

Scenario analysis for smart microgrids towards a holistic decarbonization of energy systems by using local energy sources

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ABSTRACT

This paper presents a technical-economic analysis of a microgrid system that incorporates distributed energy resources (DER) such as a photovoltaic (PV) system, battery energy storage system (BESS) and emergency generator, aimed at providing energy reliability and cost optimization in islanded or difficult-to-access areas such as the proximity of the Danube Delta from Romania. The study is centered on peak shaving, load shifting and battery management strategies enabled by BESS, which are essential for reducing energy costs during peak demand and optimizing energy usage by storing excess renewable energy and its utilization during high-demand periods and considering large market energy prices, that can vary. In other to better study the interactions between the different energy management strategies a microgrid system consisting of a renewable energy source, an energy community, a generator and BESS system was simulated using a number of possible scenarios. The analysis highlights the benefits of BESS in managing renewable energy variability, stabilizing grid frequency, and improving system resilience. Furthermore, the paper presents how software tools like Ignition, Grafana, and MariaDB are used together to monitor and manage data flow within the microgrid system, this data can be used in order to improve the algorithm.

1. Introduction

Microgrids and Renewable Energy Communities (REC) play a crucial role in the global evolution of energy systems towards greater sustainability and efficiency. Microgrids can offer innovative solutions for efficiently integrating renewable energy sources, such as solar panels and wind turbines, while simultaneously optimizing energy consumption through management techniques like "peak shaving" and "load shifting" [1–3]. A dynamic energy management model with multiple energy production sources is investigated in Ref. [2]. The integration of multiple small-size distributed energy resources, mainly with direct current production, in the local energy communities and microgrids requires proper coordination and development, which is investigated in Ref. [4]. The techniques and the proposed framework allow for balancing fluctuating energy demand and supply, which is essential for maintaining grid stability and efficiency. These systems can optimize

resource distribution in real-time, minimizing energy losses and reducing reliance on traditional energy sources [4]. The implementation of a microgrid system poses its own difficulties and challenges, both financial and technical. The challenges of managing the unpredictable nature of renewable energy sources and the benefits of using networked microgrid systems are explored in Refs. [5,6]. An advanced energy management system for multi-microgrid systems with renewables energy sources and demand response, using neural network load forecasting and optimization algorithms for reducing operational costs and increased reliability in case of main supply interruption is analyzed in Ref. [5].

A control strategy for isolated microgrids with small hydropower plants, wind turbine and energy storage, for frequency and voltage control in case of load demand fluctuations and renewable energy variations is proposed and investigated in Ref. [6].

A hybrid photovoltaic-biomass energy system for off-grid areas,

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demonstrating through technical and economic analyses that such a system can reliably provide electricity while significantly reducing emissions is carried on in Ref. [7].

The impact of different pricing models and market mechanisms on the operability of RECs revealed the need for optimization models that account for economic and regulatory variables. These models must be flexible enough to adapt to diverse legislative frameworks and market conditions, providing scalable and cost-efficient solutions [8]. As investigated in Refs. [9,10] planning and careful selection of methods represent an important element in achieving an efficient microgrid, that has the necessary conditions to control the installation properly.

The development and validation of optimization models that promote the efficient integration of renewable technologies can serve as foundation for the transition towards sustainable energy infrastructures at local, national, and international levels [11].

Adaptability is a necessary trait for a microgrid in order to properly benefit from the opportunities offered by the energy market. The use of a multi-agent system framework for networked microgrids is explored in Ref. [12]. By making use of strategic pricing mechanism and reinforcement learning it enables the participating microgrids to better make use of their own resources. By interacting with microgrids from the same cluster, they are able to minimize the grid dependency and to sell the surplus energy, and this aspect is further improved by interacting with the other microgrid clusters connected to the system.

A renewable energy source that can also be integrated with a microgrid system is represented by hydrogen. The impact of using hydrogen as an energy source is explored in Ref. [13], where the use of a hydrogen-compatible micro gas turbine and wind turbines is researched. With the help of advanced machine learning and real operation data, the synergy between the electrolyzer and the gas turbine is used to provide a robust energy storage solution that benefits both the performance of the system and its stability. During periods of high energy production, the energy that can't be used or sold to the grid can instead be used to produce more hydrogen, this way the energy can be used at a later time and minimize the grid dependency. The analysis of a PV-wind system for an island supply in presence of storage systems and complementing with green hydrogen storage, using measured data and stochastic optimization for minimizing energy costs, is carried on in Ref. [14].

The energy storage system can also be used to obtain benefits for the microgrid, to allow it to better control the volatility that comes with renewable energy sources and to diminish the curtailment in order to achieve a cost-efficient operation. This aspect is explored in Ref. [15] where the importance of the energy storage system capacity and its use in order to maximize the total available resources is highlighted.

Another tool that allows the better manage the available resources is represented by the forecast. The production of the renewable energy source, the weather and the consumption associated with the microgrid can be forecasted. This method was researched and showcased by Ref. [16] on isolated microgrid networks. By making use of data gathered from weather station and a machine learning-based clustering method, a forecasting framework for short-term generation of photovoltaic energy was created. This allows the microgrid to better use the energy available in order to maximize the possible benefits, and with the use historical data the accuracy will be improved over time.

Another essential and often overlooked aspect for microgrids is the security of the system. Without proper tools it can be affected negatively from outside, this situation having unforeseen consequences [17].

This paper deals with a simulated environment that allows the testing of different configurations and behaviors for distributed energy resources, consumers and grid operations in an area from Romania with various technical challenges. In comparison with other tools for simulating microgrid and SCADA, the proposed system has the advantage of a robust and quick to use data acquisition platform with a multitude of protocols available for a large number of equipment's. Another advantage of this tool is plug and play nature, if the system is applied to a functioning system it can be easily adapted for both monitoring and

control if the existing equipment allows it. The placement of the microgrid is in proximity to Danube Delta, Romania, an area that provides multiple technology challenges and will highlight the efficiency of different microgrid configurations. The environment aims to be modular, scalable, benefiting from an easy-to-use interface that allows the user to run and simulations to multiple scenarios in short time [18].

2. System configuration

The area comprising the Danube Delta is characterized by a power system that is not developed at the 110 kV level due to the specific nature of the area. Being an isolated, marshy and difficult to access area, it poses major challenges in terms of electricity supply. The electricity network in this region is partly connected to the national system and partly dependent on local sources, including renewable ones.

