – | – | – | ✓ | – | – |
| [25] | ✓ | ✓ | ✓ | – | – | ✓ | – | – |
| [26] | ✓ | ✓ | ✓ | ✓ | – | – | – | – |
| [27] | ✓ | ✓ | – | ✓ | – | ✓ | ✓ | – |
| [28] | ✓ | ✓ | – | ✓ | – | – | ✓ | – |
| [29] | ✓ | ✓ | – | ✓ | – | ✓ | ✓ | – |
| [30] | ✓ | – | – | ✓ | – | ✓ | ✓ | – |
| [31] | ✓ | ✓ | – | ✓ | – | ✓ | – | – |
| [32] | ✓ | – | – | ✓ | – | – | – | – |
| [33] | ✓ | – | – | ✓ | ✓ | – | – | – |
| [34] | ✓ | – | – | ✓ | ✓ | ✓ | ✓ | – |
| This paper | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

The rest of the paper is organized as follows. The mathematical modeling of the proposed structure is given in Section 2. Afterwards, different case studies are conducted, and the discussions related to the results of the study are provided in Section 3. Finally, in Section 4, the concluding remarks are explained.

## 2. Methodology

A general structure of the proposed model is demonstrated in Figure 1. As can be seen in Figure 1, WEPM that includes EVPLs in the portfolio aims to maximize its profits from buying and selling from the DA market and BM, taking into account the risk management. Besides, the WEPM can make bilateral contracts for profit maximization and later notifies this contract to the Market Operator. It should be noted that line capacities are taken into account in trading transactions for EVPLs and WPPs. In the study, power generation of WPPs, behavioral uncertainties of EVs, uncertainties regarding prices for the DA market, and BM are eliminated by using a stochastic approach. WEPM is considered to be in a price-taker position in the electricity market. In this study, it is worth underlining that agreements between EVPLs and EV owners are not considered and that the vehicle-to-grid (V2G) mode is not addressed as EV owners may not be willing to discharge their EV battery due to battery degradation. The remainder of this section covers mathematical modeling.

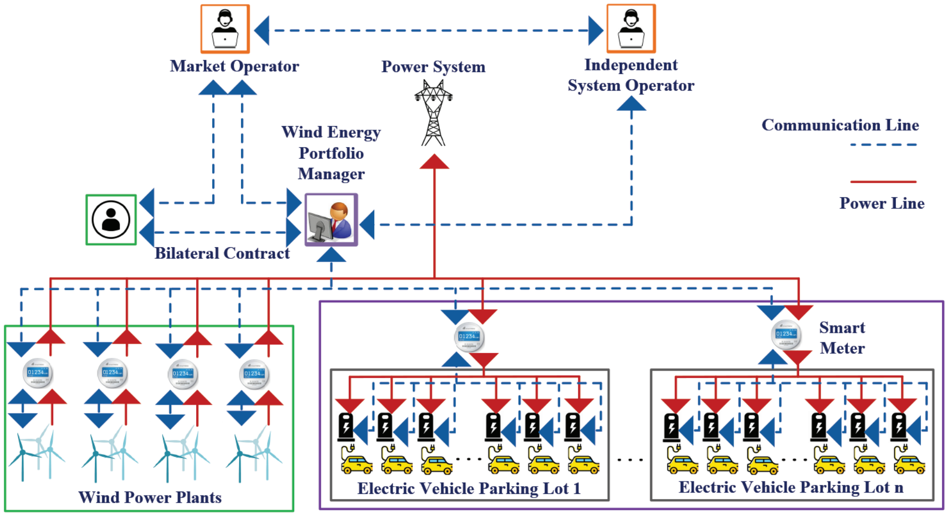

**Figure 1**. The proposed structure that WEPM containing EVPLs participates in the electricity market for maximizing profit.

### 2.1. Mathematical model of the proposed structure

WEPM's model of participation in the electricity market is created as an optimization model. The objective function in which WEPM aims to maximize profit from buying and selling transactions is given in (1). Various transactions are carried out here in the DA market, BM, and also through bilateral contracts. Since CVaR is addressed in the optimization problem, the risk aversion value has a direct effect on the expected profit to be obtained as observed in the formula. The $\beta$ parameter is used to control the level of risk while adding the CVaR to the risk-averse objective function.

$$maximize \left\{(1-\beta).(P^{bilat}_{wind}+P^{DA,sell}_{wind}+P^{BM,up}_{wind}-C^{BM,down}_{wind}-C^{DA,buy}_{EV}-C^{BM,down}_{EV}+P^{BM,up}_{EV})+(\beta.CVaR_{\alpha})\right\} \tag{1}$$

The income obtained as a result of the selling of the energy generated from the WPPs by bilateral contract is obtained by Eq. (2). Eq. (3) defines the income to be obtained by selling the energy generated from WPPs in the DA market. The income and cost incurred from WPPs as a result of energy selling and buying transactions by participating in the BM for upregulation and downregulation are given in Eqs. (4) and (5), respectively. WPPs increase their generation above their matched quantities in the DA market while selling in the BM, and on the contrary, they reduce their generation in the buying direction. The cost of energy bought from the DA market for charging of EVs in EVPLs is obtained by Eq. (6). As a result of the transactions carried out in the direction of energy buying in the BM for charging EVs, the incurred cost is obtained with Eq. (7). The income incurred during the participation of EVs in the BM for upregulation service is calculated with Eq. (8). In these circumstances, EVs are charged less than the energy bought from the DA market, and in other words, the energy is indirectly sold to BM.

