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USING HOUSEHOLD FLEXIBILITY AS A PART OF DEMAND-SIDE MANAGEMENT PROGRAMS

UPORABA MODELA FLEKSIBILNOSTI GOSPODINJSTVA KOT DELA PROGRAMOV UPRAVLJANJA NA STRANI POVPRAŠEVANJA

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Abstract

This paper presents how customer flexibility can be used in the framework of a Demand Side Management (DSM) program. It focuses on household consumers, and aims to show how slight behavioural changes can lead to optimised use of household appliances and consequently, reduced energy costs. The paper presents a solution that would enable household customers to practice their flexibility. The solution is based on linear optimisation technique (LP) which is used to redistribute the use of domestic appliances throughout the day. The results show that implementation of the proposed solution can lead to reduction of hourly electricity use and reduce the overall electricity costs of the household. The optimised use of appliances reduces the household peak load more than 40% compared to the baseline scenario for all analysed cases. The optimisation implemented on specific households allows for reducing energy costs on average by 30%.

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Povzetek

V tem članeku predstavimo, kako lahko uporabimo prilagodljivost strank v okviru programa za upravljanje povpraševanja (DSM). Osredotočimo se na gospodinjske odjemalce, saj želimo pokazati, kako lahko majhne spremembe v vedenju vodijo do optimizirane uporabe gospodinjskih aparatov in posledično do znižanja stroškov energije. V prispevku predstavimo rešitev, ki bi gospodinjskim odjemalcem omogočila, da prakticirajo svojo fleksibilnost. Rešitev temelji na tehniki linearne optimizacije (LP), ki se uporablja za prerazporeditev uporabe gospodinjskih aparatov čez dan. Rezultati kažejo, da lahko izvajanje predlagane rešitve prispeva k zmanjšanju urne porabe električne energije in tako zmanjša skupne stroške električne energije v gospodinjstvu. Optimizirana uporaba aparatov zmanjša konično obremenitev gospodinjstva za več kot 40 % v primerjavi z osnovnim scenarijem za vse analizirane primere. Optimizacija, izvedena na posameznih gospodinjstvih, omogoča znižanje stroškov energije v povprečju za 30 %.

1 INTRODUCTION

The effects of global warming and climate change are already observable. Statistics related to sea level show its constant increase [1] caused by the melting of glaciers and ice sheets as well as the thermal expansion of warm seawater. The Earth is becoming warmer due to greenhouse gases emissions in the atmosphere and the uncontrolled use of fossil fuels. To neutralise the negative environmental impacts, governments around the world are adopting strategies [2] and measures [3] to develop and use low-carbon technologies, and to increase the share of renewable energy sources (RES) in an attempt to secure the path towards decarbonisation. RES, as one of the most common solutions for decarbonisation, is related to additional challenges - the operation of power systems with high-RES penetration requires dealing with various technical challenges caused by intermittent nature of these resources. Power generation technologies based on fossil fuels are used to provide for the base load, but some of them (mainly natural gas) are commonly used to provide the required flexibility for the system. In the near future, with decreased use of fossil fuel-based technologies, RES technologies should also compensate for system flexibility.

Traditionally, electricity generation follows consumption. This approach can be revised considering that the load can have certain flexibility and thus, the consumption can change to fit the available generation. This actually defines the idea behind the DSM concept. [4] The demand side flexibility is based on the use of load and storage through the DSM concept, combined with innovative solutions. [5] In general, DSM is defined as measures, activities and programs that establish cooperation between electricity suppliers and consumers by encouraging a change in energy use which differs from their usual habits to achieve economic benefit to both parties. Both residential, [6] especially consumers with smart homes [7], [8] and industrial consumers, as discussed in [9], [10], [11] may benefit from the implementation of this concept. DSM strives to equalise the load curve, i.e. to reduce the occurrence of peaks and the duration of peak periods. That could be achieved through several approaches: demand response (DR), energy efficiency and creating opportunities for energy storage. [4]

This paper first analyses DSM programs and then presents a specific application of DSM for households, based on a simple and effective approach that optimises household consumption and redistributes the use of various electrical appliances given certain constraints. The aim is to reduce the peak of the load curve and thus, contribute to a more efficient operation of the grid and reduction of the electricity bill for the customer. The financial aspect, reduction of the electricity bill is also described through one simple example.

