

# Rolling horizon optimization based real-time energy management of a residential neighborhood considering PV and ESS usage fairness

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## HIGHLIGHTS

- A Mixed-Integer Linear Programming (MILP) framework based energy management system model.
- A rolling horizon approach to tackle with PV production uncertainties.
- Ensuring a fairness among the residential end-users for PV and ESS usage.
- Development of PV and ESS usage metrics for fairness evaluation.

## ARTICLE INFO

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## ABSTRACT

The incorporation of decentralized energy solutions, including solar photovoltaic (PV) installations and energy storage systems (ESSs), into residential communities has received substantial interest in recent times. This is driven by the objective of enhancing the self-reliance of residential zones while decreasing their reliance on centralized power grids. Effective management of these systems can yield advantages such as load equalization, cost reduction, and diminished emissions. The process of optimizing energy management in residential communities entails addressing multiple factors, including uncertainty, equity, and efficiency.

This study introduces an innovative methodology for real-time energy management in a residential community, taking into account both the equitable utilization of solar PV and ESS and the minimization of costs. The suggested technique employs rolling horizon optimization and mixed-integer linear programming (MILP) to tackle uncertainties in PV production and guarantee a fair allocation of shared resources. The outcomes of this novel approach showcase its capability to sustain cost-effectiveness while fostering equitable energy consumption.

## 1. Introduction

### 1.1. Motivation and background

Residential communities serve as critical components in energy consumption and management, as household energy use significantly contributes to the overall energy demand. The incorporation of renewable energy solutions, such as solar photovoltaic (PV) systems and energy storage systems (ESS), into residential areas has garnered interest in recent times. This is due to its capacity to decrease reliance on fossil fuels and enhance the dependability and stability of the power grid. Numerous examples from various parts of the globe illustrate this trend. One early instance of a community solar initiative oriented toward residential consumers, which integrated solar energy and storage, is the

Wright-Hennepin Electric Cooperative project in Minnesota, launched in 2013. The cooperative was able to lower peak power expenses during high-demand periods by supplying stored energy to the electrical grid [1]. Additional practical evidence supporting PV and ESS integration in neighborhoods can be found in [2], particularly in the US context. However, integrating these systems also introduces new challenges, especially regarding equitable resource utilization by individual households while effectively managing neighborhood energy.

Equitable PV and ESS usage in a residential community is vital for several reasons. First, the adoption of PV and ESS technologies has grown in recent years, leading to increased penetration of decentralized energy solutions in residential areas. This has resulted in a more intricate and dynamic power system requiring efficient energy management approaches. Second, equitable PV and ESS usage ensures that the benefits are fairly distributed among residential consumers. For example, if

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**Nomenclature****A. Sets & Indices**

|     |                               |
|-----|-------------------------------|
| $h$ | Set of optimization rounds.   |
| $r$ | Set of residential end-users. |
| $t$ | Set of time periods.          |

**B. Parameters & Constants**

|                   |                                                                        |
|-------------------|------------------------------------------------------------------------|
| $Cap_{ESS}$       | Capacity of ESS unit [kWh].                                            |
| $CE$              | Charging efficiency.                                                   |
| $DE$              | Discharging efficiency.                                                |
| $Lim_{ESS}$       | ESS charging/discharging limit [kW].                                   |
| $MMR$             | Min-max ratio allowed for fair allocation among residential end-users. |
| $N$               | Sufficiently large positive constant.                                  |
| $P_{load,r,t}$    | Power demand of residential end-user $r$ in period $t$ [kW].           |
| $P_{PV,t}$        | PV power production in period $t$ [kW].                                |
| $SoE_{ESS-des}$   | Desired state-of-energy level for ESS unit at the final time [kWh].    |
| $SoE_{ESS-init}$  | Initial state-of-energy for ESS unit [kWh].                            |
| $SoE_{ESS-min}$   | Minimum allowed state-of-energy for ESS unit [kWh].                    |
| $\gamma_{buy,t}$  | Price of buying energy from the grid in period $t$ [Euro/kWh].         |
| $\gamma_{sell,t}$ | Price of selling energy back to the grid in period $t$ [Euro/kWh].     |
| $\Delta T$        | Time granularity [h].                                                  |

**C. Decision Variables**

|                |                                                                                 |
|----------------|---------------------------------------------------------------------------------|
| $EC_r$         | ESS contribution to energy supply of residential end-user $r$ [kWh].            |
| $N_{max}$      | The minimum level component to ensure the fairness among residential end-users. |
| $N_{min}$      | The maximum level component to ensure the fairness among residential end-users. |
| $P_{ESS,r,t}$  | Power injected to residential end-user $r$ from ESS unit in period $t$ [kW].    |
| $P_{ESS-ch,t}$ | Charging power of ESS unit in period $t$ [kW].                                  |

|                   |                                                                                                                                       |
|-------------------|---------------------------------------------------------------------------------------------------------------------------------------|
| $P_{ESS-disch,t}$ | Discharging power of ESS unit in period $t$ [kW].                                                                                     |
| $P_{ESS2G,t}$     | Power injected to the grid from ESS unit in period $t$ [kW].                                                                          |
| $P_{ESS2R,t}$     | Total power injected to residential end-users from ESS unit in period $t$ [kW].                                                       |
| $P_{G,r,t}$       | Power injected to residential end-user $r$ from the grid in period $t$ [kW].                                                          |
| $P_{G2ESS,t}$     | Power injected to ESS unit from the grid in period $t$ [kW].                                                                          |
| $P_{G2N,t}$       | Power drawn by the neighbourhood from the grid in period $t$ [kW].                                                                    |
| $P_{G2R,t}$       | Total power injected to residential end-users from the grid in period $t$ [kW].                                                       |
| $P_{N2G,t}$       | Power injected back to the grid by the neighbourhood in period $t$ [kW].                                                              |
| $P_{PV,r,t}$      | Power injected to residential end-user $r$ from PV unit in period $t$ [kW].                                                           |
| $P_{PV2ESS,t}$    | Power injected to ESS unit from PV unit in period $t$ [kW].                                                                           |
| $P_{PV2G,t}$      | Power injected to the grid from PV unit in period $t$ [kW].                                                                           |
| $P_{PV2R,t}$      | Total power injected to residential end-users from PV unit in period $t$ [kW].                                                        |
| $PC_r$            | PV contribution to energy supply of residential end-user $r$ [kWh].                                                                   |
| $PEC_r$           | Combined PV and ESS contribution to energy supply of residential end-user $r$ [kWh].                                                  |
| $SoE_{ESS,t}$     | State-of-energy for ESS unit in period $t$ [kWh].                                                                                     |
| $u_{1,t}$         | Binary variable to prevent simultaneous occurrence of two-way energy transactions between the grid and the residential neighbourhood. |
| $u_{2,t}$         | Binary variable to prevent simultaneous occurrence of charging and discharging conditions of ESS unit.                                |
| $\%ESR_r$         | Percentage of ESS supply ratio for the total energy demand of residential end-user $r$ [%].                                           |
| $\%PESR_r$        | Percentage of combined PV and ESS supply ratio for the total energy demand of residential end-user $r$ [%].                           |
| $\%PSR_r$         | Percentage of PV supply ratio for the total energy demand of residential end-user $r$ [%].                                            |

one user consumes an excessive amount of energy stored in a shared ESS, others will not receive the same advantages, potentially leading to dissatisfaction and unwillingness to participate in communal energy management initiatives. Third, fair usage is essential for effectively incorporating renewable energy sources into the power grid and reducing greenhouse gas emissions. If residential consumers do not receive equitable access to PV and ESS resources, they may be deterred from participating in renewable energy initiatives or investing in PV and ESS systems, which could hinder the integration of renewable energy into the power grid.

To address these challenges, it is crucial to integrate fairness considerations into the energy management strategy of a residential community. The research in [3] underscored the significance of fairness in allocating benefits derived from shared energy resources such as ESS systems. The authors argued that without fair usage considerations, shared resource benefits may not be equitably distributed, potentially leading to disputes and dissatisfaction among residential consumers. The authors emphasized the necessity for transparent and equitable allocation mechanisms that consider the energy needs of all residential consumers.

Consequently, ensuring a fair distribution of PV and ESS resources among residential consumers is a critical aspect of residential community energy management. It is vital to consider this factor in the development and execution of efficient energy management strategies for residential communities.

