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Development of a New Operation Strategy Enabling Transactions of Flexibility Among Households for a Residential Neighborhood

Evsel Bir Mahalli Alan İçin Evler Arasında Esneklik Alışverişine İmkân Sağlayan Yeni Bir İşletim Stratejisinin Geliştirilmesi

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Abstract

This study proposes a novel energy management strategy for residential neighborhoods that enables peer-to-peer energy transactions among households without the need for energy storage or distributed generation. The proposed strategy is based on a Mixed-Integer Linear Programming (MILP) optimization model that minimizes the overall cost per household, including energy consumption cost, flexibility procurement cost, flexibility selling gain, and penalty cost caused by exceeding the limits. The strategy aims to optimize the energy consumption and production patterns of households with just inverter-based air conditioner loads, while also ensuring that the overall load limit for the neighborhood is not exceeded during certain periods. The results of the MILP-based optimization model demonstrate that the proposed strategy can significantly reduce the overall cost per household, providing a more efficient and cost-effective energy system for residential neighborhoods. The strategy utilizes a flexible energy trading platform, with a pricing mechanism designed to incentivize households to optimize their energy consumption and production patterns and support the transition to a low-carbon energy future.

Keywords: Energy management, Flexibility trading, Inverter air-conditioners, Residential neighborhood

Öz

Bu çalışmada, enerji depolama veya dağıtık üretim ihtiyacı olmadan evsel bir mahalli olan için evler arası enerji işlemlerine olanak tanıyan yeni bir enerji yönetimi stratejisi önermektedir. Önerilen strateji, enerji tüketim maliyeti, esneklik sağlama maliyeti, esneklik satış kazancı ve limitleri aşmadan kaynaklanan ceza maliyeti de dahil olmak üzere, genel maliyeti ev başına en aza indiren Karışık Tamsayılı Lineer Programlama optimizasyon modeline dayanmaktadır. Strateji, sadece inverter tabanlı klima yükleri ile evlerin enerji tüketim ve üretim desenlerini optimize etmeyi amaçlarken, aynı zamanda belirli dönemlerde mahalle genel yük limitinin aşılmamasını da sağlamaktadır. Karışık Tamsayılı Lineer Programlama tabanlı optimizasyon modelinin sonuçları, önerilen stratejinin ev başına genel maliyeti önemli ölçüde azaltabileceğini, böylece evsel mahalli alanlar için daha verimli ve maliyet etkin bir enerji sistemi sağlayabileceğini göstermektedir. Strateji, esnek bir enerji ticaret platformu kullanmakta ve düşük karbonlu bir enerji geleceğine geçişi desteklemek için tasarlanmış bir fiyatlandırma mekanizması ile evlerin enerji tüketim ve üretim desenlerini optimize etmelerini teşvik etmektedir.

Anahtar Kelimeler: Enerji yönetimi, Esneklik ticareti, Evsel mahalli alan, İnverter tabanlı klimalar

1. Introduction

With the increasing demand for energy and the rising concerns over environmental sustainability, the need for an efficient and cost-effective energy system is becoming increasingly important. Residential neighborhoods, which account for a significant portion of the total energy consumption, offer a potential opportunity for optimizing energy consumption and reducing energy costs (Nematchoua et al. 2021).

Effective energy management in residential neighborhoods is critical in achieving energy sustainability and reducing carbon emissions. The implementation of new energy management strategies can help to reduce peak demand, balance the electricity grid, and reduce the need for new power plants. Additionally, energy management can pro-

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vide a significant economic benefit by reducing energy bills for households and businesses, and potentially reducing the overall cost of electricity for the entire community (Gholinejad et al. 2021).

Effective energy management in residential neighborhoods can be enhanced by implementing innovative technologies and concepts. One of these concepts is the use of small local market platforms that enable residential end-users to trade their excess power and even their demand flexibility. These platforms can utilize different technologies, including blockchain-based peer-to-peer (P2P) trading, to facilitate secure and transparent transactions between households. By using these platforms, households can buy and sell energy based on their needs and preferences, and the energy transactions can be tracked and verified through the blockchain technology. This approach can enable households to participate in the energy market and earn additional income by selling their excess power, while also reducing their energy bills by purchasing energy from other households at lower prices. Furthermore, by trading their demand flexibility, households can also contribute to the grid stability and support the integration of renewable energy sources. Therefore, the use of local market platforms can be an effective way to enhance energy management in residential neighborhoods and support the transition to a more sustainable energy system (Wu et al. 2022).

Many studies dealing with the development of various optimization-based energy management concepts have been proposed in the literature. One such study by Jeddi et al. (2021) presented a coordinated framework for multiple home energy management systems in residential neighborhoods. This framework allowed customers to collaborate and optimize energy consumption at the neighborhood level, thus avoiding operational issues at the grid level. The study employed the alternating direction method of multipliers technique to reduce computational burden and maintain customer privacy while implementing coordinated load scheduling in a distributed manner. Simulation results showed that the proposed approach was effective in maintaining nominal network conditions while benefiting individual customers and grid operators.

Shafiullah et al. (2020) proposed a scenario-based energy management system for a local energy community using mixed-integer linear programming (MILP). The model generated scenarios with the Gaussian mixture model to consider uncertainties of demand and renewable sources, and Monte Carlo simulations were used to evaluate the effectiveness of the system. The study found that the stochastic process outperformed the deterministic process significantly in terms of cost, CO_2 emission, imported electricity from the grid, and the usage of local energy resources. The article emphasized the role of energy-neutral neighborhoods in achieving energy transition goals, but noted that uncertainties related to demand and renewable sources posed significant operational challenges for scheduling distributed energy resources.

Sidnell et al. (2021) employed a MILP model to optimize the design and operation of distributed energy resource systems in residential areas. The study found that distributed energy resource networks could reduce CO_2 emissions by 30-40% per household and be more economical than traditional energy consumption. The study also explored the use of feed-in tariffs, renewable heat incentives, and the ability to buy/sell from/to the national grid. The model was based on data from UK homes, but the approach could be applied to other regions where feed-in tariffs are popular renewable energy policy mechanisms.

