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Efficiency of Battery Systems from the Point of View of Economic Return

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Abstract
Battery energy storage systems (BESS) are becoming increasingly important and their number of applications in energy systems is constantly increasing. Although batteries cannot solve the problem of electricity storage in the long term, BESS systems have proven to be suitable for short-term provision of flexibility within the day. Their real usability is shaped by the provision of balancing services to ensure a stable supply of electricity in distribution networks. BESS systems were able to respond to the dynamic development of the electricity market in recent years and achieve excellent results from the point of view of economic return. The aim of the contribution is to present the results achieved in selected cases of BESS use and to determine their economic return. The size of the battery (installed power and capacity) is designed to be able to work in individual modes and operating cases. A critical element for the design of the battery size is the technical conditions for the provision of balancing services. On the basis of market research, we determine the costs of acquiring and operating the battery, including the need for a software superstructure for controlling the battery itself and ensuring the necessary business functions. According to the defined criteria, we evaluate the technical operation of the battery located at the point of consumption (behind the meter) using the battery model in several operating cases. Subsequently, we analyse its sales based on the development of market prices and the conditions in which the battery is placed.

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1. Introduction

Battery systems represent one of the important sources of flexibility. The use of battery systems is mainly combined with the use of storing excess electricity from renewable energy sources. The battery systems is mainly combined with the use of surplus electricity storage from renewable energy sources. The usability of batteries in connection with a renewable source of production and its optimization is solved by Ali O.M. Maka et al. (2024), where he points out the ability to use the energy potential of photovoltaic systems with a battery.
The economic advantage of using utilization in the electricity market is addressed in the studies Potential utilization of battery energy storage systems (BESS) in the major European electricity markets. Yu Hu et al. (2022) points out the lack of information in terms of economic evaluation of battery system applications due to the absence of a general framework comparing BESS applications between different applications or different markets. The objective of his work was to analyze the BESS operation under real deregulated electricity markets with the proposed general option-based BESS payoff model.
The potential of battery systems is presented in the studies Potential and challenges of Battery Energy Storage (BESS): The case of Poland, which FCR, aFRR. The study describes the use of BESS in the electricity market and balancing services such as FCR, aFRR and wholesale arbitrage where the total IRR of the project is around 18% with a payback period of around 5 years (Ziółkowski, M. 2023). According to the study Local Energy Markets Improve Investment Returns of Residential BESS by Arbitrage Opportunities, the achieved return of small battery systems in the case of electricity sharing using

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renewable energy sources in the home can reach a calculated return of approximately 12 years (Liagat et al., 2023).
However, their dominant use is in the short-term equalisation of electricity production and consumption within the day, especially in increasing the stability of the network, increasing the penetration of the use of renewable energy sources, saving fossil energy sources (Aneke and Wang, 2016). On the other hand, it would be to offer a view of the simple return of the proposed battery system in different types of operation with different system usability, like flexibility. Flexibility is the ability of a transmission system operator (TSO) to adjust the production or consumption of electricity in response to changes in demand, supply, or grid conditions (ENTSOe, 2017a). From a long-term perspective, batteries are inhibited due to their limited capacity in relation to the installed power. Currently available battery storages have a capacity to installed power ratio of 1:1 to 4:1, so they can provide flexibility in the range of one to four hours (Manso, 2016). The construction and operation of battery sources is generally recommended in connection with the construction of a self-generating renewable energy source (RES). Interesting results in this area were presented by Goulart et al. (2024) using a simple method of technical economic analysis when using a battery in combination with a renewable energy source. Hu et al. (2022) also see the economic sense in the context of wider market opportunities in the area of flexibility, thus achieving much better economic return results when using this system. In some cases, it is possible to combine individual types of flexibility according to the result of price arbitrage so that the best possible economic results are achieved (Pusceddu et al. 2021). The first successful projects of certified systems for the provision of FCR services (Energie Portál, 2022) are appearing in the Slovak market, and the number of the initial projects of other flexibility services for TSOs - aFRR is increasing.

The aim of the contribution is to point out the usability of battery systems and their economic returns in terms of the affects of the electricity market based on specific market data. By homogeneously modelling the operation of the battery system, we demonstrate the returns of its individual usage cases. In other cases, we set the break-even price for the particular battery operation case. The evaluation of these cases on the basis of market data may not always be reliable, which is also shown by the latest experience in the development of the electricity market after 2021, which changed some views of the return premises. Based on the current assessment, it is not easy to determine the trend of further market development. The software solution appears to be a key element in the operation of battery systems, which can be crucial from the point of view of enabling the most appropriate market operation of the battery according to the development of the current market situation.

