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Smart control of energy storage system in residential photovoltaic systems for economic and technical efficiency

DOMINIKA KACZOROWSKA ✉, JACEK REZMER, PRZEMYSLAW JANIK, TOMASZ SIKORSKI

Wroclaw University of Science and Technology
Wybrzeże Wyspiańskiego 27, 50-370 Wroclaw, Poland
e-mail: {✉dominika.kaczorowska/jacek.rezmer/przemyslaw.janik/tomasz.sikorski}@pwr.edu.pl

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Abstract: In recent years, due to the increasing number of renewable energy sources, which are characterised by the stochastic nature of the generated power, interest in energy storage has increased. Commercial installations use simple deterministic methods with low economic efficiency. Hence, there is a need for intelligent algorithms that combine technical and economic aspects. Methods based on computational intelligence (CI) could be a solution. The paper presents an algorithm for optimising power flow in microgrids by using computational intelligence methods. This approach ensures technical and economic efficiency by combining multiple aspects in a single objective function with minimal numerical complexity. It is scalable to any industrial or residential microgrid system. The method uses load and generation forecasts at any time horizon and resolution and the actual specifications of the energy storage systems, ensuring that technological constraints are maintained. The paper presents selected calculation results for a typical residential microgrid supplied with a photovoltaic system. The results of the proposed algorithm are compared with the outcomes provided by a deterministic management system. The computational intelligence method allows the objective function to be adjusted to find the optimal balance of economic and technical effects. Initially, the authors tested the invented algorithm for technical effects, minimising the power exchanged with the distribution system. The application of the algorithm resulted in financial losses, €12.78 for the deterministic algorithm and €8.68 for the algorithm using computational intelligence. Thus, in the next step, a control favouring economic goals was checked using the CI algorithm. The case where charging the storage system from the grid was disabled resulted in a financial benefit of €10.02, whereas when the storage system was allowed to charge from the grid, €437.69. Despite the financial benefits, the application of the algorithm resulted in up to 1560 discharge cycles. Thus, a new unconventional case was considered in which technical and economic objectives were combined, leading to an optimum benefit of €255.17 with 560 discharge cycles per year. Further research of the algorithm will focus on the development of a fitness function coupled to the power system model.

Key words: economic efficiency, energy storage system ESS, microgrid management, optimal power flow OPF, particle swarm optimisation PSO

1. Introduction

1.1. Motivation

In recent years, thanks to the rapid development of renewable energy technologies, there is a growing interest in storing energy [1]. The reason behind this are the key problems of integrating a renewable energy source (RES) with the power system such as reverse power flow in low-voltage distribution systems, large voltage fluctuations, uncertainty of generated power, maintaining power quality and economic profitability. It appears that the use of an energy storage system (ESS) and optimal power flow control can bring solutions to these problems and significant profits regardless of the type of consumer. The complexity of the optimisation problem and the choice of ways to solve it using modern methods adapted to the microgrids under study are emphasized [2].

1.2. State of the Art

For a distribution system operator (DSO), a battery-based energy storage system (ESS) can be used to improve power quality [3], minimize losses [4] or other services such as reactive power management [5, 6].

For individual consumers and prosumers, ESS can be of great importance in the technical aspect, for example, to shape the power curve exchanged with the distribution system [7, 8] and especially in the economic aspect to minimize the cost of energy consumed [9].

Currently, intensive research is being conducted on chemical energy storage technologies for grid applications focusing on features such as high efficiency, flexible energy characteristics, long life, low investment and operating costs, and environmental impact. A detailed review of the state of the art and future prospects for lithium-ion batteries is described in [10]. An analysis of the current literature on the topic of integrating energy storage systems (ESS) and renewable energy sources (RESs) also shows a significant increase in research related to optimising storage systems through energy management, which is expected to lead to effective solutions for smart grids [11].

Given the huge advances in computational intelligence (CI) methods for solving difficult, nonlinear optimisation tasks [12] and in artificial intelligence (AI) methods for forecasting generation power from renewable sources, load power forecasting, and market-based energy prices [13] modern ESS control methods could be the beginning of creating true electricity smart grids [14].

There are studies in the literature that question the economic viability of using ESS, especially in deregulated electricity markets [15, 16], which is usually the result of using simple stochastic optimisation models. This argument can be contradicted in cases where more complex control algorithms based on artificial intelligence methods are used [17, 18].

The smart grid concept involves applying CI to the current power system to achieve full control over energy demand and supply in real-time. Distributed energy management algorithms and strategies are proposed using the smart system to achieve optimal goals [19].

Power flow management can be implemented in technical and economic aspects, or by combining both aspects in the adopted objective function. The optimal selection of microgrid components, i.e., algorithms for solving problems related to the sizing, distribution and operation of storage systems, also plays a significant role [20, 21].

The basic technical aspect of managing the operation of the microgrid realizes the goal of high consumption of its own RES and minimizing the excess power flowing back to the distribution system. The paper [22] proposes a variable charging and discharging threshold method for ESS and its own adaptive intelligent technique (AIT). In [23], evolutionary dynamic programming and deep learning of artificial neural networks (ANNs) are introduced to optimally use RES and ESS to deliver critical load at all times. Based on the state of the grid system, energy dispatch control signals are generated and evaluated by the ANN. A similar approach is presented in [24] where an ANN is optimised with particle swarm optimisation (PSO). The paper [25] proposes a holistic control and power optimisation strategy for microgrids. Predictive control using the droop method and evolutionary PSO algorithm for active and reactive power control were developed. Managing both load and generation systems is considered a strategic approach to optimal microgrid operation as shown in the [26]. The optimal operation of the ESS set by the energy storage management system is usually predictive and relies heavily on knowledge of the battery's state of charge (SOC). The SOC depends on many factors (e.g., the material, electrical and thermal state of the battery), making an accurate assessment of the battery's SOC complex. A comprehensive overview of the main SOC prediction methods is presented in [27, 28]. The article [29] proposes an online control method for managing virtual ESS. An algorithm based on the Lyapunov optimisation structure was developed. The advantage of the online algorithm is that it only makes decisions based on the realization of the current states of the system, without predicting future states.

