The optimal utilization of the battery storage for a virtual prosumer participating on a day-ahead market

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***Abstract*—In this paper, a model for obtaining optimal market bid on a day-ahead market for a virtual prosumer representing a group of prosumers is presented. Optimization model gives the optimal plan of a battery storage utilization to achieve maximal profit on the day-ahead. Optimization model is applied on a case study in order to show general features of the model. The case study is made on supposed power system based on the 700 households each obtaining photovoltaic (PV) power plant rated power of 10 kW. These 700 prosumers are represented by one virtual prosumer that has available battery storage rated capacity of 50 MWh. Virtual prosumer participates in the CROPEX day-ahead market.**

Keywords - optimization, prosumer, day-ahead market, market bid, battery storage

I. Introduction

The daily population growth on Earth is leading to a global increase in electricity demand. If the current energy policy is going to be implemented, the demand for electricity would continue to grow by 1% every year until 2040 [1]. According to this report, a global increase in electricity consumption does not necessarily mean an increase in air pollution using fossil fuels. The policy of global energy actors should go towards reducing dependence on fossil fuels and turn to renewable energy sources (RES) [1].

The EU aims to reduce CO_2 emissions between 80 and 95% by 2050 in order to achieve a climate-neutral Europe [2]. Croatia, as one of the EU members, follows the directive and adopts a rulebook in which nZEB (nearly zero-energy building) is mentioned for the first time in 2015, and from 31.12.2019. becomes mandatory for all energy dependent facilities. It states that the minimum share of 20% energy used must be obtained from renewable systems [3].

The previous passive electricity consumers, by integrating renewable energy sources in their ownership, become consumers with their own production, i.e. they become prosumers.

To increase profits, prosumer can participate in the electricity market. An example of a framework for integrating the prosumer into the day-ahead and intraday electricity market can be found in [4] where a platform has been developed that represents the interface between the group of prosumers and the wholesale electricity market. A two-stage stochastic optimization model for an aggregator of small prosumers for participation in the day-ahead energy market is presented in [5]. In proposed model uncertainty of end user's behavior, PV system production, electricity demand and outdoor temperature are included. Two stage optimization model is used in [6] for the optimal joint bid of hydro power systems and wind power plants on a day-ahead electricity market. Stochastic modeling of prosumer with PV system and energy storage participating on a Nordic day-ahead energy market is presented in [7] Optimization model proposed in [8] is used for joint scheduling of a consumption and trading of the prosumer. The optimization model of the prosumer's profit maximization by participating in the electricity market is presented in [9]. The new management model used by the prosumer group was presented in [10], while [11] shows an example of an optimization model for bidding in the day-ahead market and the ancillary services market.

In this paper, a model for obtaining optimal market bid on a day-ahead market for a group of prosumers represented by one virtual prosumer is presented. It is assumed that virtual prosumer on his disposal has a battery storage which gives him flexibility in power management and enables extra income on electricity market. Optimization model gives the optimal plan of battery storage utilization to achieve maximal profit on the day-ahead market. Observed virtual prosumer in a case study represents 700 households with own electricity generation from PVs. It is assumed that all excess electricity produced by virtual prosumer can be sold on electricity market and sufficient can be bought on the same market. The electricity prices are assumed according to the day-ahead market data in Croatian Power Exchange (CROPEX). CROPEX is organized as day-ahead and intraday market [12]. Day-ahead market trading is conducted through a central auction held each day for the delivery of electricity the next day, and the uniform price rule is used to calculate the market price.

This paper consists of four chapters. Second chapter describes mathematical model for obtaining optimal bid of the virtual prosumer representing the group of prosumers on the day-ahead market. Objective function and constraints are described. In third chapter proposed optimization model is applied on the virtual prosumer representing 700 household with own electricity generation from PVs, considering battery storage. Last chapter represents results overview and conclusion.

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II. THE MATHEMATICAL MODEL FOR THE OPTIMAL BID OF THE PROSUMER GROUP

A. Mathematical formulation of the optimisation problem

The aim of this simulation is to maximize the profit of the virtual prosumer representing the group of prosumers on the electricity market taking into account battery storage.

The objective function is maximization of the profit achieved by participation in the day-ahead market and the value of stored energy in the battery at the end of the observed period. In this way, the expected changes in the electricity prices regarding the next period will be considered. The value of the stored energy at the end of the observed period then depends on the amount of stored energy in the battery and expected electricity price at which this energy will be sold.