$$P_{wind}^{bilat} = \sum_{k} \sum_{h} p_k \cdot \lambda_h^{bilat} \cdot E_{k,h}^{wind,bilat} \tag{2}$$

$$P_{wind}^{DA,sell} = \sum_{k} \sum_{l} \sum_{h} p_k \cdot p_l \cdot \lambda_{h,l}^{DA} \cdot E_{k,h}^{wind,DA} \tag{3}$$

$$P_{wind}^{BM,up} = \sum_{k} \sum_{m} \sum_{h} p_k \cdot p_m \cdot \lambda_{h,m}^{BM,up} \cdot E_{k,h}^{wind,BM,up} \tag{4}$$

$$C_{wind}^{BM,down} = \sum_{k} \sum_{m} \sum_{h} p_k \cdot p_m \cdot \lambda_{h,m}^{BM,down} \cdot E_{k,h}^{wind,BM,down} \tag{5}$$

$$C_{EV}^{DA,buy} = \sum_{s} \sum_{l} \sum_{h} p_s \cdot p_l \cdot \lambda_{h,l}^{DA} \cdot E_{s,h}^{EV,buy,DA} \tag{6}$$

$$C_{EV}^{BM,down} = \sum_{s} \sum_{m} \sum_{h} p_s \cdot p_m \cdot \lambda_{h,m}^{BM,down} \cdot E_{s,h}^{EV,down,BM} \tag{7}$$

$$P_{EV}^{BM,up} = \sum_{s} \sum_{m} \sum_{h} p_s \cdot p_m \cdot \lambda_{h,m}^{BM,up} \cdot E_{s,h}^{EV,up,BM} \tag{8}$$

CVaR, known as mean excess loss or average value at risk, is used quite widely in stochastic problems. Risk management by CVaR can be handled by adding to risk-neutral problems in a simple way. CVaR is reflected in Eq. (9) to Eq. (11). In these equations, CVaR value is calculated with the help of auxiliary variables. These auxiliary variables are $\zeta$, and $\Gamma_{k,l,m,s}$ which are scenario dependent. The value of CVaR is calculated by Eq. (9). In Eqs. (10) and (11), auxiliary variables are used to calculate this value. It should be noted that the expected profits located in bracket in Eq. (10) are not written depending on the scenarios in summation symbols. Eq. (11) expresses the limit determined for the auxiliary variable $\Gamma_{k,l,m,s}$.

There may be limitations in line usage limits due to the line capacities applied by the independent system operator due to technical failure, maintenance, line renewal, or market conditions, such as priority purchase. The inequality in (12) determines the limits for the power drawn from the grid for EVPLs to charge EVs according to the line capacity. Similarly, the inequality in (13) determines the limit values for each WPP. Herein, the power generated from WPPs over the line capacity is interrupted and the line capacity limit is maintained.

$$CVaR_\alpha = \zeta - \frac{1}{(1-\alpha)} \cdot \sum_k \sum_l \sum_m \sum_s p_k \cdot p_l \cdot p_m \cdot p_s \cdot \Gamma_{k,l,m,s} \tag{9}$$

$$\begin{aligned}\zeta - \Big( \sum_h \lambda_h^{bilat} \cdot E_{k,h}^{wind,bilat} + \sum_h \lambda_{h,l}^{DA} \cdot E_{k,h}^{wind,DA} + \sum_h \lambda_{h,m}^{BM,up} \cdot E_{k,h}^{wind,BM,up} \\ + \sum_h \lambda_{h,m}^{BM,down} \cdot E_{k,h}^{wind,BM,down} - \sum_h \lambda_{h,l}^{DA} \cdot E_{s,h}^{EV,buy,DA} - \\ \sum_h \lambda_{h,m}^{BM,down} \cdot E_{s,h}^{EV,down,BM} + \sum_h \lambda_{h,m}^{BM,up} \cdot E_{s,h}^{EV,up,BM} \Big) \le \Gamma_{k,l,m,s} \quad \forall k,s,l,m\end{aligned} \tag{10}$$

$$\Gamma_{k,l,m,s} \ge 0, \quad \forall k,l,m,s \tag{11}$$

$$E_{f,s,h}^{f,EV,cons} \le LC_{f,h}^{EVPL}, \quad \forall f,s,h \tag{12}$$

$$E_{w,k,h}^{wind,prod} - E_{w,k,h}^{wind,curt} \le LC_{w,h}^{WPP}, \quad \forall w,k,h \tag{13}$$

The equations in (14)–(19) define limit values for trading transactions carried out in the electricity market. Eqs. (14) and (15) restrict the amount of energy produced from WPPs that can be sold in the DA market and BM, respectively. The energy sold here can be as much as the remaining amount from sold through bilateral contracts. The limit of the transactions in the direction of buying for WPPs in the BM should be as much as the quantity sold to the DA market as provided by Eq. (16). The limit of the energy amount that can be bought from the DA market and BM for charging of EVs is expressed respectively in Eqs. (17) and (18), while the limit of the selling amount that can be made in the upregulation direction within the BM is defined in Eq. (19). In fact, the EVs are not discharged during the energy selling to the BM, instead, the amount of charging energy bought from the DA market or allocated from WPPs is reduced.