The economic aspect ties microgrid tasks to the electricity market, presenting a solution for an optimal schedule that allows microgrids to participate in the energy market. The analysed publications include simple deterministic rule-based energy management algorithms demonstrating the financial benefits of the proposed approach [30–32]. More advanced methods are also proposed. The paper [33] describes an ESS control strategy using the model predictive control (MPC) technique to maximize economic benefits. New approaches to predictive control (MPC) are presented in [34, 35]. They are distinguished by the fact that, given a long enough prediction horizon, a microgrid can modify its output to manage power deviations in electricity market prices. Mixed linear programming (MLP) was used to implement the optimal control model in [36]. The goal is to minimize the total operating cost of the system by making optimal use of the energy storage device and the cogeneration unit. Robust control systems for ESS have been proposed in the [37]. The global optimum of the control problem is obtained using mixed-integer linear programming (MILP). The proposed strategy provides an effective reduction in the cost of energy used. An important parameter of the method is the state of charge estimated by a partial linearization technique using nonlinear efficiency maps. The genetic algorithm (GA) technique is used in [38] to determine the optimal settings of distributed generation (DG) units. Based on energy tariffs and realistic load profiles, the developed control scenarios are evaluated. The optimal scheduling of the ESS in [39] is obtained from a neural network model. A charging and discharging plan ESS based on social costs and technological constraints calculates the algorithm PSO shown in the [40]. The algorithm considers a limited number of discharge cycles and power tariffs. A predictive algorithm using dynamic programming methods with battery aging optimisation was proposed in [41]. In real conditions, the effectiveness of the predictive schedule depends on the accuracy of the microgrid state predictions [42]. A two-layer predictive energy management system is described in [43]. The authors consider the degradation costs of ESS concerning charging depth and life, batteries and supercapacitors. The method minimizes the total operating cost and eliminates fluctuations due to prediction errors. Economic optimisation using information exchange between either the microgrid or the master system is presented in [44, 45]. Through this mechanism, the balance of supply and demand in the microgrid can be guaranteed and at the same time the cost of the system operation can be minimized. Similarly [46], uses a cooperative approach that guarantees the availability of an optimal solution, Demand response program motivates consumers to participate in the market. The model is formulated as MILP. The article [47] proposes a method for creating distributed ESS that takes into account battery degradation costs. The method aims to maximize the operating profit for aggregators participating in the electricity market, while minimizing battery degradation costs. A linear model that calculates the depth of battery degradation can be effectively included into optimisation models. The minimum cost of energy exchange between the power grid and the penalty cost of node voltage deviation is described by the objective function in [48]. An optimal scheduling model for ESS in the distribution network based on mixed integer scheduling was proposed. The scheduling method takes into account the state of health (SOH) of the ESS and SOC changes.

1.3. Research gaps and contribution of the work

The methods currently used in commercial offerings implement simple deterministic algorithms that respond to the current state of the grid. According to an analysis of the state-of-the-art research, an intensive search is going on for efficient methods of energy management in microgrids. The aim is to develop scalable, intelligent and accurate algorithms that take into consideration multiple technical and economic aspects simultaneously. Such solutions can be artificial intelligence methods.

There are three main reasons for the lack of developments that can already be implemented in microgrid systems:

- The first reason is that installations containing local generation and energy storage have only been implemented in the last decade, and research in the first place has mainly focused on optimising device parameters and their location.
- The novelty of heuristic algorithms is the second reason for the lack of effective algorithms. Only in recent years has it become possible to use efficient and versatile algorithms for solving real optimisation problems based on heuristic approaches. This has made it possible to model complex objective functions related to smart grid infrastructure while reducing numerical complexity. However, methods belonging to the computational intelligence group are at an early stage of research, so often algorithm development requires additional research on the chosen heuristic algorithm.

– The third reason for the lack of solutions is the legal and economic reorganization of the energy sector due to international commitments. To achieve economic, environmental and energy safety goals, prosumers and small producers are expected to be very active in the energy market. To implement solutions, control algorithms must base their operation on information from the energy market, which is currently due to the ongoing changes in legislation and energy market rules in many countries.

The paper presents a new algorithm that uses artificial intelligence methods which are applied to optimise the control of power flow in microgrids. The contributions are as follows:

– The method provides technically and economically efficient control with minimal numerical complexity. The objective function combines technical and economic aspects.
– The developed algorithm allows scalability to any already existing microgrid systems (industrial, urban, rural, residential, single-family house networks).
– The algorithm applies load and generation forecasts over any time horizon and with any time resolution.
– The method applies the real characteristics of the energy storage systems ensuring that technological limits are maintained. The characteristics were independently determined by the authors in a separate study.

2. System model, ESS characteristics, control algorithm, technical and economic aspects

2.1. A simplified microgrid model

The microgrid model used for power flow calculations was developed based on the actual low-voltage network in the residential building. The parameters of devices and cable connections in the model correspond to the real ones. This approach allows the simulation results to be compared with the measurements. The model of the investigated system is shown in Fig. 1, where PS – distribution system; PO – demand power; PG – generated power; PM – power of the storage. The described grid consists of an energy storage system (ESS), a photovoltaic power plant (PV) and a load. The microgrid is connected via a transformer to the distribution grid.

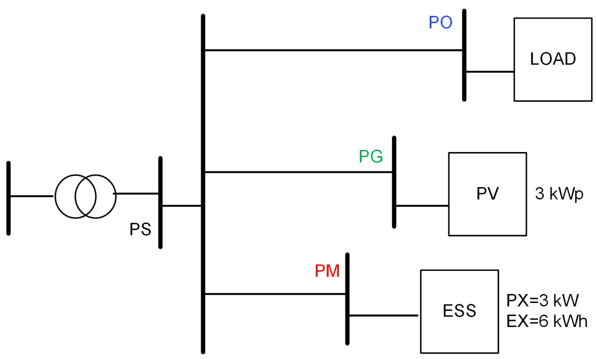


Fig. 1. The model of the microgrid

2.2. ESS characteristics

For proper control of the energy storage, its characteristics must be defined. These characteristics determine the operating constraints implemented by the manufacturer and can be an additional tool for controlling the operation of the ESS. The shape of the curves depends on technical constraints, fabrication technology, operating temperature, degradation and how the storage is controlled and managed by the energy storage management system (BMS).

As ESS equipped with Li-ion batteries have a high efficiency of 94% [49], the influence of this parameter was not included in the calculations. In addition, in comparative analyses, efficiency will equally affect the calculation results.

An important parameter of the ESS is the lifetime stated in discharge cycles. A typical value for the currently offered ESS is 3 000 cycles, which guarantees a service life of 8 to 10 years with appropriate control [10, 31].