Velik and Nicolay (2016) introduced a modified simulated annealing optimization approach to find optimal energy management strategies in grid-connected, storage-augmented, photovoltaics-supplied prosumer buildings and neighborhoods. The approach was compared to a gradient descent and a total state space search approach and found to be significantly more efficient and effective in finding better solutions.

The paper by Suresh et al. (2023) investigated how to address the economic dispatch problem of microgrids using traditional and newly introduced metaheuristic optimization algorithms. The study tested these algorithms on the IEEE 30 bus system and a microgrid facility at Wroclaw University of Science and Technology. The results showed that the ant-colony based algorithm was the most suitable in terms of convergence time, solution value, and reliability. This algorithm was used to optimize economic dispatch in the microgrid by minimizing the levelized cost of energy. The authors suggest that decentralizing electrical networks through microgrids is a promising solution for achieving sustainability in energy production.

Another paper by Zucker et al. (2016) aimed to reduce CO_2 emissions by improving the thermal behavior of a large neighborhood of buildings using a co-simulation environment. They developed a three-step workflow to create building models for a large neighborhood and used the simulation to optimize the operation of the heating plant with the goal of minimizing CO_2 emissions. The results showed that optimizing the indoor temperature controller for all buildings led to a reduction in CO_2 emissions.

Haider et al. (2022) developed a new approach for optimizing demand response in residential areas within smart grids. They used a multi-objective cost-peak optimization technique to balance cost savings and peak demand reduction and tested the approach on a residential area in Malaysia. The results showed significant improvements in cost savings and peak demand reduction compared to traditional demand response methods.

Benoit Durillon et al. (2020) developed a management system to reduce the neighborhood's peak load and load fluctuation while considering different types of load and consumer profiles. The study presented three different scenarios, and it was shown that all objectives could be fulfilled while increasing the mean consumer satisfaction by up to 13%. The study highlighted that involving consumers in the energy management system could lead to better outcomes for both consumers and the grid.

Green and Garimella (2022) investigated the use of data-driven black-box models in optimizing a single-home residential microgrid. The study found that data-driven black-box models have the potential to be used in place of grey-box models and showed the importance of demand-side management in residential energy consumption, particularly during peak hours.

Shakouri et al. (2017) proposed an intelligent energy management framework that aimed to minimize both electrical peak load and electricity cost simultaneously for a residential area with multiple households. The study concluded that the use of centralized energy management systems in residential areas could benefit both consumers and utility companies simultaneously.

Akter et al. (2020) presented an optimal energy management scheme for residential microgrids using distributed mixed integer linear programming problems. The proposed approach allowed houses to make optimal decisions without sharing private information with a central transactive energy management system. The study showed the efficacy of the presented method in distributedly optimizing energy resources in a neighborhood.

Fernandez et al. (2018) proposed a new demand-side management framework based on game theory to reduce peak energy consumption in a Sydney neighborhood. This approach enabled energy sharing among neighbors using distributed and renewable energy resources, and included a real-time pricing model and an optimization algorithm based on Nash game theory to schedule energy consumption. The results of the case studies using real building consumption data showed that the proposed framework reduced peak average ratio and energy costs for consumers by 9.17% and 9.68% respectively during summer and winter.

Gholinejad et al. (2020) presented a hierarchical energy management system for multiple home energy hubs that aimed to maximize financial profit and reduce peak energy usage. The system managed energy generation, energy storage, and energy purchase/sale of each home energy hub using a heuristic bidding strategy based on a weighted distribution of excess power among consumers. The simulator developed in MATLAB/GUI showed that the system decreased total energy cost and increased total profit.

Hu et al. (2021) and Thirunavukkarasu et al. (2022) provided useful reviews on different approaches and techniques for managing energy in residential neighborhoods, including coordination and negotiation techniques, optimization techniques, and microgrid energy management systems.

There is another group of studies dealing with local trading topic for residential neighborhoods. Singh et al. (2022) proposed a peer-matching mechanism called enTrade for designing a P2P energy trading market model between prosumers and consumers in a distributed electricity market using a game theory-based leader-follower model. Fernandez et al. (2021) proposed a community energy management system for a smart locality that facilitates local energy trading between consumers with renewable energy units, a central storage facility, and the power grid. Finally, Görgülü et al. (2022) examined the role of P2P energy trading in system operation and performed an economic analysis using a mathematical modeling approach based on MILP.

There are also further studies on decision making mechanisms for the cases in which the residential end-users can participate in local energy markets. Some review studies in this manner can be found the study of Bukar et al. (2023) to analyze different approaches applied in several literature studies.

In this context, this study proposes a new operation strategy that enables transactions of flexibility among households in a residential neighborhood with inverter-based air conditioner loads. The proposed strategy is cost minimization oriented and aims to optimize the energy consumption and production patterns of households to minimize the overall cost per household. The proposed strategy incorporates a load limit provided by the grid operator for the overall neighborhood during certain periods, and the neighborhood operator adjusts this limit equally for all households. The households that consume below the imposed limit can sell their unused energy to other households that cannot obey their power production limits. A penalty is imposed on households that exceed their allotted limit even after purchasing additional energy from other households. The proposed operation strategy utilizes a MILP optimization model that incorporates constraints such as energy balance, load limit, and flexibility procurement and selling limits to ensure the overall cost is minimized while the energy consumption and production patterns are optimized.

The contributions of this study are as follows:

- Development of a novel energy management strategy for residential neighborhoods that facilitates cost-effective flexibility transactions between households, aiming to minimize the overall cost per household and optimize energy consumption and production patterns.
- Formulation of a MILP optimization model that incorporates a flexibility-based energy trading platform, enabling peer-to-peer energy transactions and incentivizing households to optimize their energy use, thus supporting the transition to a low-carbon energy system.
- Comprehensive evaluation of the proposed concept through five different case studies, assessing the impact of varying peak power limits on a residential neighborhood during peak demand hours. The results demonstrated the effectiveness of the proposed strategy in significantly reducing the overall cost per household and provided insights into the consequences of stricter grid constraints on energy consumption and costs.
- Identification of the need for additional flexible resources in residential neighborhoods, particularly under more stringent grid constraints, highlighting potential areas for further research and development in residential energy management.