Small wind farms, installed between 2010 and 2012, are connected to the medium-voltage network. Part of the 110 kV network, in the area connected radially to the Tulcea Vest station, multiple wind farms with capacities between 15 MW and 80 MW are in operation. The consumption of Tulcea County is a maximum of 400 MW at peak load. The only station belonging to the transmission operator is the Tulcea West 400/110/20 kV station.

The installation of the third 400/110 kV 250 MVA transformer in the Tulcea station increased the injection power from the distribution towards the transmission system for taking over the production from the wind power plants connected to the distribution network, safely supplying consumers in the area and allowing operation with the 110 kV network in the Tulcea area, which is disconnected from the networks in the Constanța-Medgidia area, as shown in Fig. 1.

Many villages in the Danube Delta are not directly connected to the national grid. The following alternatives are being used:

- Diesel generators (especially in small villages such as Mila 23, Letea, Caraorman, etc)
- Solar panels + batteries (sometimes combined with generators in hybrid systems)

Problems encountered in the area:

- Difficult access: the distribution network is difficult to maintain due to the lack of road infrastructure and challenging terrain, posing problems to the grid operator.
- Limited consumption: many homes and public institutions have low and intermittent consumption due to the population density of the zone.
- Voltage instability: fluctuating voltages, frequent power outages in isolated villages.
- High costs: operating diesel generators is both expensive and polluting

One effective way to maximize renewable energy generation with photovoltaic (PV) panels while minimizing space usage is by using bifacial (dual-faced) panels. Installing these panels over a lake takes advantage of the water's reflective properties to boost energy output, while the water also helps to keep the panels cooler, improving their efficiency. The placement must be in an area that does not disturb or affect the local wildlife negatively, and the use of wind sources was avoided because of this and the marshy terrain present in the region that can't support the weight.

The combination of software's presented in the article allows rapid and efficient integration of existing equipment with a reliable control system. The interface allows for fast data acquisition and visualization, furthermore complex control algorithms can be implemented to better manage the energy inside the microgrid.

The proposed model can be used as a planning and analysis for the implementation of microgrids. For example, this tool was used to

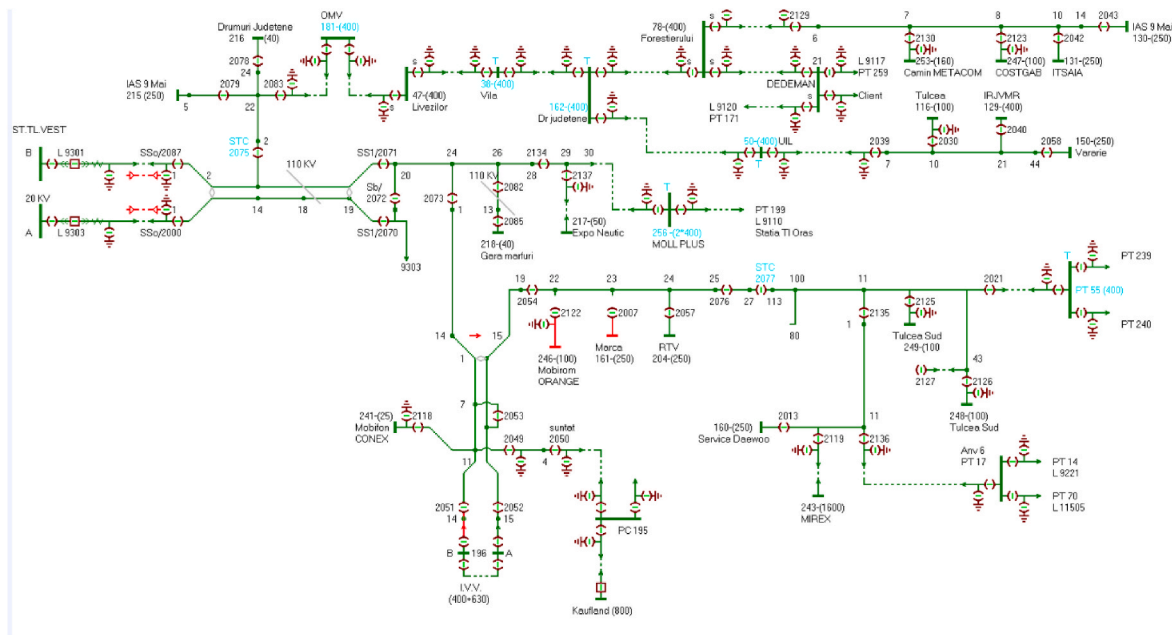


Fig. 1. The energy network from Tulcea county.

evaluate the Tulcea area, Romania, an area with wind and photovoltaic potential but isolated on the supply side of the national electricity grid. Based on weather records, consumption records every 15 min and the different equipment available in the microgrid, different operating scenarios can be chosen.

2.1. Microgrid configuration

A typical Renewable Energy Community (REC) configuration with a focus on the integration of distributed energy resources (DER) is considered in Ref. [19]. The system architecture includes the following main components:

- Photovoltaic System (PV): A 1 MWp power plant that provides renewable energy to the community;
- Battery Energy Storage System: A 750 kWh battery is used to store excess energy generated by the PV system or purchased from the upstream grid during off-peak hours. The battery can discharge energy during periods of high demand (peak shaving) or when PV generation is insufficient;
- Emergency Generator: A diesel-based emergency generator is included to ensure continuous energy supply in the event of long-term disconnection from the main supply;
- Upstream grid: The microgrid is interconnected with the mains supply, which provides supplemental energy when required and allows the microgrid to export excess energy;
- Control and Monitoring Platform: The microgrid operates through a supervisory control and data acquisition (SCADA) system using Ignition software. Ignition manages the interaction between DERs, controls energy flow, and collects data for monitoring and decision-making [20].

The microgrid operates in both grid-connected and islanding modes, allowing for resilience and energy autonomy in various areas [20,21]. The system is designed to support the critical energy consumption of a community located in proximity to Danube Delta, Romania that necessitates reliable, self-sustaining energy infrastructure. The difficult geography of the area presents complex challenges and opportunities to assess the system in multiple scenarios, further proving the potential benefits and drawbacks. The location also allows the utilization of a

mixed energy source consisting of both wind and solar plants to mitigate the dependency on upstream grid. While the system was developed for this specific case study it, its flexibility allows it to be adapted with ease to another project and run the specific algorithms and simulations.

