Electric Power Systems Research 236 (2024) 110887

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Analyses of the effects of customer flexibility on the distribution grid

Katerina Bilbiloska [a], Goran Veljanovski [b], Aleksandra Krkoleva Mateska [a,*], Petar Krstevski [a], Metodija Atanasovski [b]

[a] Ss Cyril and Methodius University in Skopje, Faculty of Electrical Engineering and Information Technologies, North Macedonia
[b] University St. Kliment Ohridski Bitola, Faculty of Technical Sciences, Bitola, North Macedonia

ARTICLE INFO

Keywords:
Demand side management
Flexibility
Optimisation

ABSTRACT

This article describes implementation of a linear programming (LP) optimization method for distribution of household appliances, with the goal of minimizing hourly load while considering customer comfort preferences. The presented method is intended to be used by customers to explore their flexibility potential. Specifically, the article demonstrates how the method can be used to shift the load to off-peak hours or to be adjusted to the generation of their own photovoltaic (PV) units. The solution is applied across four categories of residential consumers, resulting in a reduction of hourly peak load ranging from 30 % to 60 %. For prosumer households, whose consumption is adjusted to their PV generation, the reduction range is 16 % to 30 %. Furthermore, the impact of the optimized use of appliances on the operation of a distribution grid is examined in the paper. The results show improved voltage ranges and voltage profiles, as well as decrease in energy losses in all observed cases, for households with and without installed PV units.

1. Introduction

To achieve the climate goals outlined in the European Union (EU) energy strategy [1], supported by the adoption of the key legislation package. Clean Energy for all Europeans [2] and further expanded with the European Green Deal [3], it will be necessary to increase the integration of variable renewable energies in the power systems over the next few decades. At the same time, it is important to ensure that the achievement of these goals does not pose a risk to the fundamental commitment for provision of secure, continuous and affordable electricity supply for all customers. Despite the pressure caused by the energy crisis within the past two years, the diversification of electricity generation and integration of renewable energy sources (RES) are considered as substantial measures to achieve the climate goals. RES significance is further emphasized by the implementation of the REPowerEU Plan [4], which aims to accelerate the investments in clean energy and reduce European dependence on fossil fuels. To ensure sufficient changes on the demand side, which will complement the developments on the supply side, the European policy framework [2] already creates favourable conditions that encourage individual and company level behavioural changes towards energy efficiency and cost reduction to achieve active participation in the energy transition. Apart from prioritizing energy efficiency [5], the consumer-centric energy transition strongly promotes self-consumption and fosters the development of energy communities.

The forthcoming changes require a greater degree of flexibility to ensure the secure operation of power systems. As defined in [6], flexibility refers to the ability of the power system and its assets to temporarily alter normal operations in response to an external request or event. Apart from generators, which are traditional assets used to provide the required system flexibility, the existing European legislative framework also fosters the use of load and storage. This is further promoted by the establishment and operation of aggregators and suppliers that are developing innovative business models to engage residential, small commercial, and industrial customers in delivering services to the grid, as well as for participating in the electricity markets [7,8]. The participation of load and storage is also expected in the regional electricity markets [9] and local flexibility markets [10], which are in various stages of development across Europe and the USA. The significance of demand side management (DSM) programs lies in their ability to leverage demand side flexibility for various purposes. These programs allow customers to gain benefits based on changes in their electricity consumption. DSM programs can be either explicit or implicit. Explicit DSM programs seek to involve customers to respond to external requests for changes in consumption and offer financial compensation in return [11]. Implicit DSM programs are developed to engage customers'

* Corresponding author.
E-mail address: krkoleva@feit.ukim.edu.mk (A. Krkoleva Mateska).

https://doi.org/10.1016/j.epsr.2024.110887
Received 27 March 2023; Received in revised form 8 April 2024; Accepted 8 July 2024
Available online 27 July 2024

response through pricing, i.e. they encourage customers to reduce their electricity consumption during periods of high prices and shift it to periods of lower prices [11].

1.1. Literature review

The comprehensive study from [12] presents the importance of DSM and the development of an adequate market design for integration of new generation sources and promotion of prosumer participation. It also highlights the challenges of the transition from centralized to decentralized control and increased need for enhancing consumer flexibility.

The research presented in [13], shows that implementation of DSM programs can contribute to reduction of load in peak hours in all seasons, while the study presented in [14] provides insight on the potential for load shifting and peak clipping by implementation of DSM strategies. Furthermore, optimized changes in customer consumption can lead to cost reductions not just for the consumers, but also for system operators, as discussed in [15]. Considering DSM in the process of distribution network planning can alleviate costs for system operators and can be helpful in dealing with minor network constraint violations [16]. Implementation of DSM improves distribution network investment efficiency and contributes to unlocking network capacity [17]. The impact of DSM on distribution system operation is investigated in [18,19], which focus on potential use of DSM strategies for voltage control as well as in [20], which investigates the possibilities for congestion reduction.

The participation of residential customers in DSM is crucial for achieving the above-mentioned benefits. A review study on residential DSM [21] discusses the characteristics of DSM optimization methods for residential customers, including LP, which can be applied for load shifting, peak shaving and direct control. The authors of [22] investigate the use of advanced management systems which integrate demand response and aggregation to harness the potential of residential customer flexibility. However, due to the differences in lifestyles and habits between households, it is quite challenging to assess customer flexibility and to develop DSM programs altered to the specific needs and requirements of various groups of customers. To tackle this challenge, the authors in [23] analyse the patterns in appliance use by residential customers, while [24] maps the potential of DSM to appliance use patterns. A step further is done in [25], which presents a novel approach for identification for groups of customers aiming to develop personalized DSM services based on socio-demographic data. Using a customer-satisfaction oriented approach, [26] presents appliance scheduling algorithms which could be applied for residential DSM programs.

1.2. Motivation

It is not easy to engage residential customers in DSM programs, especially if the benefits are not clear to the customers or the programs require significant investments for new technologies and home automation. Namely, the implementation of DSM programs requires certain technical solutions to be in place at the customer side so that the consumption is scheduled or optimized, as described in [27]. These solutions should enable the communication with aggregators and/or suppliers and allow them to exploit customer's flexibility [28]. As the information and communication technology (ICT) sector continues to develop, it provides more opportunities to implement advanced solutions and control algorithms that enable customers to utilize their flexibility, as presented in [29]. However, these solutions should be robust and easy to apply, without incurring high investment costs for both customers and intermediate entities (aggregators/suppliers). Highly complex solutions can be impediment to large scale deployment of DSM programs. In fact, due to the more complex technical implementation requirements, implicit DSM are still not widely used across Europe [30]. The EU policy framework [2], the trend of electricity price increase [31] and the reduced costs for RES technologies [32] have spiked the interest of customers to invest in distributed energy resources, especially in PV plants. The expected benefits [33] and plug-and-use approach make this technology the first choice of prosumers. Therefore, it is likely that rooftop PV plants will dominate distributed resource technologies in low voltage distribution grids and will be enablers of increased customer flexibility alongside DSM programs.

1.3. Research gaps

The literature review describes the potential benefits from DSM, but it also highlights the implementation challenges related to the assessment of the flexibility potential of residential customers and harnessing that potential by development and implementation of adequate DSM programs. While analysing appliance use patterns [23,24] or customer clustering [25] can serve as a basis for optimal scheduling and aggregation, it does not address the present practical challenges of DSM implementation. Observing the DSM development through the Smart Grid paradigm is essential for developing solutions for the future [34,35], but it does not tackle the challenges of the period of transition of the existing grids towards the future Smart Grid. In fact, studies that reflect the current state of increased number of prosumers in the distribution grid, limited automation and smart ready technologies at residential level and low storage penetration are missing in order to address the present challenges of DSM implementation and the transition to smart grids. These types of studies are necessary to serve as guidelines for unlocking customer flexibility potential.

