Bi-level Modelling Approach to Coordinated Operation of Wind Power Plant and PV-Storage Energy Community

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***Abstract*— Uberization of the energy sector and transition towards decentralized, local production puts energy communities at the forefront of these changes. Very often they are initiators of new, low carbon investments and consequently they are becoming highly relevant market participants. This creates new power system operational challenges. The focus of this paper is on interplay and price driven collaboration between a PV-battery energy community and a wind power plant (WPP). This coordination is cast as a bilevel mixed integer linear programming (MILP) approach, modelling market participation of both entities, peer-to-peer (p2p) trading within energy community and power exchange between the energy community and WPP. The energy community is driven by the lowest energy cost for supplying its consumers, while the objective of a WPP is to maximize its profit. The results indicate that this coordination creates financial benefits for both sides as compared to individual market exposure.**

Keywords*— *aggregator; energy community; bilevel MILP model; coordinated market participation; p2p trading; wind power plant

NOMENCLATURE

The notation used in this paper is provided below:

Indices and Sets:

$d \in D$	Households
$t \in T$	Time

Parameters:

$demand_{d,t}$	Demand of household d in hour t
P^{batmax}	Max power of charging/discharging
P^{max_ex}	Max export of household
P^{max_im}	Max import of household
$P^{max\_ext\_M}$	Max export from household to market
$P^{max\_imt\_M}$	Max import from market to household
$P^{max\_ex\_total}$	Max export to market
$P^{max\_im\_total}$	Max import from market
P_t^W	Wind production in hour t
$Price^{sell}$	Aggregatorr's selling price
$price_t^{buy}$	Aggregatorr's buying price in hour t
$PV_{d,t}$	PV production in household d in hour t
SOC^{max}	Battery capacity
λ_t	Market price for hour t

Variables:

$charging_{d,t}$	Total charging of battery d in hour t
$charging_{d,t}^{CHP}$	Charging battery d in hour t with energy produced from CHP
$charging_{d,t}^{im}$	Charging battery d in hour t with imported energy
$charging_{d,t}^{PV}$	Charging battery d in hour t with energy produced from PV
$CHP_{d,t}$	CHP production in household d in hour t
$CHP_{d,t}^{demand}$	Energy produced from CHP d for demand d in hour t
$CHP_{d,t}^{export}$	Energy produced from CHP d for export in hour t
$discharging_{d,t}$	Total discharging of battery d in hour t
$discharging_{d,t}^{dem}$	Discharging from battery d in hour t for satisfying demand
$discharging_{d,t}^{ex}$	Discharging from battery d in hour t for export
$Export_{d,t}$	Total export of household d in hour t

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$Export_m^{HtoH}$	Export from household *m* to other households
$Export_{d,t}^{MARKET}$	Export from household *d* in hour *t* to the market
$Export_t^{total}$	Total export from all households in hour *t* to market
$Import_{d,t}$	Total household *d* import in hour *t*
$Import_{d,t}^{demand}$	Household *d* import in hour *t* for satisfying demand
$Import_m^{HtoH}$	Household *m* import from other households
$Import_{d,t}^{MARKET}$	Household *d* import from market in hour *t*
$Import_t^{total}$	Total import of all households in time *t* from the market
P_t^{AtoW}	Exported energy from aggregator to wind power plant in hour *t*
P_t^{WtoA}	Imported energy from wind power plant in hour *t*
$P_{d,t}^{AtoW}$	Exported energy from household *d* to wind power plant in hour t
$P_{d,t}^{WtoA}$	Imported energy from wind power plant to household *d* in hour *t*
$PV_{d,t}^{demand}$	Energy produced from PV *d* for demand *d* in hour *t*
$PV_{d,t}^{export}$	Energy produced from PV d for exprt in hour *t*
$SOC_{d,t}$	Battery *d* state of charge in hour *t*