2.2. Simulation environment

To assess the performance of the microgrid and optimize its operation under various conditions, a simulation environment was developed using a combination of Python, MariaDB, and Grafana. The following components are key to this environment:

- Hourly Energy Demand Simulation: The energy demand is simulated using historical load profiles for local communities. The demand data ranges between 1.1 MW and 2.5 MW, which reflects the variability of energy usage within the REC;
- PV Generation Simulation: PV power generation is modeled based on real-time weather conditions, including solar irradiance and temperature data sourced from publicly available weather databases [22], and hourly production data coming from PV plants;
- Battery Storage Behavior: The BESS charging and discharging cycles are modeled based on real-time energy demand and PV generation. The simulation accounts for battery capacity, maximum charging/discharging rates, and battery efficiency (90%). A custom algorithm determines whether to charge the battery from excess PV generation or discharge it to cover demand peaks [23];
- Grid Interaction Simulation: The interaction with upstream grid is simulated considering both grid import and export tariffs. The system automatically purchases energy when PV generation and battery storage are insufficient and sells excess energy back to the grid when demand is low and storage is full [24,25].

In order to create a simulation that is as close to real life as possible, data from local public weather stations and the free OpenWeather API was used for the solar irradiance during a summer period. For the energy production, data from local PV plants was used and daily forecasts, as illustrated in Fig. 2. The period of time varies from one year data sets with hourly data to monthly datasets that have a 10-min resolution. For the BESS behavior, information from battery storage systems technical specifications were used to simulate the charge/discharge behavior and

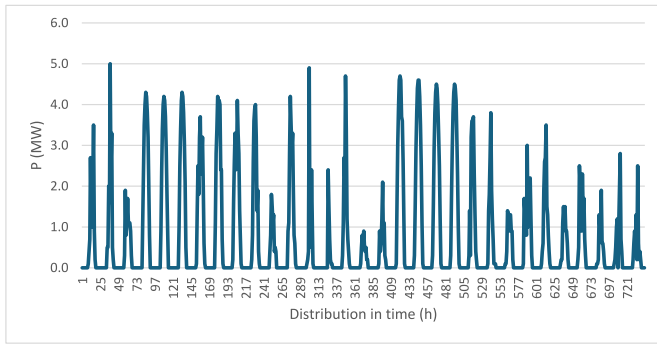


Fig. 2. Production Data from a local PV plant for June and July.

the energy loss for these processes. The data used for consumption are obtained from distribution operator records for an area. The data was curated and adapted for the simulated system and used for the scenarios presented in Table 1.

The simulation environment allows for real-time testing of various configurations, enabling the evaluation of energy flow, cost optimization, and overall system performance under a variety of different scenarios (Fig. 3). From the PCC towards the load the nominal voltage of the grid is 0.4 kV, and from the upstream grid and the PV + BESS plant the voltage is 10/20 kV.

3. Mathematical modelling

The analysis demonstrates the effectiveness of integrating a Battery Energy Storage System (BESS) for peak shaving in a microgrid environment. With a 250-kWh discharge capacity and 750 kWh storage, the system offered significant benefits in reducing peak demand, although certain limitations were observed due to the relatively modest capacity of the battery. These findings align with previous research, which highlights the role of BESS in smoothing out demand fluctuations and improving grid efficiency.

A simplified mathematical model for optimizing a microgrid system that includes distributed energy resources (DER), such as a photovoltaic system (PV), a battery energy storage system (BESS), and an emergency generator is presented. The model focuses on cost optimization and ensuring the reliability of the microgrid system [26,27]. The presented constraints ensure that the BESS acts in the way that benefits the system with a long term benefit goal instead of short term basis. These benefits can be further improved by taking into account the provision of system services to the grid while ensuring the microgrid is still functioning in the desired matter.

3.1. Decision variables

1. $P_{PV}(t)$ = Power produced by the PV system at time t [kW].
2. $P_{BESS}^{ch}(t)$ = Charging power of the BESS at time t [kW].
3. $P_{BESS}^{dis}(t)$ = Discharging power of the BESS at time t [kW].
4. $SOC(t)$ = State of charge of the BESS at time t [%].
5. $P_{GEN}(t)$ = Power produced by the emergency generator at time t [kW].

Table 1
Parameters of the presented scenarios.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Consumption (daily)	36 MWh	37.5 MWh	9.4 MWh	36.6 MWh	13.2 MWh
PV Production	6 MW	0 MW	6.2 MW	5.7 MW	5.8 MW
BESS	No	No	Yes	Yes	Yes
Cost (Euro)	4080	5100	1270	4940	1560

6. $P_{LOAD}(t)$ = Load consumption at time t [kW].

3.2. Parameters

1. C_{PV} : Cost of energy produced by the PV system [€/kWh].
2. C_{BESS} : Cost of using the BESS (includes charging/discharging and degradation costs) [€/kWh].
3. C_{GEN} : Cost of using the emergency generator [€/kWh].
4. η_{ch} : Charging efficiency of the BESS.
5. η_{dis} : Discharging efficiency of the BESS.
6. SOC_{min} , SOC_{max} : State of charge limits of the BESS [%].
7. $P_{GEN,max}$: Maximum power of the generator [kW].
8. $P_{BESS,max}$: Maximum charging/discharging power of the BESS [kW].
9. E_{BESS} : The energy stored in the BESS [kW]

3.3. Objective

Minimize the total cost of the supplied electrical energy, considering 1 h electricity market time interval:

$$\min \sum_{t=1}^T (C_{PV} \cdot P_{PV}(t) \cdot 1 + C_{BESS} \cdot (P_{BESS}^{ch}(t) + P_{BESS}^{dis}(t)) \cdot 1 + C_{GEN} \cdot P_{GEN}(t) \cdot 1) \quad (1)$$

3.4. Constraints

a) Energy Balance:

$$P_{PV}(t) + P_{BESS}^{dis}(t) \cdot 0.9 + P_{GEN}(t) \geq P_{LOAD}(t) + P_{BESS}^{ch}(t) \cdot 0.9, \forall t \in [0, 24] \quad (2)$$

3.4.1. BESS limits

$$SOC(t+1) = SOC(t) + \frac{P_{BESS}^{ch}(t) \cdot \eta_{ch} \cdot t - P_{BESS}^{dis}(t) \cdot t / \eta_{dis}}{E_{BESS}}, \forall t \in [0, 24] \quad (3)$$

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \quad \forall t \in [0, 24] \quad (4)$$

$$0 \leq P_{BESS}^{ch}(t) \leq P_{BESS,max} \quad \forall t \in [0, 24] \quad (5)$$

$$0 \leq P_{BESS}^{dis}(t) \leq P_{BESS,max} \quad \forall t \in [0, 24] \quad (6)$$

3.4.2. Generator limits

$$0 \leq P_{GEN}(t) \leq P_{GEN,max} \quad \forall t \in [0, 24] \quad (7)$$

3.4.3. PV production

$$0 \leq P_{PV}(t) \leq P_{PV,max}(t) \quad \forall t \in [0, 24] \quad (8)$$

where $P_{PV,max}(t)$ depends on meteorological conditions and the efficiency of the PV system.