The remainder of the paper is organized as follows: The mathematical background regarding the flexibility transactions oriented residential neighborhood energy management strategy is depicted in Section 2. Afterwards, the obtained results based on case studies are given in Section 3. Finally, the concluding remarks are presented in Section 4.

2. Methodology

This study proposes a new strategy for exchanging flexibility between households in a residential neighborhood, which optimizes the energy consumption and production patterns of each household to minimize overall costs. The strategy aims to reduce costs by allowing households that consume less than their allotted limit to sell their unused energy to other households that need it. The neighborhood operator sets a load limit for the overall neighborhood during certain periods, which is then distributed equally among households. A penalty is imposed on households that exceed their allotted limit, even if they purchase additional energy from other households. The strategy utilizes a mathematical optimization model to ensure that energy consumption and production patterns are optimized while minimizing costs, and considers constraints such as energy balance, load limit, and flexibility procurement and selling limits.

The objective of the proposed concept is to minimize the average cost among the residential end-users existing in the neighborhood as given in (1). Here, the individual cost of each end-user consists of an energy procurement cost, a flexibility procurement cost, a flexibility selling based benefit and a penalty cost related to the case when this end-user cannot satisfy the imposed peak load limit even after procuring the available flexible power from the neighborhood pool as shown in (2).

$$MinCost_{Av} = \frac{\sum_h Cost_h}{card(h)} \tag{1}$$

$$\begin{aligned} Cost_h = \sum_t P_{grid,h,t} \cdot \Delta T \cdot \gamma_{energ,t} + P_{flex-buy,h,t} \cdot \Delta T \cdot \gamma_{flex,t} \\ + P_{penalty,h,t} \cdot \Delta T \cdot \gamma_{penalty} - P_{flex-sell,h,t} \cdot \Delta T \cdot \gamma_{flex,t}, \forall h \end{aligned} \tag{2}$$

As given in (2), the power drawn from the grid by each household corresponds to the supply of flexible load together with the air conditioner load demand in each time period. Here, the grid operator may impose a varying peak power demand to the overall neighborhood and the neighborhood energy management unit fairly allocates this limit to each residential end-users as formulated in (4). For each household, when this maximum demand is greater than the real power demand of this household, there is a chance for this household to benefit from this gap by selling this power difference to other residential end-users in the neighborhood. On the contrary, the household can procure such a flexibility from other households when its demand is higher than the maximum allocated demand level to prevent being penalized by a higher cost corresponding to a penalization power value at the worst case. By this chance depicted in (5), the general scheme allows a platform for the end-users to trade their demand-based flexibility locally as a new contribution to the relevant literature.

$$P_{grid,h,t} = P_{load-\text{inf}lex,h,t} + P_{AC,h,t}, \forall h,t \tag{3}$$

$$P_{grid-\max,h,t} = \frac{P_{grid-\lim,t}}{card\,(h)}, \forall h,t \tag{4}$$

$$P_{grid-\max,h,t} = P_{grid,h,t} + P_{flex-sell-\max,h,t} - P_{flex-buy,h,t} - P_{penalty,h,t}, \forall h,t \tag{5}$$

The simultaneous occurrence for the allowance of flexibility selling, buying and penalizing axioms is prevented using the logical constraints given in (6)-(8). As given in (9), the selling levels of each household is restricted by the maximum allowed level formerly determined in (5). Finally, the local balance for the overall selling and buying decisions is determined in (10) ensuring that the buying action can only be possible when there is a flexible power selling possibility for another end-user and vice versa.

$$P_{flex-sell-\max,h,t} \le N \cdot u_{1,h,t}, \forall h,t \tag{6}$$

$$P_{flex-buy,h,t} \le N \cdot (1 - u_{1,h,t}), \forall h,t \tag{7}$$

$$P_{penalty,h,t} \le N \cdot (1 - u_{1,h,t}), \forall h,t \tag{8}$$

$$P_{flex-sell,h,t} \le P_{flex-sell-\max,h,t}, \forall h,t \tag{9}$$

$$\sum\nolimits_h P_{flex-sell,h,t} = \sum\nolimits_h P_{flex-buy,h,t}, \ \forall t \tag{10}$$

The ON/OFF type air conditioners are modeled to be either in zero or nominal power consumption state while the power consumption of an inverter air conditioner can fully vary between a minimum and maximum level if the air conditioner is ON as depicted in (11). The relevant indoor temperature variation regarding the air conditioner power consumption, ambient temperature as well as the air conditioner and household specifications is modeled in (12) using equivalent thermal parameter approach (Mathieu et al., 2013). The details of parameter *a* is given in (13) regarding the thermal resistance and capacitance parameters. The initialization of indoor temperature variation is realized by (14). The indoor temperature should be maintained within a dead-band limit around the temperature set point as given in (15) while this set point can only be changed by the energy management system within desired upper and lower bounds as ensured by (16).

$$u_{2,h,t} \cdot P_{AC-\min,h} \le P_{AC,h,t} \le u_{2,h,t} \cdot P_{AC-\max,h}, \forall h,t \tag{11}$$

$$T_{in,h,t} = a \cdot T_{in,h,t-1} + (1-a) \cdot [T_{out,t-1} - COP \cdot R \cdot P_{AC,h,t-1}], \forall h,t > 1 \tag{12}$$

$$a = e^{-\frac{\Delta T}{R \cdot C}} \tag{13}$$

$$T_{in,h,t} = T_{in-init,h}, \forall h, if\ t = 1 \tag{14}$$

$$T_{set,h,t} - T_{db} \le T_{in,h,t} \le T_{set,h,t} + T_{db}, \forall h,t \tag{15}$$

$$T_{\lim-down,h} \le T_{set,h,t} \le T_{\lim-up,h}, \forall h,t \tag{16}$$

3. Test and Results

The problem of the cost minimization oriented energy management strategy considering usage fairness is formulated through MILP approach. The proposed structure is tested with the GAMS v.24.1.3 software and CPLEX v.12 solver. The simulation takes less than 1 second for a horizon on a computer with Intel 7 processor and 8 GB RAM.

