CIRED 2020 Berlin Workshop (CIRED 2020)

22-23 September 2020

Theme 1: Integrating New Flexibility Tools and Principles for Planning

Peak-shaving potential of residential battery energy storage systems under power-based tariff pricing

ISSN 2515-0855
doi: 10.1049/oap-cired.2021.0329
www.ietdl.org

Nelli Nigmatulina ✉, *Nadezda Belonogova*, *Gonçalo Mendes*, *Samuli Honkapuro*

LUT School of Energy Systems, LUT University, Yliopistonkatu 34, 53850, Lappeenranta, Finland
✉ *E-mail: nelli.nigmatulina@lut.fi*

Abstract: This study analyses the flexibility potential of residential battery energy storage systems (BESSs) employed for the peak-shaving task under a power-based tariff and connected to the photovoltaic (PV) panels. The current study adds to understanding the role of BESS in the planning and operation of a decentralised electricity grid and the capability of batteries to work at wholesale or ancillary markets. The analysis is carried out for various optional values of subscribed capacities and compares the cost savings associated with each option. Several capacity subscription values are made available by Finnish distribution system operators, and one is proposed by the authors. Based on the analyses, it is cost-effective to use PV panels with BESSs for reducing energy purchases and peak powers. The flexibility assessment shows significant potential for the use of batteries for the markets or ancillary services, thereby increasing the cost-effectiveness of the battery use and supporting the resilient grid operation.

1 Introduction

The introduction of the power-based tariff to the market creates incentives for customers to change their energy consumption behaviour and thereby optimise their electricity expenses. The tariff structure consists of three components, namely an energy component, a power component and a monthly fee [1]. The customer can affect two of them by reducing energy consumption and peak powers. The photovoltaic (PV) panels are among the options to decrease the volume of energy supplied by the distribution system operator (DSO). Moreover, the falling price of the PV panels facilitates their wide distribution among customers. However, the hours of solar energy generation mismatch the time of high power demand. Most of the time, the measured peak power values are used as the basis for the power component of the tariff. Therefore, the profitability of an installed solar energy system is decreasing. The issue can be resolved using, for instance, battery energy storage systems (BESSs), especially if the peak power is not shiftable. Honkapuro *et al.* [1] highlighted the importance of using a BESS in combination with PV panels as demand-side management and business opportunity for other markets. Thus, the combination of PV panels and BESSs creates a fertile ground for optimisation of the electricity expenses under the power tariff. Moreover, in the case of a high battery flexibility potential, it enables to attract additional revenue flows from the markets or ancillary services.

The objective of this paper was to analyse the peak-shaving potential of the BESSs with several variants of subscribed capacities of the power-based tariff and to evaluate the flexibility potential of the BESSs. The paper considers four values of capacity, three of which are suggested by the Finnish DSO, and the last one proposed by the authors.

The paper is structured as follows: the 'Methodology' section is divided into four sub-sections presenting (i) the power-based tariff, its structure, and the proposed values for the analysis; (ii) a case study; (iii) the limitations and assumptions applied in the analysis and (iv) an overview of the algorithm. The 'Results' section consists of two parts presenting the technical and economic analysis of the simulations conducted in the study. Conclusions are drawn in the final section.

2 Methodology

The present business strategies of DSOs are disrupted by the increasing penetration rate of distributed energy resources and energy-efficient appliances. The volume of supplied energy decreases, and energy consumption becomes less predictive. This leads to a reduction in revenue flows from the customers, compromising the cost-reflectiveness of the present tariffs. As a response to it, the DSOs require new tariff structures corresponding to the changing environment of grid operation.

2.1 Power-based tariff

Recently, several Finnish DSOs have launched power-based tariffs for small-scale customers. The tariff comprises energy and power components, and a monthly fee. The basis of the power charge is determined differently by every DSO. It can be either the maximum value of peak power for the last 12 months, the maximum peak power in a month, or the third-highest value of peak power in a month. In the study, real prices of the DSOs are applied (Table 1). As a reference, the cost of energy consumption was calculated applying a time-of-use (ToU) tariff. Both tariffs are characterised by different energy fees during the day (from 7:00 to 22:00) and night (from 22:00 to 7:00) hours.

Throughout the paper, the term 'power band' (PB) is used. The term is applied to describe the limit of subscribed power that the customer plans not to exceed. If the limit is exceeded, the DSO levies an additional power payment on the customer.

In this paper, the PBs were determined beforehand based on the load profiles and scenario rules as a year-long or a month-long band. The principal advantage of this is encouraging the customers to reduce their monthly peak capacities for a certain proportion. The PBs are defined using the data for 2017; the test year is 2018. In the present paper, four variants are analysed:

(i) *YearPB*. Annual peak power demand.
(ii) *MonthPB*. Peak power demand of every month.
(iii) *70PB*. 70% of the peak power demand of every month.
(iv) *ThirdPB*. Third-highest power demand of every month.