The operation constraints are the energy balance constraint considering supply of prosumer load and the constraint related to the state of charge of the battery storage.

Maximize: *revenue on the electricity market*

+ *value of the stored energy*

Constraints: *energy balance,*

state of charge of the battery storage.

Limitations: *size of the discharging segments,*

size of the charging segments,

battery storage capacity.

In this model, the efficiency of charging and discharging the battery storage will be taken into account. In addition, it is assumed that the efficiency is not constant for the whole range of the charging or discharging power. In Fig. 1., an example of the linear approximation of the charging characteristic with the marked segments and the corresponding charging efficiency is presented. In the similar manner, discharging characteristic is approximated by piecewise linear function with specified segments and corresponding discharging efficiency.

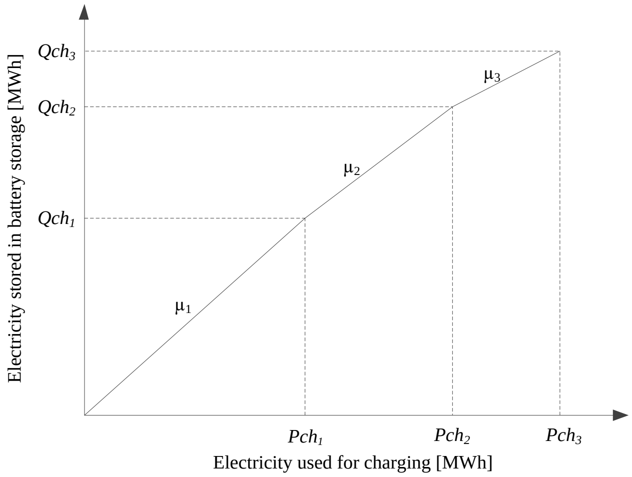

Fig. 1. An example of the linear approximation of the charging characteristic of the battery storage

Electricity stored in battery storage is defined as:

$$Qch_t = \sum_{k=1}^{n_k} \mu_k Pch_{k,t} \tag{1}$$

where:

Qch_t - electricity stored in battery storage during hour t

n_k - number of charging segments

μ_k - charging efficiency in charging segment k

$Pch_{k,t}$ - electricity used for charging in charging segment k during hour t

Electricity used from the battery storage for discharging process is defined by expression (2):

$$Qd_t = \sum_{j=1}^{n_j} \frac{1}{\eta_j} \cdot Pd_{j,t} \tag{2}$$

where:

Qd_t - electricity used from battery storage for discharging process during hour t

n_j - number of discharging segments

η_j - discharging efficiency in discharging segment j

$Pd_{j,t}$ - electricity obtained from discharging process in discharging segment j during hour t

Mathematical notation of the optimization problem for the day ahead market is:

Objective function:

$$\max. \sum_{t=1}^{n_t} \lambda_t \cdot Pda_t + \lambda_f \cdot SOC_{n_t} \tag{3}$$

Constraints:

$$Ppv_t - D_t + \sum_{j=1}^{n_j} Pd_{j,t} - \sum_{k=1}^{n_k} Pch_{k,t} = Pda_t \tag{4}$$

$$SOC_t = SOC_{t-1} - Qd_t + Qch_t \quad \text{for } t\neq 1 \tag{5}$$

$$SOC_t = SOC_{start} - Qd_t + Qch_t \quad \text{for } t=1 \tag{6}$$

Variable limitations:

$$0 \le Pd_{j,t} \le Pd_{\max j} \tag{7}$$

$$0 \le Pch_{k,t} \le Pch_{\max k} \tag{8}$$

$$SOC_{\min} \le SOC_t \le SOC_{\max} \tag{9}$$

where:

n_t	- number of hours in observed simulation
λ_t	- expected electricity price on day-ahead market in hour t
λ_f	- expected future electricity price
Pda_t	- market bid on day-ahead market in hour t
SOC_{nt}	- state of charge of the battery storage at the end of observed period
Ppv_t	- expected electricity generation in PVs in hour t
D_t	- expected electricity consumption in households in hour t
SOC_t	- state of charge of the battery storage at the end of hour t
SOC_{start}	- state of charge of the battery storage at the beginning of the observed period
$Pd_{max\ j}$	- maximal discharging power in discharging segment j
$Pch_{max\ k}$	- maximal charging power in charging segment k
SOC_{min}	- lower limit of stored electricity in battery storage
SOC_{max}	- upper limit of stored electricity in battery storage

B. *Optimization technique applied in the proposed model*

Methods of mathematical optimization can find solutions to the various problems that require minimum or maximum value of the objective function fulfilling the given constraints.