1.4. Contribution

This article presents an approach to facilitate exploitation of customer flexibility by optimal use of appliances in a household. It can serve as a transitional solution when advanced smart grid infrastructure is not present. The solution is based on a straightforward optimization approach to allow household customers to maximize the benefits of their home appliance flexibility by shifting their use during the day. The advantage of the proposed solution is that it is simple for practical implementation, it can be customized for different DSM programs and takes into account customers' comfort preferences. Unlike other solutions, as described in [36] and similarly in [37], it does not depend on hierarchical control and management of all customers within given area, but relies on customer preferences and behavioural change decisions. Considering the expected increase of penetration of rooftop PVs in low voltage grids, this article also examines the implementation of the solution to maximise the use of shiftable load during the hours with high PV generation. The advantage of the proposed solution as that it can be easily adjusted to such and possibly other additional requirements. In this manner, the realistic situation of households with rooftop PVs is considered. Finally, the article investigates the effects of the optimized consumption on the distribution grid by applying the proposed solution to various typical residential consumers.

1.5. Paper organisation

The remainder of the paper is structured as follows: The second section outlines the methodology employed in this research, encompassing the optimization method, the modelling of consumers (typical households), and the modelling of PV generation. The third section provides detailed insights into the results obtained through the application of the aforementioned methodology. The fourth section summarizes the conclusions of the paper. The fifth and sixth section include acknowledgement and references, appropriately.

2. Methodology

This section of the paper describes the optimization and modelling techniques applied for this study. The first subsection provides an overview of the LP optimization technique used to distribute the use of appliances, given the preferences of the consumers and other constraints. The second and third subsections describe load and generation models applied in this study. Fig. 1 presents a simplified workflow of the research presented in this paper. It includes a block diagram of the appliance optimization process and a description of the simulation cases considered in this study.

2.1. Optimization technique based on linear programming

The optimization is based on a LP method which is used to redistribute the use of shiftable household appliances within a 24-hour period. The goal is to minimize the objective function while considering a set of constraints that arise from the operating characteristics and typical daily use of household appliances. In other words, the constraints in the LP optimization solution arise from the preferences and habits of customers regarding their daily comfort levels. These constraints depend on customer's willingness to adjust their routines to certain acceptable extent and receive a compensation for their actions or decrease their electricity expenses. The objective function, used to minimize the hourly load L for an observed household is based on the investigations in [38] and can be formulated as follows:

$$\min_{L, x_{a,h\in R}} L, \text{ i.e.,} \sum_{a\in A} x_{a,h} - y_h \leq L, \forall h \in H \tag{1}$$

where A is the set of household devices which are considered. The variables in (1) represent the specifics of each device a, where H is the time of use of the device a and x is the power of that device in the period h. The y_h component of the sum in (1) refers to the hourly production of a PV unit and applies only to prosumers, otherwise it equals zero.

To transform customer's preferences into constraints for the LP solution, the household appliances are divided into three groups. The first group, denoted as non-shiftable appliances, encompasses appliances whose usage cannot be shifted due to customer's preference. The second group refers to shiftable devices with variable time of use but a fixed power consumption over time. The third group includes shiftable appliances which have variable time of use and variable power consumption over a certain time. It is important to note that the categorization of the appliances may vary between households, as some residents may be willing to shift the use of certain appliances while others may not be. Additionally, the number of hours of use of different appliances may vary between households. The constraints of the objective function (1) are represented with the Eqs. (2)–(5), similarly as in [38]. The constraints for the first group of appliances are given in (2),

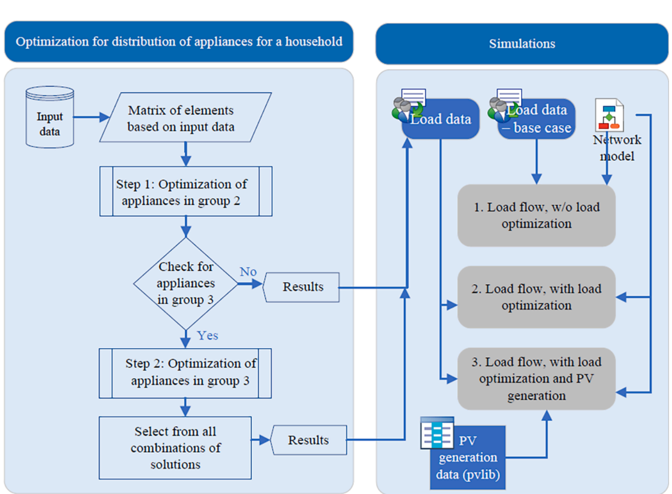


Fig. 1. Workflow description overview: simplified LP optimization and simulation cases.

where l_a is the total power for each appliance. Eq. (3) refers to the constraints for the second group, where α_a is stand-by power and β_a is the maximum power of the shiftable appliances. The hours of use of appliance a are denoted with the vector $h_{as}, h_{a(s+1)}, \ldots, h_{af}$.

$$1^T x_a = l_a, \ \forall a \in A \tag{2}$$

$$\alpha_a \leq x_{a,h} \leq \beta_a, \forall h \in \left[h_{as}, \ h_{a(s+1)}, \ldots, h_{af}\right] \tag{3}$$

$$1^T S_t = 1, 0 \leq S_t \leq 1, \ \forall t \in T \tag{4}$$

$$x_t = P_t^T S_t \tag{5}$$

The constraints for the third group of appliances are introduced by the Eqs. (4) and (5), where P_t^T represents a matrix with all possible combinations of use of an appliance and s_t is a vector that contains the state of each appliance, which can be either on or off.

The Eqs. (1)–(5) are utilized to distribute the use of shiftable household appliances during off-peak periods while minimizing the hourly load of a household and considering customer comfort. The optimization process consists of two steps: first, optimizing the use of the second group of appliances, which can be used at any time without specific constraints; second, optimizing the use of the third group of appliances, which can also be used at any time during the day, but without interruption for a certain time period. In the second step, all possible combinations of use of an appliance are considered, and one solution is randomly selected from the set of combinations that satisfy the constraints. Another option is to further filter the solution based on additional customer preferences. Since the focus is on practicality and simplicity in the solution, the first approach is considered reasonable. Ultimately, the implementation of this solution should distribute the use of the appliances within a given period and result in lower peaks in household load curves. It is noteworthy to observe that the solution implementation is specific to a household and depends on the residents' habits. Therefore, the level of reduction of load peaks will also depend on the customer's preferences. The sensitivity analyses presented in [39] show the dependence of the distribution of use of the appliances on customer comfort constraints.

2.2. Modelling of typical households

Household consumption varies due to the residents' preferences for the timing and duration of appliance use, as well as their living and working habits. To account for some of these differences, the LP optimization solution is applied on four households, assuming they consist of either, two, three or four members with various daily habits and various preferences for use of household appliances. Therefore, certain appliance can be typically used for 2 h in the afternoon in one household and for 3 h in the morning in another household. As a result, the appliance use distribution, load peak value, and its occurrence are different for the observed households. The presented household load data is indicative, based on information on household appliances from [40] as well as authors' experiences on customer habits for a typical working day. The aim is to create different load curves and apply the optimization method described in subSection 2.1. For each household type, the appliances are categorized into three groups. Refrigerators, freezers, electric stoves and entertainment (TV and other) appliances are categorized in the first group. Customers consider these appliances as non-shiftable as they prefer to use them at any period of the day, according to their needs and habits. The second group typically comprises of electric water heaters, air conditioning systems, and electric vehicle batteries. In this study, the appliances from this group can be shifted in any period of the day. The third group encompasses washing machines, dishwashers, and similar devices. Air conditioning systems are assumed to be used for both cooling and heating, which is common in countries with a moderate or Mediterranean climate. The study focuses on typical households in the Western Balkans countries, where household appliances typically have lower energy efficiency than those in EU households, resulting in higher hourly consumption. Moreover, many urban areas lack district heating systems and natural gas distribution networks, which also affects consumption and typical load curves.

The first household type, identified as H1, comprises of four members who use most of the appliances in the afternoon, with peak load occurring between 5PM and 7PM. Fig. 2 presents the use of the typical appliances throughout the day for this type of household. The second household type, denoted as H2, is also a four-person household, but their daily schedule differs slightly from household H1. It is assumed that some occupants of H2 are present in the house during the morning and early afternoon hours, which results in a shift in typical appliance use towards the morning hours, with peak at about 9AM, as shown in Fig. 3. In this household, all appliances are used for a specific duration of time, except for the electric vehicle battery. The duration of use of some of the appliances differs between households H1 and H2, reflecting the different daily habits of their residents.