An effective method for determining the real characteristics of the ESS is to use the measurements taken during device operation. The authors described the procedure in detail in [50]. For the considered case, the obtained characteristics are shown in Fig. 2, where: PLC – the available power for charging and PRC – for discharging; PLO, PRO – available power of the storage under extreme charging and discharging conditions; EX – the storage capacity; T – time step.

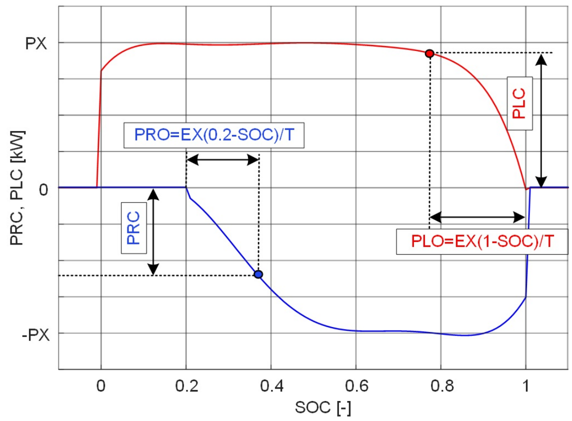


Fig. 2. Charging and discharging characteristics of the ESS

2.3. Control algorithm

The main purpose of the energy storage system control algorithm is to manage the excess or deficit of power generated by local microgrid sources.

In the first part of the analysis, the authors use a deterministic algorithm that calculates the charging or discharging power of the storage (PM) and the power exchanged with the distribution system (PS) based on the data on the generated power (PG), the demand power (PO), the storage capacity (EX) and the dispatchable power of the storage (PX). The algorithm can meet the objectives in technical and economic aspects, which is why the variable PZ was introduced, which corresponds to the demanded power of the power exchanged with the distribution system.

Depending on the sign, PZ power can be either distributed (+) or consumed (–). The essential elements of the algorithm are the characteristics of the energy storage P(SOC), based on which, depending on the state of charge (SOC), the available power for charging (PLC) and discharging (PRC) of the storage is determined. The algorithm also takes into account the available power of the storage under extreme charging and discharging conditions (PLO, PRO), which depends on the available energy in the storage. The algorithm has been used by the authors before and has been presented, for example, in [13].

The difference between deterministic and non-deterministic control is that in the second case the scenario is not used, and the ESS operating plan (PM) is determined directly as a result of the optimisation calculation. Assuming the same input conditions (PG, PO, PZ, EX and PX), the calculated operating plan of the energy storage system (PM) in the two approaches will be different. While a deterministic scenario reacts on an ongoing basis (in a given calculation step) to the values of demand and generation, a non-deterministic algorithm takes into account an entire set time interval, e.g. a 24-hour forecast. Energy storage control is optimised based on predefined generation power (PG) and load power (PO) profiles.

In the case of an analysis that takes into account technical aspects, an appropriate exchange power profile with the distribution system (PZT) is made. For the determined storage parameters: nominal capacity (EX), power (PX), and characteristics $\mathrm{P} = \mathrm{f}(\mathrm{SOC})$, the optimisation algorithm determines the optimal ESS operating plan (PM). The basic function of the optimisation goal is the best match between PS and PZ. The power value in the microgrid nodes is determined based on power flow calculations in the modelled power system. With this approach, energy costs can also be optimised, but this requires the construction of a suitable PZ profile.

In the case of economic-only optimisation, the objective function is modified. Now, it is not a question of matching the PZ profile as closely as possible, but of minimising energy costs. Based on daily forecasts of generation (PG) and load (PO), as well as variable energy tariffs, the algorithm selects the ESS operation plan (PM) such that, over the course of a day, costs are minimised and profits maximised.

It is also possible to combine technical and economic objective functions with different weights, and depending on the set weights, the algorithm will seek to make a compromise between cost and achieving a set power exchange profile (PZ). Another objective could be, for example, keeping the state of charge at an optimum level, or minimising the number of discharge cycles. The applied algorithm is shown in Fig. 3.

The following are entered as inputs: EX – maximum storage capacity, PX – maximum storage power, SOCX – minimum state of charge of the storage, $[\mathrm{PLC}, \mathrm{PRC}] = \mathrm{f}(\mathrm{SOC})$ storage characteristics. The inputs in the calculation loop for the following time steps T are: PG – generation power (–), PO – load power (+), PZ – set value for power exchange with the power system, (–) consumption, (+) dispatch, SOC – state of charge of the storage. These are calculated for successive time steps T: PM – storage power, (+) charging, (–) discharging, PS – value of power exchanged with the power system (–) consumption, (+) dispatch, SOC – state of charge of the storage. In the case of economics-based optimisation, the objective function is based on: minimising costs, maximising profits, and keeping the SOC at a certain level. The result of the optimisation is an ESS operating plan (PM).

The objective function is cost minimisation and profit maximisation. For a technical objective, it is the minimisation of the mean squared error of the fit to a set exchange curve with the power

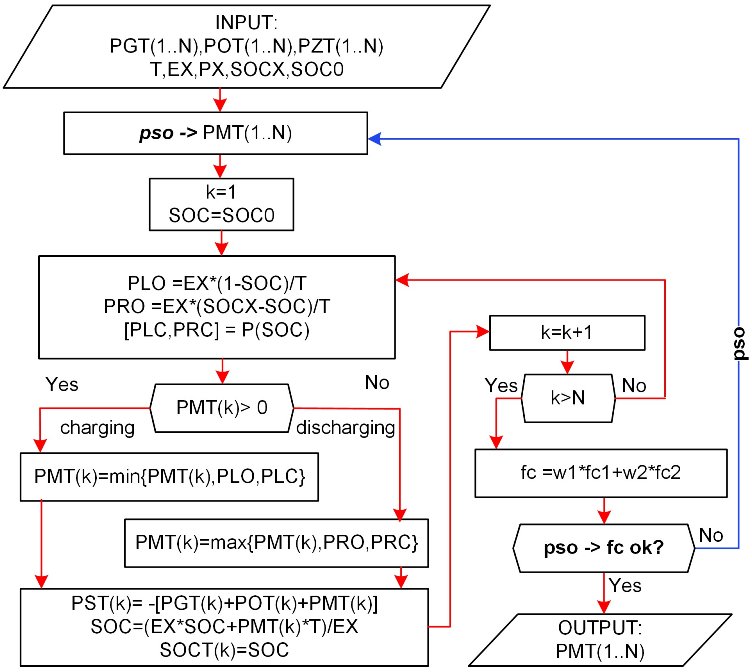


Fig. 3. Block diagram of non-deterministic storage system control

system. For a mixed objective, a combination of technical and economic goals, the objective function combines these two approaches. Before the final power of the energy storage is computed, the available power for charging or discharging is calculated based on the battery capacity, the minimum permitted state of discharge and the current state of charge. In the next step, the energy storage operation plan is determined based on its characteristics. These characteristics correspond to the technical limitations of the storage. Only by knowing these two limitations, the algorithm decides with what power it will charge or discharge the ESS.