3.4.4. Reliability

To ensure the analyzed microgrid can reliably meet energy demand, especially under critical conditions, various reliability constraints can be added. These constraints are essential for managing risks associated with the variability of renewable energy production and for preventing interruptions. Here are some examples of reliability constraints that can be integrated into the model:

3.4.4.1. Probabilistic reliability constraint. This constraint requires that the probability of meeting the energy demand $P_{LOAD}(t)$ must be greater than a certain reliability threshold α :

$$\mathbb{P}(P_{PV}(t) + P_{BESS}^{dis}(t) + P_{GEN}(t) \geq P_{LOAD}(t)) \geq \alpha \quad \forall t \in [0, 24] \quad (9)$$

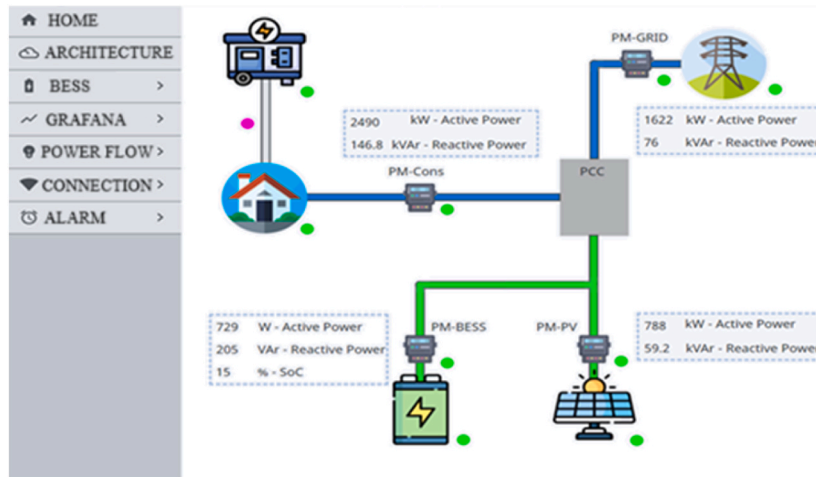


Fig. 3. The Architecture of the simulated system.

where α is a desired reliability level, for example, 0.95 or 0.99. This constraint can be implemented using stochastic optimization techniques or Monte Carlo simulations.

$P_{PV}(t)$ represents the power generated by the PV plant, its value is modeled to depend on weather conditions such as solar radiation, $P_{BESS}^{dis}(t)$ represents the power discharged by BESS and can be determined from the state of charge (SoC) as well as from the energy management strategy. $P_{GEN}(t)$ is the power produced by the generator and depends on availability of both the generator and the fuel, $P_{LOAD}(t)$ represents a variable that depends on the user's consumption profile and its fluctuations

In order to calculate the $\mathbb{P}(P_{PV}(t) + P_{BESS}^{dis}(t) + P_{GEN}(t) \geq P_{LOAD}(t))$ probability we can use either the analytic method (when the distributions are known) or the numeric method (using Monte Carlo simulations). The analytic methods are efficient for simple distributions or independent variables while the Monte Carlo simulations have greater flexibility and the ability to gestion complex dependencies and arbitrary dependencies.

The following steps must be followed in order to calculate the probability:

1. Generation of data sets: a significant number of cases are generated for the $P_{PV}(t)$, $P_{BESS}^{dis}(t)$, $P_{GEN}(t)$, $P_{LOAD}(t)$ variables (9)
2. Sum calculation: we calculate the $P_{PV}(t) + P_{BESS}^{dis}(t) + P_{GEN}(t)$ for each case
3. Sum comparison with $P_{LOAD}(t)$: We determine the proportion of cases where the sum from the previous step is greater than or equal to $P_{LOAD}(t)$

Implementation:

For each hour t we check if the computed probability satisfies the imposed reliability threshold

$$\mathbb{P}(P_{PV}(t) + P_{BESS}^{dis}(t) + P_{GEN}(t) \geq P_{LOAD}(t)) \geq \alpha$$

If the threshold is not met the decision variables must be adjusted in order to satisfy the restriction.

If the result is for example 0.98 and our reliability threshold is 0.95 then the restriction is satisfied, otherwise if the result is for example 0.56 and our threshold is 0.95 then further action is required in order to increase the probability.

Increasing the storage or production capacity is a possible action in order to satisfy the restriction, another possibility would be to decrease the load in critical moments.

Minimum Reserve Capacity Constraint.

To ensure that there is always a power reserve available in case of unexpected variations in demand or renewable energy production, we can define a minimum reserve $R(t)$:

$$P_{PV}(t) + P_{BESS}^{dis}(t) + P_{GEN}(t) \geq P_{LOAD}(t) + R(t) \quad \forall t \in [0, 24] \quad (10)$$

where $R(t)$ represents the required active power reserve, which can be a fraction of the demanded load, defined as:

$$R(t) = \beta \cdot P_{LOAD}(t) \quad (11)$$

where β is a reserve coefficient, for example, 0.1 (10 % of the demand).

3.4.4.2. Reliability constraint for BESS. To ensure that the battery energy storage system (BESS) has sufficient energy available for unforeseen future demands, a minimum state of charge (SOC) limit can be imposed:

$$SOC(t) \geq SOC_{min, fiab} \quad \forall t \in [0, 24] \quad (12)$$

where $SOC_{min, fiab}$ is a value higher than SOC_{min} , set based on reliability considerations.

3.4.4.3. Reliability constraint for emergency generator. To guarantee that the emergency generator can respond in critical situations, we can impose that it be available for a certain fraction of time or have a minimum runtime:

$$P_{GEN}(t) \leq P_{GEN, max} \quad \text{and} \quad T_{GEN} \geq T_{GEN, min} \quad \forall t \in [0, 24] \quad (13)$$

where T_{GEN} represents the total operating time of the generator over a given period and $T_{GEN, min}$ is a reliability threshold defined based on microgrid requirements.

3.4.4.4. Multiple redundancy constraint. For added safety, we can include a constraint that requires multiple redundancies, such as ensuring an alternative energy source:

$$(P_{PV}(t) \geq P_{LOAD}(t)) \quad \text{or} \quad (P_{GEN}(t) \geq P_{LOAD}(t)) \quad \forall t \in [0, 24] \quad (14)$$

This constraint ensures that either the PV system or the generator can independently cover the load.

