Techno-economic impact of solar power system integration on a DSO

Nelli Nigmatulina
Aleksei Mashlakov
LUT University
Lappeenranta, Finland
nelli.nigmatulina@lut.fi

Nadezda Belonogova
Samuli Honkapuro
LUT University
Lappeenranta, Finland

***Abstract*—The drastic cost decrease of the photovoltaic (PV) panels leads to their high penetration in the distribution grid. However, it may result in a revenue decrease for the distribution system operator (DSO) and cause a number of technical issues. The focus of the paper is to analyze the techno-economic impact of different scenarios of PV panels integration under different penetration levels behind the secondary substation. The study is based on a real data provided by the local DSO. The results suggest that the peak demand may increase drastically due to simultaneous charging of the batteries from the market. The comparison of two scenarios of the PV+BESS system operation showed that focus at peak reduction is profitable for the bigger share of customers, than focus at increase of the self-consumption rate.**

***Index Terms*—Battery Energy Storage System (BESS), Distribution System Operator (DSO), Photovoltaics (PV), power-based tariff**

I. Introduction

The distribution of small-scale energy generation transforms the traditional structure of the electric grid and turns it into a decentralized one. According to the statistics by the end of 2018, the worldwide cumulative installed capacity of grid-connected photovoltaic (PV) panels totaled 480 GW [1]. However, the high penetration of the PV panels decreases the cost-reflectivity of the energy-based tariff and its capability to cover the cost of network service. One of the solutions is the introduction of a power-based tariff (PBT), which includes monthly charges for the peak power demand of the customer. In light of these events, the coupling of PV panels and the behind-the-meter (BTM) battery energy storage (BESS) draw the researchers' attention. The recent report [2] highlights the benefits of BTM energy storages for both the prosumer and the system operator. The flattening of the prosumer's load curve and a reduction in the peak demand defer the network reinforcement and decrease the need for investments in peaking plants. In [3], the authors studied the impact of various penetration levels of PV and PV+BESS systems on the distribution grid (DG) operation, namely the power losses and the voltage profile, among others. The authors noted the positive impact of the BESSs on the reduction of peak demand on the feeder. However, the authors of [4] argued that the cost-reflectivity of the PBT may decrease as a result of the use of BESSs for peak reduction. The contradictory opinions and the lack of a techno-economic analysis of load profiles in different grid points create a fertile ground for the research.

The objective of the paper is to evaluate different scenarios of PV panel penetration rates from a technical viewpoint for the Distribution System Operator (DSO) and an economic viewpoint for the customer. Within the study, two integration scenarios were considered: the PV panels only and the combination of PV panels with a battery energy storage system (BESS). The penetration level is calculated based on the number of customers behind the secondary substation. The analysis of the energy consumption profiles was conducted at the level of a single customer, secondary and primary substations.

The paper is structured as follows. The Methodology section consists of three subsections describing the operational scenarios of the PV panels, the methodology of selecting the PV panels and BESS capacities, and the limitations and assumptions of the study. In section III, the results of the technical and economic analyses are presented. The technical analysis includes the study of annual and monthly peak demand. Finally, conclusions are drawn in section IV.

II. Methodology

A. Operational scenarios of PV panels

The study is based on real data provided by a local DSO. The data includes the information about the distribution grid and the load curves of approx. 15000 customers. The grid is located in rural and urban areas in the Helsinki region in Finland. The customers are connected to 985 secondary substations supplied by five primary substations.

The study assumes two operational scenarios of the PV panels: the PV panels only and the panels connected to the BESS. Their operation was considered in two strategies: a peak reduction and an increase in the self-consumption rate (SCR). The BESS charges either from the PV panel's excess energy or from the market. Within the analysis, the customers were provided with the power band (PB) in both strategies of BESS operation. The PB is a value of capacity that the customer intends not to exceed. Fig. 1 describes the process of PB determination. In the peak reduction strategy, the PB was determined as a difference between the monthly maximum

978-1-7281-6919-4/20/$31.00©2020 IEEE

consumption and the capacity of the BESS. In the self-consumption strategy, the power band was defined as monthly values of the peak power demand of the customer's profile according to the peak reduction strategy.