Proposed model is presented as the optimization problem of finding maximum profit solved by linear programming (LP). In order to take into account the uncertainty of expected prices on the market day ahead, a stochastic price modeling is used. Model is written in computer code programming language MATLAB, where the LP problem is solved using solver-based approach.

III. CASE STUDY

A. *Model description*

The case study is made on supposed power system based on the 700 households each obtaining PV power plant rated power of 10 kW. These 700 prosumers are represented by one virtual prosumer participating in the day-ahead market. Virtual prosumer has available battery storage rated capacity of 50 MWh. To extend the life of the battery, it is not fully discharged, and a minimum of 5 MWh is set. Maximal charging and discharging power is 7 MW. Charging and discharging characteristics are divide in three segments size of 0.5, 0.3, 0.2 of the maximal charging and discharging power. It is assumed that efficiency is equal for charging and discharging process and for the first, second and third segment amounts 0.95, 0.92, 0.88, respectively.

B. *Simulation scenario*

It is assumed that virtual prosumer is participating on a CROPEX day-ahead market for Thursday, May 21st, 2020. Expected total consumption of 700 households for observed day is presented in Fig. 2. Expected total generation of PVs that are owned by each household for observed day is presented in Fig. 3.

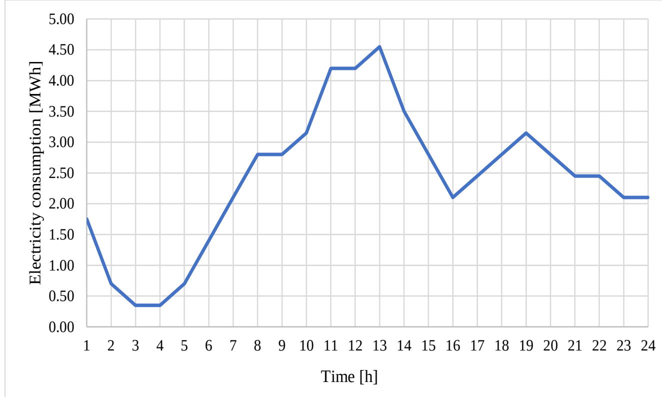

Fig. 2. Expected total consumption of 700 households for observed day

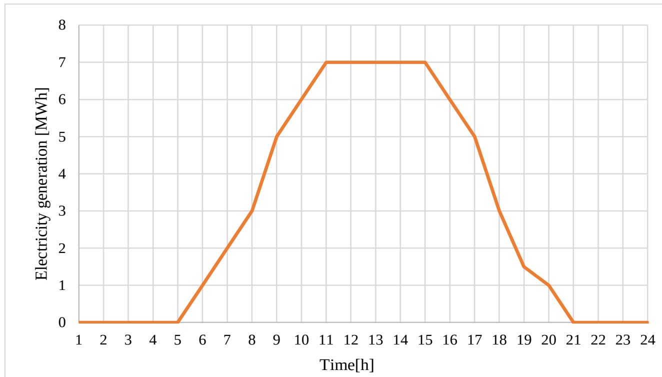

Fig. 3. Expected total generation of PVs for observed day

In order to make a plan as precise as possible, electricity prices are observed on day-ahead market on CROPEX for every hour of five specific days: last three working days (May 20th, May 19th, May 18th) and two Thursdays before observe day (May 14th, May 7th). Two Thursdays in a row are chosen to determine whether the consumption implies specific pattern that could lead to big mismatch in production planning. Fig. 4 shows electricity prices for these five days.

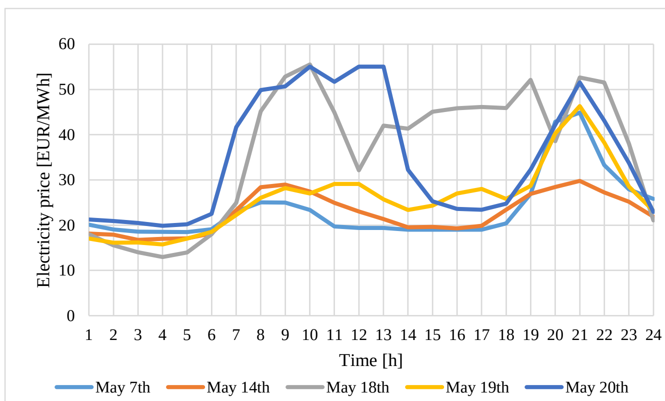

Fig. 4. Electricity prices in CROPEX day-ahead market

Five observed days makes five possible scenarios with associated probability. Table 1 shows assumed scenario probabilities for each day.

