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FACULTY OF ELECTRICAL ENGINEERING

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TECHNICAL SCIENCES APPLIED IN ECONOMY, EDUCATION AND INDUSTRY

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FACULTY OF ELECTRICAL ENGINEERING,
GOCE DELCEV UNIVERSITY, STIP, NORTH MACEDONIA

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PREFACE

The Faculty of Electrical Engineering at University Goce Delcev (UGD), has organized the Second International Conference ***Electrical Engineering, Informatics, Machinery and Automation - Technical Sciences applied in Economy, Education and Industry-ETIMA*.**

ETIMA has a goal to gather the scientists, professors, experts, and professionals from the field of technical sciences in one place as a forum for exchanging the ideas, strengthening the multidisciplinary research and cooperation, and promoting the achievements of technology and its impact on every aspect of living. We hope that this conference will continue to be a venue for presenting the latest research results and developments on the field of technology.

Conference ETIMA was held as online conference. More than sixty colleagues contributed to this event, from five different countries with more than thirty papers.

We would like to express our gratitude to all the colleagues, who contributed to the success of ETIMA'23 by presenting the results of their current research and by launching the new ideas through many fruitful discussions.

We invite you and your colleague to attend ETIMA Conference in the future as well. One should believe that next time we will have opportunity to meet each other and exchange ideas, scientific knowledge and useful information as well as to involve as much as possible the young researchers into this scientific event.

The Organizing Committee of the Conference

ПРЕДГОВОР

Меѓународната конференција ***Електротехника, Технологија, Информатика, Машинство и Автоматика-технички науки во служба на економија, образование и индустрија-ЕТИМА*** е организирана од страна на Електротехничкиот факултет при Универзитетот „Гоце Делчев“.

ЕТИМА има за цел да ги собере на едно место научниците, професорите, експертите и професионалците од полето на техничките науки и да претставува форум за размена на идеи, да го зајканува мултидисциплинарното истражување и соработка и да ги промовира технолошките достигнувања и нивното влијание врз секој аспект од живеењето. Се надеваме дека оваа конференција ќе продолжи да биде настан на кој ќе се презентираат најновите резултати од истражувањата и развојот на полето на технологијата.

Конференцијата ЕТИМА се одржа online и на неа дадоа свој придонес повеќе од шеесет автори од пет различни земји со повеќе од триесет труда.

Сакаме да ја искажеме нашата благодарност до сите колеги кои придонесоа за успехот на ЕТИМА'23 со презентирање на резултати од нивните тековни истражувања и со лансирање на нови идеи преку многу плодни дискусии.

Организационен одбор на конференцијата

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ELECTRICITY PRODUCTION OF PVPP FOR ELECTRICITY MARKET

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Abstract

The photovoltaic power plants (PVPP) have various applications. PVPPs are used for household applications, electricity production in off-grid systems, electric consumption reduction from the power grid, generation of electricity to the grid, etc. Solar energy is a primary energy source which can be converted into electricity. This type of energy source is highly dependent on the weather conditions, or in other words, they are intermittent. PVPP without supporting devices could not produce electricity directly for the energy market, since they would have too large deviations between the traded and produced electricity, what would lead to high financial penalties. Batteries are one of the possible solutions to overcome the intermittent electricity production from PVPP, by controlling the energy output. Collaboration of PVPP and battery storage systems would potentially enable a direct energy production of the PVPP on the market, and new operating options.

Key words

battery storage system, photovoltaic power plant, electricity market, pay back

Introduction

Slovak decree 309/2018 amending Act 309/2009 Coll. no longer provides support for PVPP with a surcharge. It is not possible to apply for supplemental support for PVPP power plants from January 1, 2019. The surcharge support is the only support mechanism for subsidizing the price of electricity produced from PVPPs from this date. The size of the surcharge is determined by the Ministry of Economy of the Slovak Republic (MESR) based on the evaluation of the public auction of the PVPP production price offers. There was only one auction announced on February 3, 2020. This auction was cancelled on March 31, 2020 [9]. This means that there is currently no mechanism to subsidize the price of the electricity produced from PVPP. Support by assuming responsibility for deviations and support by purchase applies only for PVPPs with an installed capacity of up to 250 kW [12].