Binary variables:

u_t^1, u_t^2, u_t^3, u_t^4	Auxilary variables for linearization
x_t^{AtoW}	Indicates exported energy from aggregator to wind warm in hour *t*
$x_{d,t}^{ex}$	Indicates total exported energy from household *d* in hour *t*
$x_{d,t}^{im}$	Indicates total imported energy to household *d* in hour *t*
$x_{d,t}^{ex\_MARKET}$	Indicates exported energy from household *d* to the market in hour *t*
$x_{d,t}^{im\_MARKET}$	Indicates imported energy from the market for household *d* in hour *t*
$x_t^{ex\_total}$	Indicates exported energy from all households to the market in time *t*
$x_t^{im\_total}$	Indicates imported energy from the market to all households in time *t*
x_t^{WtoA}	Indicates imported energy from wind power plant in hour *t*

Dual variables:

$\underline{\alpha}_t^{WtoA}$, $\overline{\alpha}_t^{WtoA}$, $\underline{\beta}_t^{AtoW}$, $\overline{\beta}_t^{AtoW}$, γ

I. INTRODUCTION

Transformation of the power system from centralized bulk system to a decentralized one means active consumers start to perceive electricity as a commodity to be traded with. Reduction of prices for domestic micro units such as rooftop PV systems [1] go along with recent regulatory framework promoting the uptake of active consumers [2]. Numerous challenges arise in finding business cases for active consumers [3] (in the paper we refer to them as prosumers, despite the fact that this phrase is omitted in reference [4]), through aggregation and coordinated market participation with other market entities, creating additional value for all stakeholders [5]. These aspects have been the focus of recent research as shown in the following literature review. In [6] authors present mixed-integer linear programming model for optimizing joint bidding strategy of a WPP and energy storage facility that participate in day-ahead energy and spinning reserve markets. Uncertainty associated with renewable generation are reduced with coordination of service provision, as well as imbalance costs. Work of authors in [4] deals with coordinated operating strategy for ESS and PV equipped households while considering provision of balancing services to the system operator. The model presents how low carbon communities could become self-sufficient, and additionally, provide flexibility to the system operator. A bilevel framework for problem of decision-making by an EV aggregator in a competitive environment is proposed in [7] where the rivalry between an aggregator and EV owners is presented. The work in [8] applies game-theoretic principles to model competition between demand response aggregators for selling excess energy stored in electrochemical storage devices directly to other aggregators in a power market as alternative to the traditional vertically integrated market. Optimal operation of large-scale storage systems owned by independent private investors is studied in [9]. The paper proposes an optimal bidding mechanism for storage units in cases with large differences in market prices in the day-ahead and hour-ahead markets due to high penetration of intermittent renewable energy resources. Stochastic programming is used to present how fluctuations on the market can be improved with integration of large storage units and how location and size of the storage increase its profit. Bilevel problem of DR aggregator participation in wholesale markets is presented in [10]. The paper takes out that the existing profit from the deployment of DR contracts by aggregators will give revenues to the aggregator which can be used for end consumers. Interactions between the merchant DR aggregator and ES investor is presented in [11]. Results of equilibrium problem with equilibrium constraints (EPEC) show how their competition brings larger cost saving to the system, comparing to the case where only one technology is used. Acting strategically, both of them can increase own profitability. Bilevel model in [12] aims to minimize generation cost in upper level and maximize self-consumption of prosumers in lower level. High penetration of prosumers leads to improved voltage stability and flattened demand profile. The work in [13] proposes plug-in electric vehicle aggregator exercising indirect load control over a fleet of vehicles and the decision-making process with determining the profit-optimal retail prices. Authors in [14] present a bilevel aggregator-utility optimization model with spot electricity prices for scheduling the energy consumption patterns of controllable loads classified in three diverse groups in the system with a high penetration of wind production showing improved energy efficiency and facilitated power balance considering intermittent wind production. Hierarchical structured multi-energy players cooperation exchanging energy with local energy system is developed in [15]. Bilevel approach is used for modeling the decision-making conflicts. Bilevel model in [16] describes DER aggregator decisions and managements of his clients with energy market participation. The paper presents how retail prices for his customers are determined, as well as the strategy for wholesale market participation. It can be noticed that none of the above papers addresses a joint coordinated market participation of energy community and renewable energy source such as WPP. In power systems where majority of electricity is produced from renewable sources, collaboration of such entities will be desirable. On one hand energy community has the capability to provide flexibility but is not prone to be exposed to volatile market prices. On the other hand, wind units can make significant profit by participating in power markets as a source of clean and low marginal cost energy, however they will mostly have to join a balancing group capable of mitigating their uncertain and variable production. This paper presents a bilevel model of a joint participation of a WPP and an energy community, acting as an aggregator of prosumers, at the energy market. Upper level problem describes aggregator cost which can be reduced by selling energy on the market and exchanging energy with the WPP. Lower level problem is wind farm profit maximization in cooperation with the aggregator. Selling more energy during period of high market prices will ensure higher profit for WPP. A bilevel model is latter described as a mathematical program with equilibrium constraints (MPEC) with upper level constraints, primal feasibility of lower level, stationarity, as well as dual feasibility of lower level problem and complementarity slackness. Fortuny-Amat Transformation is used for linearization and problem is solved using Gurobi solver.