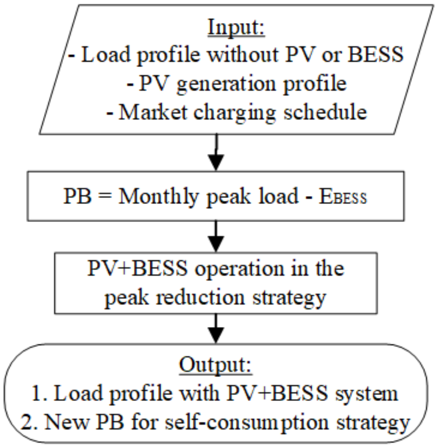

Figure 1: Determination of the power band for BESS operational strategies

Fig. 2 illustrates the schematic of the BESS operation in the peak reduction strategy. During the day the microcontroller of the battery checks the consumption of the customer and compares it with the PB. The BESS supplies the energy to the customer if the consumption is beyond the PB. The discharge power is defined as the difference between the PB and the current energy consumption. If the battery's SOC is less than 50%, the discharge power is reduced by half. In addition, the microcontroller checks the market charging schedule or the availability of solar energy surplus. Charging from the market occurs only if the current consumption of the customer is below the PB. The charging power is defined as a difference between the PB and the current consumption of the customer. The same operational principle holds for the self-consumption strategy. The only exception is that the microcontroller does not check the power band during the day. The BESS supplies the energy to the customer when it has capacity available.

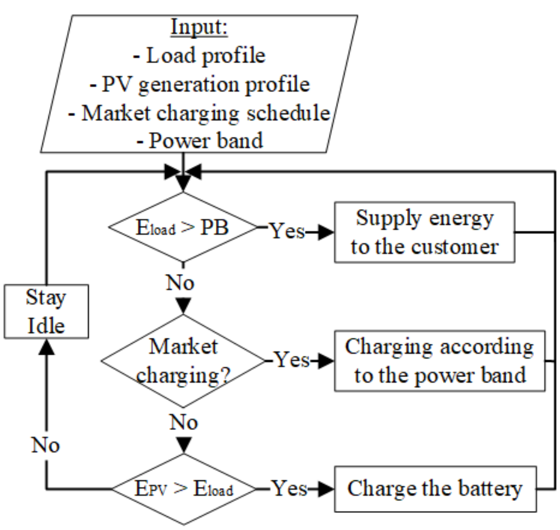

Figure 2: Operation of the BESS in the peak reduction strategy

The time of charging from the market was based on the analysis of the network tariff structure and the day-ahead price. The DSO has fixed hours of day and night tariff components. The night component is cheaper than the daytime. The analysis of the day-ahead market demonstrated that for most of the time, the lowest prices in the market are at night. However, for some days, the price was the lowest in the daytime. In such a case, the benefit of charging may not outweigh the payment for the supply of energy. Therefore, the charging of the batteries was carried out in the nighttime. Moreover, many studies have shown that energy arbitrage in the day-ahead market does not generate profit for the customer [5], [6]. Further, two time periods were selected at night: short (from 11 p.m. to 4 a.m.) and long (from 11 p.m. to 7 a.m.). Each day one of the periods was picked based on solar energy surplus at this day. The BESS charges short period, if the surplus energy is enough to charge the BESS during the daytime. Otherwise, the long period is selected.

The analysis of the secondary and primary substation profiles started with the distribution of the PV panels alone. The penetration level was increased based on the number of customers behind the secondary substation. The authors of the paper considered four levels: 25%, 50%, 75%, and 100%. In pursuit of the worst-case situation, the distribution started from the customers with the highest energy consumption to the lowest. Then, the PV panels were supplemented with BESSs. The load profile with different scenarios of the PV panels integration was analyzed from the technical and economic perspectives. The focus of the technical analysis was to evaluate the development of the annual and monthly peak demand in different grid points. The change in the monthly peak was examined in the examples of one customer and one primary and secondary substation. The annual peak demand change was analysed for all the customers and substations. The economic analysis addressed the expenses of the customers with PV panels and a BESS. The energy cost of the customer consists of three payments: the bill from the energy supplier, the distribution system operator, and the operational cost of the BESS. In the paper, the bill from the energy supplier is based on the spot price from the day-ahead market. The cost of the network service was calculated with a power-based tariff, provided by the local DSO [7]. It includes a monthly fee, a peak power component, and daytime and nighttime components. The basis for the power component was determined as a monthly maximum load of the customer. The electricity cost of the scenario with the PV panels only was applied as a reference cost.

B. Dimensioning of the PV panel and BESS capacities

In the study, the customers were granted PV panels and a BESS. The installed capacity of the PV panels was determined by a regression model. The model was built by applying data provided by the DSO about the customers with PV panels. The data includes the installed capacities of the PV panels and the customers load profiles. The energy generation profiles of the PV panels were determined by applying an open-source database Renewables.ninja [8], [9].