The third representative household, denoted as H3 represents a three-member household. It has a similar daily schedule as H1, with high use of appliances in the afternoon hours. The typical use of appliances in the household H3 is presented in Fig. 4.

The household H4 is a two-person household assumed to consist of senior citizens, such as retirees, who typically spend more time at home. Fig. 5 illustrates the typical appliance usage pattern for this household.

The graphs on Figs. 2–5 are constructed using the described household and appliance characteristics and show typical hourly consumption for the considered households. These graphs also show the time and duration of use of the appliances.

2.3. Modelling of PV generation

For the purpose of the study presented in this article, it is assumed that some of the customers are prosumers and they have installed rooftop PV modules. The input data to provide the PV output curve is obtained using Python open-source package – pvlib [41]. Using this package, an average production curve was generated for a rooftop PV system with southward orientation and 6 kW installed capacity. The hourly production of such PV system is illustrated on Fig. 6.

3. Results

This section presents the results obtained by implementation of the LP optimization method. To show the applicability of the proposed solution, the first two subsections present its application on households without PV installation and on prosumer households. The final subsection presents the effects of customer flexibility on distribution grid operation. This subsection compares simulation results for three different cases, as depicted in Fig. 1.

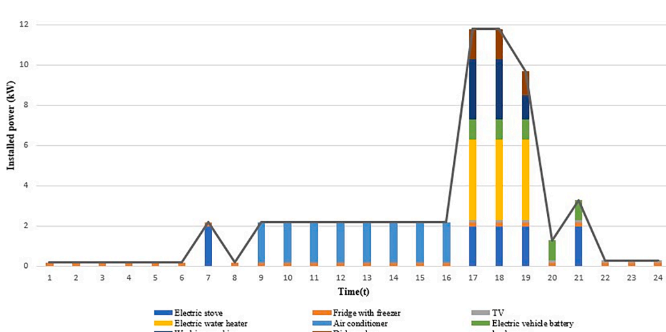


Fig. 2. Typical appliance use in household H1.

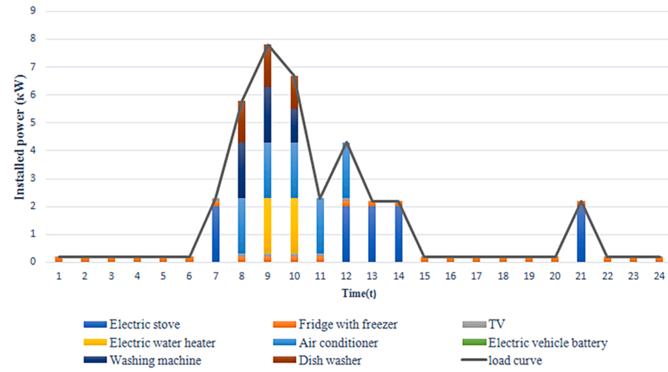


Fig. 3. Typical appliance use in household H2.

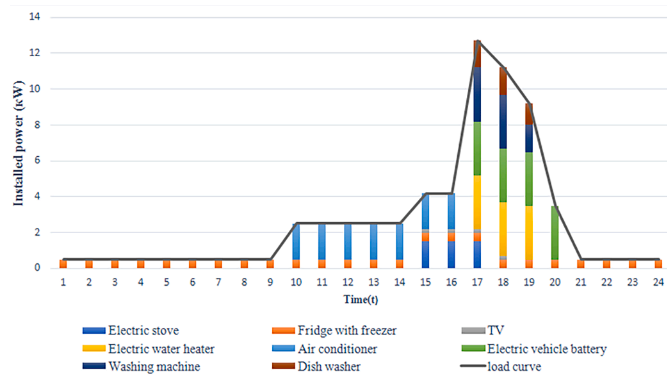


Fig. 4. Typical appliance use in household H3.

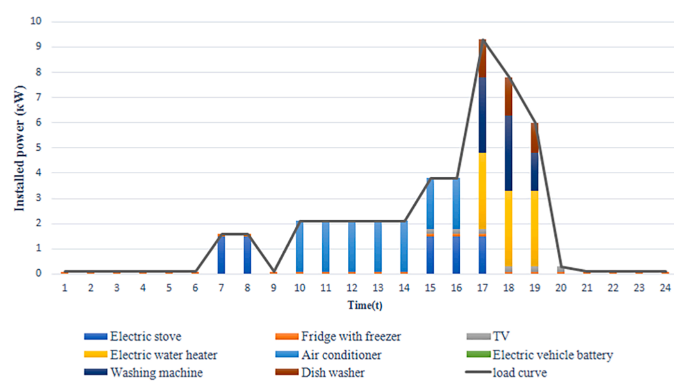


Fig. 5. Typical appliance use in household H4.

3.1. Optimized hourly use of household appliances

The LP optimization method described in this study is developed using MATLAB. The input data for the simulation comprises of the time of use and corresponding power of each household appliance for each of the households described in subSection 2.2. The objective is to minimize the load for each hour by redistributing the use of non-essential appliances. Their use is shifted to night-time hours when electricity prices are typically lower. The optimization method accounts for constraints related to customer preferences on the time, duration and rate of use of household appliances.The optimization results for the considered typical households are presented in Figs. 7–10. It can be observed that the peak load is significantly reduced (from approximately 30 % to 60 % for the different types of households) for all four households and the load redistributed to flatten the household load curve. The applied

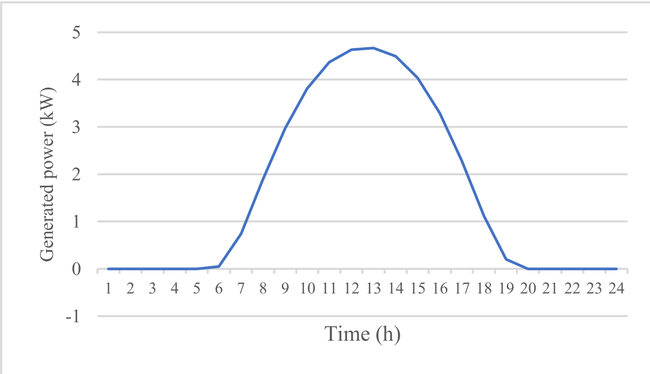


Fig. 6. PV system generation curve.

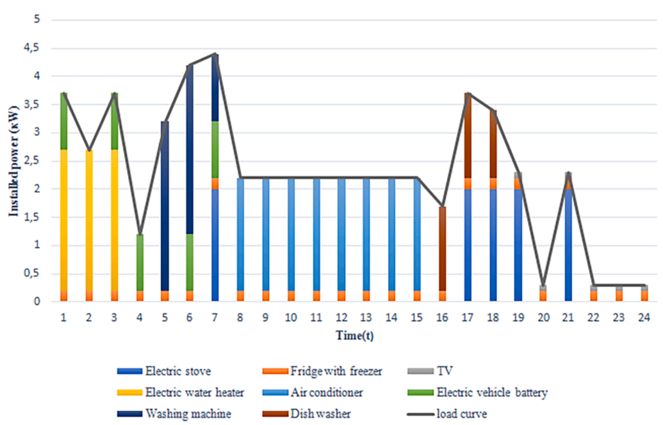


Fig. 7. Optimized appliance use in household H1.

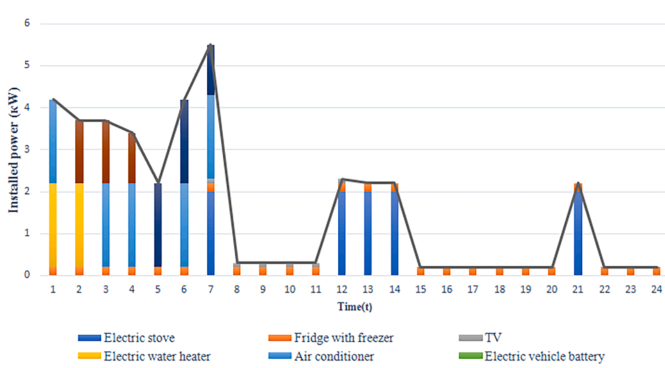


Fig. 8. Optimized appliance use in household H2.

optimization method schedules the use of the appliances from the second group in the first moment when a specific condition related to customer preferences is met. Then, it continues to fill the "gaps" in the load curve, i.e., to distribute the appliances from the third group in the off-peak hours. This is the reason why peaks in the optimized curves may occur in the early morning hours and that appliances from the second group are shifted in those hours. Applying changes in the optimization constraints may limit the period of the day when certain appliance is used, as discussed in [39].