The presented non-deterministic algorithm works based on particle swarm optimisation (PSO). The parameters of the applied PSO algorithm are shown in Table 1.

2.4. Technical and economic aspects

The application of energy storage systems for cooperation with the power grid in technical terms can have various purposes. These include: maintaining the required power quality parameters through load balancing, reducing load peaks, shifting load and generation peaks, limiting losses of transmission devices by reducing power flows, as well as voltage level control, limiting voltage asymmetry, emergency power supply and interaction with renewable energy sources. Examples of the design of the profile of power exchanged with the distribution system could be: a constant value of power, e.g. at zero; lowering load peaks to a pre-set level; lowering both load peaks and generated power peaks.

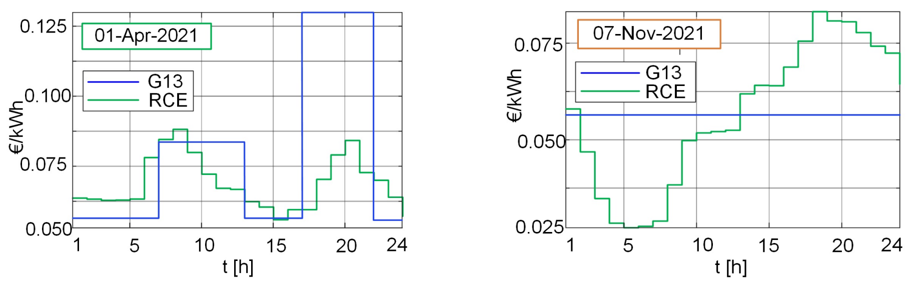
Table 1. PSO parameters

Symbol	Description	Parameter value
N	Size of search space (number of variables)	24 numbers of forecast hours
S	Swarm size	72
MaxIter	Maximum iterations	100
C1	Self-adjustment weight	1.1
C2	Social adjustment weight	1.1
Inertia	Inertia range	[0.1÷1.1]
Tol	Function tolerance	10e-4
Lb	Lower bound	– PX unlimited algorithm min(PO + PG) limited algorithm
Ub	Upper bound	PX unlimited algorithm max(PO + PG) limited algorithm

The economic analysis is based on prices for energy consumption according to the Polish G13 tariff [51]. This is a three-zone tariff, designed for households with up to 40 kW of contracted power. The G13 tariff differentiates between zones on business days (Monday–Friday):

– morning peak,
– afternoon peak (the most expensive zone),
– remaining hours of the day (the cheapest zone).

The time of each zone depends on the month. On days (Saturday-Sunday) and public holidays, one zone applies. An example of the distribution of prices per zone for the G13 tariff for a business day in the summer month (June) is shown in Fig. 4. Figure 4(a) shows the price distribution for



(a) (b)

Fig. 4. Distribution of G13 tariff and energy market prices (RCE) for two days: 1 April 2021 (a) and 7 November 2021 (b)

the business day, 1 April 2021. The morning peak applies from 7 a.m. to 1 p.m. and the afternoon peak from 5 p.m. to 10 p.m. Figure 4(b) shows the weekend, Sunday, 7 November 2021, with a single energy price for the entire 24-hour period.

Based on the G13 energy tariff and energy market data, an hourly schedule can be created for energy storage. The economic analysis is based on energy purchase prices according to the G13 tariff and energy sales prices according to energy market prices. Figure 5 shows the distribution of energy market prices for each day of 2021.

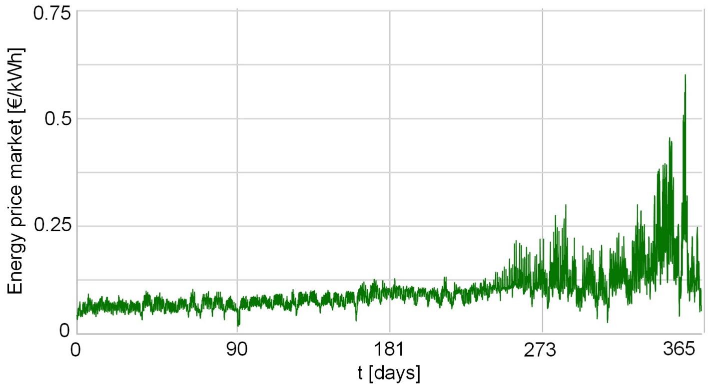


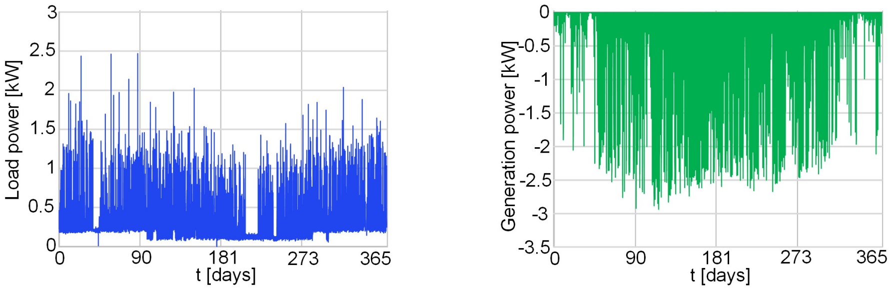
Fig. 5. Distribution of energy market prices in 2021

The development of the energy storage operating plan (PM), in economic terms, is based on a forecast of load (PO) and generation (PG) profiles as well as tariffs for purchased and sold energy. The aim is to minimise the cost of purchased energy and maximise the profit of sold energy.

3. Microgrid performance analysis

For all analyses presented in the paper, calculations were carried out for a detached house, located in Wroclaw (Poland), with an annual demand profile as shown in Fig. 6(a). There are PV panels on the roof of the building with an installed capacity of 3 kW. The annual output power of the PV installation is shown in Fig. 6(b).