**1.2. Literature overview**

The expanding body of literature on residential energy management has investigated various methodologies to address the challenges within this field. Numerous studies proposed frameworks for coordinating the operations of multiple home energy management systems in residential areas, using variable electricity prices and incentive-driven strategies to shape consumption patterns [4]. Decentralized day-ahead energy management systems were developed to alleviate grid load, consider user preferences, and reduce the peak-to-average ratio [5]. Researchers utilized mixed-integer linear programming (MILP) models to optimize the design and operation of distributed energy resource systems in the residential domain, resulting in lower CO<sub>2</sub> emissions [6].

Other research introduced comprehensive frameworks for the sustainable growth of neighborhood-scale energy systems, incorporating rooftop PV and waste-to-energy technologies [7]. Power electronic-based home energy management systems were suggested for neighborhood networks, achieving a 98% reduction in grid load [8]. Energy management and sharing strategies for residential microgrids were examined, optimizing energy utilization challenges for diverse house types [9].

Some studies accounted for uncertainty in energy management, presenting scenario-based MILP models for local energy communities implementing stochastic day-ahead scheduling operations for multi-energy systems [10]. Hierarchical energy management systems for

**Table 1**

Taxonomy table regarding the comparison of the proposed study with competitive literature studies.

| Reference  | Uncertainty Consideration | PV | ESS | Fair Allocation of Common Resources | Rolling Horizon Optimization | Additional Contributions/ Considerations                |
|------------|---------------------------|----|-----|-------------------------------------|------------------------------|---------------------------------------------------------|
| [4]        | ×                         | ×  | ×   | ×                                   | ×                            | Price-based incentives                                  |
| [5]        | ×                         | ×  | ×   | ×                                   | ×                            | Decentralized approach                                  |
| [6]        | ×                         | ✓  | ×   | ×                                   | ×                            | Heating/cooling pipelines, microgrid connections        |
| [7]        | ×                         | ✓  | ×   | ×                                   | ×                            | Waste-to-energy technologies                            |
| [8]        | ×                         | ×  | ×   | ×                                   | ×                            | Power electronic-based HEMS                             |
| [9]        | ×                         | ✓  | ×   | ×                                   | ×                            | Energy management and sharing scheme                    |
| [10]       | ✓                         | ×  | ×   | ×                                   | ×                            | Scenario-based MILP model                               |
| [11]       | ×                         | ×  | ×   | ×                                   | ×                            | Hierarchical energy management system                   |
| [12]       | ×                         | ×  | ×   | ×                                   | ×                            | Distributed reinforcement learning                      |
| [13]       | ×                         | ×  | ×   | ×                                   | ×                            | Model predictive control, Shapley value                 |
| [14]       | ×                         | ✓  | ×   | ×                                   | ×                            | Thermostat set point control, direct compressor control |
| [15]       | ×                         | ✓  | ×   | ×                                   | ×                            | Electro-thermal residential microgrid                   |
| [16]       | ✓                         | ✓  | ×   | ×                                   | ×                            | Peninsula context, Markov chain                         |
| [17]       | ✓                         | ✓  | ×   | ×                                   | ×                            | Scenario-based energy management system                 |
| [18]       | ×                         | ×  | ×   | ×                                   | ×                            | Bi-directional power flow                               |
| [21]       | ✓                         | ✓  | ✓   | ×                                   | ×                            | Integrated planning and energy management in seaports   |
| [22]       | ✓                         | ✓  | ✓   | ×                                   | ×                            | Multi-energy industrial micro-grids, DR consideration   |
| This study | ✓                         | ✓  | ✓   | ✓                                   | ✓                            | Cost minimization oriented decision making              |

multiple home energy hubs in neighborhood grids were proposed, with the objective of maximizing financial benefits and minimizing peak energy demand [11].

Researchers employed machine learning techniques in residential energy management, including distributed reinforcement learning approaches for optimizing energy scheduling across numerous residential energy hubs [12]. Model predictive control-based reinforcement learning was used to manage residential microgrids, achieving a 17.5% reduction in monthly collective costs [13]. Decision-making models for intelligent neighborhood energy systems were devised, considering renewable energy sources and electric vehicles [14].

Creative energy management strategies for electro-thermal residential microgrids were suggested, attaining improved grid power profiles and a 25% reduction in battery capacity [15]. Frameworks for energy management in residential microgrids, accounting for PV power production uncertainty, were introduced, enhancing the precision of power delivery and decreasing operational expenses [16].

Further studies explored scenario-based energy management systems for microgrids, incorporating ESSs, demand response programs, and renewable energy sources. These methods surpassed deterministic approaches in terms of loss reduction and handling uncertainties [17]. Research also scrutinized the optimal operation of intelligent households to minimize energy procurement costs, concentrating on mitigating unfair use of distribution transformer capacity [18]. Despite the numerous studies contributing to the advancement of energy management applications in residential neighborhoods, the equitable use of shared PV and ESS capacity and managing uncertainties in energy management still necessitate further refinement, as discussed in more detail in [19] and [20].

Uncertainty handling was also considered by various studies in the literature, focusing on non-residential microgrids. Iris et al. [21] examined integrated planning and energy management in seaports using smart grids, taking into account uncertain renewable energy generation. They formulated an MILP model to optimally solve the problem, addressing uncertainty through day-ahead energy management planning. Huang et al. [22] designed an intelligent demand response program for multi-energy industrial microgrids, considering PV power uncertainty and battery operational cost. To account for PV power uncertainty, they developed a data-driven PV power probabilistic forecasting model and applied a copula-based approach for sampling temporally correlated PV power scenarios from probabilistic forecasts. However, instead of addressing uncertainty in real-time through a

rolling horizon optimization approach, Iris et al. [21] incorporated day-ahead energy management planning, and Huang et al. [22] used a data-driven PV power probabilistic forecasting model combined with a copula-based approach for scenario sampling, which could still face deviations in decisions when a large difference occurs between projected or forecasted profiles in real-time operation.

While the aforementioned studies and other relevant papers in the literature have provided valuable contributions to improving energy management applications in residential neighborhoods, the equitable use of shared PV and ESS capacity has not been sufficiently addressed in decision-making related to energy management. Additionally, dealing with uncertainty in such a structure requires further reconsideration using enhanced methodologies.

### 1.3. Content and contribution of the study

In this research, an energy management system focusing on cost minimization is proposed for residential neighborhoods, taking into account the equitable distribution of shared PV and battery-based ESS resources among residents. The proposed model accommodates the uncertainty in PV generation through a rolling horizon optimization approach. A MILP optimization model is formulated to assess the impact of the proposed concept in terms of maintaining energy costs while ensuring a fair allocation of shared energy resources.

The primary contributions of this study, in comparison to the existing literature and as detailed in Table 1, are twofold:

- The equitable use of shared energy assets (PV and ESS in this study) has not been addressed in previous research on residential neighborhoods. This issue becomes increasingly relevant as renewable energy usage-based credits and incentives become more widespread globally for residential end-users, and thus cannot be overlooked in a study concerning energy management in a residential neighborhood.
- The uncertainties associated with PV generation are addressed using a real-time rolling horizon-based energy management approach, which is another contribution among existing similar studies on energy management in residential neighborhoods.

### 1.4. Paper organization

The remainder of this study is organized as follows: Section 2 deals with the mathematical modeling details of the proposed methodology.