3.2. Optimized hourly use of household appliances considering local PV generation

This section presents the outcomes of implementing the LP technique

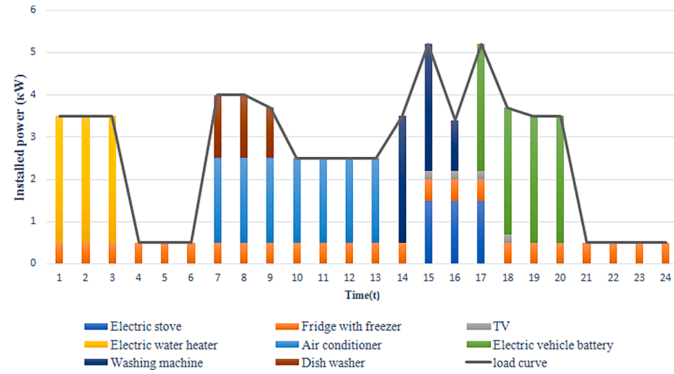


Fig. 9. Optimized appliance use in household H3.

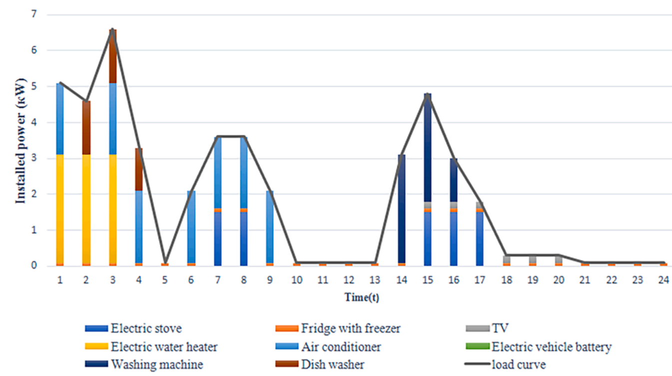


Fig. 10. Optimized appliance use in household H4.

in prosumer households. In this case, the objective is two-fold: firstly, to reduce the hourly load by distributing the use of household appliances throughout the day while taking residents' preferences into account. Secondly, the goal is to use the electricity generated by the households' PV units to the maximum possible extent. In addition to the inputs required to optimize the use of household appliances, in this case, the PV generation for each hour of the day is considered. The graphs on Figs. 11–14 show the optimized hourly use of the appliances for each representative household.

It is easy to observe that the household appliances are distributed to maximise the benefit of the PV units. The peak hours are shifted in daytime, which is reasonable due to the available local generation from the PV unit. The peak load is still reduced (from 16 % to 30 % for different household types), but not as much as in the previous case - without PV generation. The use of the appliances cannot be completely adjusted to the PV unit generation due to customer's comfort constraints, as well as the available shiftable appliances.

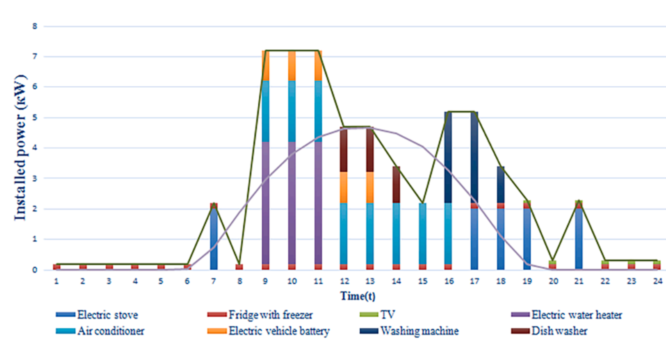


Fig. 11. Optimized appliance use in household H1 aligned to PV unit generation.

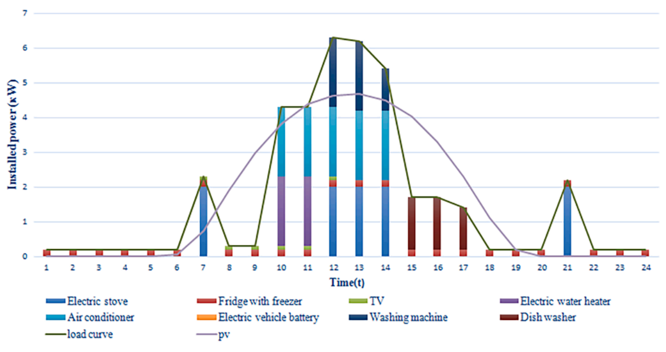


Fig. 12. Optimized appliance use in household H2 aligned to PV unit generation.

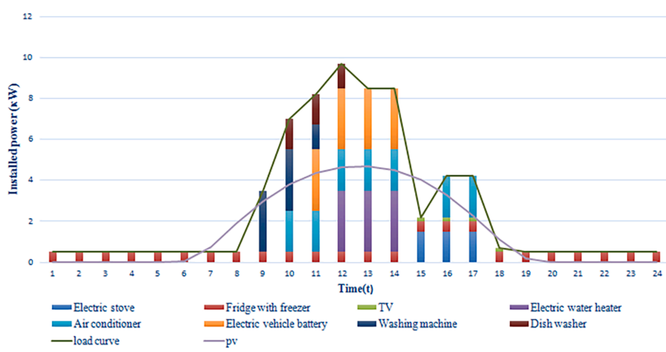


Fig. 13. Optimized appliance use in household H3 aligned to PV unit generation.

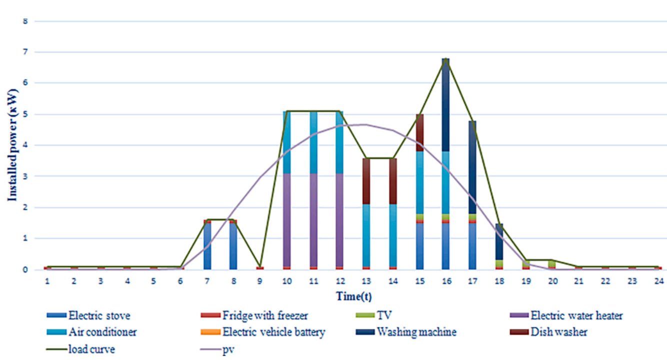


Fig. 14. Optimized appliance use in household H4 aligned to PV unit generation.

3.3. Simulation of the optimized hourly load for typical households in a low voltage distribution grid

To evaluate the impact of the optimized hourly loads on the functioning of a low voltage distribution grid, a test grid based on [42] is utilized. Fig. 15 presents a simplified diagram of the test grid. The original load curves from [42] are replaced by the hourly load curves of the representative households described in this study. A few lines in the grid are modified to increase (double) their capacity because of the higher load profiles used in this investigation. These changes are presented in the Appendix of the paper, in Table A2. A 10/0.4 kV transformer with rated power $S_n = 0{,}8$ MVA is introduced in the model to connect the low voltage test grid to a distribution network. The transformer has an on-load tap changer which sets the low voltage at the secondary winding to 0.415 kV. The Neplan software package is used to model the grid and perform the simulations. For simplicity, a single-line model is adopted.