A residential neighbourhood of 20 households is considered in this study. The relevant data are gathered using Domestic Electricity Demand Model of CREST (Centre for Renewable Energy Systems Technology) from Loughborough University. Randomized appliance allocation and occupancy variation are implemented to obtain the data of the mentioned 20 households including 2 end-users with 1 occupants, 3 end-users with 2 occupants, 4 end-users with 3 occupants, 5 end-users with 4 occupants and 6 end-users with 5 occupants. The sample power profiles of 4 different households are depicted in Figure 1. It should here be noted that "r" in the mentioned figures represents the relevant residential end-user, e.g. r20 represents residential end-user 20.

On the other hand, the outdoor temperature variation is presented in Figure 2. Moreover, the price variation considered in this study is depicted in Figure 3. It should be mentioned here that the flexibility transaction prices are 20% higher than that of the energy price in each period to reward the end-users with flexibility selling possibility regarding their lower consumption while simultaneously penalizing the end-users with flexibility buying requirement regarding their higher consumption. It should here be noted that the flat penalty cost is considered as 3 Euro/kWh. Apart from these, identical households with a thermal resistance of 2 ^{0}C/kW, a COP of 2.5, air conditioner minimum and maximum power of 0.2 and 3.5 kW, thermal capacitance of 2 kWh/^{0}C, an initial indoor temperature of 20 ^{0}C, a temperature deadband of 0.5 ^{0}C, and a lower and upper temperature set-point definition limit of 18 and 22 ^{0}C are considered.

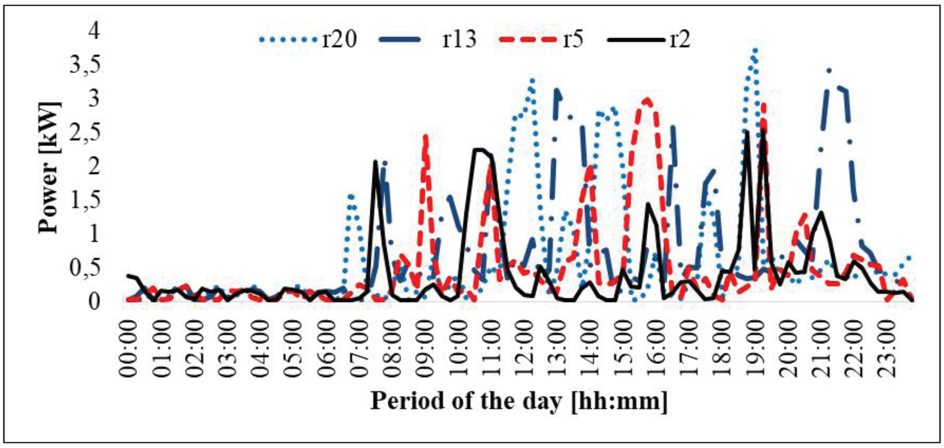

Figure 1. The power consumption of sample end-users.

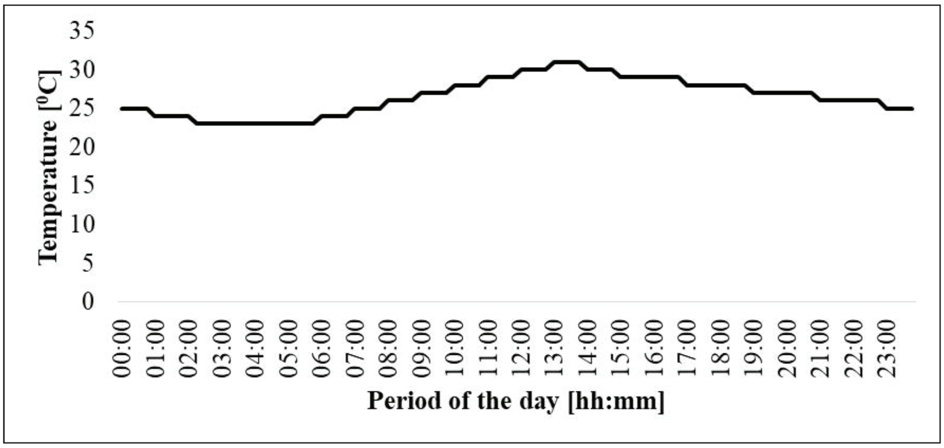

Figure 2. Outdoor temperature variation.

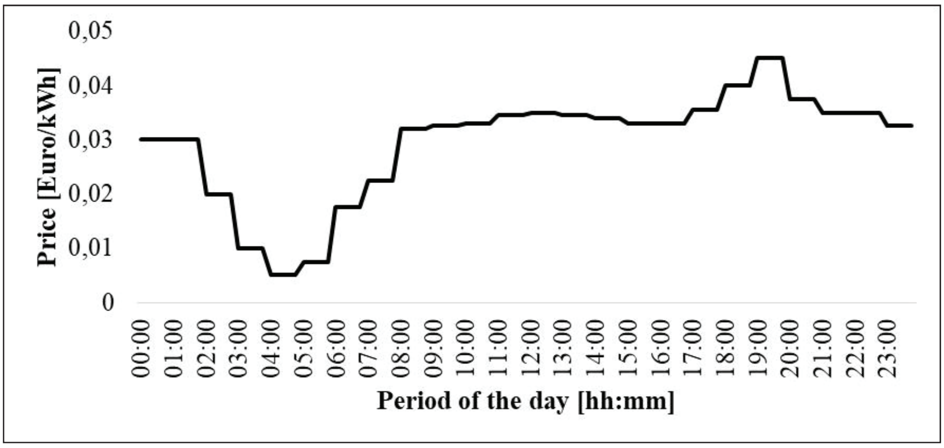

Figure 3. Energy price variation.