C. Limitations and assumptions

In the study, a number of assumptions were applied:

- The tilt angle of the assigned PV panels is 39° [10]
- The energy capacity of the BESS is equal to the installed capacity of the PV system [11]
- The payment for the supply of energy surplus to the grid was not addressed
- The cost of the PV panels was not considered in the final cost analysis
- The PV+BESS system follows one operational strategy behind the secondary substation
- The price of a BESS unit is 600 €/kWh with cycle life of 3200 cycles; the round trip efficiency is 0.9 [2]

The study follows the worst-case scenario, in which the PV panels have the same generation profiles. Besides, it is assumed that the PV panels are already installed, and the main objective is to address the cost of BESS operation. In addition, the range of hours of BESS charging from the market is the same for all the customers. Such an assumption may result in the simultaneous start of BESS charging.

III. Overview of results

A. Technical analysis

1) Single customer

The study of the single customer started from the analysis of the monthly peak demand of one arbitrarily selected customer. The customer belongs to the group of residential consumers and was provided with the PV panels of 5 kWp and a BESS of 5 kWh. Fig. 3 illustrates that the PV panels alone are not capable of decreasing the peak demand of the customer. The hours of high power demand do not match the hours of high energy production. However, the dynamics changes with the connection of the BESS to the PV panels. According to the results, the highest reduction in the peak power can be achieved by the PV+BESS system operating according to the peak reduction strategy. However, the reduction occurs only in months of high solar irradiance. The selected size of the BESS is insufficient for the reduction in peak demand with only one charging cycle per day. Therefore, the capacity of the BESS should be selected depending on the desirable reduction of peak demand, i.e., the power band.

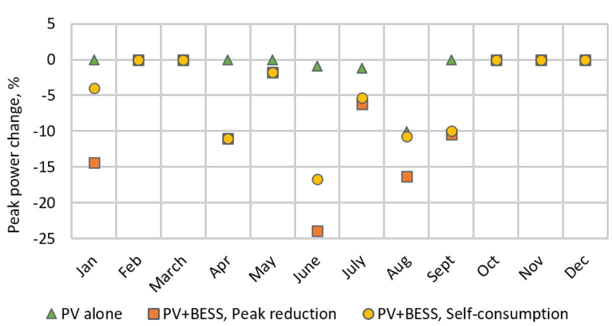

Figure 3: Peak power change, a single customer

The analysis of the SCR showed that the SCR of the PV panels alone was equal to 57%. However, the purchase of the BESS improved this value to 61% for the peak reduction strategy and to 67% for the self-consumption strategy. Further, the annual peak demand change and the SCR were analyzed in different scenarios for all the customers (Table I). As it can be seen, the focus at peak reduction reduces the annual peak demand for a larger share of customers than any other strategy under study. The connection of BESS to the PV panels increases the reduction of the peak demand at least in two times. However, it is necessary to examine the profitability of the PV+BESS operation.

Table I: The analysis of mean self-consumption rate and annual peak demand change

	PV only	PV+BESS, SCR increase	PV+BESS, peak reduction
SCR, %	42	50	47
Peak reduction, %	3.55	7	14
Unchanged peak, share of customers,%	60	40	20

2) Secondary substation level

First, the energy profile and monthly peak demand were analyzed for one of the secondary substations. The selected substation has 15 customers, 14 of which are residential and one is an industrial customer. The total energy consumption of the industrial customer is the lowest. Fig. 4 below illustrates that the increasing penetration level of the PV panels leads to the problem of the ”duck curve”. The energy consumption decreases during the hours of solar energy generation and increases with the sunset. In general, in such case the dispatchable generation has to ramp up and down several times per day, resulting in high operational cost of the power plant. Moreover, the design of such power plants may have limited load-following capability. The connection of the BESS to the PV panels facilitates the curtailment of the surplus PV energy and an increase in SCR.