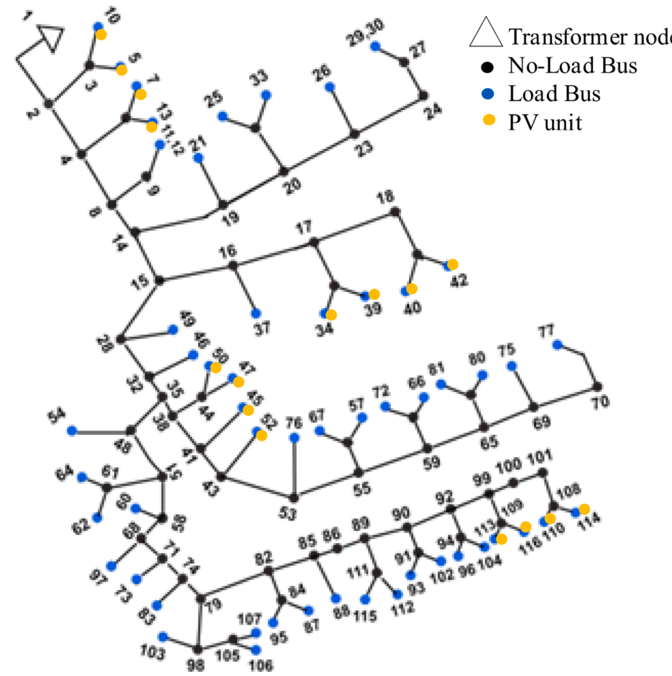


Fig. 15. A single line diagram of the low voltage test grid, based on [42].

The test grid is used to simulate and compare the following cases: (1) grid operation without optimization of the use of household appliances; (2) grid operation with applied load optimization and (3) grid operation with applied load optimization to maximise the local use of PV generation.

The four representative households are randomly distributed in the test grid.

Table A1 in the Appendix provides data on the distribution of household types in the network. Additionally, for the third case it is assumed that some households have PV generation units. The nodes with PVs are indicated on Fig. 15. The load input data for the first case are the load curves described in subSection 2.2 (without optimization), while the input data for the second case are the optimized curves presented in subSection 3.1. The input data for the third case are the optimized curves adjusted to PV unit generation described in subSection 3.2 and the PV generation curves, modelled as presented in subSection 2.3. The latter curves refer to 4 households of each household group, resulting in 16 out of 54 households to be modelled as prosumers.

For each of the three cases, load flow analyses are performed. It is assumed that the load and generation data are for the same season, capturing a typical working day for the four types of households. Several parameters are observed for a period of 24 h, including the active power at the connection point to the network, the voltage profiles and the power losses.

3.3.1. Grid operation without optimization of the use of household appliances

This case refers to distribution grid operation without optimization, considering the typical households described in subSection 2.2. This case aims to describe distribution grid operation when the customers do not have the opportunity to exercise their flexibility and they have no PV installations at their households.

The active power at the line between nodes 1 and 2 within the observed 24-hour period is presented in Fig. 16.

The analysis also includes voltage profiles and voltage ranges within the low voltage grid under study. Fig. 17 illustrates 24-hour voltage profiles for multiple nodes in the network. These nodes are selected to highlight voltage differences between nodes closer to the connection

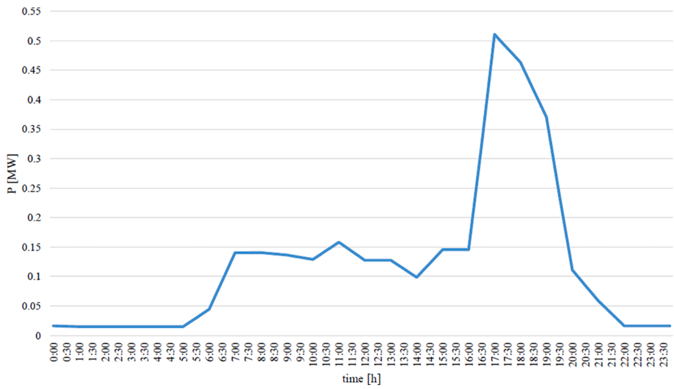


Fig. 16. Active power P [MW] at the line between nodes 1 and 2 of the observed distribution grid.

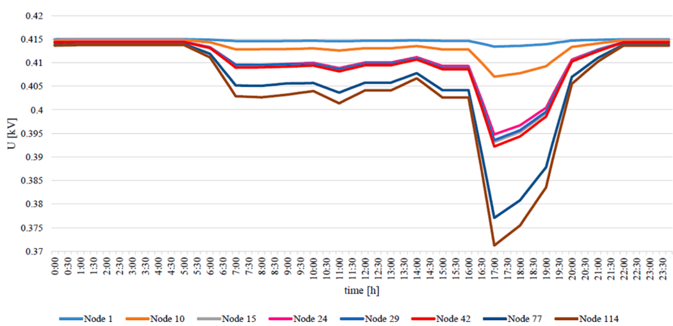


Fig. 17. Voltage profiles [kV], for nodes: 1, 10, 15, 24, 29, 42, 77 and 114.

point and peripheral nodes. As expected, the furthest nodes, specifically nodes 77 and 114, exhibit the lowest voltage values in the observed period. Moreover, the lowest values can be observed during peak hours, which correspond to the time of day when network loading is the highest.

Fig. 18 illustrates the voltage value ranges for all nodes in the network over the observed 24-hour period. The voltages are within the standard voltage limits prescribed by network operators. The lower voltage limit is approximately 93 % of the rated voltage.

3.3.2. Grid operation with optimization of the use of household appliances

The second case demonstrates low voltage grid operation when the LP optimization solution is applied to all households. Similarly to the previous case, Fig. 19 depicts the active power for the line connecting nodes 1 and 2 in the observed 24 h period. The optimized appliance usage across different households accounts for the different active power profile on that line. The active power is distributed more uniformly throughout the day. The hourly consumption is higher during the late evening and early morning hours which is related to the redistribution of the shiftable appliances. Consequently, those are the periods when the transfer of active power from the distribution grid to the observed low voltage grid is higher. The peak, which was previously observed at 5PM, is significantly reduced and shifted at night hours.

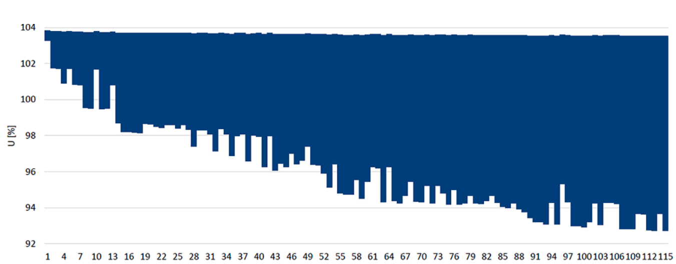


Fig. 18. Voltage ranges [%] for all of the nodes in the network.

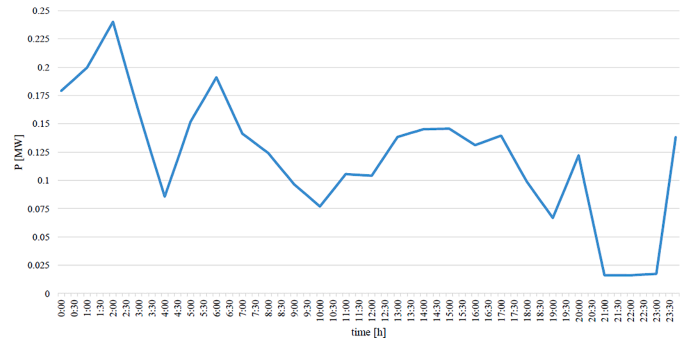


Fig. 19. Active power P [MW] at the line between nodes 1 and 2 of the observed distribution grid, with optimized appliance use.

For comparison purposes, Fig. 20 depicts the voltages at the same nodes as observed in subSection 3.3.1. The voltages at nodes 77 and 114 remain the lowest, but they are slightly higher than those shown in Fig. 17, i.e. the case without optimization. Based on this, it can be implied that there is an improvement in the voltage profiles in the observed network.

Fig. 21 shows the voltage ranges of all the nodes in the network during the observed 24-hour period. It can be concluded that with optimized appliance use, the lower voltage limit is approximately 98.5 % of the nominal voltage, which is an improvement over the non-optimized case.

The analyses further show that the overall power and energy losses for this case are lower than the case without optimization. The energy losses in this case are 0.074 MWh compared to 0.1105 MWh for the case without optimization.

3.3.3. Grid operation with optimization of the use of household appliances adjusted to PV generation

The third analyzed case shows low voltage grid operation when some of the customers are prosumers. In this case, the prosumers aim to use the flexible appliances during the hours of high PV generation, but at the same time, accounting own comfort constraints. The active power flow in the line between the nodes 1 and 2 is shown on Fig. 22. The active power is distributed in a similar manner as in the second case. However, the transfer of active power from the distribution grid to the observed low voltage grid is considerably lower due to the PV generation of the 16 prosumers connected to the low voltage grid.