2. Experimental Framework

We analyse energy flows in the provision of flexibility as a service, including the standard storage of surpluses from the production of electricity from RES, based on the operation simulation of battery systems. To perform the simulation, we use the created mathematical model. The model calculates the electricity flows of the battery for charging and discharging according to current requirements with an impact on the development of battery capacity in 1/4 hour resolution. The model is implemented in the D2000 system from IPESOFT (Garbier, 2023). To parameterize the model, we use the basic parameter of the battery:

- Battery capacity
- Usable battery capacity
- Installed capacity
- Charging and discharging efficiency
- Number of charging cycles
- Minimum battery capacity
- Battery aging
- Battery
- Maximum battery temperature
- Management system defined by the scenario used

The battery simulation requirements define the model inputs used, which are distinguished according to the defined operating scenarios described in the following section. The model inputs used are:

- Production of electricity from a renewable energy source in 1/4 hour.
- Request for signal regulation from the TSO based on realistically measured FCR and aFRR service waveforms, which are transformed into a signal of the charging and discharging requirement of the battery. During the period of provision of ancillary services, the functions of replenishing the battery by applying power corrections according to the technical specifications of the TSO are calculated.
- Evolution of the magnitude of system deviation, which is transformed into a signal of charging and discharging demand. The model in this case uses the available battery capacity to regulate the power according to the set parameters. Subsequently, the total impact on battery operation during the modeled period is calculated in 1/4 hour resolution.
- Electricity price peak and offpeak hourly.

We assess the usability of batteries as well as the investment potential of battery systems for four different cases:

- Case A: Optimising the use of self-generated electricity produced from RES, uses the natural cycle of electricity production from, for example, a photovoltaic power plant during the duration of sunshine. In times of non-production of the photovoltaic power plant, electricity is supplied from batteries to cover self-consumption (Mazzoni et. al., 2019, Datta, 2020).
- Case B: Provision of frequency and non-frequency balancing services (Lepieš, 2023) in order to stabilise the operation of the superior distribution network through the Frequency Containment Reserve (FCR) service (Oyj, 2023), automatic Frequency Restoration Reserve (aFRR) with battery recharging from the intraday market (Oyj, 2019, OKTE, 2024), manual Frequency Restoration Reserve (mFRR) (ENTSOe, 2017b).

- Case C: Regulation of deviation (counter deviation) as a non-guaranteed service for regulation against the direction of system deviation based on the prediction of the development of the ¼ hour deviation of the system of the relevant regulatory area (Decree, 207/2023).
- Case D: Providing flexibility in short-term electricity markets using the natural development of the price of electricity during the day according to peak and off-peak prices, the buy cheap, sell high system (Overall Results of Day Ahead Trading, 2024, Huang et al., 2022).

Several battery technologies can be used for this purpose. Among the most common battery technologies used for energy storage are:

- Pb – lead batteries - Lead Acid (Pavlov, 2017),
- LFC - lithium iron phosphate battery - LiFePo4 (Meng et al., 2022),
- NMC - lithium-manganese battery Cobalt Oxide (NMC) it is a type of lithium-ion battery that uses a combination of nickel, manganese and cobalt as the cathode material - Li-NMC (da Silva Lima et al., 2023),
- LTO - lithium-ion battery - Li-Titanate (Dang et al., 2023),
- VRB - redox flow batteries (RFBs) that can be composed of vanadium, zinc-bromine, all-iron, semi-solid lithium, hydrogen-bromine are some of the most common types of redox flow batteries (RFBs) that can be found in the literature (Aramedia et al., 2021).

Their basic characteristics are presented in Appendix 1. We can classify the suitability of using batteries from the point of view of short-term or long-term load of battery operation. Of the listed types of batteries, the NMC or LTO battery is most often used due to the quality and price ratio, with the wide availability of spatial solutions with the existence of extensive operational experience. Both technologies can cover all cases of assessed usability that are imposed on batteries (most strictly due to the provision of balancing services (Lepieš, 2023). Both technologies have high performance change dynamics with excellent quality for regulation. Their cyclic life can be considered average. Since we work with the most affordable battery technology on the market, choosing such an "optimal" battery to ensure all these scenarios can positively and negatively distort the resulting calculation values in terms of the final return. This may apply to variants with a smaller cyclic load in the case of Case A, Case B.