To assess the proposed concept, five different case studies are considered regarding the total peak power limit employed to the residential neighborhood at peak demand hours between 19:00-22:00 for a transformer limit of 100kW:

Case-1: No peak power limit

Case-2: A total peak power limit corresponding to the 80% of the transformer capacity is imposed between 19:00-22:00

Case-3: A total peak power limit corresponding to the 60% of the transformer capacity is imposed between 19:00-22:00

Case-4: A total peak power limit corresponding to the 40% of the transformer capacity is imposed between 19:00-22:00

Case-5: A total peak power limit corresponding to the 20% of the transformer capacity is imposed between 19:00-22:00

The results regarding Case-1 and Case-5 are shown below in Figures 4-9 to depict the impact of peak power limit at two edge cases. The grid power variation is initially shown in Figures 4 and 5 respectively for Case-1 and Case-5. As can be seen, the initial periods are generally similar while a vital difference occurs especially before the peak power limit period to avoid any possible penalty payment condition. By this pre-consumption action before the peak power limitation period, the considered households do not exceed the average power limit for Case-1 and Case-5 corresponding respectively to 5 kW and 1 kW per household. However, the peak power each household faces increases within the whole day with the implementation of harder peak power limits especially for r20, leading to a lower load factor which should also be reconsidered with further actions. This difference between different cases is mainly related to the change of air conditioner power consumption comparatively shown in Figures 6 and 7. Here, as the households and other conditions are considered identical, the air conditioner power consumption and the corresponding indoor temperature

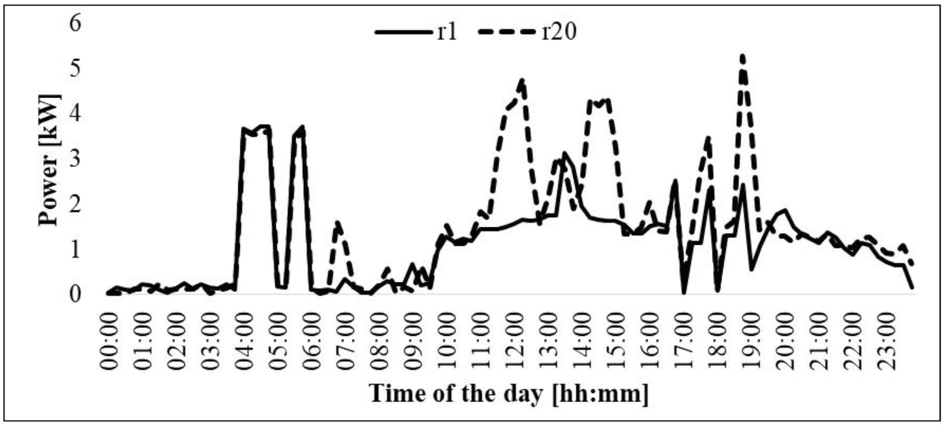

Figure 4. Grid power variation for Case-1.

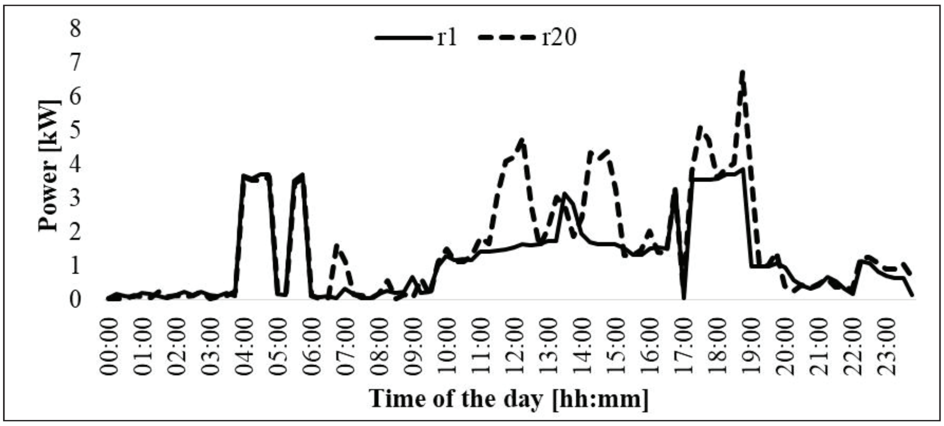

Figure 5. Grid power variation for Case-5.

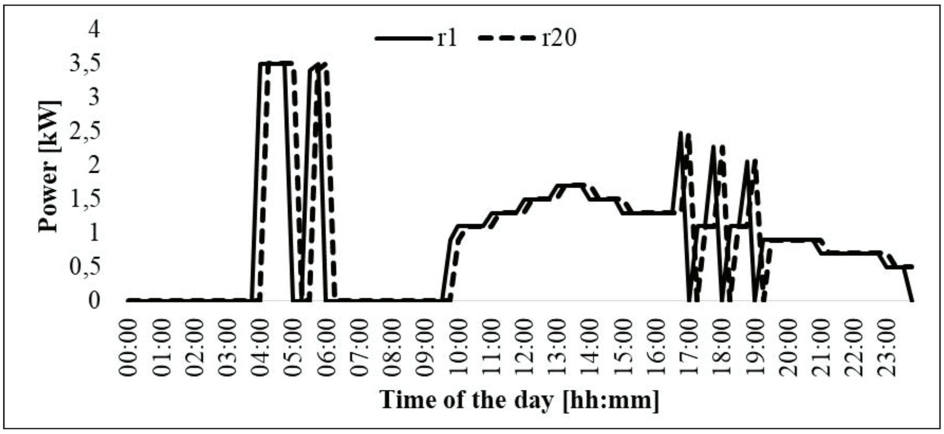

Figure 6. Air conditioner power variation for Case-1.

(shown in Figures 8 and 9) are nearly the same between different households, but differs between different cases.