Newly built PVPPs (mainly with an output of more than 250 kW) have to deal with the new rules and have to ensure the trading of the produced electricity on the energy market or produce within the trader's balance group. This energy market can be divided into 3 categories:

1) Market with long-term products (trade of electricity for a period of one month, several months or years).

2) Market with short-term products (trade of electricity for a time interval of hours to a week).

- Block market (trade in blocks lasting several hours - base, peak and off-peak loads).
- Daily or spot market (trade organized day ahead in hourly intervals).
- Intraday electricity market (trade organized one hour before production/consumption).

3) Market of the regulation electricity (trade of electricity for the purpose of equalizing deviations in the network) [4].

The price of electricity produced by newly built PVPPs will depend on the price of electricity on the market and their business strategy. The study from 2004 [1] already pointed out that the group of energy equipment (virtual power plant) with a preponderance of distributed power plants (e. g. PVPPs) is more suitable for selling electricity on the daily market. The installation of an energy storage system is useful.

The advantage of battery storage systems (BESS) is their high flexibility. They are able to respond to high dynamics of PVPP production in a short time [6] and [7]. According to IEC 62933-2-1, BESSs are classified as follows [13]:

Class A - Devices used for quick regulation. Devices are discharged and charged intermittently and cyclically (hourly or even shorter). The most important parameter of devices is their electrical power.

Class B - Devices for regular and long-lasting regulation and/or accumulation function. Important parameters of these devices are power and capacity. Charging and discharging take place in longer time intervals (lasting from hours to days).

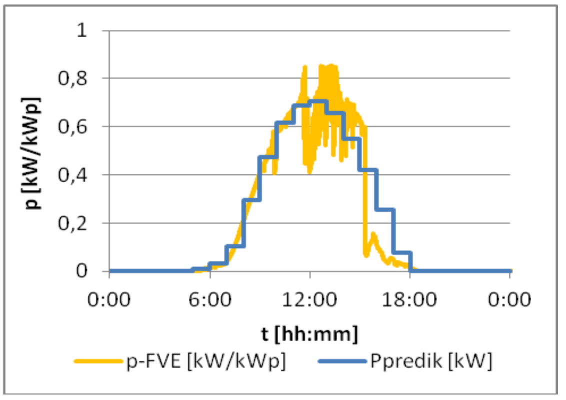
Class C - Emergency services equipment. The most important parameter of these devices is the time of secured power supply during the limited operation of the primary source. The devices are kept constantly charged, and their capacity is used only in case of failure.

Characteristics of PVPP and BESS Power production for electricity market

The primary energy source of PVPP cannot be stored, unlike thermal and water power plants. Due to the high intermittency of the primary energy source, it is difficult to operate a PVPP as a commercial power plant. On the other hand, financial independence from mineral raw materials and low ecological impact are some of the main advantages of this resource. BESSs are characterized by high flexibility and quick response to changes in the consumed and supplied power. The disadvantage of these accumulation systems is their high investment price. However, the combination of PVPP and BESS will reduce some main disadvantages of these devices.

PVPP

When trading electricity on daily market, it is necessary to contract the quantity of traded electricity before the physical supply. The electricity has to be contracted a day before supply at the daily market and 30 min before at the intraday market. The available PV generation prediction models are not able to accurately predict the PV electricity generation. Similarly, with a system of trading in hourly intervals and accounting of deviations in 15-minute intervals, it is not possible to ensure a deviation-free operation for PVPP (PVPP cannot supply constant power during one hour). The power plant is penalized for each deviation, i.e. its revenues are reduced, and the payback of the power plant is prolonged.