$$E_{k,h}^{wind,DA} \le E_{k,h}^{wind,prod,tot} - \sum_w E_{w,k,h}^{wind,curt} - E_{k,h}^{wind,bilat}, \quad \forall k,s,h \tag{14}$$

$$E_{k,h}^{wind,BM,up} \le E_{k,h}^{wind,prod,tot} - \sum_w E_{w,k,h}^{wind,curt} - E_{k,h}^{wind,bilat}, \quad \forall k,h \tag{15}$$

$$E_{k,h}^{wind,BM,down} \le E_{k,h}^{wind,DA}, \quad \forall k,h \tag{16}$$

$$E_{s,h}^{EV,buy,DA} \le E_{s,h}^{EV,cons,RT}, \quad \forall s,h \tag{17}$$

$$E_{s,h}^{EV,down,BM} \le E_{s,h}^{EV,cons,RT} - E_{s,h}^{EV,buy,DA}, \quad \forall s,h \tag{18}$$

$$E_{s,h}^{EV,up,BM} \le E_{s,h}^{EV,cons,RT}, \quad \forall s,h \tag{19}$$

The inequalities in (20) and (21) prevent the case of selling and buying for the same hour in the DA market as the portfolio manager can only make a one-way offer for each hour. The permission of the energy selling bid for WPPs to the DA market is given in Eq. (20), while the permission of the energy buying offer for EVPLs from the DA market is given in Eq. (21). The prevention of simultaneous energy selling and buying for the same hour $h$ in the BM for the portfolio is provided by Eqs. (22) and (23). The energy produced from WPPs is used taking into account the line capacities as given in Eq. (24). The energy produced from WPPs can be utilized by selling through bilateral contracts, by selling in the DA market and BM as upregulation, and for EVPLs. Besides, WPPs can provide downregulation services in the BM reducing power generation. The total energy expression for each hour $h$ generated from WPPs is given in Eq. (25), while the total energy expression during the time period $t$ is given in Eq. (26). Since it is considered that taking the average of the power at $t$ and $(t+1)$ instead of $P_{w,k,t}^{wind,prod}$ power in the processes related to the power generated from WPPs gives more accurate results, the trapezoidal rule for charging power is applied in Eq. (27).

$$E_{k,h}^{wind,DA} \leq N \cdot u_h^{DA}, \quad \forall k,h \tag{20}$$

$$E_{s,h}^{EV,buy,DA} \leq N \cdot (1-u_h^{DA}), \quad \forall s,h \tag{21}$$

$$E_{k,h}^{wind,BM,down} + E_{s,h}^{EV,down,BM} \leq N \cdot u_h^{BM}, \quad \forall k,s,h \tag{22}$$

$$E_{k,h}^{wind,BM,up} + E_{s,h}^{EV,up,BM} \leq N \cdot \left(1-u_h^{BM}\right), \quad \forall k,s,h \tag{23}$$

$$E_{k,h}^{wind,bilat} + E_{k,h}^{wind,DA} + E_{k,h}^{wind,BM,up} - E_{k,h}^{wind,BM,down} + E_{s,h}^{wind,EV} = E_{k,h}^{wind,prod,tot} - \sum_{w} E_{w,k,h}^{wind,curt}, \quad \forall k,s,h \tag{24}$$

$$E_{k,h}^{wind,prod,tot} = \sum_{t} E_{k,t}^{wind,prod,\Delta\mathrm{t}}, \quad \forall k,h, \quad t \in \Delta^t \tag{25}$$

$$E_{k,t}^{wind,prod,\Delta\mathrm{t}} = \sum_{w} E_{w,k,t}^{wind,prod,tr}, \quad \forall k,t \tag{26}$$

$$E_{w,k,t}^{wind,prod,tr} = \frac{(P_{w,k,t}^{wind,prod} + P_{w,k,(t+1)}^{wind,prod})}{2} \cdot \Delta_T, \quad \forall w,k,t \tag{27}$$

Eq. (28) states that the energy consumed by EVs in real-time consists of energy bought from the DA market, energy bought or sold from/to the BM market, and energy produced from WPPs. Herein, the selling transactions to the BM has the effect of reducing the total charging power of EVs. The total energy expression for each hour $h$ to charge EVs is given in Eq. (29), while the total energy required for charging EVs during the time period $t$ is calculated in Eq. (30). Similar to Eq. (28), in Eq. (31), the trapezoidal rule is applied in the operations performed for charging EVs.

The Eq. (32) ensures that the charging power of EV batteries cannot be greater than the allowed charging rate. It is stated in Eq. (33) that EVs are not charged when they are not in EVPL, that is, the charging power is equal to 0. It is explained in Eq. (34) that the state-of-energy expression of EVs at each time period $t$ is equal to the sum of the state-of-energy at the time $(t-1)$ and the energy charged at the time interval $t$ and $(t-1)$ . The fact that the state-of-energy of EV batteries is equal to or less than the maximum allowed energy limits when charging batteries is ensured by Eq. (35). Eq. (36) is used to assign the energy states of EVs when they arrive at EVPL, while Eq. (37) ensures that the EVs leave the EVPL with the desired energy states.

$$E_{s,h}^{EV,buy,DA} + E_{s,h}^{EV,up,BM} - E_{s,h}^{EV,down,BM} + E_{s,h}^{wind,EV} = E_{s,h}^{EV,cons,RT}, \quad \forall s,h \tag{28}$$

$$E_{s,h}^{EV,cons,RT} = \sum_{t} E_{s,t}^{EV,cons,RT,\Delta \mathrm{t}}, \quad \forall s,h, \quad \tau \in \Delta^{t} \tag{29}$$

$$E_{s,t}^{EV,cons,RT,\Delta \mathrm{t}} = \sum_{f}\sum_{y} E_{f,y,s,t}^{EV,ch}, \quad \forall s,t \tag{30}$$

$$E_{f,y,s,t}^{EV,ch} = \frac{P_{f,y,s,t}^{EV,ch} + P_{f,y,s,(t+1)}^{EV,ch}}{2} \cdot \Delta_T, \quad \forall f,y,s,t \tag{31}$$