The individual cells of the batteries are connected to the racks and they include other components ensuring their overall functionality. The basic components of batteries include (Mandy, 2023, Commission regulation 2017/1485):

- Two-way converters AC/DC.
- AC and DC switchboard including fuse.
- Auxiliary switchboards - own consumption, UPS, measurement and control.
- Cooling system (HVAC).
- Fire protection system (EPS).
- Storage management system – BMS.
- Internal or external design - depending on the situation.

The mentioned complex of components is sufficient for connecting the battery to the existing infrastructure when outputting power to the LV switchboards of existing entities. Ensuring the supply and implementation of the following components is not usually part of the BESS system.

In subsequent calculations, we abstract from the associated characteristics:

- VVN connection, protection and fuse,
- transformer NN/VN,
- invoicing measurement system,
- HRM and connection to ASDR PDS,
- construction work,

However, for battery management from the point of view of the considered cases, it is necessary to take into account software elements. The software ensures the command of the battery for the charging and discharging mode, as well as sufficient interdependence with business activities for the implementation of automated business activities and connection with the market:

- integration on TSO,
- integration into trading systems of the organised short-term market,
- prediction systems in connection with the operation of RES.

To calculate the returns, we work with the proportion design of the basic variant of the battery so that the battery can be used optimally for all the proposed cases. The key parameter is the minimum battery performance and its capacity for providing balancing services. The parameters of balancing services are defined in the TSO technical conditions (SEPS, 2023, Moradzadeh et al., 2021). To store electricity from RES, we use the optimal size of the photovoltaic power plant, taking into account the designed power and battery capacity. The resulting battery proportions are valued according to market research of available manufacturers for CAPEX and OPEX items. We specify the technical parameters in the following parts of the article. For the proposed cases of battery system operation, we model the electric energy flows and their impact on the used technology using the calculation tools of the IPESOFT company in 15-minute cycles during one calendar year (Garbier, 2023). We link the resulting technical values of the operation with market data, thereby determining the generated financial income. For the evaluation of the economic return, we model individual cases of operation, which provide a comprehensive view of the income generated by the use of the battery system according to the proposed cases. We define the net return according to the Free ROI (Return on Investment) method (Caleton and Hurman, 2021). The amount of return in years is influenced by the sensitivity of economic inputs and we evaluate the potential for the electricity market development.

To determine the size of the battery, we will start from the most limiting case B) Provision of frequency and non-frequency services – balancing services for TSOs. Other cases are not tied to technical conditions and allow any combination of performance and battery capacity. From this point of view, we design a battery system so that the ratio of performance and capacity is in the optimal range of each case. The minimum battery power for the provision of balancing services (PpS) is set at 1 MW. The basic conditions for the provision of balancing services are defined in the SOGL regulation and the technical conditions of the relevant TSO (Lepieš, 2023, ENTSOEe, 2017b, Commission regulation 2016/631). Battery performance and capacity vary with respect to the type of service provided, including a minimum margin for battery capacity reduction during lifetime, including the difference between installed and usable capacity (Moradzadeh et al., 2021). When providing PpS, we consider FCR, aFRR, mFRR services. In principle, for the FCR service it is necessary to install a battery with a power of 1.25 MW / 1 MWh for min. value of FCR = 1 MW and 1 MW / 2 MWh for min. value aFRR = 1 MW. Taking into account the minimum reserve of battery capacity and installed power for the purposes of revenue simulation, we use battery parameters 6 x BESS 0.8C - or 6 x 440 kW/550 kWh = 2.64MW/3.3 MWh with "Behind the Meter" installation, i.e. at the point of consumption, taking into account the necessary reserves. The proposed battery size allows to provide balancing services in the following ranges:

- 1MW aFRR,
- 2 MW FCR
- 1 MW mFRR

Table 1. Overview and explanation of basic battery parameters

Installed power 2,64 MW	Permanently achievable active power of the converters measured on the AC side.
Installed capacity 3,3 [MWh]	Total capacity of battery cells at the beginning of life (BoL - Beginning of Life).
Usable capacity SoC 5. 98 [%]	Usable capacity (BoL) taking into account the minimum and maximum operational charge state of the SoC (SoC - State of Charge).
One-way efficiency 95%	Efficiency in one direction (charging or discharging), includes all losses, including cooling and other self-consumption.
Cyclic lifespan 6 570 [-]	Guaranteed number of cycles after which the battery reaches the end of its cyclic lifespan (EoL - End of Life). The end of the cyclic lifespan is defined by the decrease of the capacity to the level of SoH = 60% (State of Health). Given for different levels of depth of discharge DoD (Depth of Discharge). If the cyclic life exceeds the value of the calendar life, the limit becomes the calendar lifespan depending on the manufacturer's guarantees, app. 15 years.