3.4.4.5. Explanation. The objective is to minimize the total costs of meeting energy consumption, considering contributions from the PV system, BESS, and generator.

The constraints ensure that energy demand is met, and the power and state of charge limits for the BESS are respected. The BESS state of charge is updated at each time interval to reflect the stored energy.

This model can be expanded with additional variables and constraints to better reflect the characteristics of the microgrid. Thus, the mathematical model can include constraints that represent energy management strategies. These strategies are essential for the efficient use of available resources and for optimizing microgrid performance based on priorities, such as cost reduction, maximizing renewable energy usage, or minimizing reliance on the emergency generator [28].

3.4.5. Examples of energy management strategy-based constraints

3.4.5.1. Maximizing renewable energy usage (PV). Prioritize using energy from the PV system before resorting to the BESS or generator. We can add a constraint to ensure maximum use of available solar energy:

$$P_{PV}(t) = \min(P_{LOAD}(t), P_{PV,max}(t)) \quad \forall t \in [0,24] \quad (15)$$

This constraint ensures that PV energy is used to its maximum possible capacity, reducing the need for energy from other sources.

3.4.5.2. BESS charging and discharging policy. To extend battery life and optimize energy use, we can impose BESS charging and discharging rules:

BESS Charging: BESS charges when there is excess PV energy (after meeting demand):

$$P_{BESS}^{ch}(t) \leq \max(0, P_{PV}(t) - P_{LOAD}(t)) \quad \forall t \in [0, 24] \quad (16)$$

BESS Discharging: BESS discharges preferentially during peak demand times to reduce generator dependency:

$$P_{BESS}^{dis}(t) \leq P_{LOAD}(t) \text{ when } P_{GEN}(t) > 0 \quad (17)$$

3.4.5.3. Minimizing use of the emergency generator. To reduce the costly and polluting use of the emergency generator, we can impose a constraint for minimal use:

$$P_{GEN}(t) > 0 \text{ only if } P_{PV}(t) + P_{BESS}^{dis}(t) < P_{LOAD}(t) \quad (18)$$

This rule ensures that the generator is activated only when all other options are insufficient.

3.4.5.4. Energy conservation during night or low-demand periods. If the microgrid includes a BESS, an energy conservation strategy can be implemented to reserve sufficient energy for nighttime or low-demand periods:

$$SOC(t) \geq SOC_{threshold} \text{ before a specific time, for example, 6:00 p.m.} \quad (19)$$

where $SOC_{threshold}$ is a predefined minimum charge level to ensure enough stored energy for nighttime hours.

4. Case study results

4.1. Data acquisition and storage

Data for the simulation was gathered from a variety of sources, including: historical energy demand data for rural communities, real-time weather data (solar irradiance, temperature) from weather service APIs, BESS charge/discharge profiles based on manufacturer specifications. All collected data is stored in a MariaDB database. The database is structured with four key tables:

- BESS data table: Storing battery status (charge/discharge rates, efficiency, capacity).
- Consumer data table: Storing energy demand profiles for various time intervals.
- PV generation table: Capturing PV output data based on simulated weather conditions.

- upstream grid interaction table: Storing data on grid energy imports/exports and corresponding costs.

The Grafana platform was used for visualizing energy flows, battery status, and grid interaction in real-time, as illustrated in Figs. 4 and 5. This platform allows for continuous monitoring and the evaluation of key performance indicators such as total energy costs, renewable energy utilization, and grid dependency.

The workflow diagram illustrated in Fig. 6 highlights the interactions between MariaDB, Ignition, Grafana and the local equipment. Ignition acts as the interface between the hardware elements and the software parts. The data coming from the equipment is interpreted using Ignition and stored in a DB from where both the simulation program and the visualization take the necessary information. The content is visualized with ease using a HMI made with Ignition that has the possibility of directly sending commands to the connected equipment.

4.2. Simulation parameters and data

The microgrid system was simulated with the following parameters:

- PV capacity: 1 MW
- BESS charge/discharge capacity: 250 kWh
- BESS storage: 750 kWh
- Battery efficiency: 90 %
- Hourly demand range: 1100 kW–2500 kW
- Simulation period: 24 h, divided into hourly intervals.

Data was generated for both energy demand and PV generation. The hourly demand fluctuates between 1100 kW and 2500 kW, while the PV generation was adjusted based on a simplified weather model, simulating lower output during morning and evening hours, with peak generation in the afternoon.

4.3. System validation and testing

Scenario Testing: Simulating various operational scenarios, including periods of high demand, low PV generation, and island operation.

In order to evaluate how changes in parameters such as battery capacity, PV output, and demand variability affect system performance, a number of different scenarios were proposed in this paper:

The first scenario is the default state of the system where the production is lower than the consumption, therefore there is the need to buy the necessary energy from the upstream grid (Fig. 7). This is the usual scenario and grants a better understanding of how the system works.

In this scenario the total consumption is 36 MWh during the day and the PV manages to produce 6 MWh. On this day a reduction of 16 % was managed compared to a system that has no PV plant. The following scenarios have the scope to highlight the benefits of using a BESS and peak shaving techniques [29]. The total energy cost for this day is: 4080 euro instead of 4896 euro. The second scenario is that the PV plant is offline and we are required to buy all the energy from the upstream grid (Fig. 8). The scope of this scenario is to help us better visualize the impact of the PV + BESS plant on the community and to better grasp its advantages.

The consumption in this scenario is 37.5 MWh. The range can vary between 30 and 40 MWh depending on the load. The total energy cost for this day is 5100 euro.

The third scenario presented in Fig. 9 presumes a consumption lower than the maximum PV production. This scenario allows the microgrid to store the excess energy in the BESS for later use, either to do system services or to use in case of emergency.