The voltages of the selected nodes are presented on Fig. 23 and the voltage ranges are presented on Fig. 24. Again, the peripheral nodes have the lowest voltages in the observed network, but they are higher than in the previously analysed cases. Apart from the optimization of the load, this is also due to the active power injections from the PV units.

The diagram shown on Fig. 24, depicting the voltage ranges in this particular case, verifies the improved voltage profiles. The lower voltage

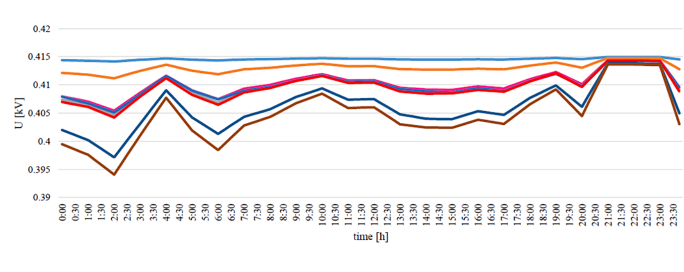


Fig. 20. Voltage profiles [kV], for nodes: 1, 10, 15, 24, 29, 42, 77 and 114, with optimized appliance use.

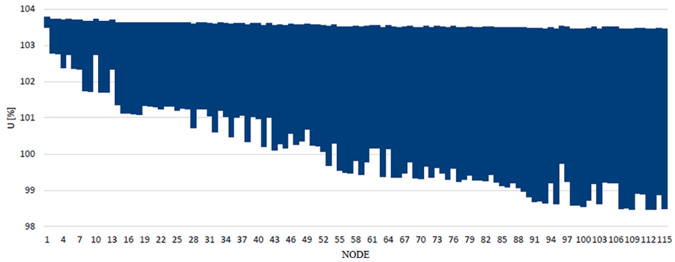


Fig. 21. Voltage ranges [%] for all of the nodes in the network, with optimized appliance use.

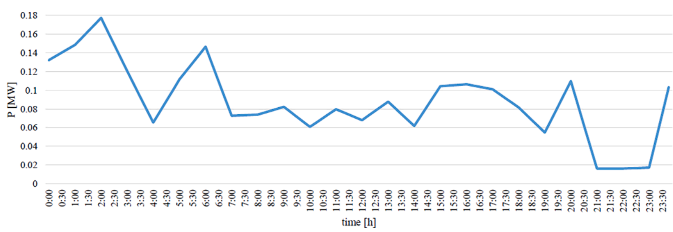


Fig. 22. Active power P [MW] at the line between nodes 1 and 2 of the observed distribution grid, with optimized appliance use adjusted to PV generation.

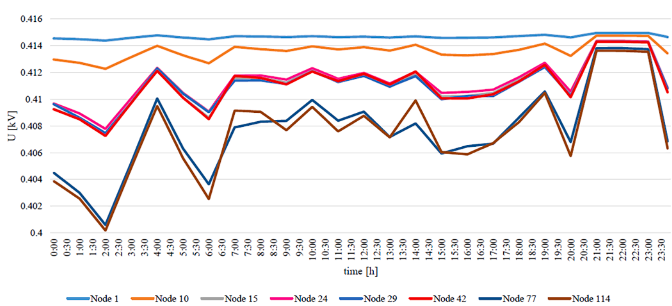


Fig. 23. Voltage profiles [kV], for nodes: 1, 10, 15, 24, 29, 42, 77 and 114, with optimized appliance use adjusted to PV generation.

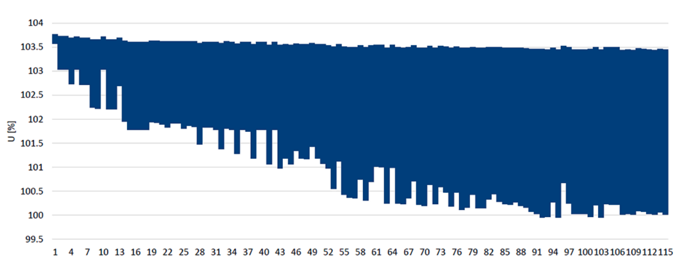


Fig. 24. Voltage ranges [%] for all of the nodes in the network, with optimized appliance use.

limit is almost equal to the nominal voltage. The energy losses are 0.033 MWh and are lower than in the previous two cases.

In the context of this case, it is interesting to observe the active power distribution on several lines in the distribution network, i.e., the section starting at node 15 and endng at nodes 40 and 42, excluding peripheral lines between the nodes 16 and 37 and nodes 17 and 31 (see Fig. 15). The power transfer through the lines is observed for the three cases discussed in this section and one additional case - grid operation without load optimization, but with connected PV units. The case is added for comparison purposes, but it also reflects a possible development in the low voltage grids in near future. For the clarity, the results are organized in two groups: firstly, the cases without optimization are observed, and secondly, the cases that include the proposed LP optimization for household use. On the following graphs the load is represented as positive power and the generation as negative.

Fig. 25 illustrates the cases without optimization. It is easy to observe that because of the different patterns in consumption and generation (Fig. 25, b) a portion of the generated power will be exported to the low voltage grid. The benefit for the customer will depend on the adopted model for remuneration. In such case the energy losses in the distribution grid are 0.0898 MWh and are higher compared to the losses observed in subSection 3.3.2.

The Fig. 26 illustrates the cases where the use of household appliances is optimized with the described solution. In both cases illustrated on Fig. 26 the active power on the observed lines is distributed more evenly. The applied LP solution enables the customers to adjust their consumption to the PV generation and use their flexibility more efficiently (Fig. 26, b), which results in lower flows in the observed lines and is associated with lower losses in the low voltage grid. These results also serve as indication that network upgrades may be postponed for the future.

4. Conclusion

This paper presents a simple LP optimization method for the distribution of the use of household appliances. The presented solution, which can be included in DSM programs, is preferred for its simplicity in implementation and ability to accommodate the diverse needs of consumers. The study also demonstrates that this approach can be tailored to suit the needs of prosumers, enabling them to coordinate their use of shiftable appliances with the output of PV systems. Ultimately, this article confirms that by exercising their flexibility, customers can contribute to improved distribution grid operation.

The method can be easily implemented in various households and doesn’t require use of complex equipment, making it adaptable for a wide range of households. Available ICT and home automation systems enable customers to easily implement the proposed solution by specifying their preferences and automating the process. This means that each household will have an optimized curve dependant on the preferences of its inhabitants and the availability of a generation unit at their

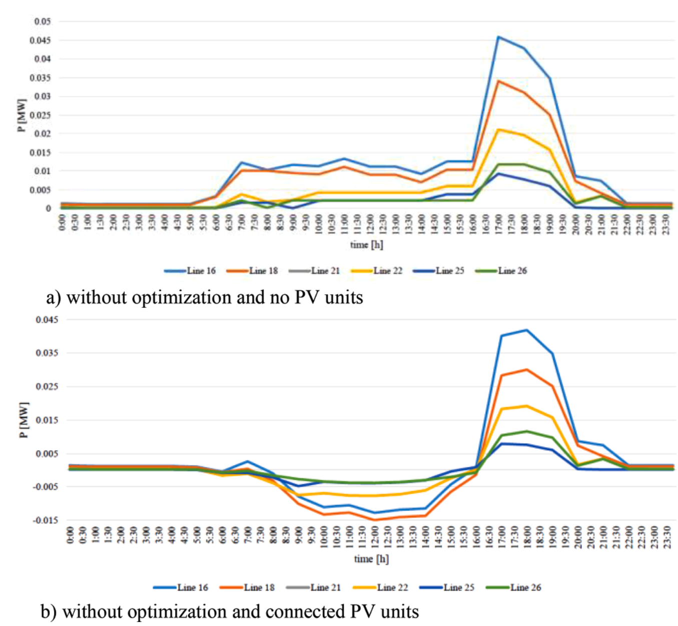
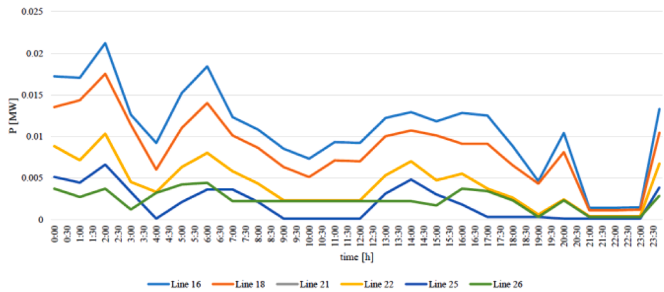
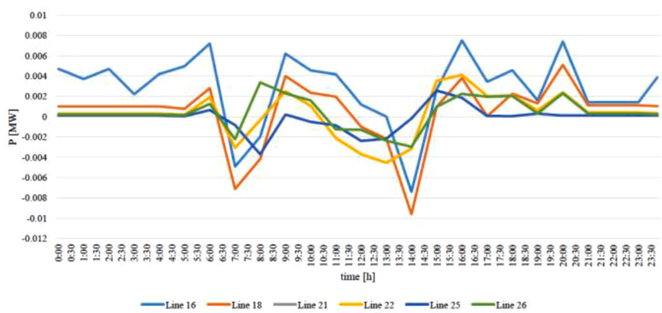