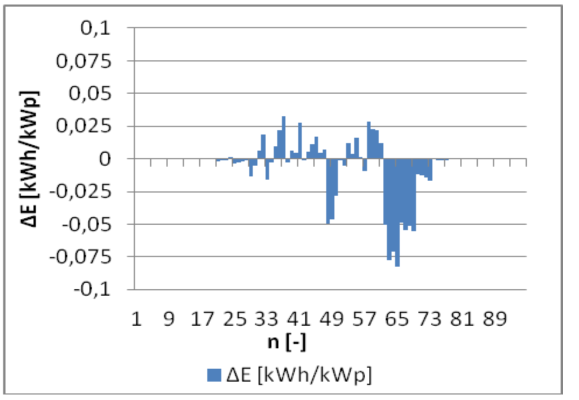


Fig. 1. Real and predicted (traded) energy production of PVPP

Fig. 2. Generated energy deviations at 15 min accounting intervals

Source: Measured data at Institute of Materials and Machine Mechanics of the Slovak Academy of Sciences.

In the next we will use production data of the PVPP installed at the Institute of Materials and Machine Mechanics of the Slovak Academy of Sciences (IMMM SAS). The difference between the predicted amount of delivered power for trading hours (p_{predik}) and the real course of PVPP generation (p_{PV}) in proportional units converted to installed power is seen in the **Error! Reference source not found.**. Predicted amounts of electricity were provided by Solargis Ltd. The real production of experimental PVPP was 4.53 kWh per installed kWp (the prediction was 4.98 kWh) on the analysed day. The sizes of deviations in individual 15-minute trading intervals are shown in Fig. 2, where n is the departure interval number. 0shows the result of accounting for the delivered electricity for a given day on the daily market. In this case, the power plant's income is reduced by 12.1% due to deviation payments.

Table 1 The dayly result of settlementa

Sign	Value	Total price	Label
E_{prod}	4,97 kWh/kWp	0,4873 €/kWp	Price of production
E_{neg}	0,741 kWh/kWp	0,0587 €/kWp	Payment for negative deviations
E_{poz}	0,298 kWh/kWp	0,0002€/kWp	Payment for positive deviations
E_{sum}	4,97 kWh/kWp	0,4284 €/kWp	Income

The source of electricity prices on the daily market and the prices of the deviation fee is OKTE, a.s. (Organizer of the short-term electricity market), https://www.okte.sk/sk/kratkodoby-trh/zverejnenie-udajov-dt/celkove-vysledky-dt/ and https://www.okte.sk/sk/zuctovanie-odchylok/zverejnenie-udajov/odchylka-sustavy/

On the considered day, the converted income per kWh of electricity produced would be 0.0862 €/kWh. If the power plant would produce electricity with the income mentioned above throughout the year with an annual production of approximately 1150 kWh/kWp [2], it would have an income of 99.13 €/kWp. The investment price for a PVPP is around 860 €/kWp [3], but it also depends on the size of the installation. In the above-mentioned case, the power plant would pay back the investments in 8.64 years (operating costs are not considered). However, such operation is too risky and is completely dependent not only on the electricity prices but also on the accuracy of the prediction of PVPP production. A trading strategy for such an operation could be to trade a slightly lower amount of electricity compared to the prediction, because the price of positive deviations is significantly lower than the price of negative ones.

BESS

The high flexibility of supplied and withdrawn power allows the BESS to charge in times of low electricity prices and discharge in times of high electricity prices. The price of electricity is unknown at the time of preparation of the trade (i.e. at the time of contracting the quantities). This means that if the BESS operator has to estimate the price during trading day D at time D-1 [11], if he chooses an arbitrage trading (i.e. buying electricity at a time of low price and selling at a time of high price). In this study, the price is estimated as the average price of the last 100 business days. The BESS model was created on the basis of experimental measurements of the laboratory battery system of the IMMM SAS with a power of 20.4 kW and a total capacity of 49.7 kWh. The installed capacity of the PV plant is 15.52 kWp [8]. It is possible to determine the operation with the greatest income using a non-linear programming optimization algorithm. The model was created based on the input datasheet parameters and the measured parameters of the IMMM SAS devices. The optimization task was solved by GAMS software and manual correction. The diagram in Fig. 3 shows the course of the price c [€/MWh] on the daily market and the amount of electricity supplied to the system (negative values) and withdrawn (positive values) from and to the BESS in relation to the total storage capacity.