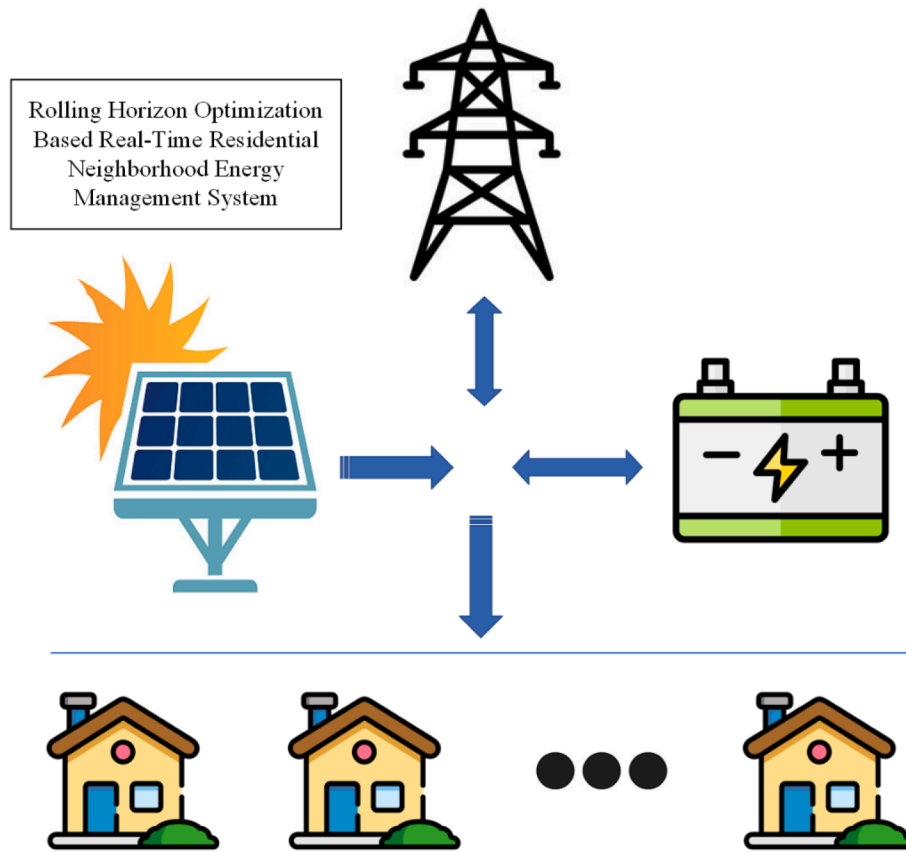


Fig. 1. A general scheme of the proposed residential neighbourhood energy management structure.

Then, Section 3 presents the case studies based analyses and the relevant obtained results. Finally, Section 4 provides the concluding remarks.

## 2. System description and methodology

### 2.1. General overview of the proposed scheme

In this research, a residential neighborhood with shared PV and ESS facilities is examined (see Fig. 1). The equitable use of these shared PV and ESS resources among residential end-users is considered during the energy management of the neighborhood, aiming to increase the residents' willingness to participate in joint energy investments by ensuring equal benefits from these resources. The energy management of the aforementioned residential neighborhood is achieved through an MILP-based optimization approach. Uncertainties related to PV power generation are addressed using a rolling horizon method. Compared to other methods for handling uncertainty, such as stochastic programming and robust optimization, rolling horizon optimization offers distinctive advantages by delivering near-optimal solutions while incorporating new information over time. This makes it a practical and effective approach for tackling complex optimization problems, particularly in situations with dynamic or changing parameters. The details of the proposed rolling horizon optimization-based MILP model are presented in Table 2.

### 2.2. Real-time rolling horizon optimization model

The objective function of the stated problem is given in Equation (1), which consists of two components stemming from the selling and buying directions of energy flow between the neighborhood and the grid. The summation over the time horizon represents the total cost of operation for the neighborhood. It is crucial to note that while the objective function covers all periods in the optimization horizon, the rolling

horizon method only optimizes decision variables for the upcoming periods starting from the current optimization round  $h$  since previous intervals have already been set to their optimal values.

$$\text{MinimizeCost} = \sum_t (P_{G2N,t} \cdot \Delta T \cdot \gamma_{\text{buy},t} - P_{N2G,t} \cdot \Delta T \cdot \gamma_{\text{sell},t}) \quad (1)$$

The power balance for the point of common coupling of the neighbourhood is depicted in (2). Here, the PV production, ESS discharging power as well as the power procured from the grid by the neighbourhood equals to the summation of power injected back to grid from the neighbourhood, ESS charging power as well as the total load demand of the residential end-users.

$$P_{PV,t} + P_{ESS-\text{disch},t} + P_{G2N,t} = P_{N2G,t} + P_{ESS-\text{ch},t} + \sum_r P_{\text{load},r,t}, \forall t \geq h \quad (2)$$

The decomposition of PV power production into the power directed to the grid, ESS unit and residential end-users from the PV system is depicted in (3). Here, the total PV power directed to the residential end-users is the summation of the individual power injections to each end-user as in (4).

$$P_{PV,t} = P_{PV2G,t} + P_{PV2ESS,t} + P_{PV2R,t}, \forall t \geq h \quad (3)$$

$$P_{PV2R,t} = \sum_r P_{PV,r,t}, \forall t \geq h \quad (4)$$

In a similar manner, the decomposition of the power flow between grid and the neighbourhood is presented via (5)–(7). The grid power injected to neighbourhood is composed of the power values directed to ESS and residential end-users from the grid as given in (5), while the individual power transfer values to end-users results in the total grid-to-residential power transfer as in (6). The power given to the grid by the PV production and ESS discharging results in the neighbourhood-to-grid power transfer in each time period as in (7). The logical constraints to

**Table 2**

The details of the developed rolling horizon optimization based MILP model.

| Step | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
|------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1    | Initialize parameters: <ul style="list-style-type: none"> <li>Capacity of ESS unit [kWh].</li> <li>Charging efficiency.</li> <li>Discharging efficiency.</li> <li>ESS charging/discharging limit [kW].</li> <li>Min-max ratio allowed for fair allocation among residential end-users.</li> <li>Sufficiently large positive constant. Power demand of residential end-user <math>r</math> in period <math>t</math> [kW].</li> <li>PV power production in period <math>t</math> [kW].</li> <li>Desired state-of-energy level for ESS unit at the final time [kWh].</li> <li>Initial state-of-energy for ESS unit [kWh].</li> <li>Minimum allowed state-of-energy for ESS unit [kWh].</li> <li>Price of buying energy from the grid in period <math>t</math> [Euro/kWh].</li> <li>Price of selling energy back to the grid in period <math>t</math> [Euro/kWh].</li> <li>Time granularity [h].</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
| 2    | Define the MILP objective function: <ul style="list-style-type: none"> <li>Minimize the total energy cost</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
| 3    | Define decision variables: <ul style="list-style-type: none"> <li>ESS contribution to energy supply of residential end-user <math>r</math> [kWh].</li> <li>The minimum level component to ensure the fairness among residential end-users.</li> <li>The maximum level component to ensure the fairness among residential end-users.</li> <li>Power injected to residential end-user <math>r</math> from ESS unit in period <math>t</math> [kW].</li> <li>Charging power of ESS unit in period <math>t</math> [kW].</li> <li>Discharging power of ESS unit in period <math>t</math> [kW].</li> <li>Power injected to the grid from ESS unit in period <math>t</math> [kW].</li> <li>Total power injected to residential end-users from ESS unit in period <math>t</math> [kW].</li> <li>Power injected to residential end-user <math>r</math> from the grid in period <math>t</math> [kW].</li> <li>Power injected to ESS unit from the grid in period <math>t</math> [kW].</li> <li>Power drawn by the neighbourhood from the grid in period <math>t</math> [kW].</li> <li>Total power injected to residential end-users from the grid in period <math>t</math> [kW].</li> <li>Power injected back to the grid by the neighbourhood in period <math>t</math> [kW].</li> <li>Power injected to residential end-user <math>r</math> from PV unit in period <math>t</math> [kW].</li> <li>Power injected to ESS unit from PV unit in period <math>t</math> [kW].</li> <li>Power injected to the grid from PV unit in period <math>t</math> [kW].</li> <li>Total power injected to residential end-users from PV unit in period <math>t</math> [kW].</li> <li>PV contribution to energy supply of residential end-user <math>r</math> [kWh].</li> <li>Combined PV and ESS contribution to energy supply of residential end-user <math>r</math> [kWh].</li> <li>State-of-energy for ESS unit in period <math>t</math> [kWh].</li> <li>Binary variable to prevent simultaneous occurrence of two-way energy transactions between the grid and the residential neighbourhood.</li> <li>Binary variable to prevent simultaneous occurrence of charging and discharging conditions of ESS unit.</li> <li>Percentage of ESS supply ratio for the total energy demand of residential end-user <math>r</math> [%].</li> <li>Percentage of combined PV and ESS supply ratio for the total energy demand of residential end-user <math>r</math> [%].</li> <li>Percentage of PV supply ratio for the total energy demand of residential end-user <math>r</math> [%].</li> </ul> |
| 4    | Define constraints: <ul style="list-style-type: none"> <li>Neighborhood power balance</li> <li>Power decompositions for PV, ESS, and grid-neighborhood transactions</li> <li>Logical constraints</li> <li>ESS model</li> <li>Residential end-user power balance</li> <li>Fairness metrics and limits</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
| 5    | Solve the MILP optimization problem with rolling horizon approach: <ol style="list-style-type: none"> <li>For each time step, update PV power production</li> <li>Solve the MILP problem</li> <li>Update the energy allocation results</li> </ol>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |
| 6    | Output the optimized energy allocation decisions for PV and ESS utilizations together with all kind of transactions                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |

prevent the simultaneous occurrence of two-way transactions between the grid and neighbourhood are given in (8) and (9).