II. MODEL DESCRIPTION

A. Model of energy community and wind power plant

The energy community is represented by two types of households characterized by specifics of units installed for local production. Similar model is presented in [4]. Conceptual scheme of the energy community and WPP is shown in Fig 1. The model is focused on the market cooperation, hence power system network constraints are not included is the model. One group of households is equipped with a PV panel and a battery storage, and the other group with a CHP unit and a battery storage. Thermal energy generation/demand is not explicitly modelled, meaning CHP units act as a generator with the cost of produced energy in satisfying electricity demand and assuming large enough thermal storage to decouple electricity and heat. Further work will be extended with realistic CHP unit modelling of both electricity and thermal energy. Energy community acts as an aggregator of those two household groups and its cost function is modeled as (1):

$$Min \sum_{t\in T} (price^{CHP} \cdot CHP_t + price_t^{buy} \cdot Import_t^{total} - price^{sell} \cdot Export_t^{total}),\ \forall t\in T \qquad (1)$$

The objective is to minimize total cost for procuring energy from CHP units and market while trying to gain profit by selling energy on the market in certain hours. In the initial case we consider constant selling price of 0.1 €/kWh, modelling a realistic case where energy community has a long-term contract with fixed prices to hedge the risk of volatile market prices. Aggregators buying price differs during night (22h-8h) 0.07 €/kWh and day hours (8h-22h) 0.14 €/kWh, describing a realistic case of two-tariff system as the most common contract between a retailer and final consumer. In the latter case the aggregator is exposed to day-ahead market prices. Marginal cost of energy produced from CHP unit is 0.03 €/kWh. Exchange of energy between the aggregator and WPP is done at zero cost, following the logic of coordinated participation with a common goal. This means that the WPP tries to maximize its profit by storing produced energy in energy communities' local battery storages during periods of low market prices. At the same time, the community benefits as it lowers its costs for energy procurement on the market and from CHP units. These relationships are described in the upper level model, with the following equations:

Each household d imports energy either from the market, WPP or from other households (2):

$$Import_{d,t} = Import_{d,t}^{MARKET} + P_{d,t}^{WtoA} + \sum_{m\in D} Export_m^{HtoH} \quad \forall d\in D,\ \forall t\in T \qquad (2)$$

and exports energy to the market, WPP or other households (3):

$$Export_{d,t} = Export_{d,t}^{MARKET} + P_{d,t}^{AtoW} + \sum_{m\in D} Import_m^{HtoH} \quad \forall d\in D,\ \forall t\in T \qquad (3)$$

Note that Equations (2) and (3) explicitly model exchange of energy between households within the community as p2p trading, ensuring the maximization of local consumption of locally produced low cost electricity (third member of Equations (2) and (3)).