Subsequently, we determine the CAPEX and OPEX costs for the assessed storage variant. CAPEX costs correspond to the scope of delivery in the sense of Behind the Meter BESS installation; OPEX costs represent the supplier's basic care and service (remote supervision, preventive inspection and warranty replacement of damaged parts in a defined time interval). The costs were determined in the form of a market survey based on indicative offers of the average price of suppliers in the market in the Slovak Republic.

Table 2. Specified costs of battery storage

Variant	BESS 0,8C
Installed power	440 kW
Installed capacity	550 kWh
CAPEX (*) (investment costs)	300 000 €
OPEX (*) (operating costs)	3 500 €/year

In the case of provision differences of balancing services, it is essential to ensure communication with the TSO, including ensuring the algorithmic purchase of electricity on the market. A similar solution is used to provide flexibility in short-term markets with an automated interface for the daily and intraday market. These solutions require a complex software solution that ensures automated battery operation. For the performance of these activities, we are considering the costs of a superstructure control system with the determination of the CAPEX range = €70,000 to €200,000 (depending on the management cases). We calculate the OPEX costs simply as 20-32% of the purchase price of the SW, including integration on the TSO, integration on the short-term market and system certification. Prices are set on the basis of indicative offers (Garbier, 2023).

The share of investment costs for CAPEX and OPEX items depends on the case used and we define them as follows:

- Case A: Optimising the use of self-generated electricity produced from RES - control is provided by the BMS battery system (without the need to use a superior control system):
  - BESS: 2,64MW/3,3 MWh
    CAPEX 1 566 000,- €
    OPEX 18 800,- €/year
  - SW:
    CAPEX 0,- €
    OPEX 0,- €/ year
- Case B: Providing frequency and non-frequency balancing services
  - BESS: 2,64MW/3,3 MWh
    CAPEX 1 566 000,- €
    OPEX 18 800,- €/year
  - SW: FCR
    CAPEX 100 000,- €
    OPEX 32 000,- €/year
  - SW aFRR, mFRR
    CAPEX 200 000,- €
    OPEX 52 000,- €/year
- Case C: Regulation of deviation and counter deviation
  - BESS: 2,64MW/3,3 MWh
    CAPEX 1 566 000,- €
    OPEX 18 800,- €/year
  - SW:
    CAPEX 70 000,- €
    OPEX 14 000,- €/year
- Case D: Providing flexibility in short-term electricity markets
  - BESS: 2,64MW/3,3 MWh
    CAPEX 1 566 000,- €
    OPEX 18 800,- €/year
  - SW:
    CAPEX 120 000,- €
    OPEX 24 000,- €/year

In addition to the mentioned costs, we calculate the other operational costs:

These costs cover ensuring the connection and output of the battery, including ensuring the distribution of electricity according to the legislation of the Slovak Republic (approved prices in 2023 and 2024). We implement the method of calculating operating costs from the point of view of applying existing fees uniformly for each considered case:

- Fee for system operation and system services €22,1976/MWh (URSO, 2023)
- Fee for electricity distribution and system losses €10,781/MWh (Price list of ZSD, 2023)
- Reserved capacity for very high voltage €4,554/MW/month (Price list of ZSD, 2023)

The resulting costs are listed separately in each case according to the simulated electricity flows.

Defining the revenue side and basic principles:

The revenues and costs of BESS operation in the mode of optimising the use of electricity from RES were determined by means of a simulation calculation according to the following principles:

Case A: Optimising the use of self-generated electricity produced from RES (see Appendix 2)