$$P_{G2N} = P_{G2ESS,t} + P_{G2R,t}, \forall t \geq h \quad (5)$$

$$P_{G2R,t} = \sum_r P_{G,r,t}, \forall t \geq h \quad (6)$$

$$P_{N2G,t} = P_{PV2G,t} + P_{ESS2G,t}, \forall t \geq h \quad (7)$$

$$P_{G2N} \leq N \cdot u_{1,t}, \forall t \geq h \quad (8)$$

$$P_{N2G} \leq N \cdot (1 - u_{1,t}), \forall t \geq h \quad (9)$$

The ESS power decomposition in two-way operation are represented using (10)–(12). The ESS charging power can be supplied by PV unit and grid as shown in (10). On the other hand, the power discharged from the ESS unit can be directed to grid and/or the residential end-users as in (11), where the summation of individual end-user power transfer values forms the power transfer from ESS unit to residential end-users as in (12).

$$P_{ESS-ch,t} = P_{PV2ESS,t} + P_{G2ESS,t}, \forall t \geq h \quad (10)$$

$$P_{ESS-disch,t} = P_{ESS2G,t} + P_{ESS2R,t}, \forall t \geq h \quad (11)$$

$$P_{ESS2R,t} = \sum_r P_{ESS,r,t}, \forall t \geq h \quad (12)$$

The logical constraints in (13) and (14) hinder the simultaneous occurrence of the discharging and charging transactions of ESS. The state-of-energy variation of the ESS unit is defined as in (15) dependent on ESS charging and discharging power values and efficiencies. The initialization of ESS state-of-energy is provided by (16) while state-of-energy of ESS unit is lower and upper bounded by (17). The state-of-energy value should be greater than its initial value at the end of the evaluation horizon as ensured by (18).

$$P_{ESS-disch,t} \leq \text{Lim}_{ESS} \cdot u_{2,t}, \forall t \geq h \quad (13)$$

$$P_{ESS-ch,t} \leq \text{Lim}_{ESS} \cdot (1 - u_{2,t}), \forall t \geq h \quad (14)$$

$$\text{SoE}_{ESS,t} = \text{SoE}_{ESS,t-1} + P_{ESS-ch,t} \cdot \Delta T \cdot \text{CE} - \frac{P_{CESS-disch,t} \cdot \Delta T}{\text{DE}}, \forall t \geq h, \text{ift} > 1 \quad (15)$$

$$\text{SoE}_{ESS,t} = \text{SoE}_{ESS-init}, \forall t \geq h, \text{ift} = 1 \quad (16)$$

$$\text{SoE}_{ESS-min} \leq \text{SoE}_{ESS,t} \leq \text{Cap}_{ESS}, \forall t \geq h \quad (17)$$

$$\text{SoE}_{ESS,t} \geq \text{SoE}_{ESS-des}, \forall t \geq h, \text{ift} = T_{final} \quad (18)$$

The power balance for each residential end-user is given in (19) in which the load demand is supplied by the contributions of common PV and ESS units as well as the grid to the residential end-user premises.

$$P_{PV,r,t} + P_{ESS,r,t} + P_{G,r,t} = P_{load,r,t}, \forall r, \forall t \geq h \quad (19)$$

The metrics used to ensure the fairness for the usage of PV and ESS units among residential end-users are shown in (20). The PV Supply Ratio (PSR) index shown in (20.a) reveals the ratio of total supplied PV based energy to each end-user within the total energy demand of the mentioned end-user. Similarly, (20.b) and (20.c) including ESS Supply Ratio (ESR) and PV + ESS Supply Ratio (PESR) respectively give the ratio of ESS and PV + ESS based energy supply within the total energy demand for each end-user. On the other hand, the PV Contribution (PC), ESS Contribution (EC) and PV + ESS Contribution (PEC) correspond to the total supplied energy for each end-user from PV, ESS, and PV + ESS units respectively. Here, a fairness among the portions in each demand or directly the total energy value reveals different concepts which have a different philosophy behind, thus an in-depth evaluation for different concepts regarding also different common system components may provide interesting insights.

$$\%PSR_r = 100 \cdot \frac{\sum_t P_{PV,r,t} \cdot \Delta T}{\sum_t P_{load,r,t} \cdot \Delta T} \quad (20.a)$$

$$\%ESR_r = 100 \cdot \frac{\sum_t P_{ESS,r,t} \cdot \Delta T}{\sum_t P_{load,r,t} \cdot \Delta T} \quad (20.b)$$

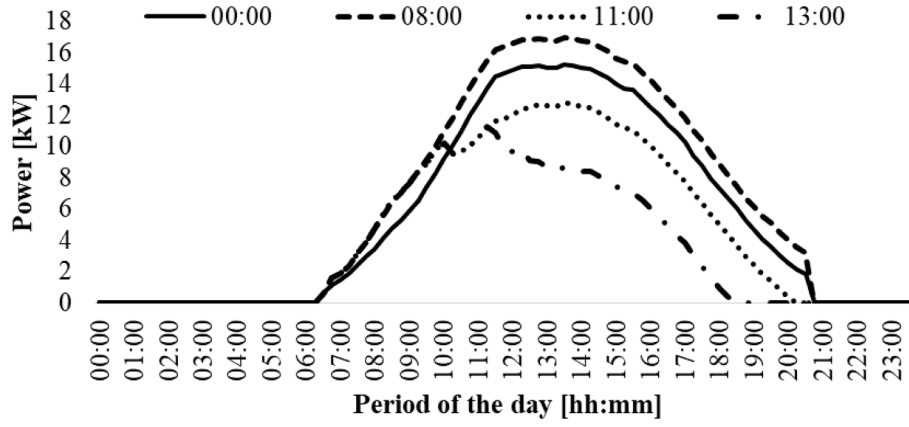


Fig. 2. PV power production profile for different horizons.

$$\%PESR_r = 100 \cdot \frac{\sum_t (P_{PV,r,t} + P_{ESS,r,t}) \cdot \Delta T}{\sum_t P_{load,r,t} \cdot \Delta T} \quad (20.c)$$

$$PC_r = \sum_t P_{PV,r,t} \cdot \Delta T \quad (20.d)$$

$$EC_r = \sum_t P_{ESS,r,t} \cdot \Delta T \quad (20.e)$$

$$PEC_r = \sum_t (P_{PV,r,t} + P_{ESS,r,t}) \cdot \Delta T \quad (20.f)$$

Finally, the fairness of the PV and ESS usage among residential end-users is ensured by (21) and (22). This concept inspired from [23] (the mentioned study mainly provided insights for the fairness among end-users enrolled in a thermostatically controllable loads oriented demand response program, which has no relevance to the concept proposed in this study) provides a basis to ensure an acceptable similarity between the PV, ESS or PV + ESS usage levels those residential end-users will likely have. Here, defining min-max ratio ( $MMR \geq 1$ ) exactly as 1 means all the residential end-users should benefit from the PV, ESS or PV + ESS units at the same level. Defining this parameter close to 1 will ensure a greater fairness, however this may result in an infeasible problem. Thus, this brings an interesting point in terms of sensitivity of the energy management system's decisions on the value of this parameter. It should here be noted that only one constraint can be imposed among the constraints given in (21.a)–(21.f) considering the fairness objective of the evaluation.

$$N_{min} \leq \%PSR_r \leq N_{max} \quad (21.a)$$

$$N_{min} \leq \%ESR_r \leq N_{max} \quad (21.b)$$

$$N_{min} \leq \%PESR_r \leq N_{max} \quad (21.c)$$

$$N_{min} \leq PC_r \leq N_{max} \quad (21.d)$$

$$N_{min} \leq EC_r \leq N_{max} \quad (21.e)$$

$$N_{min} \leq PEC_r \leq N_{max} \quad (21.f)$$

$$N_{max} \leq MMR \cdot N_{min} \quad (22)$$

### 3. Test and results

The development of a cost-minimization focused energy management strategy, which takes into account usage fairness, is expressed using a mixed-integer linear programming (MILP) approach. The proposed framework is examined using the GAMS v.24.1.3 software and the CPLEX v.12 solver. The input data and simulation results are presented in the respective subsections of this section.