Exchange with the market is limited for both import (4), as well as exported (5), as a way of modelling rated power of point of common coupling (PCC). Simultaneous import and export in the same hour are not possible (6):

$$Import_{d,t}^{MARKET} \leq P^{max\_im\_M} \cdot x_{d,t}^{im\_MARKET} \quad \forall d\in D,\ \forall t\in T \qquad (4)$$

$$Export_{d,t}^{MARKET} \leq P^{max\_ext\_M} \cdot x_{d,t}^{ex\_MARKET} \quad \forall d\in D,\ \forall t\in T \qquad (5)$$

$$x_{d,t}^{im\_MARKET} + x_{d,t}^{ex\_MARKET} \leq 1,\ \forall d\in D,\ \forall t\in T \qquad (6)$$

Similar is done for each household and limited by (7) and (8) without a possibility of simultaneous import and export in the same hour (9). These limitations are defined by the household connection power to the local distribution network:

$$Import_{d,t} \leq P^{max\_im} \cdot x_{d,t}^{im} \quad \forall d\in D,\ \forall t\in T \qquad (7)$$

$$Export_{d,t} \leq P^{max\_ex} \cdot x_{d,t}^{ex} \quad \forall d\in D,\ \forall t\in T \qquad (8)$$

$$x_{d,t}^{im} + x_{d,t}^{ex} \leq 1,\ \forall d\in D,\ \forall t\in T \qquad (9)$$

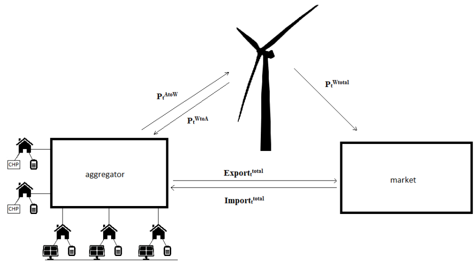

Figure 1 Coordinated market participation

Energy imported in each household is used for supplying demand and for batery charging (10):

$$Import_{d,t}=Import_{d,t}^{demand}+charging_{d,t}^{import} \quad \forall d\in D,\ \forall t\in T \qquad (10)$$

Energy exported from each household is a result of battery discharging and energy produced from PV (11):

$$Export_{d,t}=discharging_{d,t}^{expor}+PV_{d,t}^{export} \quad \forall d\in D,\ \forall t\in T \qquad (11)$$

Demand is supplied from battery, PV (or CHP) and imported energy (12):

$$demand_{d,t}=discharging_{d,t}^{demand}+PV_{d,t}^{demand}+CHP_{d,}t+ +Import_{d,t}^{demand} \forall d\in D, \forall t\in T \qquad (12)$$

Production from PV is used for battery charging, demand supplying and export (13), as well as production from CHP (14):

$$PV_{d,t}=charging_{d,t}^{PV}+PV_{d,t}^{demand}+PV_{d,t}^{export}\ \forall d\in D,\ \forall t\in T \qquad (13)$$

$$CHP_{d,t}= charging_{d,t}^{CHP}+CHP_{d,t}^{demand}+CHP_{d,t}^{export} \quad \forall d\in D, \forall t\in T \qquad (14)$$

Battery is charged with energy produced from PV (or CHP) and imported energy (15). Battery is discharged for demand supplying and export (16):

$$Charging_{d,t}=charging_{d,t}^{import}+charging_{d,t}^{PV}+ charging_{d,t}^{CHP} \quad \forall d\in D, \forall t\in T \qquad (15)$$

$$Discharging_{d,t}=discharging_{d,t}^{demand}+discharging_{d,t}^{export} \quad \forall d\in D,\ \forall t\in T \qquad (16)$$

Charging and discharging actions are limited with maximum rate (17-18):

$$Charging_{d,t} \leq P^{batmax} \forall d\in D,\ \forall t\in T \qquad (17)$$

$$Discharging_{d,t} \leq P^{batmax}\ \forall d\in D,\ \forall t\in T \qquad (18)$$

Storage state of charge is expressed as (19):

$$SOC_{d,t}=SOC_{d,t-1}+0.9charging_{d,t}- discharging_{d,t} \quad \forall d\in D,\ \forall t\in T \qquad (19)$$