Table 1 Tariff fees [2, 3]

Tariff component	Power tariff	ToU tariff
day energy fee, c/kWh	2.59	4.82
night energy fee, c/kWh	1.35	2.05
power fee, €/kW	1.59	—
monthly fee, €/month	17.5	13.02

In the Discussion section, the peak shaving potential, flexibility potential and the operational cost of the batteries will be analysed for all PBs.

2.2 Data set overview

The study is based on the data of a Finnish DSO operating in a rural area. The information includes the automatic meter reading (AMR) data for 15,000 customers with an hourly resolution, installed capacity of the PV panels for 150 customers, and solar energy generation curves since the installation of the panels. In the study, AMR data of ~650 residential customers were gathered and analysed. The selection was based on the following criteria: location in the rural area, type of customer, the connection of customers to different secondary substations, and the highest energy consumption among the customers connected to a substation. The analysis of the load profile at the level of secondary substations is outside the scope of this paper.

Next, the PV panels and BESS were assigned to every customer. The installed capacities of the PV panels were determined by a linear regression model. The model is based on information about the installed capacity of the PV panels and the mean daily electricity consumption of the customers. The energy generation profiles were provided by the open-source database Renewables.ninja [4, 5]. Next, the customer was granted a BESS. The value of the battery energy capacity was calculated as 1 kWh per installed kW_p of the PV panels [6].

2.3 Assumptions and limitations

In the present study, the following limitations are applied:

- The battery charges if the PV panels have an energy surplus.
- If the state of charge (SOC) of the battery is <50% and the customer's consumption is under the PB, the battery charges from the PV panels.
- The PV panels are the only source for charging the battery.
- If the value of shortage is more than the available capacity of the battery, the battery discharges for half of its available capacity.
- The PV panels supply energy to the customer continuously.

In addition, the following assumptions are made:

- The BESS cost is 752 €/kWh, the round-trip efficiency is 80%, and the end of life is approached after 3000 cycles with a depth of discharge of 80% [7].
- Calendar and cycling ageing are outside the scope of the paper.
- The investment cost of the PV panels is not considered.
- The cost calculation does not include remuneration for the injection of energy into the grid.

The investment cost of the PV panels is outside the scope of this paper. It is assumed that the investments will take place in any case, and the focus is to examine whether a BESS would also be invested in. Throughout the simulation, PV panels are used as the only source for charging the BESS. The charging at hours of down-regulation prices may lead to exceeding the predefined PB. Moreover, the increase in power demand from the DSO at night hours may cause undesirable effects in the network. Besides, the methodology assumes charging of the BESS if the PV panels do not possess excess energy, and the customer's consumption is under the PB. The solution enhances the chances of the battery to affect the peak powers, especially in seasons of low solar irradiance.

2.4 Description of the algorithm

The design of the algorithm for the analysis of the data was based on the peak-shaving technique and the presence of a controller. The PV panels continuously supply energy to the customer. The controller is programmed to follow the load curve and store the excess energy from the PV panels to the battery. Besides, the BESS is charged from the PV panels if the customer's consumption is under the PB. If the power demand exceeds the PB, the controller sends a signal to the battery to supply the shortage. The BESS operates within the minimum and maximum SOC values, which were determined as less destructive for the battery's state of health. The simulations were carried out for a period of one year. The decision-making tool was built by using Python.

3 Results

The results were treated as follows. First, a technical analysis of the simulations was carried out. The initial and processed aggregated annual energy consumptions were examined and compared. Further, the potential of peak shaving by the PV-BESS system was analysed for every PB. The analysis also included a study of the flexibility potential of the batteries for operation in the markets or execution of services. Then, an economic analysis was conducted to examine the electricity expenses under various PBs.

3.1 Technical analysis

The results of the simulation show that the share of energy purchased from the grid decreased by 24% for every PB. Table 2 illustrates energy consumption by source for the PBs. The correlation between the share of PV panels and BESS for every PB is worth noting. The BESS portion grows with a decrease of the PB leading to the increase of BESS operational hours. Simultaneously the PV panels share decreases. It means that with the decrease of PB, the battery increases the frequency of discharging events when the PV panels do not possess surplus energy.