#### 3.1. Input data

Several studies in the literature have implemented a deterministic approach for photovoltaic (PV) production, particularly in a day-ahead evaluation context. However, actual PV production can deviate considerably from predicted profiles, potentially resulting in discrepancies in operational plans. Consequently, adapting to real-time situations can provide a more accurate performance assessment for PV-integrated systems. Fig. 2 [24] displays various PV production profiles

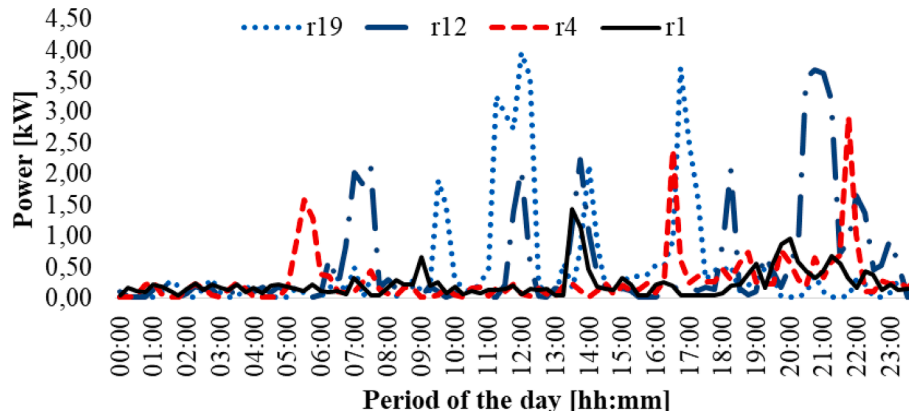


Fig. 3. Sample residential load demand profiles.

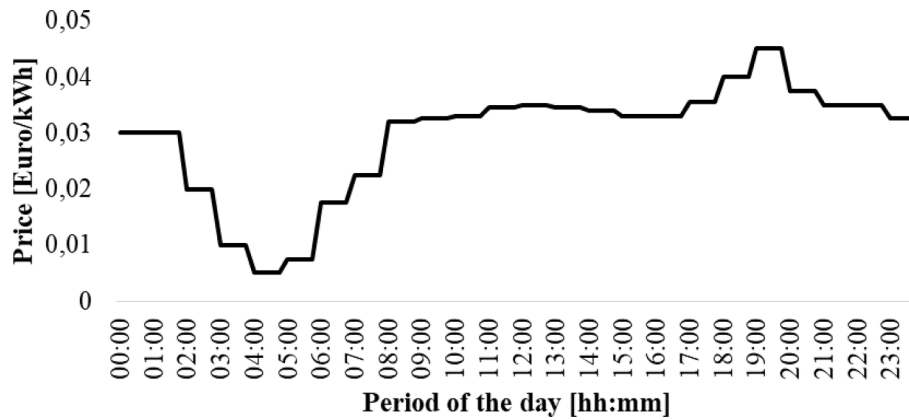


Fig. 4. Energy price variation.

throughout the day for a 20 kW PV system. It is evident that a day-ahead assessment using the data at 00:00 would substantially deviate from a realistic evaluation, even when compared to the data at 11:00. This deviation grows even more significant when examining the data at 13:00. Therefore, the energy management strategy's adaptability to uncertain input variations is crucial, as demonstrated in this study.

A residential neighborhood consisting of 20 households is considered in this research. Relevant data are collected using the Domestic Electricity Demand Model of CREST (Centre for Renewable Energy Systems Technology) from Loughborough University [25,26]. Randomized appliance allocation and occupancy variation are employed to obtain data for the 20 households, which include two end-users with one occupant, three end-users with two occupants, four end-users with three occupants, five end-users with four occupants, and six end-users with five occupants. A weekday in May, with initial location and thermal dynamic settings in CREST, is considered for data generation. Fig. 3 shows sample power profiles of four different households. Meanwhile, Fig. 4 depicts the price variation considered in this study. It should be noted that identical prices are used for two-way energy transactions between the neighborhood and the grid. Additionally, ESS capacity is set at 15 kWh, while the minimum and initial state-of-energy (SoE) levels are defined as 3 kWh and 7.5 kWh, respectively.

### 3.2. Simulation results and comparison

In order to assess the effectiveness of the proposed methodology for the energy management of residential neighbourhoods, seven case studies are considered as summarized below (it should here be mentioned that Eqs. (1)–(20) are already employed in all the mentioned case studies):

- **Case-1:** No fairness limitation is imposed in the optimization model by ignoring Eqs. (21) and (22).
- **Case-2:** Only %PSR<sub>r</sub> based fairness is considered by imposing (21.a) and (22).
- **Case-3:** Only %ESR<sub>r</sub> based fairness is considered by imposing (21.b) and (22).
- **Case-4:** Only %PESR<sub>r</sub> based fairness is considered by imposing (21.c) and (22).
- **Case-5:** Only PC<sub>r</sub> based fairness is considered by imposing (21.d) and (22).
- **Case-6:** Only EC<sub>r</sub> based fairness is considered by imposing (21.e) and (22).
- **Case-7:** Only PEC<sub>r</sub> based fairness is considered by imposing (21.f) and (22).

Initially, the importance of using a rolling horizon approach instead of a deterministic evaluation is assessed. A comparative demonstration of all relevant decision variables is presented in Figs. 5–13, with Case-1 (no fairness limitation imposed) considered for comparison. The day-ahead results reveal the system's response to PV input at 00:00. Additionally, Fig. 5 demonstrates the first and last input values of PV data for the rolling horizon approach, highlighting how real-time values may differ significantly, potentially impacting projected decisions.

Figs. 6 and 7 display the two-way power transactions between the grid and the neighborhood. Lower price periods correspond to times when more power is drawn from the grid, as expected. During the highest price periods, power is injected back into the grid. However, additional periods in the afternoon see substantial energy transfer back to the grid, particularly due to a portion of PV production shown in Fig. 8. The other component of the neighborhood-to-grid power transfer

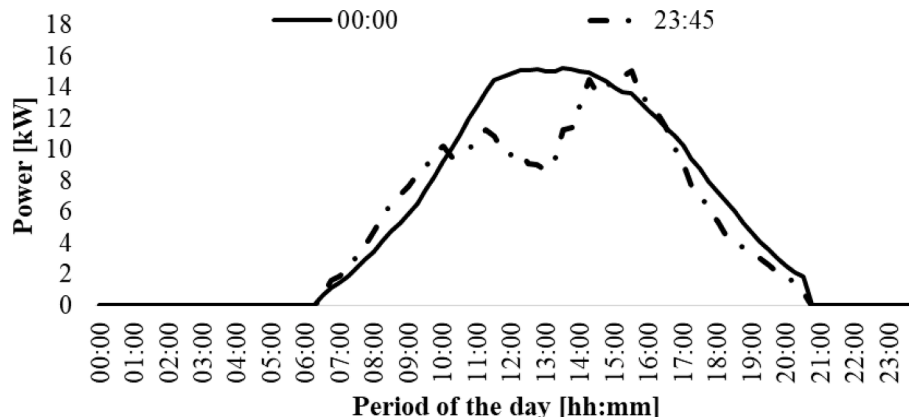


Fig. 5. PV production variations for day-ahead and real-time decision making comparison [00:00 = day-ahead, 23:45 = real-time].