The following scenario (Fig. 10) represents an ideal use of the PV + BESS system that allows the maximum benefits possible [30]. The excess energy produced by the PV is used to fill the BESS as much as the state of

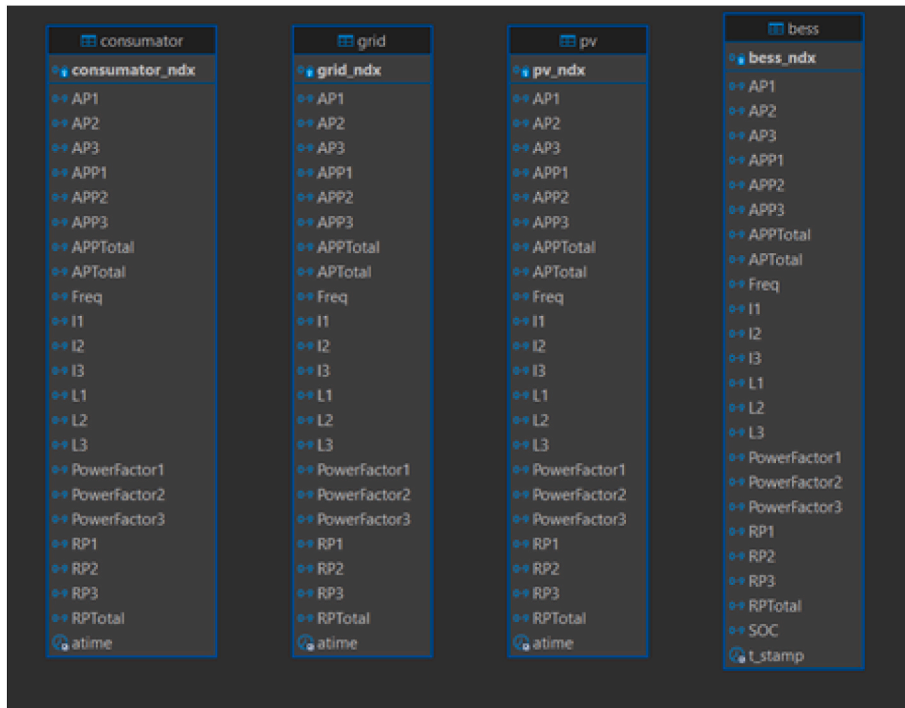


Fig. 4. The simulated variables that are stored in the DB.



Fig. 5. Grafana visualization of data.

charge allows. When the consumptions exceed the production, we can use the stored energy to further reduce the energy from upstream grid. In total, the PV plant produced 6.2 MWh. While the production exceeded the reduced consumption at some points, only 400 kWh were stored and later discharged from the batteries during the simulations. The total energy cost for this day is 1270 euro and without the storage the cost would be 2120 euro. The scenario highlights the necessity of a good storage system when we have a regenerable energy source.

With a bigger battery and a bigger energy source we can achieve better flexibility and a lot more energy can be saved for later use.

The fourth scenario (Fig. 11) makes use of the battery to maximize profit using peak shaving.

The BESS was used to reduce the consumption on the hours where

the price and load are the highest and load the BESS during the night when the prices are lower. The battery discharged 750 kW in the system, and if the PV plant had a better production than the consumption, the BESS could have been charge during the day and repeat the process, but that would require a greater PV plant. In this scenario 5.7 MWh were produced, 36.6 MWh consumed, and 30 MWh bought from upstream grid. The total energy cost for this day is: 4940 euro and without the BESS + PV the cost would be 6006 euro. While the amounts are similar to previous scenarios, the overall price paid for the energy is reduced by utilizing the batteries during the peak hours.

The last scenario (presented in Figs. 11 and 12) presumes that from technical issues that the connection with the upstream grid is no longer possible, working in islanding mode. During exceptions such as this one

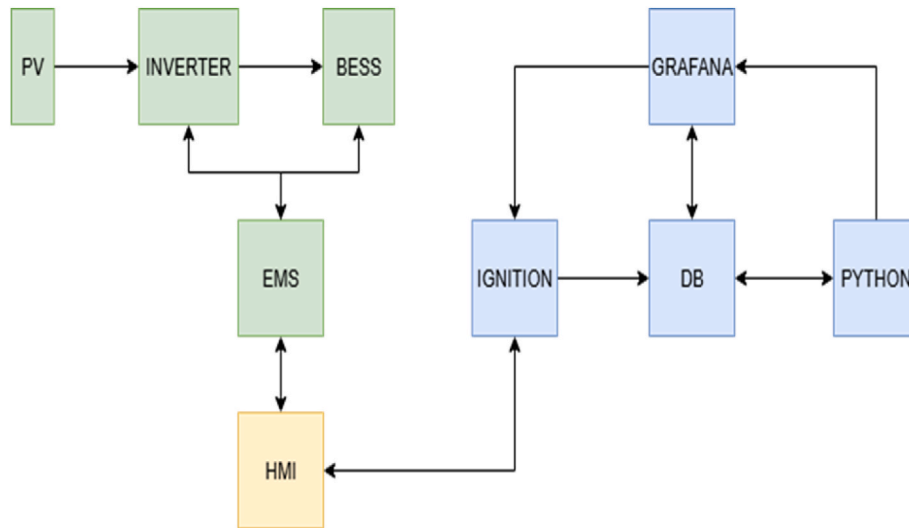


Fig. 6. Workflow diagram.

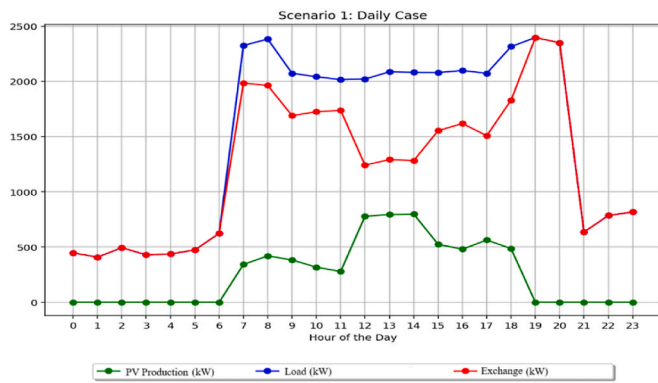


Fig. 7. Scenario 1 – daily case.

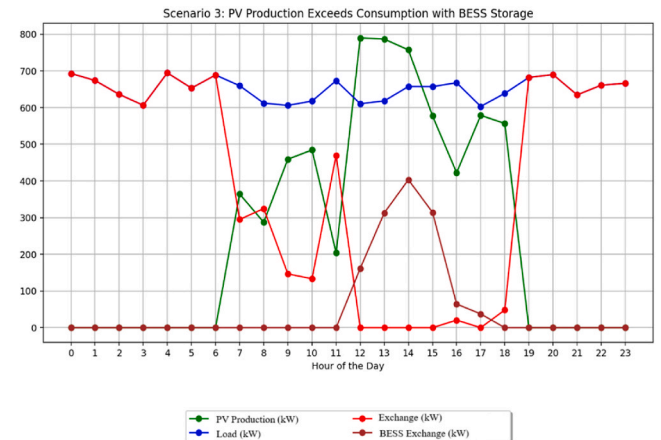


Fig. 9. Scenario 3 – PV + BESS with reduced Consumption.