$$P_{f,y,s,t}^{EV,ch} \le R_{f,y}^{EV,ch}, \quad \forall f,y,s, \quad t \in [T_{f,y,s}^{a}, T_{f,y,s}^{d}] \tag{32}$$

$$P_{f,y,s,t}^{EV,ch} = 0, \quad \forall f,y,s, \quad t \notin [T_{f,y,s}^{a}, T_{f,y,s}^{d}] \tag{33}$$

$$SoE_{f,y,s,t}^{EV} = SoE_{f,y,s,(t-1)}^{EV} + \eta_{f,y}^{EV,ch} \cdot P_{f,y,s,t}^{EV,ch} \cdot \Delta_T \quad t \in (T_{f,y,s}^{a}, T_{f,y,s}^{d}] \tag{34}$$

$$SoE_{f,y,s,t}^{EV} \le E_{f,y}^{EV,max}, \ \forall f,y,s, \quad t \in [T_{f,y,s}^{a}, T_{f,y,s}^{d}] \tag{35}$$

$$SoE_{f,y,s,t}^{EV} = SoE_{f,y}^{EV,ini}, \quad \forall f,y,s, \quad t = [T_{f,y,s}^{a}] \tag{36}$$

$$SoE_{f,y,s,t}^{EV} = E_{f,y}^{EV,des}, \quad \forall f,y,s \quad t = [T_{f,y,s}^{d}] \tag{37}$$

It should here be noted that all the variables in the aforementioned equations are positive variables, and accordingly the relevant nonnegativity constraints are not further stated in the relevant places.

## 3. Simulation results

In this study, the problem that WEPM aims to maximize the profit obtained through participation in the electricity market also including EVPLs in portfolio structure and taking into account risk management and line capacities is addressed in mixed integer linear programming (MILP) framework. The proposed methodology is tested using GAMS v.24.1.3 software and CPLEX v.12 solver. The input data and related results from different case studies carried out to demonstrate the effectiveness of the proposed methodology will be discussed in the subsections below, respectively.

### 3.1. Input data

As uncertainties are encountered in many optimization problems in real life and these should be taken into account, driving behaviors of the EVs before coming to the EVPL, electricity market prices, and wind power generation uncertainties are considered via scenario-based stochastic approach in this study.

Twenty different scenarios are considered for the DA market and BM electricity prices. The DA market and BM prices consisting of 20 different real prices for Sweden (SE3) and Turkey are given in Figures 2 and 3. Electricity market price data cover the date from 1 January to 20 January 2020. It should be stated that while two separate prices as upregulation and downregulation are applied in Sweden BM, the single price application is valid in Turkey BM. Sweden DA market and BM electricity prices are extracted Nord Pool AS[1], while Turkey DA market and BM electricity prices are acquired from EPİAŞ[2]. Besides, WEPM can also make bilateral contracts with fixed prices of 23.5 €/MWh in Sweden and 46 €/MWh in Turkey. Time period $t$ is determined as 5 min while $\alpha$ value is taken as 0.9.

The portfolio manager manages a total of 200 EVs which in an EVPL, 10 of each of 10 EVs with different characteristics, and 2 EVPLs in total. These EVs are BMW-i3, Chevy Volt, Fiat 500-E, Ford Focus Electric, Kia Soul EV, Mercedes B-Class, Mitsubishi i-MiEV, Nissan LEAF, Tesla Model-S, Volkswagen E-Golf. Data on the technical characteristics of EVs are extracted from Cars P[3]. For EV driving behaviors, 4 different scenarios are considered. For the scenarios created for EV uncertainties, the method in [38] was used. Detailed information can be obtained in the relevant reference. While EVs are assumed to leave from EVPLs with a full charge state, the contracts that EV owners have made with the EVPL owner regarding charging cost are not included in this study. For Scenario 1, the data regarding the residence times of EVs for 100 EVs in EVPL 1 are given in Figure 4. From the data in this figure, it can be said that the arrival and departure times of EVs are distributed throughout the day.

WEPM is considered to include 4 WPPs in the portfolio, and 3 different generation scenarios belonging to them were obtained as a result of organizing the data from National Renewable Energy Laboratory. Generations depending on the scenarios for each WPP can be seen in Figure 5. Besides, the line capacities determined for WEPM participants are depicted in Figure 6.

### 3.2. Simulation and results

The performance of the proposed model has been examined with 8 different case studies. These case studies were created considering different values of the risk aversion factor and whether bilateral contracts are realized or not.

- **Case-1:** WEPM participates in Sweden DA Market and BM. Besides, WEPM may make bilateral contracts. $\beta$ value is determined as 1.
- **Case-2:** WEPM participates in Sweden DA Market and BM. Besides, WEPM may make bilateral contracts. $\beta$ value is determined as 0.6.
- **Case-3:** WEPM participates in Sweden DA Market and BM. Besides, WEPM may make bilateral contracts. $\beta$ value is determined as 0.

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[2] EPİAŞ Transparency Platform (2021). Turkey Electricity Market Prices [online]. Website https://seffaflik.epias.com.tr/transparency/piyasalar/gop/ptf.xhtml [accessed 24 March 2021].