- The battery storage is charged in the event of electricity production from photovoltaic energy and discharged in the event that the photovoltaic power plant is without electricity supply.
    - At the same time, the condition is observed that the charging of the storage takes place at the time of the PV plant delivering to the network and the discharging of the storage at the time of the withdrawal of electricity from the network.
- Peak and off-peak price spread is used to calculate revenues. Using the off-peak price, the impact of the photovoltaic power plant investment is cleared.
- PV power is identical to the power of BESS inverters to enable storage of total PV production.
- Charging and discharging management is performed by the battery management system BMS with extended features.
- The simulation is carried out according to pre-planned flexibility or after the close of the daily market (according to the type of contract) and is further checked in real time against the assumption of PV production.
- On the revenue side, the considered profit from the difference between high and low prices is adjusted for losses during charging and discharging in the balance area of the Slovak Republic.
    - Average peak and off-peak price spread of €96.81/MWh is used in the calculations (Overall results of day ahead trading, 2024).
    - The average price of electricity in the balance area of the Slovak Republic is at the level of €101.60/MWh (Overall results of day ahead trading, 2024).
- On the revenue side, the cost savings for distribution fees (Price list of ZSD, 2023) are considered, which is created by the supply of electricity from battery storage at a time when electricity would otherwise be taken from the system. In the calculations, we base costs according to the revenues of the regulator of the Slovak Republic.

Case B: Providing frequency and non-frequency balancing services FCR, aFRR, mFRR (see Appendix 3)

- When providing the FCR service, the operation simulation is carried out based on the local measurement of the network frequency (Garbier, 2023). The battery storage provides positive regulatory power delivery services (discharge) based on the control signal from the TSO in the case of aFRR, mFRR service.

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On the revenue side, sales for availability are considered, which is paid by the TSO at a rate per €/MW/h of the availability provided. For the calculation, the TSO prices of the Slovak Republic are used as the average result of the daily selection procedures (URSO, 2023). Average marginal price of daily tenders on the Slovak market (Garbier, 2023):

- FCR availability €60.28 MW/h
- aFRR availability €55.60 MW/h
- mFRR availability €27.34 MW/h

- For the FCR service, the revenue for regulating electricity is not calculated, according to TSO rules. On the revenue side, sales for the supplied regulating electricity for the aFRR and mFRR service are considered according to the applicable market rules (Decree 246/2023).
- In the course of regulation, an energy deficit arises in the storage, which is continuously compensated by withdrawal from the network. In the case of the FCR service, battery recharging is charged at the price of the deviation. With the aFRR and mFRR service, the withdrawal from the network is automatically purchased on the intraday electricity market (VDT OKTE) through the superior BESS information system.
- The electricity taken in this way is valued at the estimated price on the VDT market, which is based on historical values on the daily market (D-1 ISOT). The cost of purchased electricity is included in the item recharge costs.
- The value of the withdrawal from the network is charged with distribution fees, distribution fees are included in the calculation in the costs of recharging. In the calculations, we base costs according to the revenues of the regulator of the Slovak Republic (URSO, 2023, Price list of ZSD, 2023).

Case C: Deviation control (anti-deviations)

The battery storage provides regulation services of the operator's balance area through add-on software - the balance area regulator. Based on the prediction of the direction of the system deviation, the controller affects the charging / discharging direction of the BESS so that power changes act against the direction of the system deviation. For price calculation, the balance area of the Slovak Republic is included.

- On the revenue side, the considered revenues for the positive deviation of the clearing entity (counter-deviation) are netted of losses from the negative deviation caused by the BESS regulation in the event of an error in the prediction of the direction of the systemic deviation. The considered accuracy of the prediction of the direction of the system deviation is 87% (the accuracy was determined on the basis of outputs from the real operation of existing prediction systems) (Garbier, 2023).

- The price of the deviation is determined on the basis of real historical prices for individual simulated periods (2023, 2024) of the balance area of the Slovak Republic. The average price of a positive deviation is €125.95/MWh and a negative deviation -€5.49/MWh (OKTE, 2024).
- During regulation, there is no energy deficit in the storage – the regulation system maintains the state of charge automatically within the specified range and reacts to system deviation only in the direction that the current state of energy in the storage allows (discharges only if there is enough energy, charges only if there is a shortage of energy).
- The value of withdrawal from the network is burdened by distribution fees (Price list of ZSD, 2023), distribution fees are included in the calculation in the charging costs. In the calculations, we base costs according to the revenues of the regulator of the Slovak Republic (URSO, 2023, Price list of ZSD, 2023).