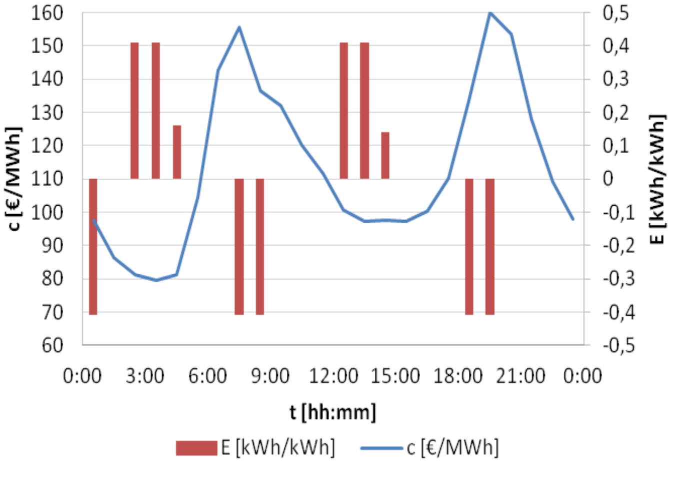


Fig. 3. Simulated supply and withdrawal of BESS and electricty prices on the market
Source: Measured data at Institute of Materials and Machine Mechanics of the Slovak Academy of Sciences

The model estimated the resulting daily billing income at 0.0782 € per kWh of installed capacity (after correction due to the change in the state of charge before and after operation). However, the prices on the market were more favourable, and with such operation, the accumulators would reach revenues of 0.0914 € per kWh of installed capacity. Accumulators would do 2 complete cycles, which means that the income for one cycle would be 0.0391 €/kWh. If the price of electricity was know at the time of closing the deal on the market, it would be possible to the income by 14.2%.

The price of BESS currently varies in a wide range. It depends primarily on the technology, but also on the total installed capacity. Published prices [10] are at the level of 350-730 €/kWh. The price of the system installed at IMMM SAS was approximately €1,000/kWh of the installed capacity of the lithium-ion storage system (LiFePO4). In the model we considered a price of €900/kWh. The simplified estimated number of cycles during which the investment will be returned can be determined as follows:

$$n = \frac{I + O}{z} \tag{1}$$

where n is the number of cycles of the accumulator, I is the investments of the BESS installation in €/kWh, O represents the costs associated with the operation for the given period/number of cycles and z represents the income of the BESS for one cycle in €/kWh.

If the accumulator system would operate according to the above shown diagram (Fig. 3) at the same prices, it would pay back the investment input according to eq. (1) after 23 017 cycles (without considering operating costs). This value is significantly above the maximum lifetime of this technology in the number of cycles, but also in years of operation (23 017 cycles are approximately 31.5 years). The most common systems are declared for 6 000 cycles or occasionally for 10 000 cycles. At the given prices, such an operation is unfavourable for BESS, and the income is significantly affected by the electricity prices on the market. The study **Error! Reference source not found.** compares individual European electricity markets in terms of suitability for the BESS arbitrage. The results of this study showed, that for the German market (mainly influencing the Slovak market), the arbitrage strategy is suitable only for 15% of the year.

Joint production of PVPP and BESS

The laboratory PVPP with BESS at IMMM SAS enables experimental operation for the simulation of various conditions. The results of simulation models and measurements on these devices are processed to verify the profitability of PVPP operation in cooperation with BESS.

Compensation of PVPP production with BESS

It was found at IMMM SAS that to equalize the production of the PVPP to the predicted (traded) power, the battery capacity is required, which is comparable to the energy that the PVPP is able to supply for 0.4 to 0.8 hours at the installed power. The size of the required capacity depends primarily on the accuracy of the prediction of the PVPP's production. Since machine learning (artificial intelligence) is based on historical data, the prediction becomes more and more accurate. Therefore, we would use the capacity coefficient k_{cap} = 0.7 hours for the simulation model. This means that, for example, an accumulator with a capacity of 0.7 kWh would be sufficient for a PVPP with an installed capacity of 1 kWp. The price of such a system for 1 kWp of installed PV power would then be:

$$N_{SYS} = N_{BESS} \cdot k_{cap} + N_{PVPP} \tag{2}$$

where N_{SYS} is the total price of the system per kWp of installed PV, N_{BESS} is the price of 1 kWh of BESS and N_{PVPP} is the price of 1 kWp of PV. Such a system will have an input cost of 1 487 €/kWp.