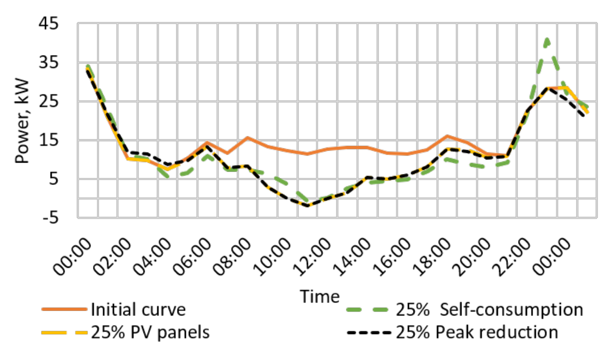

Figure 4: Example of the energy flow within a day at a secondary substation

Next, an analysis of the monthly peak power demand was conducted. As in the example of the single customer, the distribution of the PV panels did not affect the monthly peak demand due to the majority of residential customers. The analysis of BESS operation in the peak reduction strategy showed the most significant reduction in the peak power demand during the months of high solar energy generation (Fig. 5). Moreover, the increase in the penetration level boosts the peak reduction. With the 25% penetration level, the peak demand may increase slightly in some months. However, further penetration only mitigates the first peak.

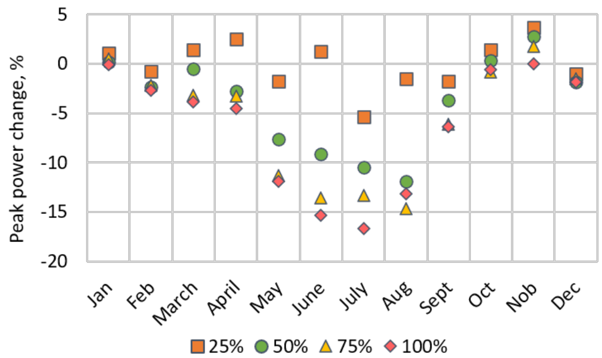

Figure 5: Monthly peak demand change in the peak reduction strategy of the PV+BESS system; the secondary substation

The results of the self-consumption strategy illustrate the drastic increase in the peak power demand with an increase in the penetration level within a year. The peak demand increases first by an average of 18% with the 25% penetration and reaches a 44% growth with the 100% penetration. The main cause of such dynamics is the simultaneous charging of the batteries at 11 p.m. By this time the batteries have supplied the previously stored solar energy and are ready to charge. The applied charging strategy demonstrates the worst-case operational scenario. In addition, the selected strategies of BESS operation have different PBs. The power band value in the self-consumption strategy is greater than in the peak reduction strategy, which results in a higher volume of supplied energy.

The dynamics of the annual peak demand change was analyzed on a set of 985 secondary substations (Fig. 6). In the peak reduction strategy, the mean decrease in the peak steadily grows from 2.3% for the 25% penetration level to 4.7% for the 75% penetration level. After the 75% penetration, the peak reduction stays the same. The annual peak demand is not affected by the distribution of the PV+BESS systems among customers with a low energy consumption.

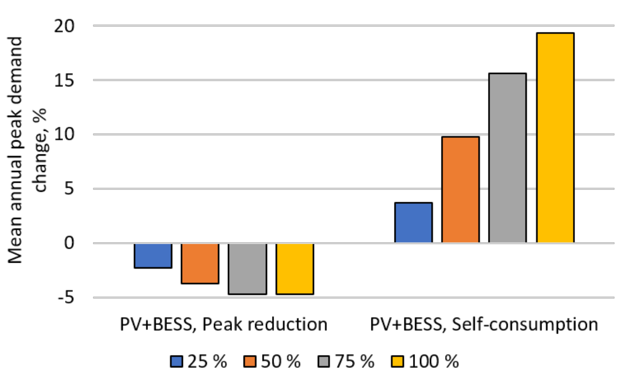

Figure 6: Annual peak demand change in the PV+BESS operational strategies; the secondary substation

In the self-consumption strategy, the analysis showed a growth in the annual peak demand with a penetration level increase. The 25% penetration level increases the annual peak demand by 3.74% on average. With the 100% penetration level, the peak demand increases fivefold. These results concurred with the previous findings in the example of one single secondary substation. Thus, it is preferable that the third party (e.g., aggregator) controls the charging of the batteries to prevent the increase of the peak demand.

3) Primary substation level

One of the primary substations was selected to examine the change in the monthly peak demand. The examined substation supplies 315 secondary substations. The results of the PV-panels-only scenario depict the same dynamics as at the level of a secondary substation: the reduction in the energy demand during the time of high PV generation and unaltered monthly peak demand values. The analysis of the PV+BESS scenario for the peak reduction showed that for most of the months, the monthly peak demand increases with the 25% penetration level (Fig. 7). However, the further dynamics varies in the months of high and low solar irradiance. In months of low PV generation, a further penetration level only increases the peak demand. However, in the month of high solar irradiance, the values of peak power demand decline. The reason for such behavior is the small size of the batteries for the vast majority of the customers. The units are not capable of reducing the peak with one charging cycle. Ultimately, it proves the above hypothesis that the size of the BESS has to be chosen according to the desired peak reduction.