Case D: Providing flexibility in short-term electricity markets

- Battery storage is charged at times of low prices and discharged at times of high prices.
- The simulation is prepared for two business cases depending on the type of contractual relationship with the electricity supplier:
  - Flexibility on the daily market – in the case of transferred responsibility for the deviation and valuation of the contract for the supply / purchase of electricity at the spot price of the OKTE daily market (ISOT D-1). Activation of the flexibility is scheduled in advance after the close of the daily market at time D-1 (Overall results of day ahead trading, 2024).
  - Flexibility on the intraday market – in case of own responsibility for the deviation and active algorithmic purchase and sale of electricity on the OKTE VDT market. Algorithmic buying and selling is ensured by the superior BESS information system.
- On the revenue side, the considered profit from the difference between high and low price is cleaned of charging and discharging losses.
- On the cost side, distribution fees are considered. In the calculations, we base costs according to the revenues of the regulator of the Slovak Republic (URSO, 2023, Price list of ZSD, 2023).
- The development of the maximum and minimum price of electricity is shown in Appendix 3. The average electricity price spread on the daily market was reached at the level of €96.81/MWh and on the intraday market at €98.78/MWh (Overall results of day ahead trading, 2024).

3. Findings and Discussion

In order to assess the economic return, a basic model of the battery system was selected for all cases so that its usability and economic return could be assessed. Investment and operating costs for the battery system were determined for each defined case. The modelling of the battery operation in the calculation model takes into account the stated criteria according to the individual cases and described principles. The result of the calculation is the calculated total costs and total revenues according to the way the battery is used and the development of prices on the electricity market, including the derived economic return. In the following overview Appendix 4, we present the achieved results from the simulation according to defined criteria and individual cases.

Case A: Optimising the use of self-generated electricity produced from a photovoltaic power plant shows a low economic return of 18.18 years. This is caused mainly by the insufficient difference in the price of electricity between peak and off-peak, as well as by the lower cyclic usability of the battery. In this case, we exclude the investment of the photovoltaic power plant from the calculation by using the off-peak price, the price of which corresponds to the length of depreciation of the connected photovoltaic power plant. The cost saving on distribution fees caused by the nature of the use of this case also has a positive effect on the return. Battery utilisation results from the ability to store excess electricity production and its delayed consumption in relation to the used total capacity of the battery. If we were to increase the battery capacity and thus the amount of charged and discharged energy, the return of such a system would decrease only slightly due to the increase in CAPEX items for added battery cells, which make up the highest share of investment costs. The cyclic life of the system is at the level of 20 years and is above the payback level.

Case B: Providing frequency and non-frequency balancing services on battery systems proves to be an effective investment from the point of view of economic return. This solution cannot be dispensed with without a fully automated superior control system, which ensures communication with the TSO and performs automated algorithmic trading operations, which will subtly increase the demands on the overall investment. For the FCR and aFRR service, the assessment of the economic return from the point of view of energy projects is at an excellent level of 1.95 and 4.85 years. The resulting return depends mainly on the total payment for the traded availability, which may drop significantly due to the market connection to the Mari and Picasso platforms. With the mentioned battery solution, the break-even point of return at the battery lifetime level is €10/MW/h for the FCR service and €22/MW/h for the aFRR service. If we assess the provision of the mFRR service, its low return of 18.73 years results mainly from the low price for availability and the low usability of the battery, which is caused by the low number of service activations. The use of the battery for the provision of balancing services achieves a high cycle life of over 25 years.

Case C: Regulation of deviation (anti-deviation) as a non-guaranteed service for regulation against the direction of system deviation has its justification. Although in our calculations, the payback of this solution is at the level of 15 years, at the time of high price deviations (in the years 2021÷2022) it was at the level of 1.8 years. This solution is often used as a backup business case for the provision of balancing services in the event of a "favourable" development of the deviation price. The breaking point only occurs when the price for the deviation exceeds €200/MWh, when this solution starts to pay off. However, the current market trend indicates a negative return development far beyond the battery life, which does not favour this solution.

Case D: Providing flexibility in short-term electricity markets is based on the natural way of using the battery, using the basic principle of electrical energy storage. Case A works in a similar way (charging electricity in times of excess and its consumption in times of shortage). The basic principle is to use the low prices of electricity by purchasing it during the off-peak time and to consume this electricity from the battery during its highest purchase price during the Peak time. This solution uses the natural development of the price of electricity during the day and is directly dependent on the price difference over time. In the above calculations, this solution has the worst return and is almost unusable in practice. However, this situation would change with an increase in the spread price difference above €230/MWh, which would mean significantly cheap electricity during the off-peak and, conversely, expensive electricity during its peak.