The overall results are summarized in Table 1 for all cases. As seen, when a penalty condition is not faced, the average cost is nearly the same in Cases 1-4 clearly depicting how the penalty conditions are aimed to be avoided as much as possible. However, even the average cost is maintained, the minimum cost among the end-users decreases (reaching 10%) while the maximum cost increases (around 4%) when harder limits are imposed from Case-1 to Case-4. Finally, Case-5 is the only case when a penalty cost is imposed to some of the households as there is not sufficient flexibility in the overall neighborhood. This leads to the neighborhood to exceed the imposed overall demand limit as seen in Figure 10 specifically for peak demand periods. This depicts that more flexible resources are needed for such a neighborhood under harder grid constraints.

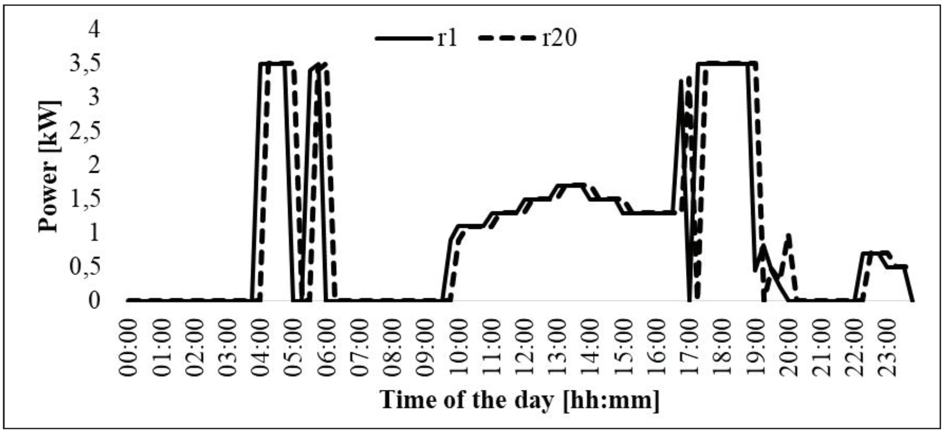

Figure 7. Air conditioner power variation for Case-5.

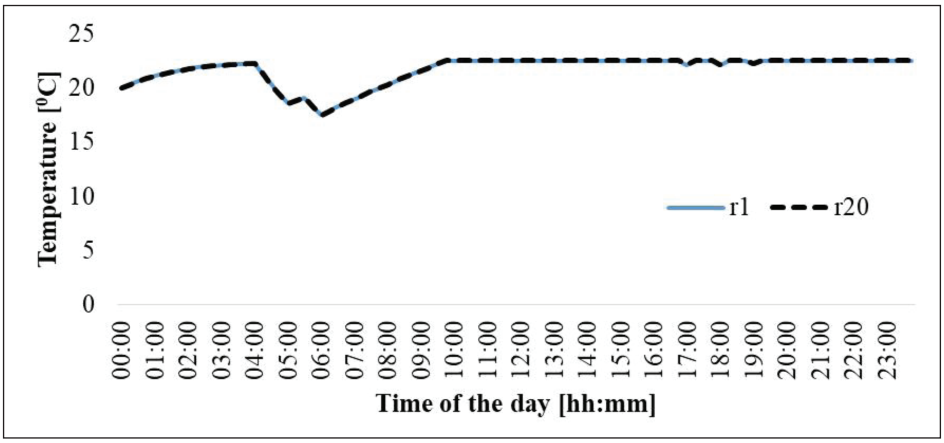

Figure 8. Indoor temperature variation for Case-1.

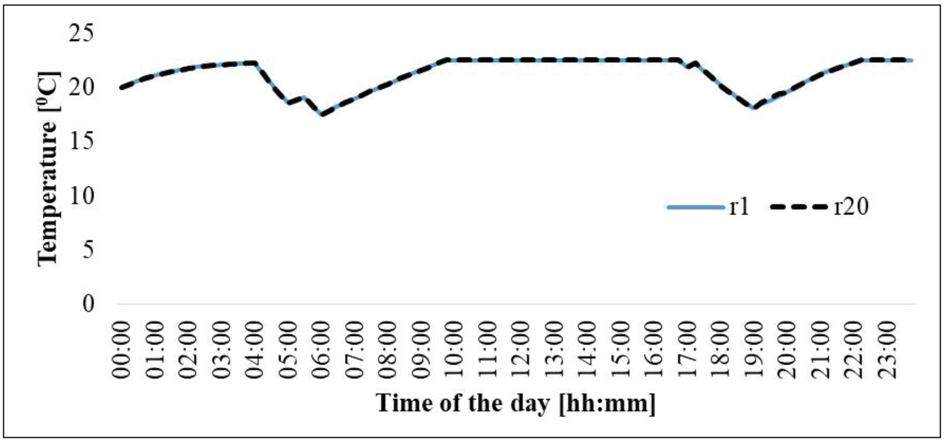

Figure 9. Indoor temperature variation for Case-5.

Table 1. Comparative analysis of the results of different cases.

Case	Min. cost [Euro]	Max. cost [Euro]	Av. Cost [Euro]	Total. flex. [kW]	Total pen. [kW]
Case-1	0.7675	1.1501	0.9543	4.107	0
Case-2	0.7675	1.1506	0.9543	6.844	0
Case-3	0.7526	1.1797	0.9543	29.133	0
Case-4	0.6893	1.2037	0.9550	69.604	0
Case-5	0.7886	5.5164	1.6491	98.003	16.37

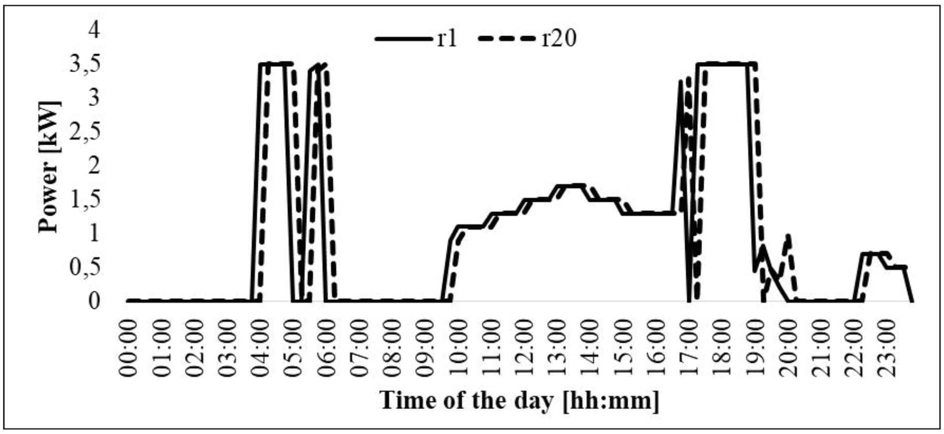

Figure 10. Total neighborhood power demand for Case-5 during peak power limit periods.