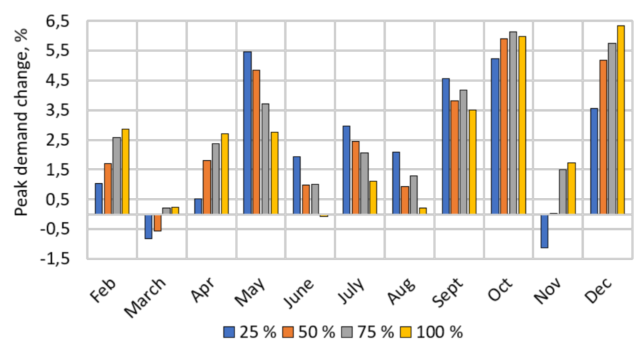

Figure 7: Monthly peak demand change in the peak reduction strategy of the PV+BESS system; the primary substation

The results of the self-consumption strategy demonstrate that the primary substation is affected by an increase in the penetration level even more than the secondary substation. The simultaneous start of charging the BESSs significantly increases the peak power demand at the primary substation level, up to 32%. With the 100% penetration level this value increases twofold.

Further, the mean value of the change in the peak demand was analyzed for all the primary substations. Fig. 8 depicts the increase in the peak demand with a rise in the penetration level for both strategies of the PV+BESS system. In the self-consumption strategy, the peak consumption increases by 13%

only with the 25% penetration level. The growth is even higher than at the secondary substation level. With the 100% penetration level, the peak demand increases to 45%. In the peak reduction strategy, the peak consumption increases slightly. This dynamics also differs from the secondary substation level.

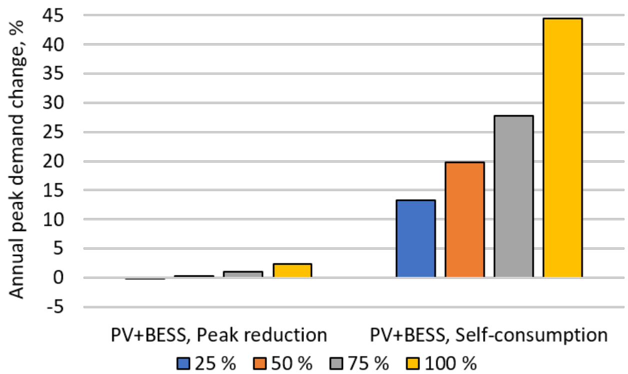

Figure 8: Annual peak demand change in the PV+BESS operational strategies; the primary substation

At the primary substation level, the peak consumption increases as a result of the simultaneous start of the BESS charging. In the peak reduction strategy, the increase is less than 5% with the 100% penetration level. However, the operation of the PV+BESS system for self-consumption shows two times as high growth in the peak consumption as for the secondary substations.

B. Economic analysis

First, the detailed review of expenses was conducted for one arbitrarily selected customer. As shown in Fig. 9, the customer does not benefit from the PV+BESS system for any of the applied strategies because of the operational cost of the BESS. The bill from the DSO does not differ very much between the scenarios. Focusing on an increase in the SCR brings more savings than the peak reduction strategy. However, the active operation of the BESS implies its high operational cost. Thus, with the assumed cost of the BESS, this strategy is not advantageous for this specific customer.

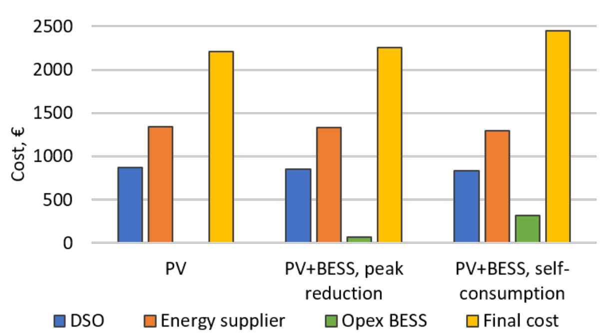

Figure 9: Analysis of one single customer expenses

Next, the energy bills of all customers were examined. With the applied inputs, the operation of the BESS under the peak reduction strategy is beneficial for a larger share of customers than the self-consumption strategy (Fig. 10). The further decline in the BESS costs will decrease their operational cost and increase the share of customers benefiting from the BESS.