The authors analysed the operation of the discussed microgrid in terms of five cases. The first and second example concerns the control of energy storage in terms of the implementation of the technical aspect. The performance of a deterministic algorithm was compared with an algorithm, using computational intelligence (CI). The authors then moved on to the implementation of the economic aspect, using the CI algorithm. Two cases were examined: energy storage does not cooperate with the distribution grid; storage cooperates with the distribution grid. The final analysis is a combination of the technical aspect and the economic aspect.



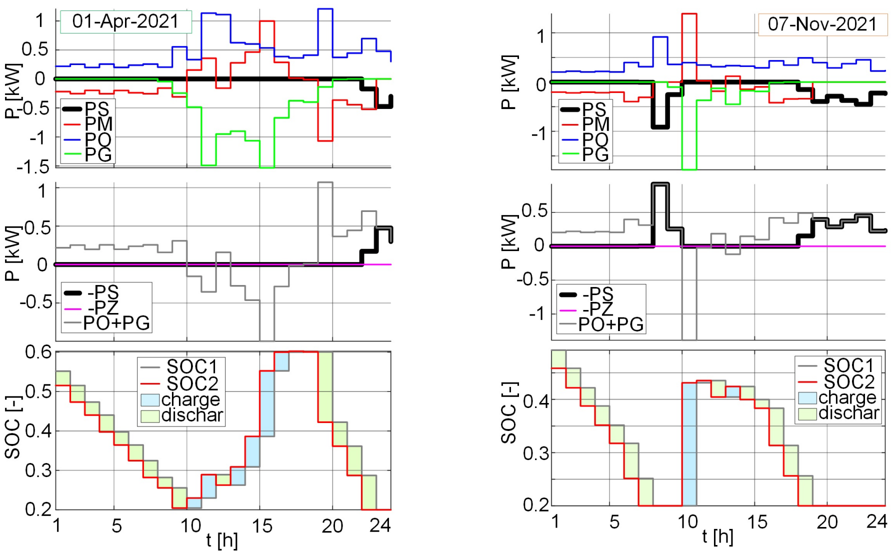
(a) (b)

Fig. 6. Distribution of demand power (a) and generated power (b) during the year 2021 for the analysed household with PV photovoltaic installation

3.1. Technical aspect, deterministic algorithm (DE PZ0)

The analysis of microgrid operation began with the most common scenario, i.e. the attempt to reduce the power taken from the distribution system to zero. The discussed case is a technical aspect and is usually proposed by companies that offer photovoltaic installations and energy storages. As a first step, the implementation of the aspect was undertaken using a deterministic algorithm.

Figure 7 shows the outcome of the control algorithm (power flow and variation of the energy storage state of charge) for two days: 1 April 2021 (a) and 7 November 2021 (b). Symbols in the



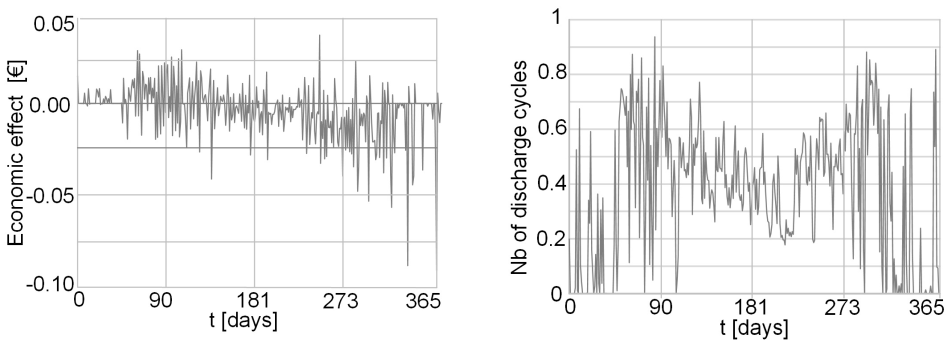
(a) (b)

Fig. 7. Power flow and variation in the state of charge of the ESS for the first case: technical aspect, deterministic algorithm (DE PZ0): (a) 1 April 2021; (b) 7 November 2021

figures indicate: PS – power exchanged with the distribution system, PM – charging or discharging power of the energy storage, PO – demand power, PG – generated power, SOC1, SOC2 – state of charge of the ESS at the beginning and end of the hour.

When analysing the curves in the figures, it is possible to see that on 1 April the energy storage worked more intensively, allowing it to reduce the power drawn from the distribution grid to zero almost throughout the entire day. The storage only ran out of energy at around 10 p.m. On the other hand, on 7 November, there are more instances of energy storage under-performance, with the control target not being met twice: between 8 a.m. and 10 a.m. and after 7 p.m. The situation is caused by the lower power generated by the photovoltaic installation. The operation of the storage system can be seen very well if one considers the variation of the state of charge. You can then see that on 1 April, the ESS is charging from 10 a.m. to 5 p.m. In contrast, on 7 November, it is charging at high power for an hour around 10 a.m., then at lower power around 1 p.m.

The second result of observing the operation of the grid after applying the algorithm, was an economic analysis. Figure 8(a) shows the profit and loss for each day of 2021 (positive values are profits, negative values are losses). Figure 8(b) shows the number of storage discharge cycles. The relatively frequent presence of losses may be worth noting. The number of cycles, on the other hand, is relatively small, not exceeding one discharging cycle per day.



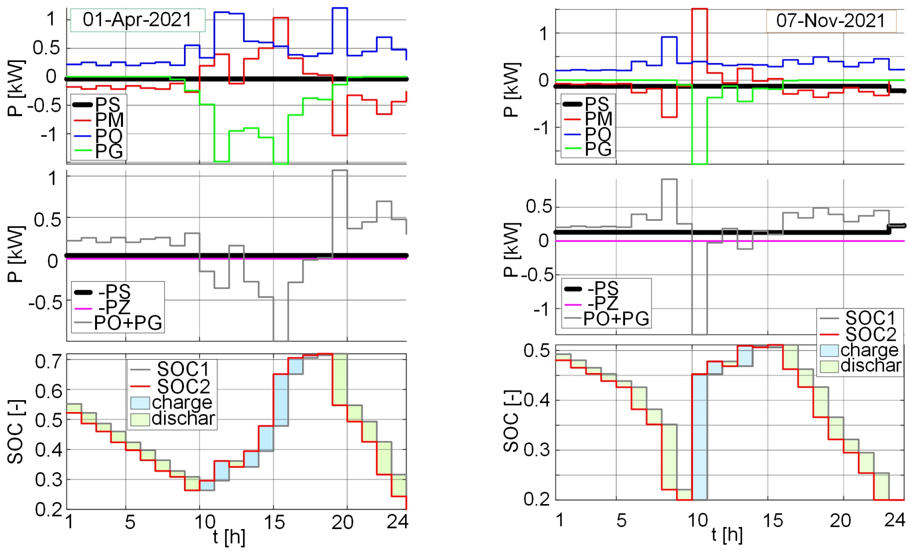
(a) (b)