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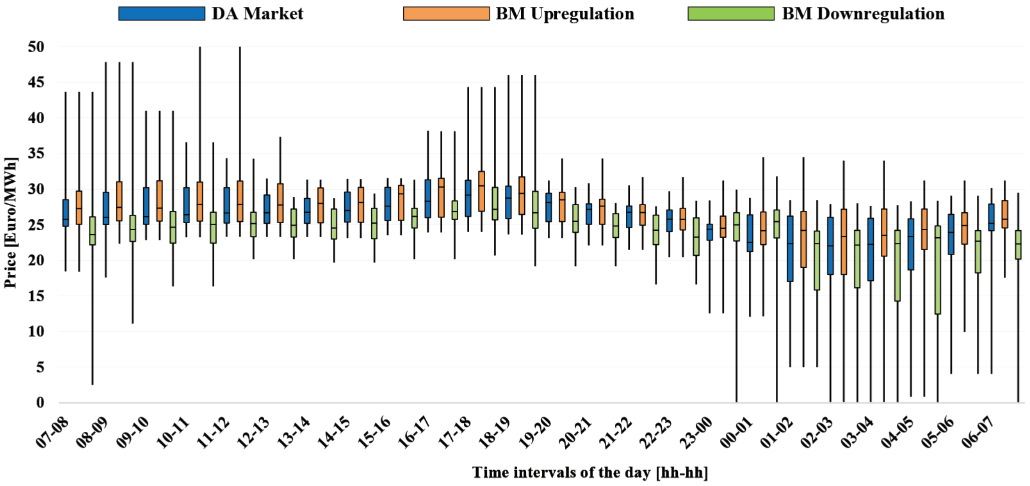

**Figure 2**. Boxplot of Sweden DA market and BM price scenarios.

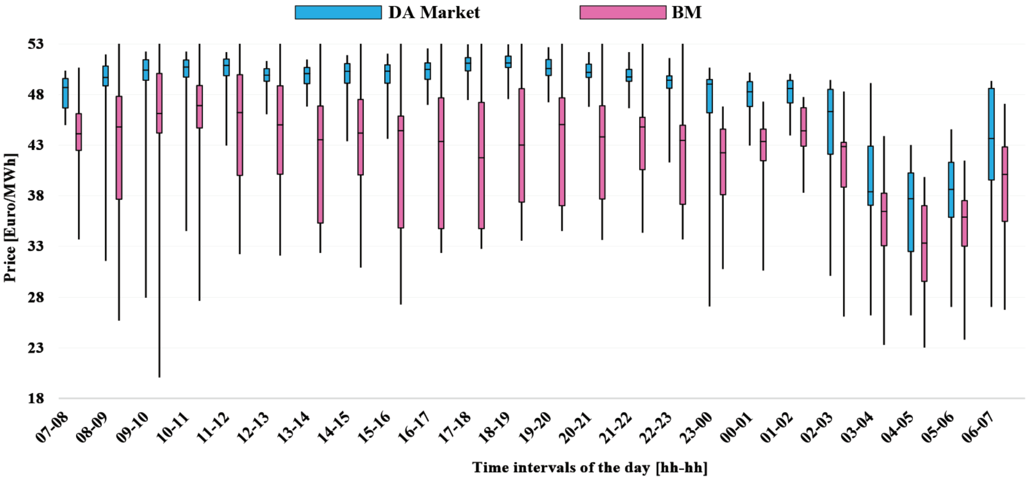

**Figure 3**. Boxplot of Turkey DA market and BM price scenarios.

- **Case-4:** WEPM participates in Turkey DA Market and BM. Besides, WEPM may make bilateral contracts. $\beta$ value is determined as 1.
- **Case-5:** WEPM participates in Turkey DA Market and BM. Besides, WEPM may make bilateral contracts. $\beta$ value is determined as 0.6.
- **Case-6:** WEPM participates in Turkey DA Market and BM. Besides, WEPM may make bilateral contracts. $\beta$ value is determined as 0.
- **Case-7:** WEPM participates in Sweden DA Market and BM. WEPM does not make bilateral contracts. $\beta$ value is determined as 0.6.
- **Case-8:** WEPM participates in Turkey DA Market and BM. WEPM does not make bilateral contracts. $\beta$ value is determined as 0.6.