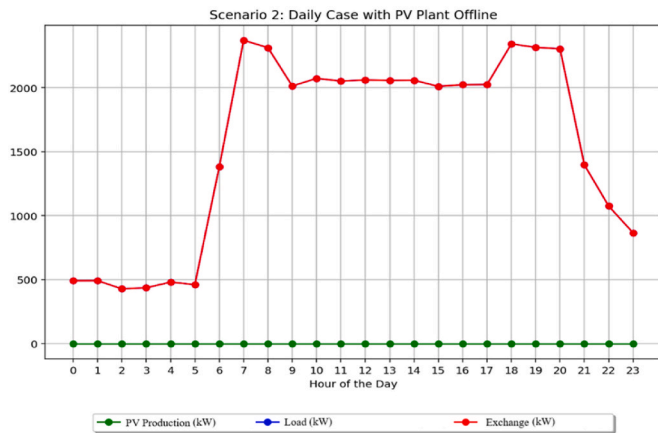


Fig. 8. Scenario 2 – consumption without PV.

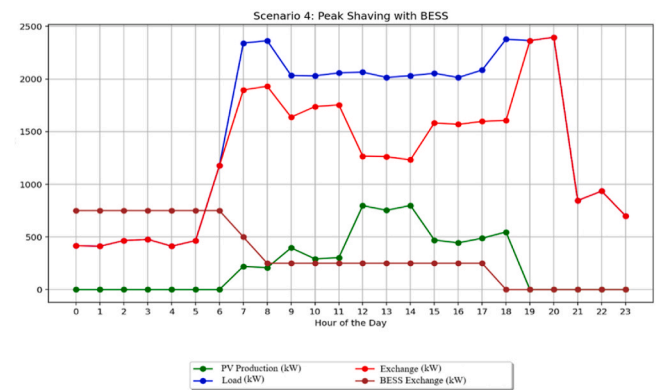


Fig. 10. Scenario 4 – peak shaving.

we only supply power to the critical consumers and we try to maximize the power we can supply from the PV + BESS system.

Because of the nature of our energy source the scenario presumes the existence of an emergency generator that can sustain the critical load for a limited time. The PV + BESS system alone is unable to fully satisfy the energetical needs but it can greatly reduce the strain from the generator during the day, substituting it for about 7 h.

4.4. Interpretation of findings

The peak shaving algorithm effectively reduced demand during peak hours by discharging stored energy, lowering the grid-supplied load. This resulted in a reduction in demand from during peak periods, which avoided expensive peak tariffs and reduced stress on the local grid. However, due to the 750-kWh storage capacity, the system could only

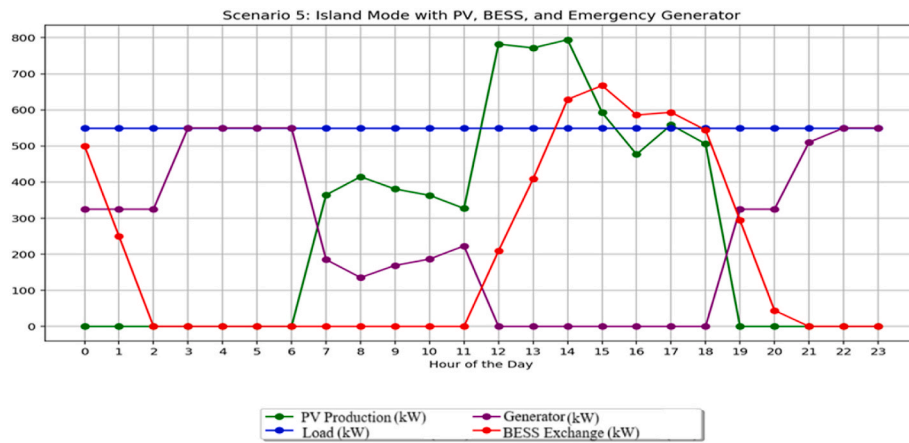


Fig. 11. Scenario 5 – PV + BESS + GEN1.

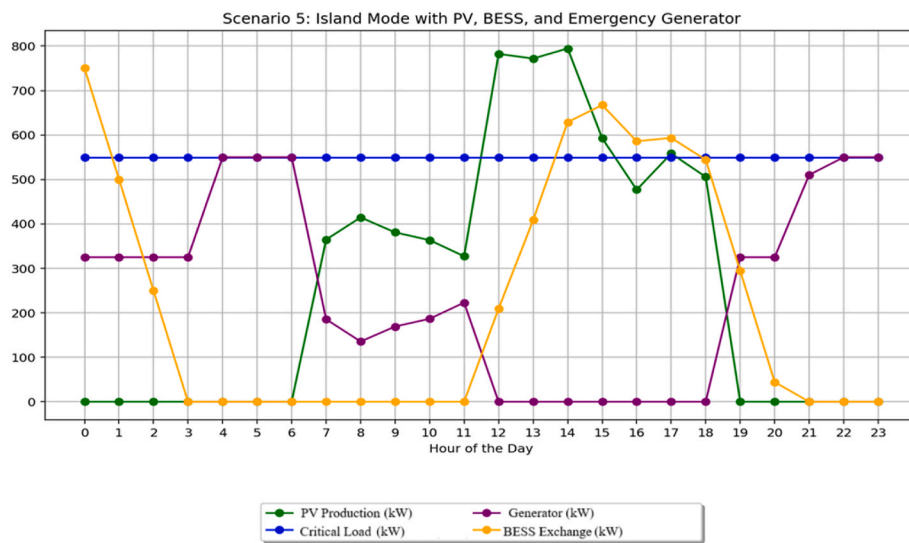


Fig. 12. Scenario 5 – PV + BESS + GEN2.

handle shorter peak durations or smaller demand spikes, leaving larger peaks still reliant on external grid energy.

The results highlight the potential of even moderate storage systems to reduce energy costs. However, a larger battery capacity would have allowed for greater reductions in demand, especially during prolonged high-demand periods. While the system demonstrated significant improvements, the battery’s storage limitations constrained its full potential.

The economic benefits of peak shaving were clear, with energy costs reduced by 10–15 %. By reducing reliance on grid energy during peak demand hours, the microgrid used its storage capacity to lower operational expenses. This was achieved despite the limited battery size, showing the viability of smaller energy storage systems for cost optimization. However, larger storage systems would likely yield even greater cost savings, particularly for microgrids experiencing sustained demand surges. Substantial economic gains can be realized with peak shaving, though the full benefits depend on battery capacity and discharge rates.