Total export and import to or from the market in hour t is calculated as (20) and (21) and is limited by maximum export (22) and import (23). Simultaneous export and import in the same hour t are not allowed (24):

$$Export_t^{total}=\sum_{d\in D}export_d^{MARKET}\ \forall t\in T \qquad (20)$$

$$Import_t^{total}=\sum_{d\in D}import_d^{MARKET}\ \forall t\in T \qquad (21)$$

$$export_t^{total}\leq P^{max\_ex\_total}\cdot x_t^{ex\_total}\ \forall t\in T \qquad (22)$$

$$import_t^{total}\leq P^{max\_im\_total}\cdot x_t^{im\_total}\ \forall t\in T \qquad (23)$$

$$x_t^{im\_total} + x_t^{ex\_total} \leq 1,\ \forall t\in T \qquad (24)$$

Total exchanged energy between WPP and aggregator for each hour is given in (25) and (26) for both directions (WPP to aggregator and vice versa), as well as impossibility of simultaneous exchanging in both directions in the same hour t (27):

$$P_t^{WtoA}=\sum_{d\in D} P_{d,t}^{WtoA}\ \forall t\in T \qquad (25)$$

$$P_t^{AtoW}=\sum_{d\in D} P_d^{AtoW}\ \forall t\in T \qquad (26)$$

$$x_t^{WtoA} + x_t^{AtoW} \leq 1,\ \forall t\in T \qquad (27)$$

Lower level problem is WPP energy in hour t from WPP and exchanged energy between aggregator and WPP power plant (28):

$$max \sum_{d\in D}(P_t^{W}+P_t^{AtoW}-P_t^{WtoA})\cdot \lambda_t, \forall t\in T \qquad (28)$$

For clarity, dual variables of the lower-level problem are listed after the corresponding constraints following a colon. Total energy produced by WPP is will be sold in the market and this is indirectly modelled by (29):

$$\sum_{t\in T}P_t^{WtoA}=\sum_{t\in T}P_t^{AtoW}\ :\ \gamma \qquad (29)$$

What equation (29) refers to is the equality of total energy exchanged in both direction during a day, meaning that the total energy send from WPP to energy community needs to be equal to the one traded (at zero cost) in opposite direction. By modelling this, none of the two entities gains a favorable position compared to the other, the work in coordination and not as competing entities. Energy exchanged in both directions is limited with (30) -(33):

$$P_t^{WtoA} \geq 0 : \underline{\alpha}_t^{WtoA}, \forall t\in T \qquad (30)$$

$$P_t^{AtoW}\geq 0 : \underline{\beta}_t^{AtoW}, \forall t\in T \qquad (31)$$

$$P_t^{WtoA}\leq P^{maxAtoW}\cdot x_t^{WtoA}: \overline{\alpha}_t^{WtoA}, \forall t\in T \qquad (32)$$

$$P_t^{AtoW}\leq P^{maxWtoA}\cdot x_t^{AtoW}: \overline{\beta}_t^{AtoW}, \forall t\in T \qquad (33)$$

B. *MPEC formulation*

Model described in section A has a bilevel structure and cannot be solved using commercial solvers. It is converted into a mathematical program with equilibrium constraints (MPEC). The MPEC model is formulated as upper level problem (1-27), primal feasibility of lower level problem (29-33), stationarity (34-35) and dual feasibility and complementary slackness (36-39):

$$\gamma+\underline{\alpha}_t^{WtoA}-\overline{\alpha}_t^{WtoA}= \lambda_t, \forall t\in T \qquad (34)$$

$$-\gamma+\underline{\beta}_t^{AtoW}-\overline{\beta}_t^{AtoW}=- \lambda_t, \forall t\in T \qquad (35)$$

$$P_t^{WtoA} \geq 0 \perp \underline{\alpha}_t^{WtoA}\geq 0, \forall t\in T \qquad (36)$$

$$P^{maxAtoW}\cdot x_t^{WtoA}-P_t^{WtoA} \geq 0 \perp \overline{\alpha}_t^{WtoA}\geq 0, \forall t\in T \qquad (37)$$

$$P_t^{AtoW} \geq 0 \perp \underline{\beta}_t^{AtoW} \geq 0, \forall t\in T \qquad (38)$$

$$P^{maxWtoA}\cdot x_t^{AtoW}-P_t^{AtoW}\geq 0 \perp \overline{\beta}_t^{AtoW} \geq 0, \forall t\in T \qquad (39)$$