Fig. 8. Economic aspect (a) and number of energy storage discharge cycles (b) for the first case: technical aspect, deterministic algorithm (DE PZ0)

3.2. Technical aspect, computational intelligence algorithm (CI PZ0)

The technical aspect implementation case described in section 3.1 was then executed with an algorithm based on computational intelligence (CI). The result of the application of the control algorithm is shown in Fig. 9. As before, the analysis applies to 1 April 2021, Fig. 9(a), and 7 November 2021, Fig. 9(b).

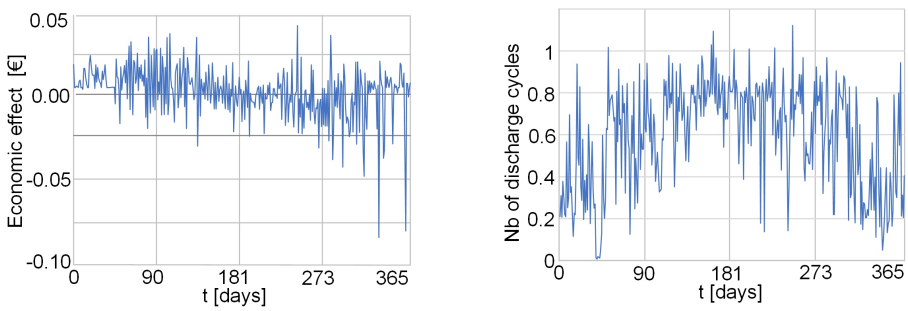
By analysing the obtained curves (Fig. 9), the main difference between deterministic and heuristic control can be seen. Applying the deterministic algorithm, either the consumed power is equal to zero or it is relatively far from the target value. In contrast, using the CI algorithm, we are never on the given straight line, but are always close. This is because the heuristic algorithm relies



(a) (b)

Fig. 9. Power flow and variation in the state of charge of the ESS for the second case: technical aspect, computational intelligence algorithm (CI PZ0): (a) 1 April 2021; (b) 7 November 2021

on generation and demand forecasts, and schedules the operation to minimise the distance from the target line throughout the 24 hours. In contrast, the deterministic algorithm runs hour-by-hour. If the ESS has enough stored energy, it will meet the demand, regardless of whether this energy is useful to it later or not. Similarly to section 3.1, in this case the authors also carried out an economic analysis (Fig. 10). It can be seen that there is a visible decrease in losses compared to



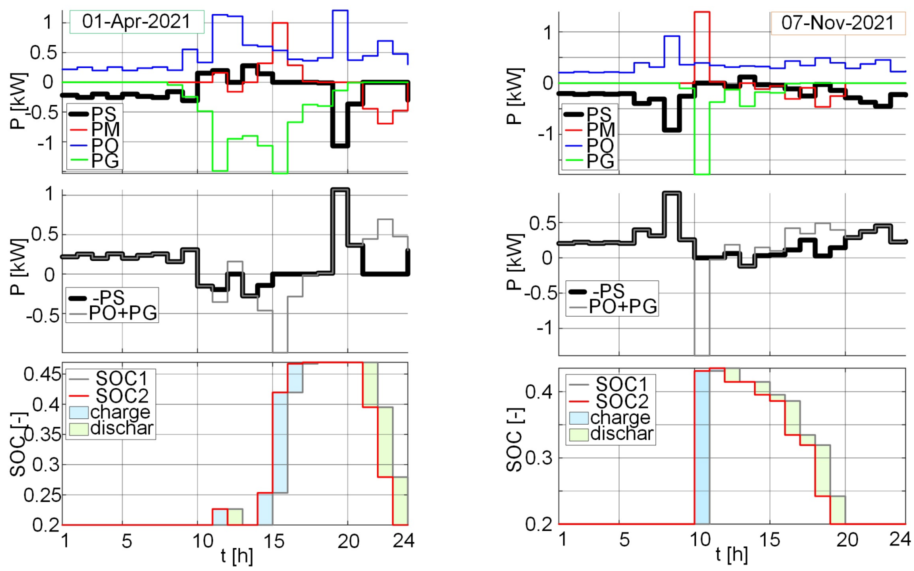
(a) (b)

Fig. 10. Economic aspect (a) and number of energy storage discharge cycles (b) for the second case: technical aspect, computational intelligence algorithm (CI PZ0)

the previous case, while the daily number of storage discharging cycles increases. However, it still does not exceed one per day.

3.3. Economic aspect, computational intelligence algorithm (CI), ESS does not cooperate with the grid (CI LIM)

In the next step, the authors applied the CI algorithm for the energy storage control to optimise the economic effect, i.e. minimise losses and maximise profits. An additional constraint was introduced into the algorithm, the storage can be charged utilising only the power generated by the PV plant. Discharging, on the other hand, can only occur to meet the demand. The power flow is shown in Fig. 11.

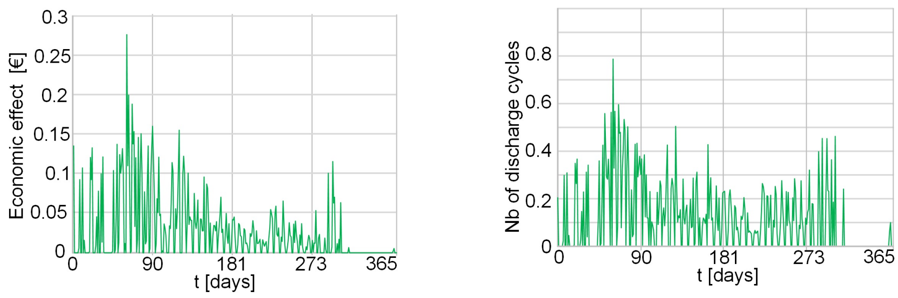


(a) (b)

Fig. 11. Power flow and variation in the state of charge of the ESS for the third case economic aspect, computational intelligence algorithm (CI), ESS does not cooperate with the grid (CI LIM): (a) 1 April 2021; (b) 7 November 2021

By analysing the obtained curves, it can be seen that for most of the day, the demand is covered by the power system. The energy storage starts working when there is an excess of generated power, which it uses to recharge itself, to partially cover the demand later. The curve of power taken from the system has not been aligned to zero, but has been flattened.