The course of PV power delivery to the grid (p_{dod} [kW/kWp]) and the course of PV production (p_{FVE} [kW/kWp]) are shown in Fig. 4. The graph also shows the state of charge (SOC [%]) during the simulation. At a given operation, the BESS would perform 0.7 cycles. It is apparent, that the BESS capacity would by significantly used in the early evening hours due to the inaccurate prediction of the PVPP production. The inaccuracy in the total daily production caused the BESS to be completely discharged after the daily cycle. With such an operation, an income of 0.5026 €/kWp could be achieved. Since at the end of the cycle, the accumulators were discharged more than at the beginning, it is necessary to correct for this income by the cost of recharging the accumulators. After this correction, the income would be 0.4113 €/kWp. The recharge price was determined from the average price during the given day. With such an income, the simplified investment would return is 14.4 years, where the BESS would perform 3670 cycles, which is within the lifetime of the accumulators.

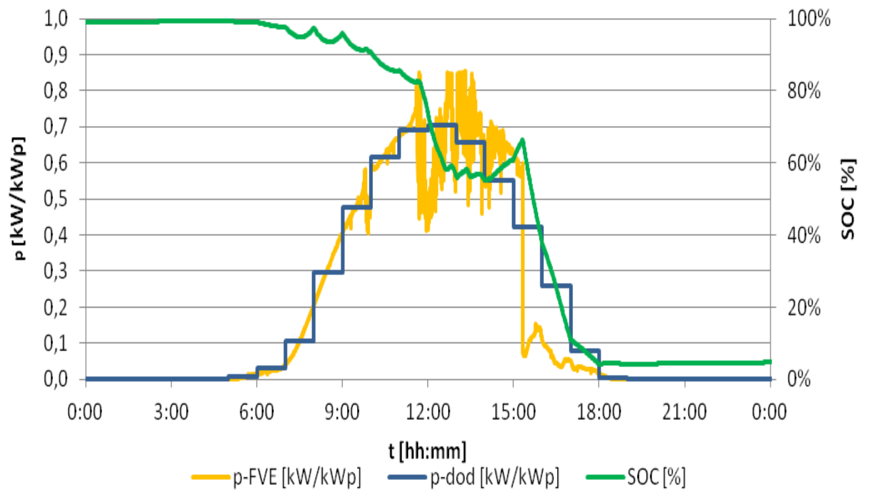


Fig. 4. Simulated supply of linked PVPP and BESS - compensation operation
Source: Measured data at Institute of Materials and Machine Mechanics of the Slovak Academy of Sciences

Active trading of joint PVPP and BESS

For simulations of active electricity trading the entire capacity of BESS of IMMS SAS was used. This BESS is able to accumulate 3.2 hours of operation of the PVPP at the installed capacity (k_{cap} = 3.3 hours). The investment costs of such a system is up to 3,740€/kWp of the installed PV plant. With these BESS is possible not only power compensation, but also selling electricity on the market when it is expensive and recharging the BESS when it is convenient. In this case, the optimization task was solved using GAMS software and manual correction.