TABLE I. SCENARIOS OF ELECTRICITY PRICES WITH ASSOCIATED PROBABILITIES

	May 20th	**May 19th**	**May 18th**	**May 14th**	**May 7th**
Scenario probability	0.45	0.25	0.15	0.1	0.05

Expected electricity prices for May 21st are calculated according to five observed days with associated possibilities and presented in Fig. 5. Day with highest probability will have the most influence in expected electricity prices.

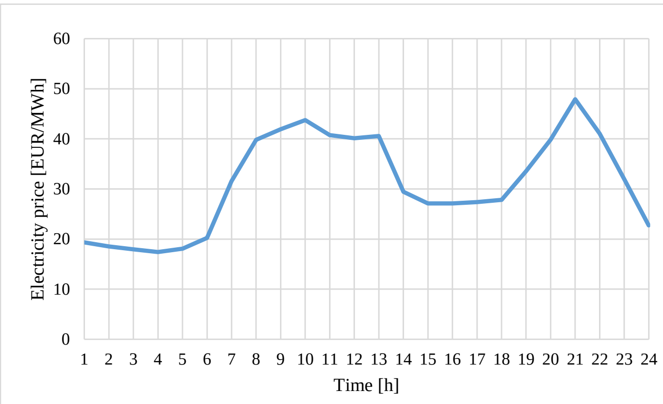

Fig. 5. Expected electricity prices for May 21st

The state of charge of the battery storage at the beginning of the observed period amounts 20% of the maximal battery storage capacity, i.e. 10 MWh. It assumed that expected future price at which stored energy will be sold is 30 EUR/MWh.

Production from the PVs are used to cover the own consumption. Energy surplus will be used for charging the battery or will be sold on the CROPEX. In hours where there is a lack of energy, battery storage will be discharged, or energy will be purchased from the CROPEX. The optimization model will give the optimal plan of battery storage utilization and the optimal bid on day-ahead market will be obtained.

C. *Results*

Optimal battery storage utilization for each hour is obtain. In Fig. 6 and Fig. 7 charging and discharging plan for observed battery storage are presented, respectively. These diagrams show the charging or discharging power of each charging/discharging segment in each hour of the observed day. Fig. 8 shows the state of charge of observed battery storage.