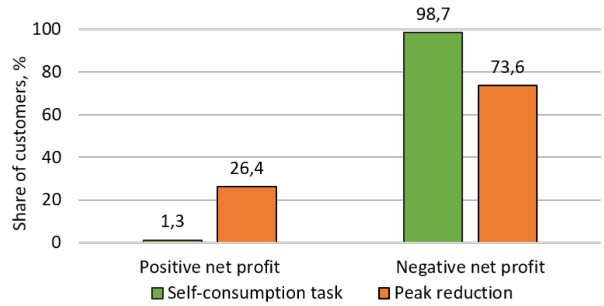

Figure 10: Analysis of customers' profits in the PV+BESS system operational strategies

Ultimately, the DSO revenue streams will decrease with a wide distribution of the PV+BESS systems, especially if the customers follow the peak reduction strategy and keep their consumption within the predefined PBs. However, it may not guarantee a decrease in the peak demand at the level of secondary or primary substations. Therefore, the tariff structure and component prices may not reflect the operational cost of the network service. Thus, further studies on the network service cost for the DSO are required.

IV. Conclusion

The main objective of the current study was to assess the techno-economic impact of different PV panel penetration rates in various scenarios and grid points. The results showed that the PV panels alone do not impact the annual peak demand at any grid point. However, the picture changes with the connection of a BESS to the PV panels. The peak demand decreases at the level of a single customer and a secondary substation if the PV+BESS system is focused on the reduction of peak demand. However, it may increase at the level of a primary substation. The peak consumption increases significantly in all grid points if the PV+BESS systems aim at an increase in the SCR, which happens as a result of the simultaneous BESS charging. Therefore, the BESS charging should be managed and controlled either by the aggregator or the DSO. One of the most significant findings of this study is that it is profitable to use the PV+BESS system for the peak reduction scenario for 26% of the customers out of the total of 15000. Taking into account the results of the technical analysis, the operation and maintenance of the distribution grid may not be covered because of the reduction in the revenue streams from the customers. The current study only examined the profitability at the level of a single customer. However, a further economic analysis must be conducted to assess the network operation and reinforcement costs of every scenario.

References

[1] IRENA, "Future of Solar Photovoltaic: Deployment, investment, technology, grid integration and socio-economic aspects," Abu Dhabi, 2019.

[2] IRENA, "Electricity storage valuation framework. assessing system value and ensuring project viability," Abu Dhabi, 2020.

[3] T. M. Blasi, T. S. P. Fernandes, D. N. Gevers, A. R. A. andPatrício R. Impinnisi, C. L. da S. Pinto, and P. M. R. da V. Damasceno, "Evaluation of the impacts of renewables sources and battery systems in distribution feeders with different penetration levels," in *2019 IEEE PES Innovative Smart Grid Technologies Conference - Latin America (ISGT Latin America)*, Gramado, Brazil, Brazil, 2019.

[4] I. S. F. Gomes, Y. Perez, and E. Suomalainen, "Coupling small batteries and PV generation: A review," *Renewable and Sustainable Energy Reviews*, vol. 126, July 2020.

[5] M. U. Hashmi, A. Mukhopadhyay, A. Bušić, and J. Elias, "Optimal control of storage under time varying electricity prices," in *2017 IEEE International Conference on Smart Grid Communications (SmartGrid-Comm)*, Dresden, Germany, 2017.

[6] B. Zakeri and S. Syri, "Value of energy storage in the nordic power market - benefits from price arbitrage and ancillary services," in *2016 13th International Conference on the European Energy Market (EEM)*, Porto, Portugal, 2016.

[7] L. E. Oy, "Verkkopalveluhinnasto," Available at https://www.lahtienergia.fi/fi/sahkoverkko/hinnastot-sopimusehdot/verkkopalveluhinnasto.

[8] I. Staffell and S. Pfenninger, "Using bias-corrected reanalysis to simulate current and future wind power output," *Energy*, vol. 114, pp. 1224–1239, November 2016.

[9] I. Staffell and S. Pfenninger, "Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data," *Energy*, vol. 114, pp. 1251–1265, November 2016.

[10] M. Z. Jacobson and V. Jadhav, "World estimates of PV optimal tilt angles and ratios of sunlight incident upon tilted and tracked PV panels relative to horizontal panels," *Solar Energy*, vol. 169, pp. 55–66, 2018.

[11] R. Luthander, J. Widen, J. Munkhammar, and D. Lingfors, "Self-consumption enhancement and peak shaving of residential photovoltaics using storage and curtailment," *Energy*, vol. 112, pp. 221–231, October 2016.