Fig. 1 below illustrates the mean decrease of peak power for the residential customers with applied values of PBs. As expected, the results prove that the capability of the battery to reduce the peak demands depends on solar energy generation, if it is the only source for charging the batteries. 70PB showed the most

Table 2 Energy consumption by source

Energy source, %	70PB	Third PB	MonthPB	YearPB
BESS	0.8	0.24	0.14	0.01
PV panels	12.9	13.28	13.35	13.44
grid	86.3	86.48	86.51	86.55

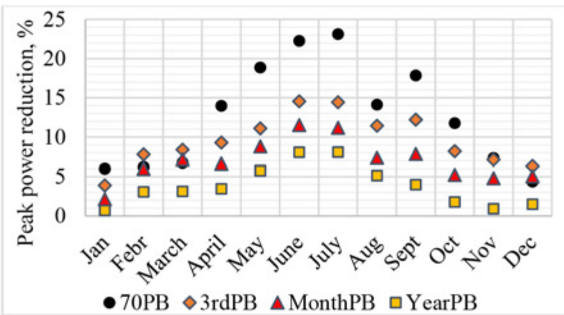

Fig. 1 *Mean reduction of peak power among customers*

Table 3 Share of peak power provided by PV–BESS system

	70PB	Third PB	MonthPB	YearPB
peak power, %	31	32	29	44

significant reduction of peak demand among all PBs. The highest reduction by this PB was by 23% in July. The values of PBs were defined based on the previous year that can mean that the customers' peak demands increased in the next year. Despite the promising results from the customer point of view, the flexibility potential of the batteries requires to be analysed.

Further, the share of peak power supplied by PV–BESS system was evaluated (Table 3). The biggest share of power supplied by the PV-BESS system belongs to YearPB. The PB was defined as the highest peak power within a year, meaning a reduction in only substantial power peaks. Thus, such a PB reduces the operational time of the BESS within a year and keeps it charged only for the highest peaks. The results of 70PB and third PB showed approximately the same results for a peak reduction of 31%. The operating time of the BESSs is much higher for these PBs compared with YearPB. Owing to the lacking possibility to charge the battery from the markets, the BESSs do not possess enough capacity to shave the peaks in some periods. Especially, in the months of low solar irradiance.

Next, the analysis of the flexibility potential of the batteries was studied. In general terms, the flexibility potential is defined as the time when the BESS is in the idle mode and has the capacity within the minimum and maximum values. Fig. 2 displays that the flexibility potential of the batteries varies depending on the amount of solar irradiance. In the months of low solar energy production, the PBs possess decreased flexibility potential, comparing with a period of high solar energy production. However, it is worth mentioning that according to the results, the batteries are available >50% of the time every month. Therefore, the customer with PV-BESS system has an option to reduce its electricity expenses by reduction of electricity purchased from the grid and to attract additional revenue streams from day-ahead or balancing markets, or from ancillary services.

Ultimately, the results of the technical analysis demonstrate that the methods chosen in the study have a clear advantage of stimulating the customers to decrease their energy consumption. However, the PBs and the size of the BESS have to be selected based on the load profiles of the customers and in particular, the types of power peaks. Moreover, the definition of the PB has to consider the customer's willingness to use the flexibility of the battery for further purposes. This, however, is a topic of future studies.

3.2 Economic analysis

The economic analysis examines the cost of energy consumption for four PBs and compares it with the reference cost. In the first step, the operational cost of battery cycling was calculated. The methodology in equations (1)–(4) described in [8] was applied. Once the

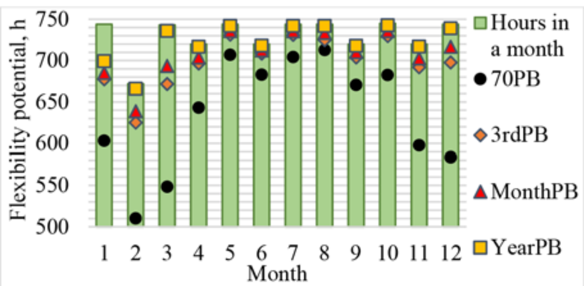

Fig. 2 *Mean flexibility potential of the BESS*

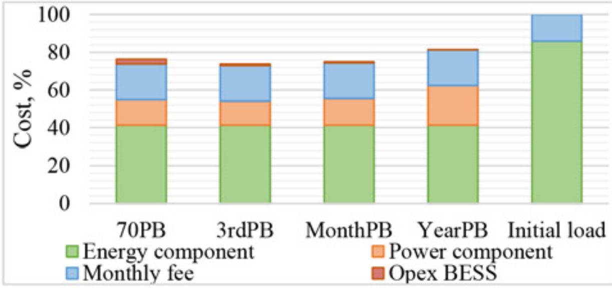

Fig. 3 *Cost comparison of energy consumption*

operational cost was defined, the energy component cost of the tariff was considered:

$$E_{\text{cost}} = \sum\left(E(t)\cdot \text{fee}_{\text{day}}\right) + \sum\left(E(t)\cdot \text{fee}_{\text{night}}\right), \quad (1)$$

where $E(t)$ is the mean hourly energy consumption at time t, and fee_{day}, $\text{fee}_{\text{night}}$ are the day and night energy fees.