Figure 12 shows the economic analysis of the case. It can be seen that, unlike the previous two cases, this time there are no losses. The economic optimisation has therefore reduced costs significantly.

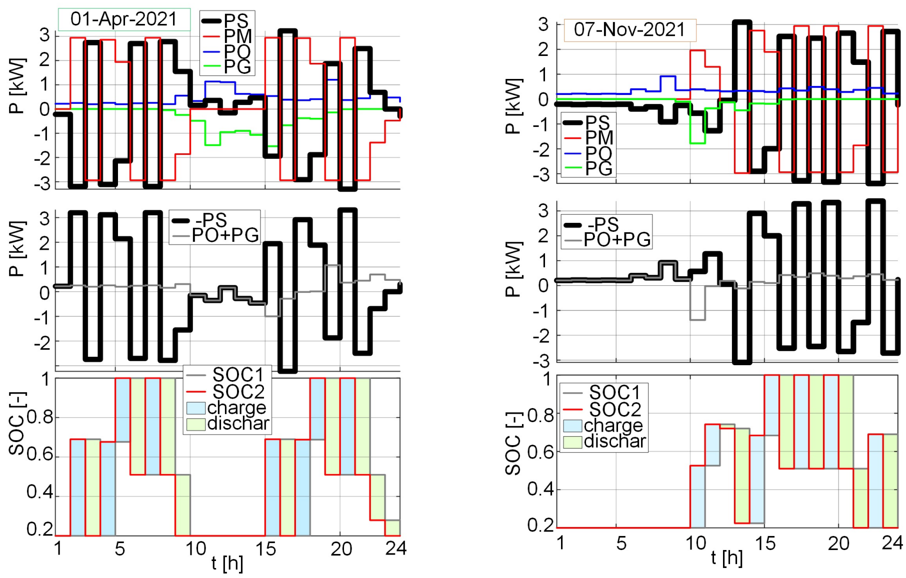


(a) (b)

Fig. 12. Economic aspect (a) and number of energy storage discharge cycles (b) for the third case: economic aspect, computational intelligence algorithm (CI), ESS does not cooperate with the grid (CI LIM)

3.4. Economic aspect, computational intelligence algorithm (CI), ESS cooperates with the grid (CI NO LIM)

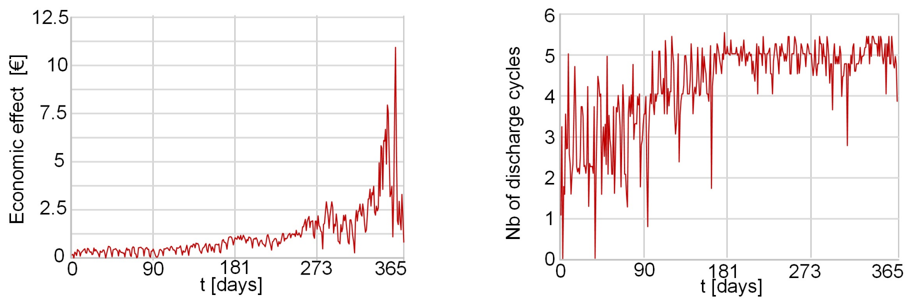
The following step considers a similar case as in section 3.3, but this time no constraint is imposed on the storage system due to its interaction with the distribution system. The operation of the storage is therefore only limited by its capacity and characteristics. The power flow is shown in Fig. 13.



(a) (b)

Fig. 13. Power flow and variation in the state of charge of the ESS for the fourth case economic aspect, computational intelligence algorithm (CI), ESS cooperates with the grid (CI NO LIM): (a) 1 April 2021; (b) 7 November 2021

Examining the power flow, there is a difference from the previous case. Since the energy storage does not limit the power consumption from the distribution system, the algorithm is very active in reducing losses and maximising profits, which translates into frequent charging and discharging of the storage. While this significantly minimises costs and increases profits, it also increases the daily number of discharging cycles of the storage up to five. The situation is well illustrated in Fig. 14.



(a) (b)

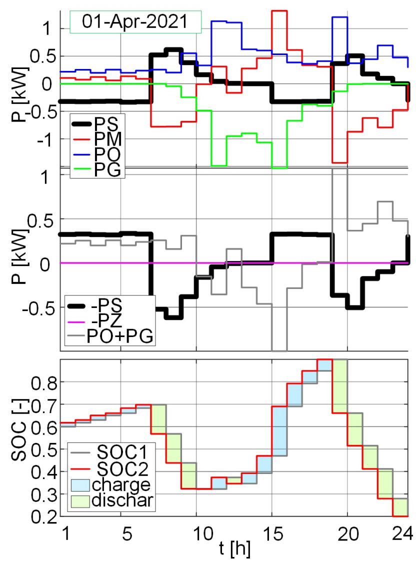
Fig. 14. Economic aspect (a) and number of energy storage discharge cycles (b) for the fourth case: economic aspect, computational intelligence algorithm (CI), ESS cooperates with the grid (CI NO LIM)

3.5. Technical and economic aspect, computational intelligence algorithm (CI), ESS cooperates with the grid (CI MIX)

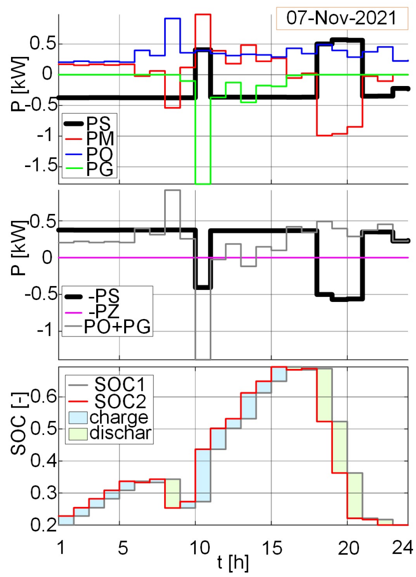
Looking at the cases considered so far, it can be seen that the best economic results were obtained in section 3.4, but such a high number of discharging cycles is not acceptable. It is therefore necessary to partially reduce the cooperation between the storage and the distribution system. Section 3.5 therefore proposes a final solution, which is to combine two aspects, the technical and the economic aspect. In the case considered, the objective function consists of minimising costs and maximising profits, as well as minimising the mean squared error of the distance from a straight line with a value of zero. The economic aspect had a weighting of 1, while the technical aspect had a weighting of 0.05. This allowed for a significant improvement in the economic results and a simultaneous reduction in the number of storage discharging cycles to an acceptable value. Figure 15 shows the power flow, while Fig. 16 shows the economic analysis.