4. Conclusions

In this study, a novel energy management strategy for residential neighborhoods was introduced, enabling cost-effective flexibility transactions among households. The MILP optimization model aimed to minimize the overall cost per household while optimizing energy consumption and production patterns of households with inverter-based air conditioner loads. The approach incorporated a flexibility-based energy trading platform that facilitated peer-to-peer energy transactions, encouraging households to optimize their energy use and support the transition to a low-carbon energy system.

The effectiveness of the proposed concept was assessed through five different case studies that examined the impact of peak power limits on a residential neighborhood during peak demand hours between 7-10 PM for a transformer limit of 100kW. The cases ranged from no peak power limit to peak power limits constituting 20% to 80% of the transformer capacity during peak hours. The results from Cases 1 and 5 were presented, illustrating the impact of peak power limits at the two extremes.

The grid power variation was initially similar in both cases; however, a notable difference occurred before the peak power limit period, as households adjusted their consumption to avoid possible penalty payments. This pre-consumption action ensured that households did not exceed the average power limit in both cases. Nonetheless, implementing stricter peak power limits increased peak power throughout the day, resulting in a lower load factor that requires further consideration.

The difference between the cases was primarily associated with changes in air conditioner power consumption. The overall results indicated that when penalty conditions were not faced, the average cost remained nearly constant for Cases 1-4, highlighting that the strategy aimed to avoid penalty conditions as much as possible. However, as stricter limits were imposed from Case 1 to Case 4, the minimum cost among end-users decreased, while the maximum cost increased. Case 5 was the only scenario where a penalty cost was imposed on some households, suggesting that additional flexible resources are necessary for neighborhoods under more stringent grid constraints.

The MILP-based optimization model's results demonstrated the proposed strategy's effectiveness in significantly reducing the overall cost per household, indicating its potential for broader applicability in various residential neighborhoods. In summary, this energy management strategy presents a promising approach for creating a more efficient and cost-effective energy system in residential neighborhoods, laying the groundwork for further research and development in this field. As future work, it would be valuable to consider additional flexible resources and explore the integration of renewable energy sources, storage systems, and demand response programs to further optimize the energy management and enhance grid resilience.

5. Nomenclature

Sets

h	Set of residential end-user.
t	Set of time periods.

Parameters

C	Thermal capacitance [kWh/^{0}C].
COP	Air conditioner coefficient of performance.
N	Sufficiently large positive constant.
$P_{AC\text{-}max,h}$	Maximum power rating of air conditioner of residential end-user h [kW].
$P_{AC\text{-}min,h}$	Minimum power rating of air conditioner of residential end-user h [kW].
$P_{grid\text{-}lim,t}$	Maximum allowed total power limit for residential neighborhood in period t [kW].
$P_{grid\text{-}max,h,t}$	Maximum allowed power limit for residential end-user h in period t [kW].
$P_{load\text{-}inflex,h,t}$	Inflexible power demand of residential end-user h in period t [kW].
R	Thermal resistance [^{0}C/kW].
T_{db}	Temperature deviation in dead-band operation of an air conditioner [^{0}C].
$T_{in\text{-}init,h}$	Initial indoor temperature of residential end-user h [^{0}C].
$T_{lim\text{-}down,h}$	Lower limit of thermostat set-point decision [^{0}C].
$T_{lim\text{-}up,h}$	Upper limit of thermostat set-point decision [^{0}C].
$T_{out,t}$	Outdoor temperature in period t [^{0}C].
$\gamma_{energy,t}$	Energy price in period t [Euro/kWh].
$\gamma_{flex,t}$	Flexible transaction price in period t [Euro/kWh].
$\gamma_{penalty}$	Penalty price in period t [Euro/kWh].
ΔT	Time granularity [h].

Variables

$P_{AC,h,t}$	Air conditioner power demand of residential end-user h in period t [kW].
$P_{flex\text{-}buy,h,t}$	Flexible power bought by residential end-user h in period t [kW].
$P_{flex\text{-}sell,h,t}$	Flexible power sold by residential end-user h in period t [kW].
$P_{flex\text{-}sell\text{-}max,h,t}$	Maximum flexible power that can be sold by residential end-user h in period t [kW].
$P_{grid,h,t}$	Grid power of residential end-user h in period t [kW].
$P_{penalty,h,t}$	Penalized power consumption of residential end-user h in period t [kW].
$T_{in,h,t}$	Indoor temperature of residential end-user h in period t [0C].
$T_{set,h,t}$	Thermostat set-point temperature of residential end-user h in period t [^{0}C].
$u_{1,h,t}$, $u_{2,h,t}$	Binary variables.