Conditions (36-39) are linearized using the Fortuny-Amat Transformations with the introduction of auxiliary binary variables and M as sufficiently large constant (40-47):

$$P_t^{WtoA} \leq M\cdot u_t^{1}, \forall t\in T \qquad (40)$$

$$\underline{\alpha}_t^{WtoA} \leq M\cdot(1-u_t^{1}), \forall t\in T \qquad (41)$$

$$P^{maxWtoA}\cdot x_t^{WtoA}-P_t^{WtoA} \leq M\cdot u_t^{2}, \forall t\in T \qquad (42)$$

$$\overline{\alpha}_t^{WtoA} \le M\cdot(1-u_t^2),\ \forall t\in T \tag{43}$$

$$P_t^{AtoW} \le M\cdot u_t^3,\ \forall t\in T \tag{44}$$

$$\beta_t^{AtoW} \le M\cdot(1-u_t^3),\ \forall t\in T \tag{45}$$

$$P^{maxAtoW}\cdot x_t^{AtoW} - P_t^{AtoW} \le M\cdot u_t^4,\ \forall t\in T \tag{46}$$

$$\overline{\beta}_t^{AtoW} \le M\cdot(1-u_t^4),\ \forall t\in T \tag{47}$$

Finally, the model is described with (1-27), (29-33), (34-35) and (40-47).

III. CASE STUDY

Solar production for the first group of households is presented in Figure 2. Figure 3 shows demand profile of both groups of households. Demand 1-3 are households equipped with PV, and 4-6 with CHP unit. WPP production and market prices for three different cases are given in Fig 4. Households details are provided in Table I.

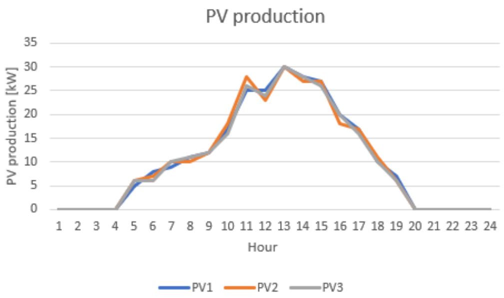

Figure 2 PV production

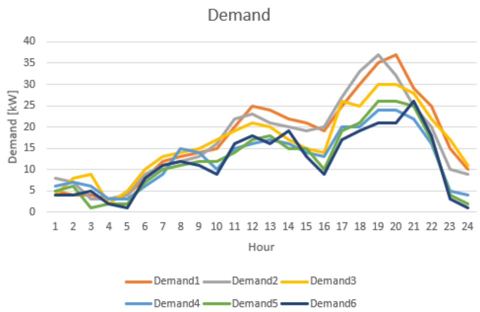

Figure 3 Demand profile

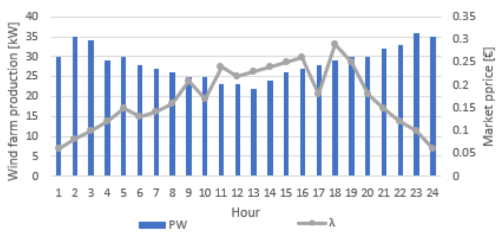

Figure 4 Wind power plant production and market prices

TABLE I. HOUSEHOLDS EQUIPMENT

Households	***Battery***	***PV***	***CHP***
1-3	5 kW/10 kWh	30 kW	-
4-6	5 kW/10 kWh	-	15 kW