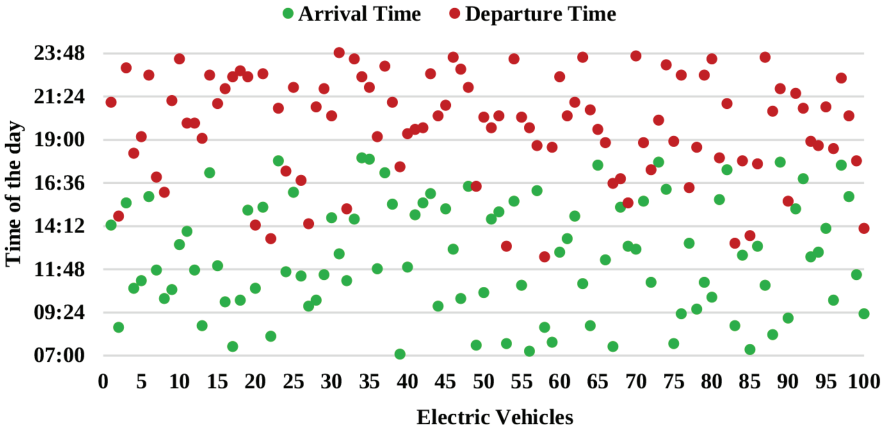

**Figure 4**. Distribution of 100 EVs' arrival and departure times in EVPL 1 in Scenario 1.

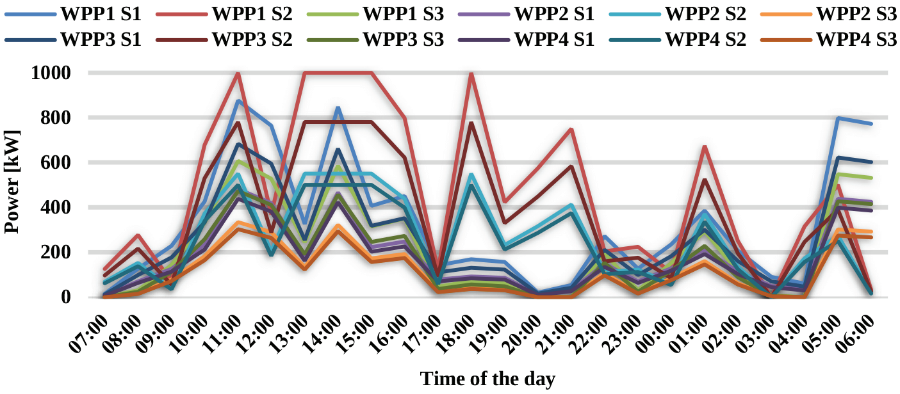

**Figure 5**. Power generation scenarios (S1, S2, S3) for WPPs.

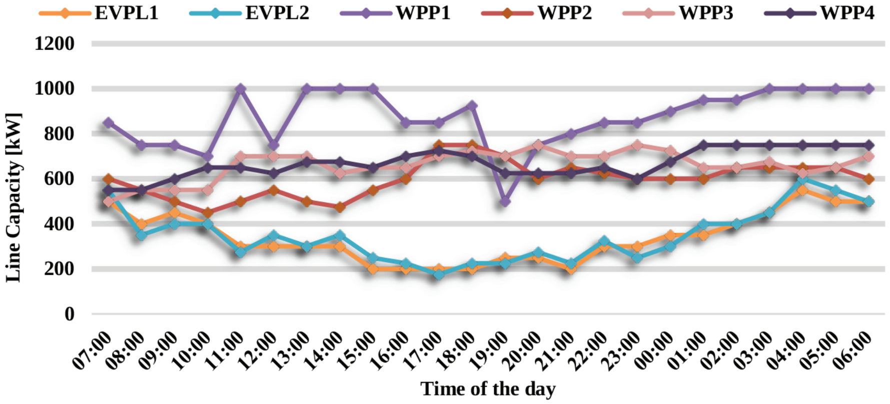

**Figure 6**. Line capacities determined for WEPM participants.

For each case study, detailed data on the quantities offered/bidden to the DA market and BM and the cost/profits related to them, the energy amounts of bilateral contracts and profits achieved, the energy amounts allocated to charging EVs from WPPs, and CVaR values are covered in Table 2. The most profitable situation among the case studies was realized with 999.84 € in Turkey in Case-6, where WEPM made bilateral contracts and participated in the DA market and BM by taking the risk aversion factor as 0. However, in this case, the problem is handled risk-neutral. For the same risk aversion factors, the profits in Turkey were higher than in Sweden. The most noticeable result was that the maximum profit obtained in Sweden was less than the minimum profit obtained in Turkey. According to the results of the study, the trade volume made through bilateral contracts increased with increasing of the risk aversion factor. Energy selling through bilateral contracts took place at most in Case-4 when the value is 1. An important result is that for Sweden, the greatest value of the energy allocated from WPPs to charge EVs was not achieved at the highest level of the risk aversion factor. Comparing Case-7 and Case-8, where no bilateral contracts are realized, with Case-2 and Case-5, it can be concluded that there is a decrease in the total portfolio earning in the absence of bilateral contracts. As expected for both countries, as risk aversion increased, the CVaR value increased while the expected profit decreased. The CVaR values decreased in Case-7 and Case-8 where there were no bilateral contracts compared to Case-2 and Case-5. It should also be noted that the volume of transactions carried out in the DA market and BM in the direction of buying and selling varies inversely in Sweden and Turkey generally according to the change in the $\beta$ value.

**Table 2**. Comparison of results obtained from the simulations.

| Case studies | Bilateral contract | | DA market | | | | BM | | | | Energy amount from WPPs to EVPLs [kWh] | Total expected profit [Euro] | CVaR [Euro] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Bid | | Bid | | Offer | | Bid for Upregulation | | Offer for Downregulation | | | | |
| | Amount [kWh] | Profit [Euro] | Amount [kWh] | Profit [Euro] | Amount [kWh] | Cost [Euro] | Amount [kWh] | Profit [Euro] | Amount [kWh] | Cost [Euro] | | | |
| Case-1 | 7701.09 | 180.98 | 7345.72 | 191.05 | 245.43 | 6.88 | 7061.68 | 199.32 | 2795.22 | 69.26 | 183.76 | 495.21 | 295.30 |
| Case-2 | 3166.68 | 74.42 | 8437.17 | 228.78 | 313.02 | 8.95 | 11411.25 | 321.55 | 2721.59 | 66.83 | 1695.58 | 548.96 | 294.45 |
| Case-3 | 2650.20 | 62.28 | 6209.01 | 170.00 | 693.04 | 19.39 | 14161.92 | 397.35 | 2347.61 | 57.23 | 209.05 | 550.01 | 270.58 |
| Case-4 | 8485.72 | 390.34 | 12100.15 | 597.03 | 381.90 | 18.14 | 665.89 | 29.83 | 3509.14 | 93.42 | 1111.34 | 905.65 | 563.97 |
| Case-5 | 4492.74 | 206.67 | 18413.65 | 914.87 | 220.14 | 10.45 | 109.83 | 4.92 | 2815.61 | 118.85 | 535.58 | 997.16 | 563.38 |
| Case-6 | 3966.79 | 182.47 | 19054.34 | 945.49 | - | - | - | - | 3040.65 | 128.13 | 211.26 | 999.84 | 500.64 |
| Case-7 | - | - | 7635.76 | 204.65 | 411.46 | 11.44 | 15385.37 | 417.92 | 2629.19 | 64.88 | 472.67 | 546.26 | 285.56 |
| Case-8 | - | - | 22619.59 | 1087.04 | - | - | 369.20 | 13.94 | 3008.31 | 126.75 | 584.60 | 974.23 | 528.70 |