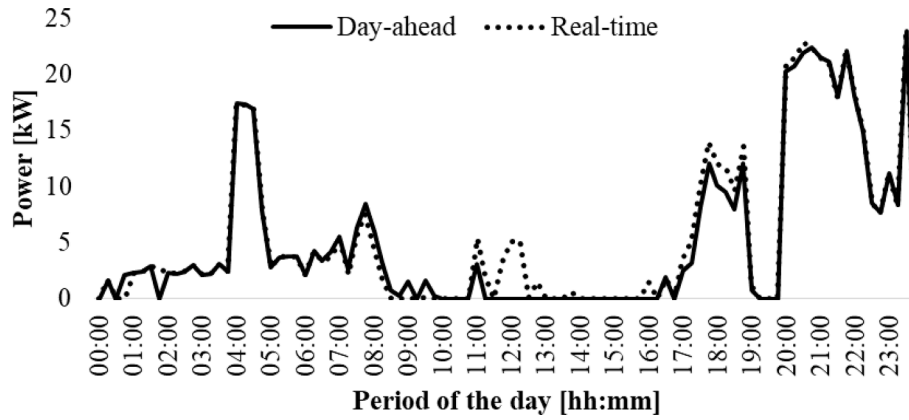


Fig. 6. Power drawn from the grid by the neighbourhood.

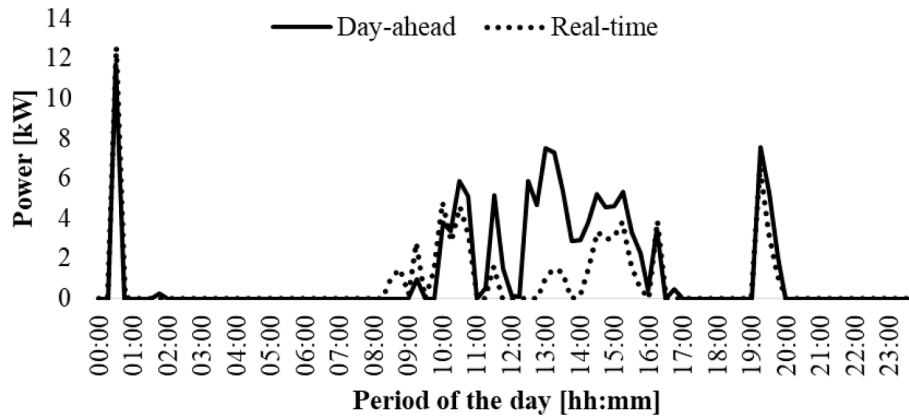


Fig. 7. Power injected back to the grid from the neighbourhood.

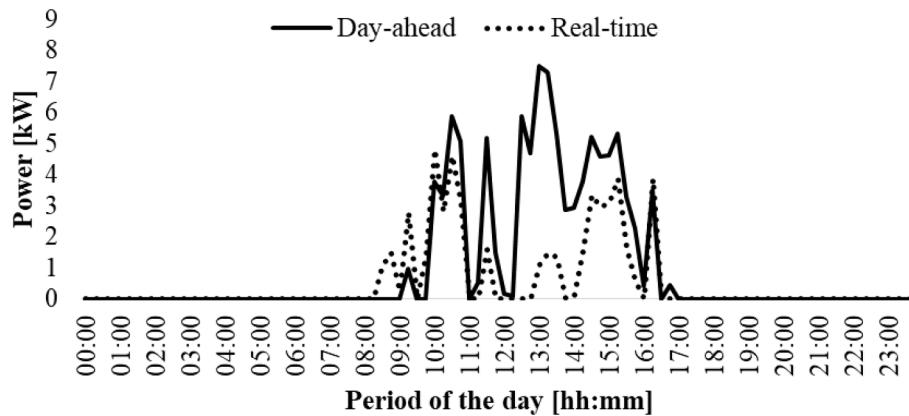


Fig. 8. PV-to-grid power injection variation.

is shown in Fig. 9, where two periods—an early and a late time within the day—are decided for ESS to discharge, corresponding to higher price periods, especially in the evening hours. Figs. 6–8 reveal that day-ahead and real-time operation differ significantly, which would impede an effective evaluation of a developed management strategy when day-ahead conditions are considered.

The power transfer from the grid to the neighborhood, shown in Fig. 6, includes two components presented in Figs. 10 and 11. The first part, depicted in Fig. 10, reveals the power transfer to residential end-users, while the other part, displayed in Fig. 11, represents the power drawn by the ESS from the grid. Since PV-to-ESS power transfer is always zero in all conditions, the power variation in Fig. 11 directly results

in the total charging power for ESS, as shown in Fig. 12.

ESS discharging, on the other hand, comprises the ESS-to-residential end-users power transfer variation shown in Fig. 13, along with the previously mentioned ESS-to-grid power transfer. These two power transfer variations result in the total ESS discharging power depicted in Fig. 14. The charging and discharging power transactions for ESS eventually lead to the state-of-energy variation shown in Fig. 15. Midnight and evening periods are generally used for ESS discharging, while charging-oriented energy transfer occurs early in the morning and late at night. Another observation from all ESS-related figures is that day-ahead and real-time decisions change only slightly for ESS units. Finally, the total power drawn by residential end-users from the PV

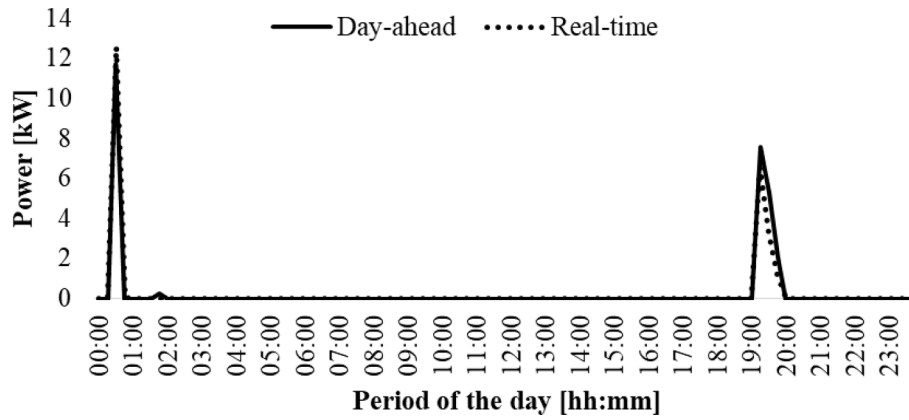


Fig. 9. ESS-to-grid power injection variation.

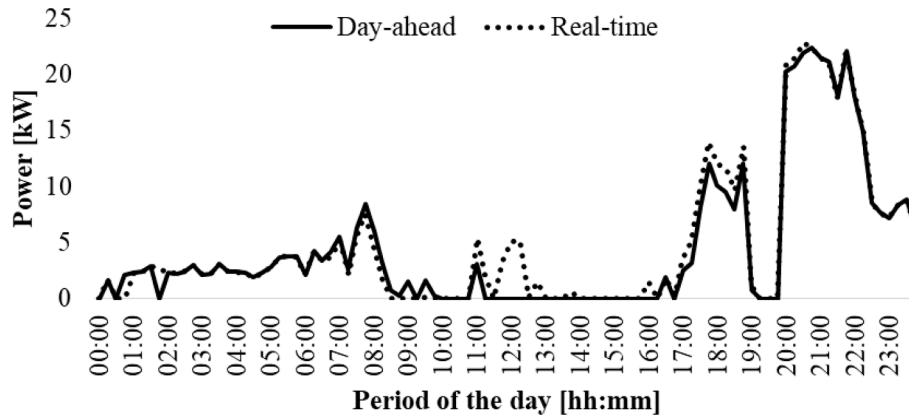


Fig. 10. Grid-to-residential end-users power transfer variation.

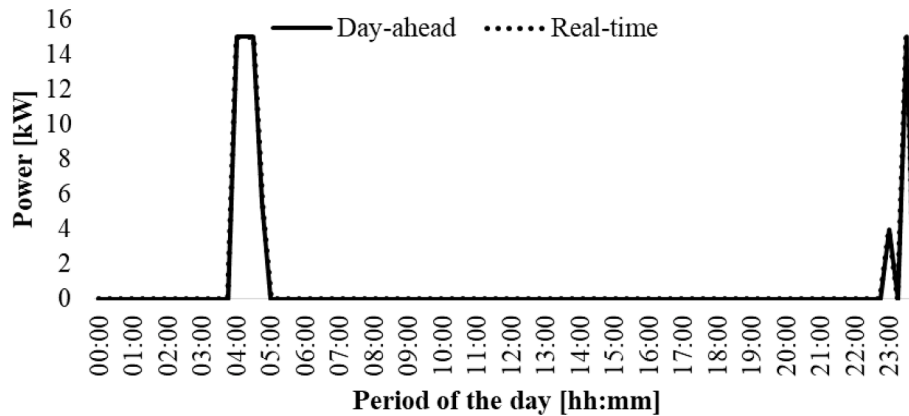


Fig. 11. Grid-to-ESS power transfer variation.

system is presented in Fig. 16.