The monthly fees are the same for every PB and calculated as the multiplication of the monthly fee by the number of months in a test period. After that, the power component was calculated. Within the analysis, two options of power component calculations were considered. The first is based on the definition of maximum year and month consumption of the processed load profiles. These values were applied for the calculation of 70PB, MonthPB, and YearPB power component cost. The second option is used for the calculation of the thirdPB power cost component and applies the values of the third-highest consumption of each month. The calculation of the power component was implemented by the next formula:

$$\text{Power component} = \sum_{n=1}^{N} (\text{PB}(n)\cdot \text{fee}_{\text{P}}), \quad (2)$$

where PB(n) is the value of the maximum or third consumption in month n, and fee_{P} is the power fee.

Eventually, the final total cost of energy consumption can be determined and compared with the cost of the initial load profile with ToU tariff. Fig. 3 illustrates the results of the calculation. The figure demonstrates the total reduction of electricity distribution cost for all variants of the PBs from 19 to 26%. Hence follows that the savings compensate for the operational cost of the batteries.

ThirdPB is featured by the lowest total expenses and power component cost. Thus, the applied scheme for the economic calculation of thirdPB is advantageous as it ignores the first two peaks in the month, which can be caused by rare events. The combination of final cost, peak-shaving and flexibility potential makes this PB preferable for customers.

4 Conclusion

The purpose of the current study was to determine the flexibility potential of the BESS under the power-based tariff and a variation of PBs. This work contributes to existing knowledge of BESS application with PV panels and power-based tariff by providing a flexibility potential analysis of BESS and economic analysis of energy consumption for a variety of PBs.

Despite the exploratory nature, this study offered some insights into the use of various PBs for PV-BESS system and cost calculation strategies. The results of the study have demonstrated the reduction of energy purchased from the grid by approximately the same value for all PBs – 24%. Further, the flexibility potential analysis revealed that the mean monthly flexibility potential of the batteries is >50% of the time. However, it differed for every month and depended on solar energy generation from the PV panels. The economic study demonstrated the advantage of calculating the power component of the power-based tariff based on the third-highest monthly peak rather than the yearly or monthly peaks. Further, the analysis showed that the operational cost of the batteries may be compensated by economic savings, gained from the use of power-based tariff and reduction of peak powers. However, it highly depends on the type of the customer's load profile and especially, the peak shape.

A further study could access the impact of the peak power reduction at the level of secondary and primary substations and analyse the power flow. Besides, more research is needed to access the cost-effectiveness of the batteries applying the flexibility potential for other markets or services.

5 References

1 Honkapuro, S., Haapaniemi, J., Haakana, J., *et al*.: 'Development options for distribution tariff structures in Finland'. 14th Int. Conf. on the European Energy Market (EEM 2017), Dresden, 2017

2 Helen Sähköverkko Oy: 'Tuotteet Helen Sähköverkko Oy', Available at: https://www.helensahkoverkko.fi/palvelut/tuotteet (accessed 15 February 2020)

3 Lahti Energia Oy: 'Verkkopalveluhinnasto', Lahti Energia Oy. Available at: https://www.lahtienergia.fi/fi/sahkoverkko/hinnastot-sopimusehdot/verkkopalveluhinnasto (accessed 5 March 2020)

4 Pfenninger, S., Staffell, I.: 'Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data', *Energy*, 2016, **114**, pp. 1251–1265

5 Staffell, I., Pfenninger, S.: 'Using bias-corrected reanalysis to simulate current and future wind power output', *Energy*, 2016, **114**, pp. 1224–1239

6 Luthander, R., Widén, J., Munkhammar, J., *et al*.: 'Self-consumption enhancement and peak shaving of residential photovoltaics using storage and curtailment', *Energy*, 2016, **112**, pp. 221–231

7 Beaudin, M., Zareipour, H., Schellenberg, A., *et al*.: 'Energy storage for mitigating the variability of renewable electricity sources'. Energy Storage for Smart Grids. Planning and Operation for Renewable and Variable Energy Resources (VERs), San Diego,, 2015, pp. 1–33

8 Nigmatulina, N., Tikka, V., Belonogova, N., *et al*.: 'Scheduling of an energy storage system operation with regard to the market price behavior'. 16th Int. Conf. on the European Energy Market (EEM), Ljubljana, 2019