In the case where WEPM is located in Sweden, data on the distribution of the total power generated from WPPs in Case-2 for Scenario 1 related to wind generation is given in Figure 7. At 09:00, 13:00, 14:00, 15:00, 19:00 and 22:00, an offer was made to the BM for downregulation. This means that WPPs will not produce as much as energy offered to the DA market. In terms of energy, a total of 7272.67 kWh of energy was sold to the BM in the direction of upregulation while a total of 4567.09 kWh of energy was sold to the DA Market. In some hours, a share of the power generated from the WPPs which is a total of 1695.59 kWh for a day was reserved to charge EVs. Besides, bilateral contracts were made for night hours after 22:00.

Figure 8 indicates the power distributions for Scenario 3 in Case-5 that the transactions are realized with Turkey electricity market prices. When the total hourly power produced is examined, it can be observed that the selling to the DA market has a large share, which is 10349.43 kWh and constitutes approximately 66% of the total produced energy. Besides, compared to the Case-2 given in Figure 7, the bidding/offering was given less for downregulation and upregulation in the BM. A total of 535.58 kWh of energy was reserved for EVPLs throughout the day. The amount of energy sold through bilateral contracts was 4025.37 kWh.

The distribution of hourly power consumed in EVPLs in Case-4 for Scenario 3 related to EVs' behavior is given in Figure 9. For this case, EVs were charged with power from WPPs, power bought from the DA market, and BM. Besides, biddings were realized in the BM for upregulation direction. In terms of energy, EVs were charged mostly with energy purchased from the BM.

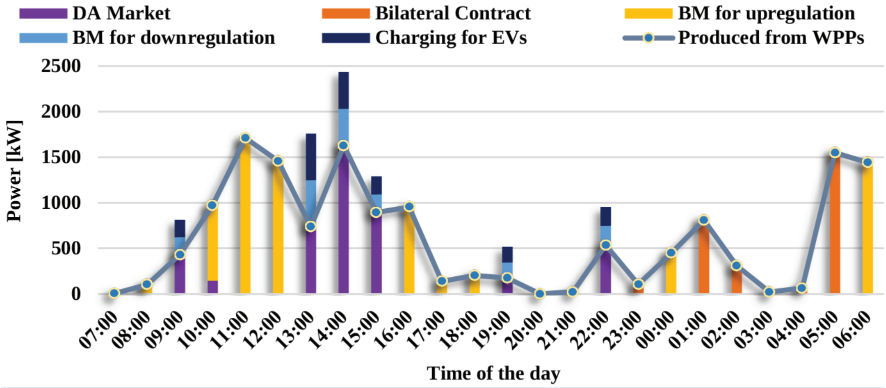

**Figure 7**. Power distribution related to WPPs in Case-2 for Scenario 1 related to wind energy generations.

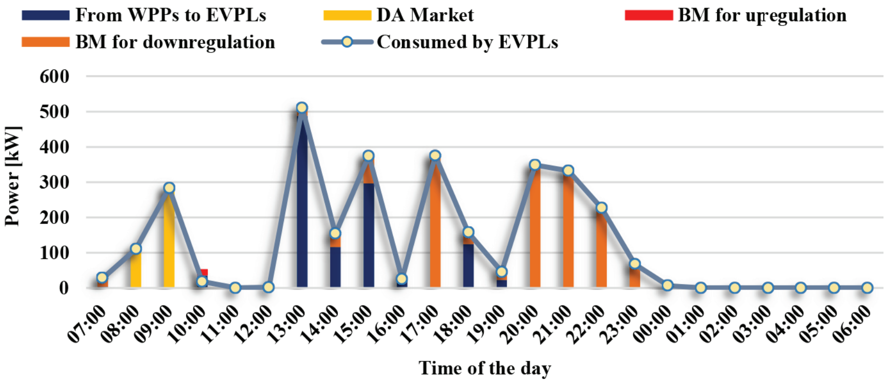

**Figure 8**. Power distribution for WPPs in Case-5 for Scenario 3 related to wind energy generations.

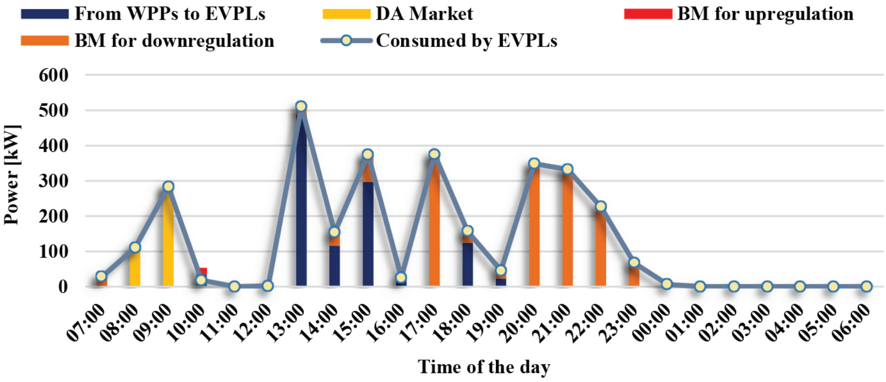

**Figure 9**. Power distribution in terms of EVPLs in Case-4 for Scenario 3 related to EV behaviors.

In Figure 10, to illustrate how the value of risk aversion has an impact on the charging of EVs, the changes in the state-of-energy levels of EV's battery in EV driving Scenario 3 for the Volkswagen E-Golf 2 (WO2) and