6. References

Akter, M.N., Mahmud, M.A., Haque, M.E., Oo, A.M.T. 2020. An optimal distributed energy management scheme for solving transactive energy sharing problems in residential microgrids. Applied Energy, 270: 115133. DOI: 10.1016/j.apenergy.2020.115133

Bukar, A.L., Hamza, M.F., Ayub, S., Abobaker, A.K., Modu, B., Mohseni, S., Brent, A.C., Ogbonnaya, C., Mustapha, K., Idakwo, H.O. 2023. Peer-to-peer electricity trading: A systematic review on current developments and perspectives. Renewable Energy Focus, 44: 317-333. DOI: 10.1016/j.ref.2023.01.008

Durillon, B., Davigny, A., Kazmierczak, S., Barry, H., Saudemont, C., Robyns, B. 2020. Decentralized neighbourhood energy management considering residential profiles and welfare for grid load smoothing. Sustainable Cities and Society, 63: 102464. DOI: 10.1016/j.scs.2020.102464

Fernandez, E., Hossain, M.J., Mahmud, K., Nizami, M.S.H., Kashif, M. 2021. A bi-level optimization-based community energy management system for optimal energy sharing and trading among peers. Journal of Cleaner Production, 279: 123254. DOI: 10.1016/j.jclepro.2020.123254

Fernandez, E., Hossain, M.J., Nizami, M.S.H. 2018. Game-theoretic approach to demand-side energy management for a smart neighbourhood in Sydney incorporating renewable resources. Applied Energy, 232: 245-257. DOI: 10.1016/j.apenergy.2018.09.171

Gholinejad, H.R., Adabi, J., Marzband, M. 2021. An energy management system structure for Neighborhood Networks. Journal of Building Engineering, 41: 102376. DOI: 10.1016/j.jobe.2021.102376

Gholinejad, H.R., Loni, A., Adabi, J., Marzband, M. 2020. A hierarchical energy management system for multiple home energy hubs in neighborhood grids. Journal of Building Engineering, 28: 101028. DOI: 10.1016/j.jobe.2019.101028

Görgülü, H., Topçuoğlu, Y., Yaldız, A., Gökçek, T., Ateş, Y., Erdinç, O. 2022. Peer-to-peer energy trading among smart homes considering responsive demand and interactive visual interface for monitoring. Sustainable Energy, Grids and Networks, 29: 100584. DOI: 10.1016/j.segan.2021.100584

Green, C., Garimella, S. 2021. Residential microgrid optimization using grey-box and black-box modeling methods. Energy and Buildings, 235: 110705. DOI: 10.1016/j.enbuild.2020.110705

Haider, H.T, Muhsen, D.H., Al-Nidawi, Y.M, Khatib, T., See, O.H. 2022. A novel approach for multi-objective cost-peak optimization for demand response of a residential area in smart grids. Energy, 254: 124360. DOI: 10.1016/j.energy.2022.124360

Hu, M., Xiao, F., Wang, S. 2021. Neighborhood-level coordination and negotiation techniques for managing demand-side flexibility in residential microgrids. Renewable and Sustainable Energy Reviews, 135: 110248. DOI: 10.1016/j.rser.2020.110248

Jeddi, B., Mishra, Y., Ledwich, G. 2021. Distributed load scheduling in residential neighborhoods for coordinated operation of multiple home energy management systems. Applied Energy, 300: 117353. DOI: 10.1016/j.apenergy.2021.117353

Mathieu, J.L., Koch, S., Callaway, D. S. 2013. State estimation and control of electric loads to manage real-time energy imbalance, IEEE Transactions on Power Systems, 28: 430–440. DOI: 10.1109/TPWRS.2012.2204074

Nematchoua, M.K., Nishimwe, A.M.-R., Reiter, S. 2021. Towards nearly zero-energy residential neighbourhoods in the European Union: A case study. Renewable and Sustainable Energy Reviews, 135: 110198. DOI: 10.1016/j.rser.2020.110198

Shafiullah, D.S., Vergara, P.P., Haque, A.N.M.M., Nguyen, P.H., Pemen A.J.M. 2020. Gaussian Mixture Based Uncertainty Modeling to Optimize Energy Management of Heterogeneous Building Neighborhoods: A Case Study of a Dutch University Medical Campus. Energy and Buildings, 224: 110150. DOI: 10.1016/j.enbuild.2020.110150

Shakouri, H., Kazemi, A. 2017. Multi-objective cost-load optimization for demand side management of a residential area in smart grids. Sustainable Cities and Society, 32: 171-180. DOI: 10.1016/j.scs.2017.03.018

Sidnell, T., Clarke, F., Dorneanu, B., Mechleri, E., Arellano-Garcia, H. 2021. Optimal design and operation of distributed energy resources systems for residential neighbourhoods. Smart Energy, 4: 100049. DOI: 10.1016/j.segy.2021.100049

Singh, K., Gadh, R., Singh, A., Dewangan, C.L. 2022. Design of an optimal P2P energy trading market model using bilevel stochastic optimization. Applied Energy, 328: 120193. DOI: 10.1016/j.apenergy.2022.120193

Suresh, V., Janik, P., Jasinski, M, Guerrero, J.M., Leonowicz, Z. 2023. Microgrid energy management using metaheuristic optimization algorithms. Applied Soft Computing, 134: 109981. DOI: 10.1016/j.asoc.2022.109981

Thirunavukkarasu, G.S., Seyedmahmoudian, M., Jamei, E., Horan, B., Mekhilef, S., Stojcevski, A. 2022. Role of optimization techniques in microgrid energy management systems—A review. Energy Strategy Reviews, 43:100899. DOI: 10.1016/j.esr.2022.100899

Velik, R., Nicolay, P. 2016. Energy management in storage-augmented, grid-connected prosumer buildings and neighborhoods using a modified simulated annealing optimization. Computers & Operations Research, 66: 248-257. DOI: 10.1016/j.cor.2015.03.002

Wu, Y., Wu, Y., Cimen, H., Vasquez, J. C., Guerrero, J.M. 2022. Towards collective energy Community: Potential roles of microgrid and blockchain to go beyond P2P energy trading. Applied Energy, 314: 119003. DOI: 10.1016/j.apenergy.2022.119003

Zucker, G., Judex, F., Blöchle, M., Köstl, M., Widl, E., Hauer, S., Bres, A., Zeilinger, J. 2016. A new method for optimizing operation of large neighborhoods of buildings using thermal simulation. Energy and Buildings, 125: 153-160. DOI: 10.1016/j.enbuild.2016.04.081