4. Summary and conclusion

The mentioned calculations indicate that the solution to the long-term problem of storing electrical energy from renewable sources is not economically attractive in the long term. The investment requirement of battery systems predetermines their use in the short-term period at the level of hours and minutes, where they excel in their performance and regulatory ability in balancing immediate imbalances in the distribution network. If we evaluate battery systems as an investment, the clear conclusion is its use for the regulation of frequency and non-frequency services for TSOs, where it achieves excellent results. The model solution in the case of providing balancing services such as FCR and aFRR+ currently achieves the best return in the range of two to five years. This trend is also confirmed by the increasing number of installations of battery systems on the Slovak market for the provision of frequency and non-frequency services, which will be counted in tens of MW.

Although market conditions favour this trend for the time being, the subsequent integration of balancing services markets as part of the integration into the Mari and Picasso platforms may bring about a turnaround. If we evaluate the development of the prices of balancing services in Europe (ENTSOe, 2023), the payment for availability will reduce the return of the system and will reach the level of the lifetime of the BESS. If individual TSOs are to guarantee the quality and frequency stability of the network, they should consider the intentions of preserving local providers, which results mainly from the nature of frequency regulation, which takes place exclusively in individual locations by the FCR service. In this context, small players such as battery system operators will be sensitive to price instability, which is becoming a common phenomenon in the energy market.

The limitations of the presented study results are associated with the accuracy of the data used in relation to the time and state of the battery systems, self-consumption, etc. However, they are sufficient for the needs of evaluating the economic return. At the same time, the study is oriented to a specific time, to selected types of batteries that are suitable for the given purpose. The study focused on evaluating one type of battery and its behaviour in different uses. The choice of one type of battery is optimal from the point of view of all investigated methods of their use. Nevertheless, it may not be the most optimal for a specific given purpose (specific case, CASE A or CASE B, etc.), which can cause inaccuracy from the point of view of the impact on the purchase price of BESS versus the economic return. The use of battery systems in different situations is influenced by different areas and factors associated with them. These areas can be both local and global in nature. Thus, the limitations of this article include the fact that it does not examine all areas and factors affecting the use of battery systems. This limitation is an opportunity for further research to explore other areas affecting the deployment and use of battery systems.

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Appendix 1

Table 3. Basic characteristics of individual battery types

Characteristics	Pb (Lead Acid)	LFP (LiFePo4)	NMC (Li-NMC)	LTO (Li-Titanate)	VRB (Vanadium Redox Flow)
Cell voltage	2.0 V	3.3V	3.6V	2.3V	1.55V
Energy density	50 Wh/kg	120 Wh/kg	200 Wh/kg	80 Wh/kg	20 Wh/kg
Number of cycles (80% DoD)	300	5000 – 10 000	5000 – 8 000	20 000	“unlimited”
C-rate (ratio of kW output and kWh capacity)	< 0.2	<= 1	<= 1	< 4	< 0.3
Calendar lifespan	4-6 years	10-20 years	10-20 years	20 years	5 years electrolyte filling
Investment costs	low	medium	medium	high	high

Appendix 2

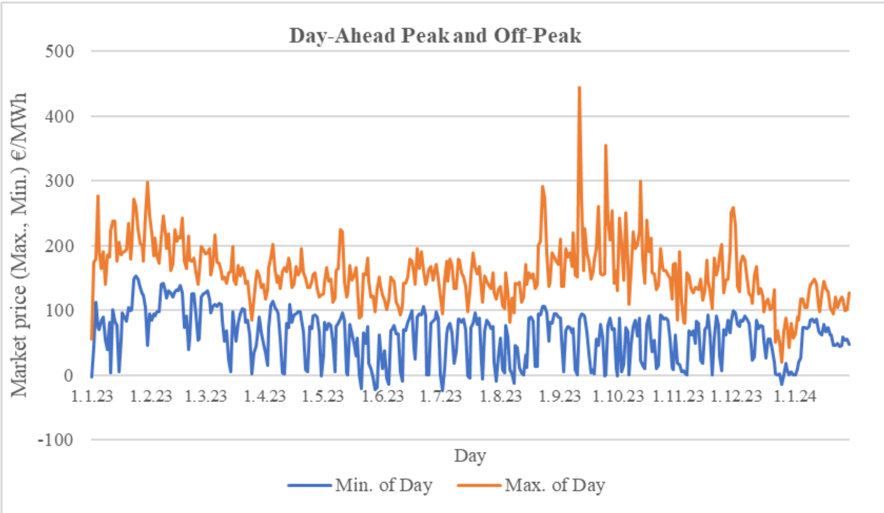

Fig. 1. Daily price development at the market since 2023 (Min., Max) (OKTE, 2024)