Fig. 25. Active power P [MW] observed at six lines over 24 hour period for the lines between nodes 15–16 (line 16), 16–17 (line 18), 17–18 (line 21), 18–36 (line 22), 36–40 (line 25) & 36–42 (line 26).



a) with applied load optimization and no PV units



b) with applied load optimization and connected PVs

Fig. 26. Active power P [MW] observed at six lines over 24 hour period for the lines between nodes 15–16 (line 16), 16–17 (line 18), 17–18 (line 21), 18–36 (line 22), 36–40 (line 25) & 36–42 (line 26), with optimized appliance use.

premisses. The optimized use of shiftable household appliances may cause general trends of increased consumption in the periods of low prices if customers are aware of these periods.

The analyses on the distribution grid operation presented in this article are based on four types of households, which are randomly distributed in the low voltage grid. A more realistic approach would require considering a higher variety of representative households as well as considering options with certain diversity in the orientation, installed capacity and level of penetration of the rooftop PV units. However, the general observations from the presented analyses are valid and indicate that engaging customers' flexibility benefits both customers and grid operators. The analyses show that the peak hourly consumption of the four types of households with applied optimization is between 30 % and 60 % lower compared to the cases without optimization. When adjusting the appliance use to the PV output, the peak hourly consumption of the households is higher compared to the case without prosumers, due to the objective for more effective use of the PV output. In this case, the decrease of the peak consumption varies between 16 % and 30 % compared to the cases without optimization for the observed household types. In both cases the appliance use is distributed more evenly within the observed 24-hour period.

The impact of the optimized use of appliances on a low voltage distribution grid is also examined in the paper. The results reveal that the optimization leads to improved voltage ranges and voltage profiles, including for the peripheral nodes of the network. Similar improvements are observed in the case of prosumers. Furthermore, the results suggest that network upgrades may be postponed for some time in low voltage grids where customers are engaged in DSM programs or are prosumers.

Overall, the implementation of the described method offers a two-fold benefit. Firstly, customers can exercise their flexibility by participating in DSM programs and potentially reduce their electricity bills, or they can adapt their appliance usage to their own PV generation. Secondly, distribution grid operators can benefit from improved voltage profiles and reduced power and energy losses. The implementation of such solutions can be facilitated by appropriate regulatory frameworks.

CRediT authorship contribution statement

Katerina Bilbiloska: Conceptualization, Methodology, Formal analysis, Software, Writing – original draft. **Goran Veljanovski:** Conceptualization, Methodology, Visualization, Software. **Aleksandra Krkoleva Mateska:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Petar Krstevski:** Investigation, Validation, Writing – review & editing. **Metodija Atanasovski:** Supervision, Validation, Writing – review & editing.

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.

Acknowledgments

This research has been supported by the Horizon Europe project Transition to sustainable future through training and education (TRANSIT), grant agreement number 101075747. The paper reflects only the authors' views and neither the Agency nor the Commission are responsible for any use that may be made of the information contained therein.

Appendix

The Table A1 presents the distribution of household types (as defined in subSection 2.2) in the distribution network analysed in this article.

Table A1
Distribution of households by type in relation to nodes of the observed distribution network.

Household type	Nodes (as numbered on Fig. 15)
H1	10,11,33,37,42, 47,54,67,81,87,88,97,102,116
H2	5,12,26,34,45,49,57,64,73,80,95,96,110,115
H3	7,21,29,30,39,46,52,62,66,72,75,83,104,107,112,114
H4	13,25,40,50,60,76,77,93,103,106,113

Table A2 presents the changes in parameters in relation to data from [42].

Table A2
Changed parameters related to data from [42].

	Original data		Applied changes	
Lines (from node x to node y)	R_1	X_1	R_1	X_1
1–2, 2–4, 4–8, 8–14, 14–15	0.446	0.071	0.223	0.0355
2–3, 4–6, 8–9	1.15	0.088	0.575	0.044
14–19	0.089	0.0675	0.0445	0.03375
15–28	0.274	0.073	0.137	0.0365