IV. RESULTS

The results of the optimization are shown for a single day. However, the model can be easily expanded to cover any time period of interest. In the first case, fixed buying and selling prices for aggregator are considered, while in the second case the aggregator is exposed to the spot market prices (both selling and buying), and in the third case buying prices are dynamic market prices, and selling price is a fixed rate. WPP has higher profit (Table II) when coordinating its participation with the energy community in all cases. Table III compares aggregator independent cost with coordinated behavior. In the first case, aggregator's cost is lower in coordinated participation, as well as in third case with fixed selling price. In dynamic price scheme, WPP has the lowest profit increase, while aggregator cost is 0.54 % higher than in independent participation. In joint market participation, it pays off for WPP to sell more during 11th-16th hours when the first peak prices occur, meaning that aggregator will reduce its selling energy, but during the 18th-22nd hours, aggregator buys less than in independent participation. As active consumers share their storage with WPP, fixed buying and selling prices will reduce their exposure to volatile market prices and ensure lower energy procurement cost. Figure 5 presents aggregator export and import from (to) the market for coordinated cases. Negative values are exports to the market and positive ones are imports from the market. Figure 6 shows interchanged energy between aggregator and WPP for the first case. Negative values are exports from aggregator to wind power plant, and positive ones are imports from WPP. Interchanged energy between them is limited by 10 kWh per hour, although this again can be any value (or even a free variable). In 9th and during 11th -15th hours when market prices are highest, WPP imports energy from the aggregator and increases its own profit. During 17th - 22nd hour, WPP imports the energy from the aggregator. It needs to be kept in mind that at the end of the day a balance between import and export needs to be maintained.

TABLE II. WIND POWER PLANT PROFIT

	Independent participation (€)	***Coordinated participation (€)***	***Profit increase in %***
Case 1	112.79	115.09	2.04
Case 2	112.79	113.18	0.35
Case 3	112.79	115.23	2.16

TABLE III. AGGREGATOR COST

	Independent participation (€)	***Coordinated participation (€)***
Case 1	89.55	87.15
Case 2	100.68	101.22
Case 3	117.04	111.61

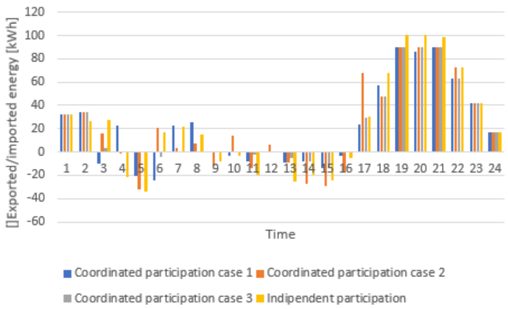

Figure 5 Energy import and export to (from) market

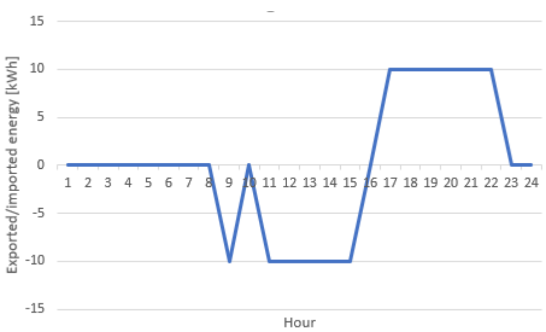

Figure 6 Imported and exported energy from the aggregator to the wind power Plant

V. CONCLUSION

Significant integration of renewable energy sources and small battery storages in the distribution system creates new opportunities for household market participation. Instead of only consuming the energy, households will become prosumers and, aggregated as a single market entity, capable of providing different services to the system or other market participants. The challenge lays in finding opportunistic business cases for new entities, especially when it comes to those with high levels of renewable generation in their portfolio. The novelty of the paper is in the bilevel model for coordinated participation of energy community, acting as an aggregator, and WPP in the energy market. The research has shown how joint participation brings benefits for both sides. For the sake of simplicity, the validly of the proposed business model is demonstrated by flexible joint participation on the day-ahead market only. Further research will focus on additional benefits which could arise from joint participation in multiple markets, such as adding balancing market participation to alleviate uncertainty of wind forecasts, as well as provision of multiple services to both market and system operator. From the results presented here, a reasonable assumption is that energy community aggregator will play a role of flexibility provider, reducing the imbalances caused by errors in forecasting generation from WPP but also its own households equipped with PV units. In such context, the energy communities take over the role of balancing group leaders as they ensure equilibrium of schedules announced on a day-ahead and those delivered in real time markets. By doing this, they further increase the benefits of local prosumers, most likely seen as electricity bill reductions.

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