The rolling horizon optimization approach provides more realistic evaluations for the proposed energy management concept compared to day-ahead consideration. However, it should be noted that the rolling horizon-based approach may face increased computational burden, potential response instability, implementation challenges, and other issues, despite offering improved adaptability and responsiveness to changing conditions.

A more in-depth analysis of how fairness consideration may affect decisions is presented in Table 3, which compares the results obtained from different case studies. When no fairness limitation is imposed (Case-1), PV and ESS usage differ significantly between end-users,

leading to minimum–maximum %PSR<sub>r</sub> values of 13.32–89.82%, also valid for the other five indices. By defining the MMR as 1.2, it becomes clear that PV, ESS, and PV + ESS usage becomes fair depending on the targeted index in various case studies. Another interesting observation is that the total cost changes acceptably, reaching a maximum increase of ~ 5% in the worst case when fairness constraints are additionally imposed. In particular, PV-oriented fairness does not even have an impact on cost when comparing Case-2 and Case-5 to Case-1, and Case-4 and Case-7 to Case-3 and Case-6, respectively. Therefore, fair allocation for on-site common facilities can be achieved with minimal cost impact, which is crucial for encouraging more participation in joint investments. This could be further compensated if renewable energy-oriented credits

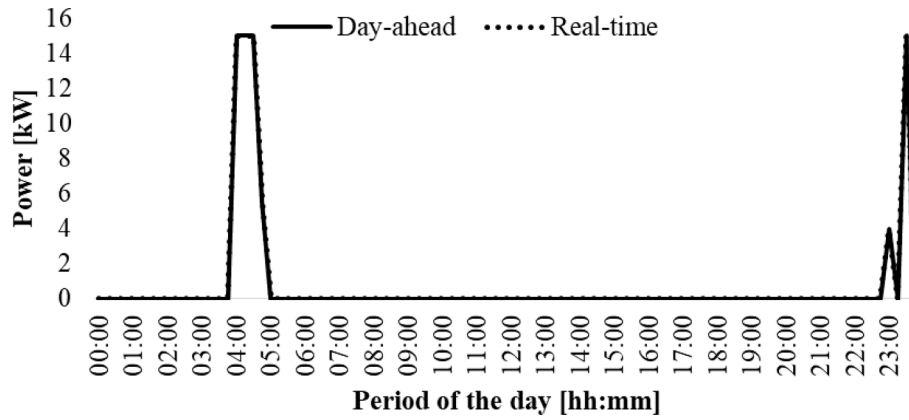


Fig. 12. ESS charging power variation.

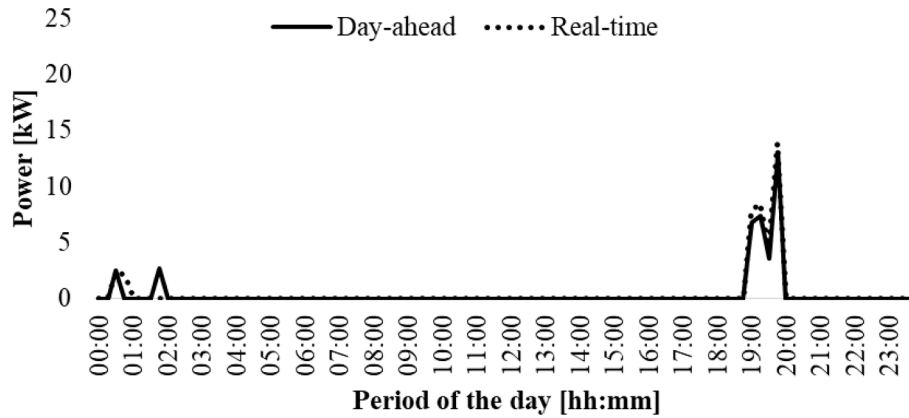


Fig. 13. ESS-to-residential end-users power transfer variation.

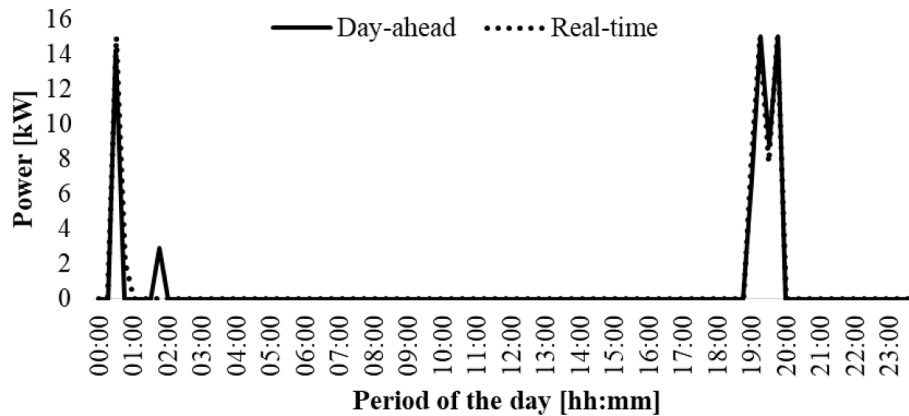


Fig. 14. ESS discharging power variation.

become more widely available in the future. While implementing each fairness constraint improves the fairness of the corresponding metric, it compromises the fairness of the other five metrics. However, placing greater emphasis on  $\%PSR_r$  and  $PC_r$ -based fairness results in less fairness violation for the other metrics, as observed in the results presented in Table 2. Ultimately, the choice of fairness regarding the ratio of common facility role in load energy or the direct contribution of the common facility depends on the decision-maker, which should be discussed further among community participants.

To further assess the responsiveness of the proposed approach during high levels of uncertainty, a sensitivity analysis is conducted based on high levels of deviation in possible real-time generation from day-ahead

projections. In this context, the day-ahead PV production profile is reduced to 50% of its original value, resulting in a deviation of 50% from a day-ahead projection downward or a 100% deviation upward if the reference is set at 50%. This can be seen as the existence of high levels of uncertainty in both directions of deviation. It should be noted that only  $\%PSR_r$ -based fairness is considered by imposing (21.a) and (22), as the other conditions have already been comparatively analyzed in the previous sections of the study.

The obtained results are shown in Figs. 17 and 18 for two-way energy transactions between the grid and the neighborhood. It is evident that although the power drawn by the neighborhood from the grid differs in the two conditions, this difference is more pronounced in the

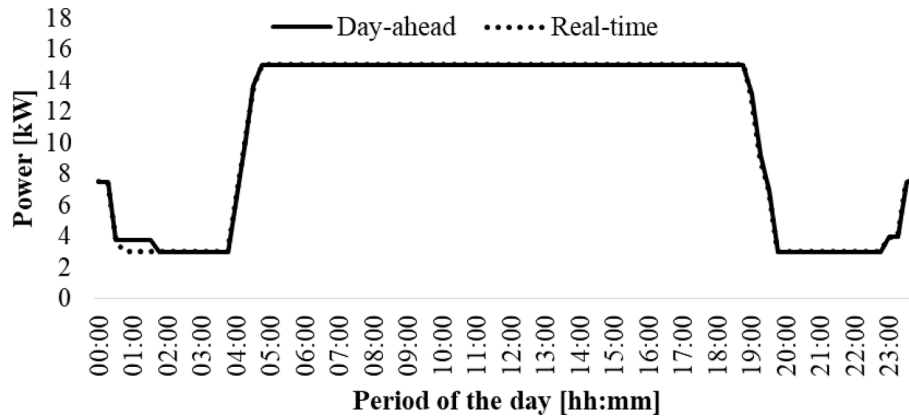


Fig. 15. ESS state-of-energy variation.