4.5. Implications for microgrid development

This study underscores the importance of matching battery storage capacity with the expected peak demand patterns in microgrid designs. For microgrids with moderate energy needs, a 250 kWh BESS with 750

kWh storage can provide significant relief during peak periods. However, in communities or applications with more sustained peak demands, a larger BESS would be more effective. Incorporating real-time management systems to optimize battery usage based on grid tariffs and forecasted demand could further enhance cost savings.

By relying on the BESS during peak hours, the microgrid increased its energy autonomy, reducing dependency on external grid energy and contributing to overall grid stability. This is especially significant for remote or hard-to-reach locations, where access to reliable grid power is uncertain. The ability to discharge stored energy during peak hours reduces stress on the grid, potentially deferring the need for costly infrastructure upgrades.

4.6. Scenario discussion

The simulation results reveal how a microgrid can adapt to varying operational scenarios, demonstrating both the flexibility and limitations of integrating Battery Energy Storage Systems (BESS) and photovoltaic (PV) systems with the grid. The different scenarios offer valuable insights into the microgrid’s performance in diverse conditions:

In the default scenario, where production is lower than consumption, the microgrid requires supplemental energy from the upstream grid. This highlights the need for balancing demand with renewable energy production to minimize external energy reliance.

The scenario where the PV plant is offline shows the vulnerability of the system to renewable energy fluctuations. Having the BESS provides resilience but highlights the importance of diversified energy sources or grid support to maintain stability.

In the case where PV production exceeds consumption, the microgrid can effectively store excess energy in the BESS for later use, demonstrating its role in enhancing energy efficiency. The ability to use stored energy for system services or emergency situations significantly enhances the microgrid's reliability.

The fourth scenario, where the battery is used to maximize profit, underscores the economic advantages of utilizing storage assets efficiently, especially during fluctuating market conditions. By optimizing battery usage, the system can reduce costs and increase revenue through strategic energy management.

The islanding mode scenario, where the microgrid is disconnected from the SEN, emphasizes the critical role of the BESS and PV system in maintaining energy supply to essential services. This scenario highlights the resilience of the microgrid in maintaining power for critical consumers during emergencies, although long-term operation would require careful resource management and planning beforehand.

In summary, the simulation confirms that microgrids equipped with BESS offer a viable and flexible solution for enhancing energy security, cost efficiency, and resilience. Each scenario highlights the strengths and weaknesses of the system in various operational states. Although the reliance on distributed energy sources introduces some vulnerabilities, particularly when grid connections are lost or renewable generation fluctuates, the advantages of storage systems in providing backup power and optimizing energy use are clear. Continued technological improvements and optimization of storage and generation strategies will further enhance the benefits of microgrids, making them a critical component in the transition toward sustainable, resilient energy infrastructures.

5. Conclusions

Although microgrids offer a valuable alternative for maintaining energy connectivity in remote or hard-to-reach locations, they also present certain disadvantages. One of the primary issues is their reliance on distributed generation sources, such as solar and wind, which are inherently variable due to weather conditions. Additionally, high initial costs and the technological complexity of integrating multiple energy sources and storage systems pose significant hurdles to widespread adoption.

Despite these challenges, microgrids have great potential that will be realized with continued technological and technical advancements. Energy storage, frequency stabilization, balancing production and consumption, and the use of renewable energy sources are key factors in the transition towards a sustainable energy system with minimal harmful emissions. By utilizing predictive algorithms for production and consumption, system services can be provided that offer financial benefits to operators, although this depends on the quality of the system and the expertise of the individuals managing it. Additionally, one advantage is the reduction in the amount of energy purchased from the upstream grid.

The deployment of microgrids at scale can play a critical role in reducing the demand for energy from polluting sources or imports. Furthermore, in areas affected by natural disasters, microgrids equipped with local production and battery storage systems can maintain power to local consumers, even when disconnected from the main grid. This capability is vital for ensuring the continuous operation of critical infrastructure like hospitals, buying time for repair efforts and stabilizing the community during outages.

The primary limitation of this study was the battery's storage capacity. With only 750 kWh of available storage, the system could not fully cover all peak demand periods, leading to partial reliance on grid energy during extended peaks. A larger BESS would enable greater

autonomy and more comprehensive peak shaving, improving both cost efficiency and grid relief. Additionally, the study used simulated data for energy demand and PV generation, which may not fully reflect real-world conditions.

Several areas for future research have been identified:

- **Larger Battery Systems:** Implementing and testing larger BESS capacities would provide insights into the scalability of peak shaving and the full extent of cost savings and energy management improvements.
- **Integrated Energy Management:** Combining peak shaving with other strategies like load shifting or demand response could optimize energy management further. Such strategies would help shift non-essential loads to off-peak periods, maximizing the utility of stored energy.
- **Real-World Testing:** Conducting trials using actual demand data and real-time PV generation would help validate the effectiveness of the peak shaving algorithms in diverse microgrid environments.
- **Forecast and Machine Learning:** In order to better manage the existing system and make the best use out of it, a number of forecasting tools would provide a lot more flexibility. By making use of the historical data acquired from the microgrid we can introduce it into a machine learning algorithm such as XGBoost and obtain relevant information that allow the administrator to better manage the energy flux. The forecast can be made for the weather, energy consumption and production. The relevant meteorological data can be acquired through an API from a specialized tool, stored in the connected MariaDB database and compared with data acquired from local public weather stations in order to analyze its efficiency. After the implementation of this tools, the acquired data can be used to improve the energy management of the system and obtain the best possible financial benefits.

In conclusion, microgrids represent a key technological advance for the future of energy systems, with their potential benefits far outweighing the current limitations. As technology evolves and costs decrease, the barriers to adopting microgrids will diminish. Existing disadvantages, such as dependency on distributed generation and the need for high upfront investments, are likely to be mitigated over time, allowing the advantages of microgrids—such as energy independence, resilience, and sustainability—to be fully realized.

CRedit authorship contribution statement

Alexandru-Sorin Nistor: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Data curation, Conceptualization. **Georgiana Balaban:** Writing – review & editing, Validation, Methodology, Formal analysis, Conceptualization. **Virgil Dumbrava:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Alexandra Catalina Lazaroiu:** Writing – review & editing, Resources, Project administration, Conceptualization. **Francisco Riganti Fulginei:** Validation, Resources, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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