Tesla Model-S 2 (TES2) included in the EVPL 1 which is located in Sweden in Case-1 and Case-2, and for the Chevy Volt 5 (CHE5) and Tesla Model-S 9 (TES9) included in the EVPL 1 which is located in Turkey in Case-4 and Case-5 are given. The EVs reached the maximum charge level values earlier in Case-1 and Case-4 than in Case-2 and Case-5. The EVs left the EVPL with a full charge level. Considering the EVs included here and not specified here, it can be stated that EVs generally reach the full charge level earlier with the increase in the risk aversion factor.

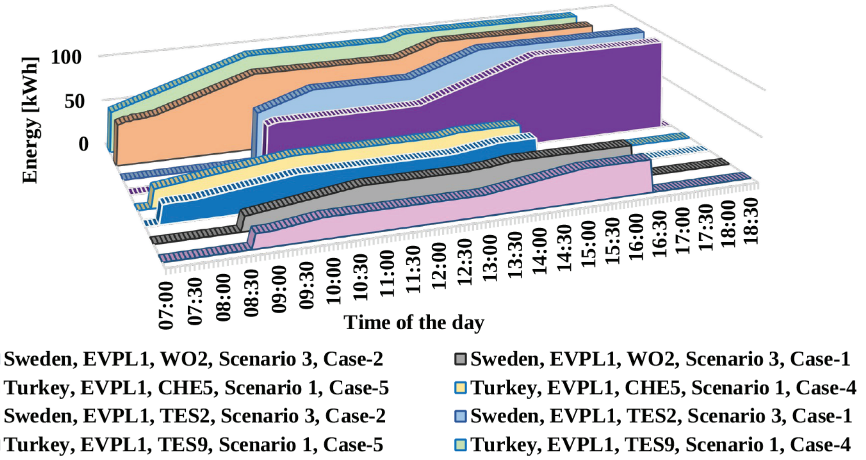

**Figure 10**. State-of-energy levels of WO2 and TES2 located in EVPL 1 in Case-1 and Case-2, and CHE5 and TES9 located in EVPL 1 in Case-4 and Case-5.

Since wind energy is a clean and renewable resource, it is desired to meet the generation from these sources as much as possible, but limitations in line transmission capacities are imposed by the independent system operator for various reasons. This undesirable situation causes a certain amount of curtailment in WPPs. According to line capacities and wind power generation scenarios, it should be stated that there was a curtailment of 21.85 kWh in Scenario 1, 663.18 kWh in Scenario 2 in WPPs. The highest curtailment occurred in WPP3 with 154.69 kWh for Scenario 2 related to wind power generation between 14:00 and 15:00, and a total curtailment of 452.67 kWh occurred throughout the day.

## 4. Conclusion

A risk-averse optimization model was proposed in which portfolio managers including WPPs and EVPLs aim to maximize their profits by participating in the electricity markets, taking into account line capacities. WEPM could take place in the DA market and BM, and it could also trade through bilateral contracts. The uncertainties in the proposed structure regarding EV driving behaviors, wind power generations, and electricity market prices, were handled in a stochastic manner. Also, several case studies were conducted considering the different values of the risk aversion factor and bilateral contract situations. The EVPLs included 10 EVs from each of the 10 different EVs commercially available. While 4 different scenarios were created for EV driving behaviors, 3 different scenarios were created by changing the real data for the power generation of 4 WPPs. Besides, actual electricity market data from Sweden and Turkey were used.

Although the most profitable situations occur when $\beta$ is taken 0, the problem is taken as risk-neutral in these cases. In this respect, it would be appropriate for the portfolio manager to choose the appropriate $\beta$ value and take action accordingly. Besides, according to the results obtained from the study, as the risk aversion factor increased for both countries, the profit decreased while the CVaR value is increased. This decrease reached the level of 10% in both markets when $\beta$ was changed from 0 to 1. The gain in the situation where WEPM is located in Turkey and takes the $\beta$ value as 1 is greater than WEPM is located in Sweden and considers the problem as risk-neutral. It also showed that the risk aversion factor has a direct effect on the charge of EVs which was obtained by observing that EVs have different times to catch full charge level under different $\beta$ values for the same country. In many case studies, the volume of trading carried out in the DA market and the BM changed in the opposite direction in Sweden and Turkey according to the change in $\beta$ value. When the line capacity limits were considered, curtailments in wind power reaching 452.67 kWh in a case were observed.

The proposed portfolio structure facilitates the management of wind energy resources in terms of their participation in the electricity markets, on the other hand, it can ensure that these resources take a stronger position in the electricity markets. Besides, the opportunity to eliminate energy imbalances within the portfolio can be obtained. In terms of EVPLs added to the portfolio, it can provide a good opportunity for both charging management and economical charging of EVs.

The current concept considers the problem from one direction without the consideration of the possibly conflicting targets of the power producers as well as aggregators. As an extension of the current concept, the implementation of a bilevel approach in this manner together with the consideration of different types of power producers as well as energy storage system integration can be studied. Besides, the consideration of the V2G concept in this manner together with the relevant degradation concern for EV batteries can be an interesting issue for a future study.

## Acknowledgment

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