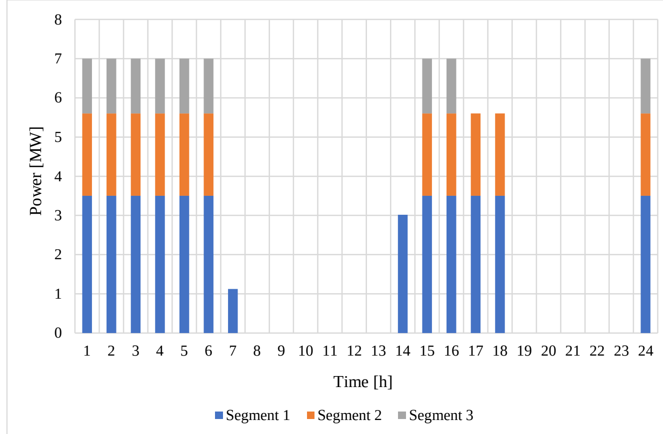

Fig. 6. Charging plan for the observed battery storage

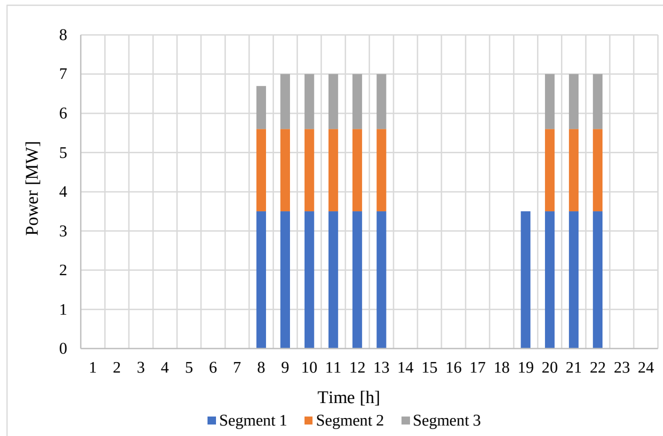

Fig. 7. Discharging plan for the observed battery storage

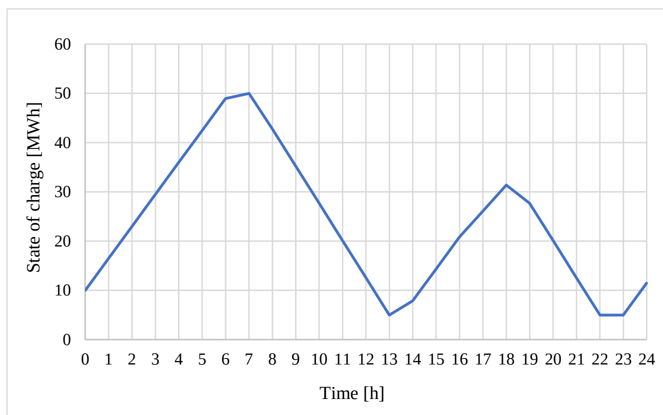

Fig. 8. State of charge of the observed battery storage

As can be seen in Fig. 6-8, battery storage is being charged in in hours 1-7, 14-18 and in hour 24. State of charge reaches maximum capacity of the battery storage at the end of 7th hour. Battery storage is being discharged in hours 8-13 and 19-22. Battery storage is discharged to the minimum value at the end of hours 13 and 22. The market bid for the observed virtual prosumer is presented in Fig. 9.

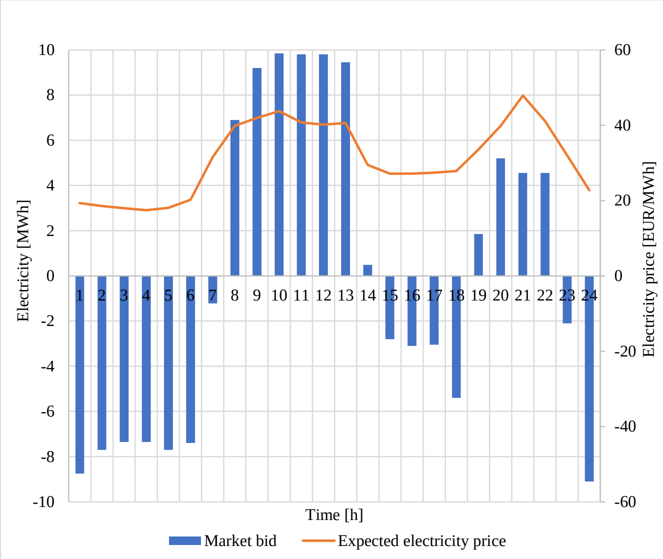

Fig. 9. Market bid on the CROPEX day-ahead market

As can be seen, the virtual prosumer sets buying bids in hours 1-7, 15-18 and 23-24. Selling bids are placed for hours 8-14 and 19-22. In Fig. 10, comparison of the profit in each hour on the CROPEX day-ahead market with or without battery storage is presented. In a scenario without battery storage, market bids only depend on the difference of the power generated from PVs and household power consumption in each hour.

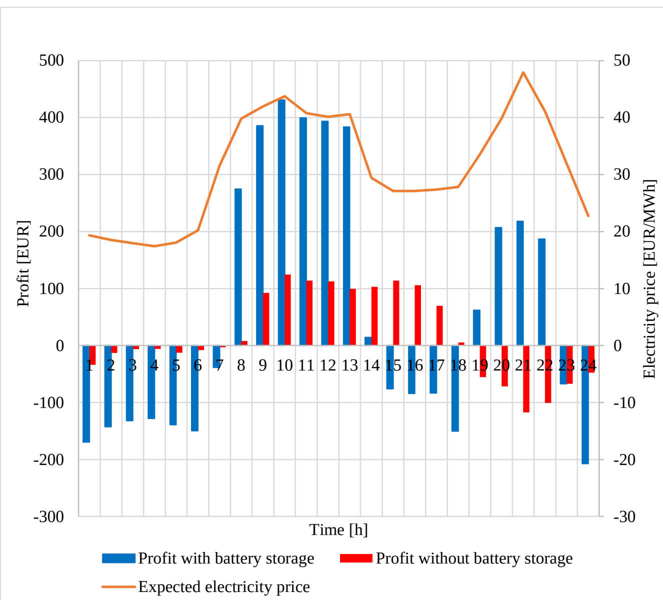

Fig. 10. Expected profit in each hour on the CROPEX market

Cumulative profit of the virtual prosumer with and without battery storage is shown in Fig. 11. In case when the virtual prosumer does not own the battery storage, the expected profit for the observed day is 405.9 EUR. Total expected virtual prosumer profit for the observed day in the case with battery storage is 1388.7 EUR, which shows the benefit of the battery storage in the amount of 982.8 EUR for the observed day.