References

[1] European Commission, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, the Committee of Regions and the European Investment Bank A Framework Strategy for a Resilient Energy Union with a forward-Looking Climate Change Policy, COM/2015/080 final */Brussels, 25.02.2015.
[2] Clean Energy for all Europeans package,[online] https://energy.ec.europa.eu/topics/energy-strategy/clean-energy-all-europeans-package_en, accessed 10 April 2022.
[3] European Commission, Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee for the Regions, The European Green Deal, COM (2019) 640 final, [online], https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2019%3A640%3AFIN, accessed 10 April 2022.
[4] European Commission, Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee for the Regions REPowerEU Plan, COM(2022) 230 final, Brussels, 18.05.2022, [online], https://energy.ec.europa.eu/system/files/2022-05/COM_2022_230_1_EN_ACT_part1_v5.pdf, accessed on 12 April 2022.
[5] Directive (EU), 2018/2002 of the European Parliament and of the Council of 11 December 2018 amending Directive 2012/27/EU on energy efficiency, OJ L 328 (2018) 210–230, 21.12.
[6] M. Zenebe Degefa, I. Bakken Sperstad, H. Sæle, Comprehensive classifications and characterizations of power system flexibility resources, Electr. Power Syst. Res. 194 (2021) 107022, https://doi.org/10.1016/j.epsr.2021.107022.
[7] D. Schwabeneder, C. Corinaldesi, G. Lettner, et al., Business cases of aggregated flexibilities in multiple electricity markets in a European market design, Energy Convers. Manage. 230 (2021) 113783, https://doi.org/10.1016/j.enconman.2020.113783.
[8] P. Krstevski, A. Krkoleva Mateska, S. Borozan, Models for integration of flexibility sources in regional electricity markets, in: Proc. 57th International Scientific Conference on Information, Communication and Energy Systems and Technologies (ICEST), North Macedonia, 2022, pp. 1–4, https://doi.org/10.1109/ICEST55168.2022.9828756. June.
[9] J. Ponoćko, A. Krkoleva Mateska, P. Krstevski, Cross-border DSM as a complement to storage and RES in congestion management markets, Int. J. Electr. Power Energy Syst. 148 (2023) 108917, https://doi.org/10.1016/j.ijepes.2022.108917.
[10] X. Jina, Q. Wua, H. Jiab, Local flexibility markets: literature review on concepts, models and clearing methods, Appl. Energy 261 (2020) 114387, https://doi.org/10.1016/j.apenergy.2019.114387.
[11] A. Abiri-Jahromi, N. Dhaliwal, F. Bouffard, Demand Response in Smart Grids', in Integration of Demand Response Into the Electricity Chain - Challenges, Opportunities and Smart Grid Solutions, (ISTE Ltd, John Wiley & Sons, 2015, pp. 1–9.
[12] S. Panda, S. Mohanty, P. Kumar Rout, B. Kumar Sahu, S. Mohan Parida, I. Sekhar Samanta, M. Bajaj, M. Piecha, V. Blazek, L. Prokop, A comprehensive review on demand side management and market design for renewable energy support and integration, Energy Rep. 10 (2023) 2228–2250, https://doi.org/10.1016/j.egyr.2023.09.049.
[13] V. Venizelou, N. Philippou, M. Hadjipanayi, et al., Development of a novel time-of-use tariff algorithm for residential prosumer price-based demand side management, Energy 142 (2018), https://doi.org/10.1016/j.energy.2017.10.068, 663-646.
[14] R. Dharani, M. Balasubramonian, T. Sudhakar Babu, et al., Load shifting and peak clipping for reducing energy consumption in an Indian University Campus, Energies (Basel) 14 (2021) 558, https://doi.org/10.3390/en14030558.
[15] J. Ponoćko, J.V. Milanović, A. Krkoleva Mateska, P. Krstevski, S. Borozan, Existing approaches to wide-scale DSM deployment to facilitate transmission network flexibility - results of the survey in South-East Europe, in: Proc. 2019 IEEE PES Innovative Smart Grid Technologies Europe, Romania, 2019, pp. 1–5, https://doi.org/10.1109/ISGTEurope.2019.8905484. October.
[16] F.M. Gatta, A. Geri, M. Maccioni, A. Palazzoli, P. Sancioni, Low voltage electric distribution network planning with demand control, Electr. Power Syst. Res. 226 (2024) 109950, https://doi.org/10.1016/j.epsr.2023.109950.
[17] G. Strbac, Demand side management: benefits and challenges, Energy Policy 36 (2008) 4419–4426, https://doi.org/10.1016/j.enpol.2008.09.030.
[18] R.A. Fuhrmann, R.V.A. Monteiro, S.C. Dhulipala, et al., Demand side management strategy for distribution networks Volt/Var control: a FCS-model predictive control approach, J. Control Autom. Electr. Syst. 31 (2020) 1499–1507, https://doi.org/10.1007/s40313-020-00632-6.
[19] M. Azarnia, M. Rahimiyan, P. Siano, Offering of active distribution network in real-time energy market by integrated energy management system and Volt-Var optimization, Appl. Energy 358 (2024) 122635, https://doi.org/10.1016/j.apenergy.2024.122635.
[20] K. Coninx, M. Moradzadeh, T. Holvoet, Combining DSM and storage to alleviate current congestion in distribution grids, in: Proc. 2016 IEEE PES Innovative Smart Grid Technologies Europe, Slovenia, 2016, pp. 1–6, https://doi.org/10.1109/ISGTEurope.2016.7856202. October.
[21] S. Panda, P. Mohanty, P. Kumar Rout, B. Kumar Sahu, M. Bajaj, H. Zawbaa, S. Kamel, Residential demand side management model, optimization and future perspective: a review, Energy Rep. 8 (2022) 3727–3766, https://doi.org/10.1016/j.egyr.2022.02.300.
[22] P. Jadhav, D. More, S. Reddy Salkuti, Smart residential distribution energy management system with integration of demand response and aggregator, Clean. Respons. Consump. 9 (2023) 100115, https://doi.org/10.1016/j.clrc.2023.100115.
[23] C. Cruz, M. Tostado-Véliz, E. Palomar, I. Bravo, Pattern-driven behaviour for demand-side management: an analysis of appliance use, Energy Build. 308 (2024) 113988, https://doi.org/10.1016/j.enbuild.2024.113988. ISSN 0378-7788.
[24] M. Barsanti, S. Yilmaz, C.R. Binder, Beyond the average consumer: mapping the potential of demand-side management among patterns of appliance usage, Energy Res. Soc. Sci. 111 (2024) 103463, https://doi.org/10.1016/j.erss.2024.103463.
[25] H. Wen, X. Liu, M. Yang, B. Lei, C. Xu, Z. Chen, A novel approach for identifying customer groups for personalized demand-side management services using household socio-demographic data, Energy 286 (2024) 129593, https://doi.org/10.1016/j.energy.2023.129593.
[26] Y. Zhang, Y. Hu, H. Fang, Consumer satisfaction-oriented residential appliance scheduling algorithms, Syst. Sci. Control Eng. 9 (1) (2021) 663–672, https://doi.org/10.1080/21642583.2021.1978899.
[27] S. Teimourzadeh, O.B. Tor, M.E. Cebeci, et al., Enlightening customers on merits of demand-side load control: a simple-but-effiecint-platform, IEEE Access. 8 (2020) 193238–193247, https://doi.org/10.1109/ACCESS.2020.3032745.
[28] V. Lakshmanan, M. Marinelli, A.M. Kosek, et al., Impact of thermostatically controlled loads' demand response activation on aggregated power: a field experiment, Energy 96 (2016) 705–714, https://doi.org/10.1016/j.energy.2015.11.050.
[29] A. Krkoleva Mateska, V. Borozan, P. Krstevski, et al., Controllable load operation in microgrids using control scheme based on gossip algorithm, Appl. Energy 210 (2018) 1336–1346, https://doi.org/10.1016/j.apenergy.2017.06.049, 2018.
[30] Smart Energy Demand Coalition, 'Explicit Demand Response in Europe - Mapping the Market 2017', (SEDC), April 2017, [online], https://www.smarten.eu/wp-content/uploads/2017/04/SEDC-Explicit-Demand-Response-in-Europe-Mapping-the-Markets-2017.pdf, accessed on 21 March 2022.
[31] Analysis, Eurostat statistics data transparency. [online], https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics.
[32] IRENA (2022), Renewable power generation costs in 2021, International Renewable Energy Agency, Abu Dhabi. [online], https://www.irena.org/publications/2022/Jul/Renewable-Power-Generation-Costs-in-2021, accessed on 12 March 2023.
[33] G. Martinopoulos, Are rooftop photovoltaic systems a sustainable solution for Europe? A life cycle impact assessment and cost analysis, Appl. Energy 257 (2020) 114035, https://doi.org/10.1016/j.apenergy.2019.114035.
[34] M.U. Saleem, M.R. Usman, M.A. Usman, C. Politis, Design, deployment and performance evaluation of an IoT based smart energy management system for demand side management in smart grid, IEEE Access. 10 (2022) 15261–15278, https://doi.org/10.1109/ACCESS.2022.3147484.
[35] S. Ali, et al., Demand response program for efficient demand-side management in smart grid considering renewable energy sources, IEEE Access. 10 (2022) 53832–53853, https://doi.org/10.1109/ACCESS.2022.3174586.
[36] S. Zheng, X. Jin, G. Huang, et al., Coordination of commercial prosumers with distributed demand-side flexibility in energy sharing and management system, Energy 248 (2022) 123634, https://doi.org/10.1016/j.energy.2022.123634.
[37] S.-V. Oprea, A. Bara, Mind the gap between PV generation and residential load curves: maximizing the roof-top PV usage for prosumers with an IoT-based adaptive optimization and control module, Energy 248 (2022) 123634, https://doi.org/10.1016/j.energy.2022.123634.
[38] Z. Zhu, J. Tang, S. Lambotharan, et al., An integer linear programming based optimization for home demand-side management in smart grid, in: Proc. 2012 IEEE PES Innovative Smart Grid Technologies, USA, 2012, pp. 1–5. January.
[39] K. Bilbiloska, A. Krkoleva Mateska, P. Krstevski, Optimization of Customer Flexibility within Implicit Demand Side Management Programs, in: Proc. 2022

18th International Conference on the European Energy Market (EEM), Slovenia, 2022, pp. 1–6, https://doi.org/10.1109/EEM54602.2022.9921143. September.

[40] Power Consumption of Typical Household Appliances, https://www.daftlogic.com/information-appliance-power-consumption.htm, accessed 12 December 2021.

[41] W.F. Holmgren, C.W. Hansen, M.A. Mikofski, Pvlib python: a python package for modeling solar energy systems, J. Open. Source Softw. 3 (29) (2018) 884, https://doi.org/10.21105/joss.00884.

[42] Low voltage network – IEEE Data port, https://ieee-dataport.org/keywords/low-voltage-network.