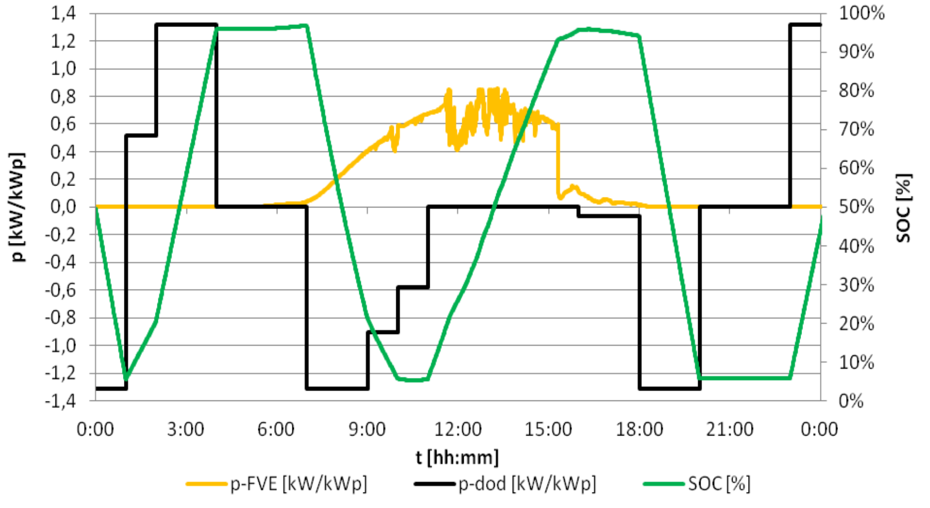


Fig. 5. Production and consumption of linked PVPP and BESS - active trading simulation Source: Measured data at Institute of Materials and Machine Mechanics of the Slovak Academy of Sciences

The power production and consumption curve (p_{dod} [kW/kWp]) of supply and consumption can be seen in Fig. 5. At the given prices, it is possible to achieve an income of 0.7153€/kWh and during the day BESS would complete 2.25 cycles. The simple return on investment would be 20.8 years at 17079 cycles. The currently available batteries (with technology like BESS installed at IMMM SAS), are not yet capable of such high number of cycles during their lifetime.

However the high investment costs of the PV plant and BESS in the case of the IMMM SAS is utilised in Microgrid thermal system which use produced electricity to store heat in a rock exchanger as well as expanded thermal reservoirs using a heat pump. The photovoltaic electricity is consumed by TESS thermal battery, when the heat is transformed and stored in the TESS based on PCM. Although overall investment costs have increased, the usage of PV has grown to 6.3 hours on average per year but rising a ratio of PV electricity utilisation for heating and cooling processes.

Conclusions

Today, renewable energy sources such as PVPPs are still very demanding for investments and are difficult to integrate into the electricity market among entities whose portfolio mainly includes power plants using fossil and other fuels or water energy as a primary source of energy. The financial complexity of BESS fundamentally hinders their construction, even if they could eliminate the intermittency of PVPPs.

The study pointed out that BESSs alone are not suitable for market trading. However, the connection of BESS to PVPP has a positive effect on the return of the system. A very important input in the payback analysis is the capacity of the BESS itself in relation to the installed power of PVPP. Of the analyzed scenarios, the most advantageous would be the one where the battery capacity was 70% of the hourly PVPP production at the installed capacity. In other scenarios, the investment would not be returned during the lifetime of the BESS. It is important to mention that at given market prices, standalone PVPP without BESS had a shorter payback than with BESS, even though PVPP revenues were reduced by penalties due to the generation of deviations.

This study focused on scenarios with three different capacities of BESS compared to PPVP installed power. There was analyzed only one operation day with one daily pack of market electricity prices. For further deeper analyses, it is necessary to statistically evaluate many operating conditions at different electricity prices and different installed BESS capacity. Extension by TESS contributes positively on PVPP utilisation although bring complexity of such systems but positive impact to minimise risks of penalties due to the generation of deviations.

It is important to note that nowadays the minimum tradable quantity on the daily and intraday electricity market is 0.1 MWh. Therefore, the opportunity to trading on the market is narrowed down to a small number of power plants with an output of the order of 1 MW and above. At the current time new smaller power plants could not trade electricity on the market because their deviations would depend not only on the prediction but also on the difference between the estimated output and the multiples of the minimum amount of tradable electricity. They have to supply electricity to the balance group of purchaser.

On the other hand, from the end of November 2022 the shortest time block for intraday market trading is a 15-minute block. It is possible to close deals up to 30 minutes before the actual delivery. This means that with a successful trade, it is possible to reduce PVPP deviations even during the day of supply.

The flexibility of electricity supply and consumption, or control the power factor by BESS, can also be used for other services in the electricity system. To find the application of BESS in the electricity system, it is necessary to carry out a comprehensive analysis of the possibilities and its contribution, not only from the technical aspect, but also from the financial aspect. Such options are, for example, availability when starting from the blackout, primary, secondary, or tertiary power regulation, local voltage regulation by supply and withdrawal of reactive power and others. Through a complex analysis, it would be possible to find the most advantageous distribution of the use of the total BESS capacity for individual services.

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