To compare the effects of all five cases more clearly, Fig. 17 shows a summary in the form of a bar chart: economic effects, Fig. 17(a), and the annual number of storage discharge cycles, Fig. 17(b).

An observation can be made that, using the first two energy storage control strategies, the use of storage results in economic losses. With the third strategy, the economic results are negligible. In these cases, the annual number of discharge cycles is low. For the last two strategies, the economic effect is much better, while the annual number of energy storage discharge cycles increases. The last strategy is a sort of compromise between the economic and technical effect

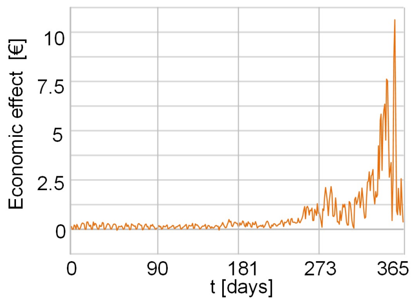


(a)

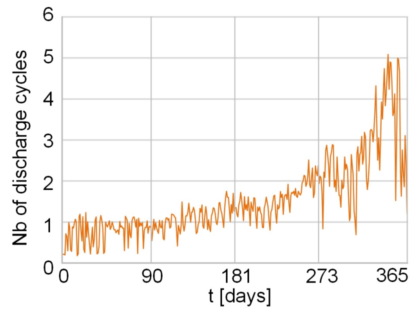


(b)

Fig. 15. Power flow and variation in the state of charge of the ESS for the fifth case: technical and economic aspect, computational intelligence algorithm (CI), ESS cooperates with the grid (CI MIX): (a) 1 April 2021; (b) 7 November 2021



(a)



(b)

Fig. 16. Economic aspect (a) and number of energy storage discharge cycles (b) for the fifth case: technical and economic aspect, computational intelligence algorithm (CI), ESS cooperates with the grid (CI MIX)

of the number of discharge cycles. This makes it possible to draw the more general conclusion that an improvement in the technical effect carries with it a deterioration in the economic result.

The results of the calculations for the annual simulations are given in Table 2.

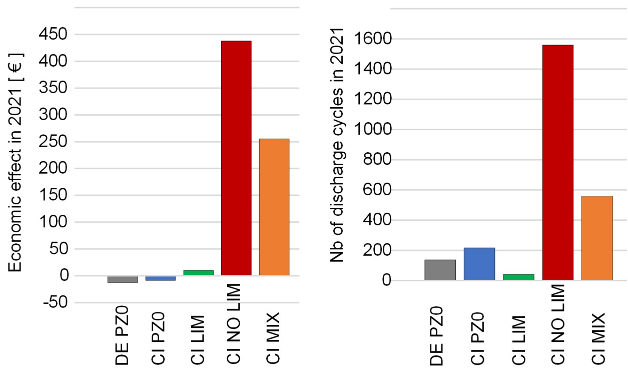


Fig. 17. Summary of the considered cases. Economic aspect (a) and number of energy storage discharge cycles (b) for the entire year 2021

Table 2. Economic aspect and number of energy storage discharge cycles

Algorithm	Economic effect in 2021 [€]	Number of discharge cycles in 2021
DE PZ0	–12.78	136
CI PZ0	–8.68	216
CI LIM	10.02	41
CI NO LIM	437.69	1 560
CI MIX	255.17	560

4. Conclusions

The paper presents an ESS control algorithm that is based on computational intelligence methods. The objective function focuses on economic aspects, such as minimising the cost of the consumed energy, as well as technical aspects, such as compensating to zero the power exchange between the microgrid and the distribution system.

The key factor is the problem of assessing the viability of the investment under real market conditions, i.e. minimising energy storage costs. A method of cost analysis for Li-ion batteries taking into account different unit costs and discharge cycle lengths is discussed in [10].

In the paper, annual simulations of the performance of an ESS operating in a residential microgrid with a PV system placed on the roof are carried out. The study applies real load and generation measurements. An assumption was made that the installed ESS has a rated power of 3 kW and a capacity of 6 kWh. The operation simulations were carried out for the whole year, scheduling the ESS operation daily according to 1-hour load and PV generation forecasts. The economic effect of the control for the adopted energy sales and purchase tariffs in 2021 depends on the algorithm used. Daily and annual energy costs/profits and the number of storage discharge cycles were used as a measure of ESS control efficiency.

The results of the CI algorithm were compared with the effects provided by deterministic control, which enforced the minimisation of power exchange with the distribution system, aiming to maximise the consumption of locally produced energy. The optimal control is the last considered case, which combines technical and economic aspects. The algorithm was based on the CI, the objective function combined both aspects. The application of the algorithm resulted in a profit of €255.17, with 560 discharge cycles. The control in technical aspects is characterised by discharge cycles of 136 to 216 and results in financial losses ranging from €8.68 to €12.78. The control in terms of economic aspects with no restrictions on charging from the grid yields a profit of €437.69, but the number of discharge cycles of 1 560 is unacceptable due to the lifespan of the ESS. As the results of the study illustrate, maximising the use of locally produced energy is not always associated with minimising energy costs, and the effect can be worse than in a system without a storage system. This is due to fluctuations in the market prices of energy sold and energy purchased in multi-zone tariffs.

In the prosumer billing systems which are currently favoured, it is recommended to use a control algorithm that, with zero annual economic gain, for example, maximises the lifetime of the ESS. The computational intelligence method allows the objective function to be adjusted to find the optimal balance of economic and technical effects.

Recommendations for further research include: the development of extended objective functions that, without deteriorating the direct economic effects, will support microgrid operation, e.g. by improving power quality, minimising voltage fluctuations at microgrid nodes, load symmetrisation, extending storage system life, etc. To do so, the objective function will require parameters calculated in an accurate suitably adapted power system model.

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