Appendix 3

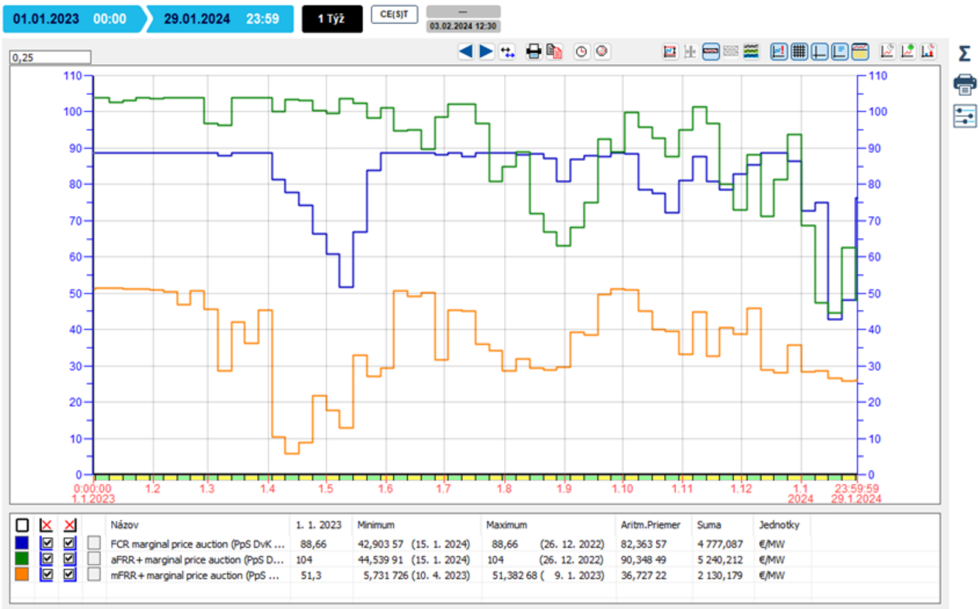

Fig. 1. Weekly development of the marginal price of services (balancing services) since 2023 (Garbier, 2023).

Appendix 4

Table 4. Output from the simulation of the battery system operation

Item	Case A	Case B			Case C	Case D	
	BESS + FVE	**FCR**	**aFRR+**	**mFRR+**	**Deviation**	**Flexibility D**	**Flexibility VDT**
BATERY	BESS 2.64 MW / 3.3 MWh						
Used power for regulation	2.0	2.0	1.0	1.0	2.0	1.0	1.0
CAPEX	(€)	(€)	(€)	(€)	(€)	(€)	(€)
Battery	1 566 000	1 566 000	1 566 000	1 566 000	1 566 000	1 566 000	1 566 000
Control system	0	100 000	200 000	200 000	70 000	140 000	140 000
OPEX	(€/year)	(€/year)	(€/year)	(€/year)	(€/year)	(€/year)	(€/year)
Battery	18 800	18 800	18 800	18 800	18 800	18 800	18 800
Control system	0	32 000	52 000	52 000	14 000	28 000	28 000
RK fees	0	109 296	54 654	54 648	109 296	54 654	54 654
Recharge costs	-13 058	32 251	184 032	18 123	44 438	3 896	3 896
PROFIT	(€/year)	(€/year)	(€/year)	(€/year)	(€/year)	(€/year)	(€/year)
Annual return	91 886	1 048 872	673 959	237 858	295 496	87 586	134 336
Annual return - net	91 886	907 325	435 274	165 087	141 761	29 036	29 036
RETURN OF INVESTMENT	(years)	(years)	(years)	(years)	(years)	(years)	(years)
	18.18	**1.95**	**4.85**	**18.73**	**15.01**	**Non-refundable**	**58.86**
ELECTRIC FLOW	(MWh)	(MWh)	(MWh)	(MWh)	(MWh)	(MWh)	(MWh)
Discharging (MWh)	874	727	622	36	2 245	971	971
Charging (MWh)	968	844	735	42	2 538	1 076	1 076
OPERATYNG CYCELS	(cycles)	(cycles)	(cycles)	(cycles)	(cycles)	(cycles)	(cycles)
Cycles / year	328,50	238	231	238	1 092	365	365
Cyclic lifespan	6 570	6 570	6 570	6 570	6 570	6 570	6 570
LIFESPAN	(years)	(years)	(years)	(years)	(years)	(years)	(years)
	20.0	27.6	28.4	27.6	**6.0**	**16.4**	**18.0**