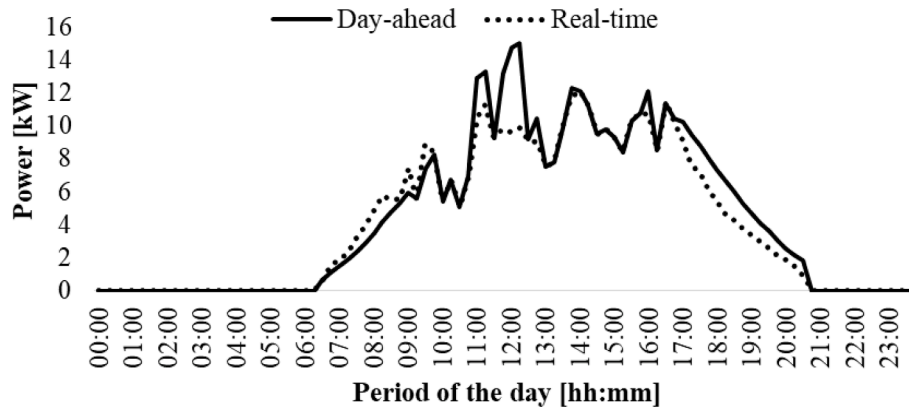


Fig. 16. PV-to-residential end-users power transfer variation.

Table 3

Comparison of different case studies.

| Case   | %PSR <sub>r</sub> [%] |       | %ESR <sub>r</sub> [%] |       | %PESR <sub>r</sub> [%] |       | PC <sub>r</sub> [kWh] |       | EC <sub>r</sub> [kWh] |      | PEC <sub>r</sub> [kWh] |       | Cost change [%] |
|--------|-----------------------|-------|-----------------------|-------|------------------------|-------|-----------------------|-------|-----------------------|------|------------------------|-------|-----------------|
|        | Min                   | Max   | Min                   | Max   | Min                    | Max   | Min                   | Max   | Min                   | Max  | Min                    | Max   |                 |
| Case-1 | 13.32                 | 89.82 | 4.77                  | 10.35 | 20.15                  | 89.95 | 1.24                  | 11.10 | 0.01                  | 1.06 | 1.68                   | 11.14 | Base            |
| Case-2 | 42.82                 | 51.38 | 0.21                  | 11.96 | 43.03                  | 59.82 | 2.45                  | 7.81  | 0.01                  | 1.72 | 2.79                   | 8.44  | +%0.38          |
| Case-3 | 23.83                 | 74.95 | 5.01                  | 6.02  | 29.82                  | 79.98 | 1.72                  | 8.91  | 0.28                  | 0.87 | 2.15                   | 9.51  | +%4.95          |
| Case-4 | 33.93                 | 54.67 | 1.39                  | 12.79 | 46.72                  | 56.07 | 2.26                  | 8.43  | 0.16                  | 1.33 | 2.84                   | 8.74  | +%5.01          |
| Case-5 | 24.91                 | 62.62 | 0.99                  | 27.01 | 36.39                  | 65.55 | 3.57                  | 4.29  | 0.07                  | 3.89 | 3.65                   | 8.19  | +%0.03          |
| Case-6 | 17.51                 | 77.02 | 2.75                  | 8.85  | 23.21                  | 81.79 | 1.37                  | 9.17  | 0.47                  | 0.56 | 1.86                   | 9.72  | +%4.97          |
| Case-7 | 32.62                 | 61.81 | 0.87                  | 28.73 | 34.03                  | 84.79 | 3.12                  | 5.72  | 0.10                  | 1.72 | 4.85                   | 5.82  | +%5.81          |

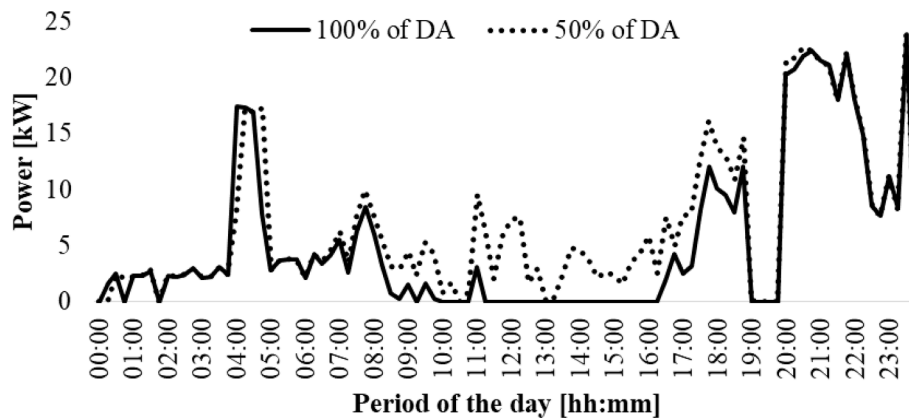


Fig. 17. Comparative analysis of power drawn from the grid by the neighbourhood for sensitivity analysis.

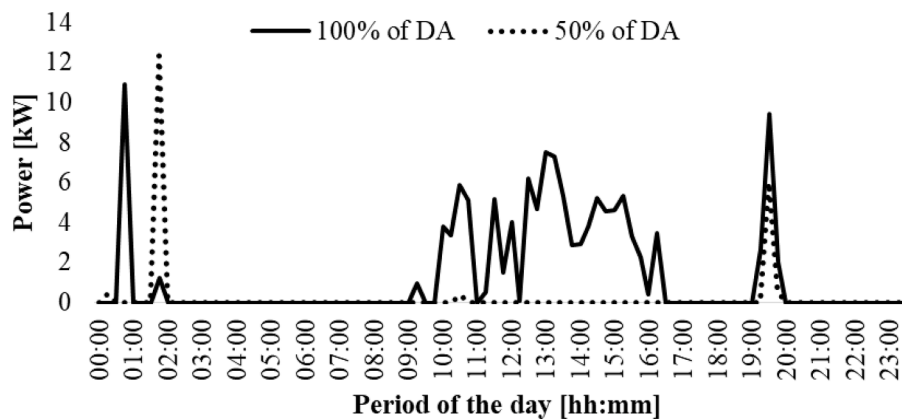


Fig. 18. Comparative analysis of power injected back to the grid from the neighbourhood for sensitivity analysis.

comparative variation analysis of the power injected back into the grid by the neighborhood. The %PSR<sub>r</sub> values range from 44.04–52.84 and 26.94–32.33, respectively, for 100% and 50% day-ahead PV production cases, satisfying the imposed fairness limitations in both conditions. As seen, even when conditions change significantly, the proposed structure can adapt to these new operating conditions, ensuring that the imposed target limits are met. In addition to analyzing the impacts of power-based variations, as demonstrated above, further analysis could be performed for response stability by dramatically reducing the time period, although this is beyond the scope of the current study.

#### 4. Conclusions

The rising need for environmentally friendly and economically viable energy solutions has driven the integration of PV systems and ESSs in residential communities. Ensuring equitable allocation of shared resources, such as communal PV and ESS units, among residents is essential for maintaining the sustainability and cost-effectiveness of these energy solutions. This research introduces a MILP optimization model focused on cost minimization for residential neighborhoods, taking into account equitable distribution of shared PV and battery resources. The proposed model also incorporates a rolling horizon optimization strategy to address uncertainties in PV production. A comprehensive analysis of the influence of fairness on the overall cost and performance of the energy management system in a residential community is provided. Results demonstrate that the rolling horizon optimization method offers more accurate assessments for the proposed energy management concept compared to day-ahead forecasts. Imposing fairness constraints led to a more balanced utilization of PV and ESS units among end-users, with a maximum increase of 5% in total cost under the worst-case scenario, which is deemed acceptable. Consequently, equitable allocation of on-site shared facilities can be achieved with minimal cost impact.

This study may also contribute to the advancement of the smart energy community concept in policy making and design practice from these perspectives:

- **Informing Policy and Regulation:** The findings of this study can inform policymakers and regulators on the importance of incorporating fairness considerations in the design and implementation of smart energy communities. By demonstrating the feasibility of achieving fair energy allocation without significantly increasing costs, this research can support the development of policies and incentives that promote the adoption of shared renewable energy resources in residential neighborhoods.
- **Guiding Design Practice:** The results of this study can serve as a valuable reference for designers and engineers seeking to develop energy management systems for smart energy communities. By

highlighting the importance of fairness considerations and showcasing the benefits of a rolling horizon optimization approach, this research can help inform the development of more efficient, equitable, and sustainable energy management solutions.

Future studies are encouraged to broaden the sources of uncertainty to include residential load demand and energy transaction prices while also considering the impact of demand flexibility on the concept of fair usage.

#### CRedit authorship contribution statement

**Fatma Gülşen Erdinç:** Conceptualization, Methodology, Software, Writing – original draft.

#### 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.

#### Data availability

No data was used for the research described in the article.

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