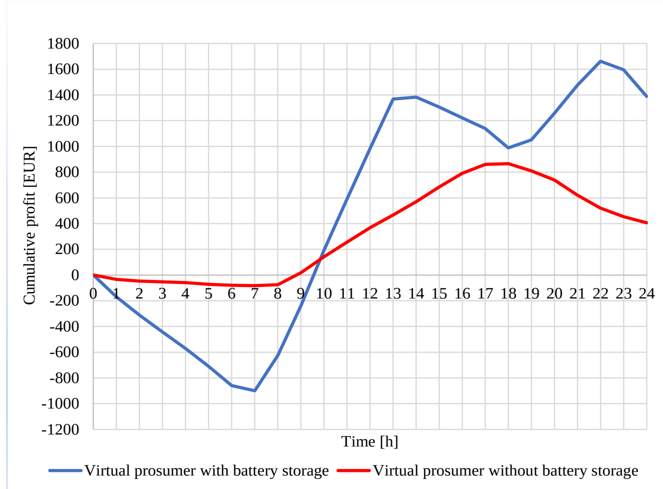

Fig. 11. Comparison of the cumulative profit with and without battery storage

IV. Conclusion and Further Work

This paper presents optimization model for virtual prosumer biding on day-ahead market taking into consideration battery storage utilization. Virtual prosumer represents a group of prosumers on the market. In order to show possibility of making efficient short-term plan, model is applied to the case study. The results show a significant benefit in virtual prosumer profit in the case when it involves battery storage unlike the case when the prosumer does not have the battery storage available. The future work can be addressed on stochastic nature of input data such PV generation and household consumption. Furthermore, bidding on intraday market could be taken into consideration.

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References

[1] International Energy Agency (IEA), *World Energy Outlook 2019 – Analysis - IEA*. 2019.

[2] EUROPEAN COMMISION, *COM(2011) 112 - A Roadmap for moving to a competitive low carbon economy in 2050 — European Environment Agency*. 2011.

[3] Ministarstvo graditeljstva i prostornoga uređenja RH, "Tehnički propis o racionalnoj uporabi energije i toplinskoj zaštiti u zgradama," 2015.

[4] J. M. Zepter, A. Lüth, P. Crespo del Granado, and R. Egging, "Prosumer integration in wholesale electricity markets: Synergies of peer-to-peer trade and residential storage," *Energy Build.*, vol. 184, pp. 163–176, Feb. 2019.

[5] J. P. Iria, F. J. Soares, and M. A. Matos, "Trading small prosumers flexibility in the day-ahead energy market," in *IEEE Power and Energy Society General Meeting*, 2018, vol. 2018-January, pp. 1–5.

[6] G. Knežević, D. Topić, M. Jurić, and S. Nikolovski, "Joint market bid

of a hydroelectric system and wind parks," *Comput. Electr. Eng.*, vol. 74, pp. 138–148, Mar. 2019.

[7] C. Agathokleous, L. A. Tuan, and D. Steen, "Stochastic operation scheduling model for a Swedish prosumer with PV and BESS in Nordic day-ahead electricity market," in *2019 IEEE Milan PowerTech, PowerTech 2019*, 2019.

[8] M. Lotfi, C. Monteiro, M. S. Javadi, M. Shafie-Khah, and J. P. S. Catalao, "Optimal Prosumer Scheduling in Transactive Energy Networks Based on Energy Value Signals," in *SEST 2019 - 2nd International Conference on Smart Energy Systems and Technologies*, 2019.

[9] S. Ramyar, A. L. Liu, and Y. Chen, "A Power Market Model in Presence of Strategic Prosumers," *IEEE Trans. Power Syst.*, pp. 1–1, Aug. 2019.

[10] J. Iria and F. Soares, "Real-time provision of multiple electricity market products by an aggregator of prosumers," *Appl. Energy*, vol. 255, p. 113792, Dec. 2019.

[11] J. Iria, F. Soares, and M. Matos, "Optimal bidding strategy for an aggregator of prosumers in energy and secondary reserve markets," *Appl. Energy*, vol. 238, pp. 1361–1372, Mar. 2019.

[12] "Croatian Power Exchange CROPEX." [Online]. Available: https://www.cropex.hr. [Accessed: 22-May-2020].