1.1 DSM Programs

The DSM concept includes measures, activities and programs that establish cooperation between suppliers and consumers of electricity. It encourages a change in habits related to energy usage in order to achieve economic benefit for both parties. From the point of view of energy suppliers and operators of transmission and distribution systems, DSM strives to equalise the load curve, i.e. to reduce the occurrence of peaks and duration of periods with peaks. The DSM concept assumes that consumers' comfort is not compromised [12] and that their normal economic operation is maintained. [13], [14] As mentioned above, depending on the specific way of implementation of DSM, different subcategories could be defined: DR, energy efficiency and energy storage. DR is one of the most used concepts in the DSM framework. It defines change in energy use by consumers compared to their normal consumption, as a response to external signal. DR is an effective approach to use consumers' flexibility to change the inelastic consumption into elastic, and at the same time, provide benefits for the consumer through predetermined incentives. [15] In this context, the consumers are usually classified in separate groups as industry, commercial consumers and households. [15] For example, industrial consumers can participate in DR programs if their production process is not disturbed, while for commercial consumers the heating and cooling systems or the lighting can be managed in a manner that allows response to price or other signals. There is great potential for the application of DR in the residential sector, but this largely depends on the implementation of smart devices that can automatically respond to changes without the need for manual adjustment. [16]

Depending on the way of implementation, DSM programs can be divided into two categories, explicit (incentive) programs and implicit (price-based) programs. Explicit programs aim to change electricity usage by consumers in response to a request or signal from a supplier or other entities, in return for receiving payment for service or other benefits. [17] These programs allow end users to participate in the wholesale, capacity and balancing markets in accordance with the network rules. They can participate in these markets directly or be represented through a specific entity - aggregator, created for that purpose. Namely, the aggregators represent a number of customers and use their flexibility to allow them to participate in explicit DR programs. [18] The balancing services become increasingly interesting for explicit demand side flexibility, as discussed in [19]. Furthermore, introducing electric vehicles as providers of demand side flexibility increases the potential benefits of explicit DSM. [20] A recent study [21] showed that industrial and aggregated DSM providers can also participate in the congestion management markets, which are under development across Europe. As a general categorisation, explicit DSM programs encompass direct load control, curtailable service, demand bidding, emergency demand response, capacity market and ancillary market programs. The implicit programs are based on dynamic definition of the price, i.e. the price of electricity changes during various periods of the day. The consumption should respond to the changes in the electricity prices, which should result in lower consumption during the periods of high prices. Compared to explicit programs, the implicit programs do not foresee direct consumer participation in the electricity markets. However, the price-induced customer behaviour impacts electricity markets, as discussed in [22]. The programs are typically offered by the suppliers and allow the customers to change their consumption in relation to the offered tariffs. In this category, time of use tariff, critical load pricing, extreme day price programs, extreme day price with peak (critical) load and real time price (variable price) are included. The design of tariffs requires considering a number of factors to provide adequate results in cost reduction, as discussed in [23] and [24].

The practical implementation of these programs depends on several factors including appropriate regulatory framework, developed electricity markets that foster the participation of both load and generation for providing bids and offers in all market timeframes, especially related to reserve capacity and balancing energy. [25] In addition to this, application of appropriate information and communication technologies (ICT) is considered an enabler for the practical implementation of DSM programs. The ICT solutions should be applied both at supplier/aggregator level and customer level. It is important to use cost-effective solutions that would be affordable and simple to use, especially when these programs should be applied at small customers and households. [26]

2 DSM APPLICATION FOR HOUSEHOLDS BASED ON LINEAR OPTIMISATION

The integration of DSM in the households is a complex problem primarily due to the different devices used, as well as the specific habits of the users. The main goal when implementing DSM in a household is not to force change the habits of the users, but to motivate their engagement, considering their comfort constraints. Application of DSM for households could be integrated through simple and effective approach that optimises household consumption and redistributes the use of various electrical appliances given certain constraints. The aim is to reduce the peak of the load curve and thus, contribute to a more efficient operation of the grid and reduction of the electricity bill for the customer. The solution presented in this paper distributes the use of certain devices within a 24-hour period, aiming to minimise the household load at each hour of the observed period.

2.1 Method

The method used in this paper is based on LP. The LP optimisation technique is implemented to distribute the use of household electric appliances within specific time periods. The LP process considers the user-defined constraints related to various categories of devices. The basic idea of the developed solution is to determine in which period of the day a specific appliance should be used, with aim to reduce electricity costs, to reshape the load curve and to provide certain service for distribution system operator. If LP is used to find an optimal use schedule of household appliances, then that would mean to determine household appliance use during the day in order to minimise the load in each hour of the day. The LP optimisation is based on the Eq. (1.1) - (1.5), [27]:

$$\min_{L, x_{a,h \in \mathbb{R}}} L, \text{i.e.}, \sum_{a \in A} x_{a,h} \leq L, \forall h \in H \tag{1.1}$$

$$1^T x_a = l_a, \forall a \in A \tag{1.2}$$

$$\alpha_a \leq x_{a,h} \leq \beta_a, \forall h \in [h_{as}, h_{a(s+1)}, \ldots, h_{af}] \tag{1.3}$$

$$1^T s_t = 1, 0 \leq s_t \leq 1, \forall t \in T \tag{1.4}$$

$$x_t = P_t^T s_t \tag{1.5}$$

where A is set of devices, a represents a device, H is time of use of the device, x is installed power of the device, l_a is the current power of the device in given time period, α_a, β_a are the lower and upper bond of the device a, $h_{as}, h_{a(s+1)}, \ldots, h_{af}$ represent the time of use of the device a, P_t^T is the matrix with possible use combinations of a device and s_t is the vector with binary elements that indicate the state of the device.

For the purpose of this research, the household appliances are classified in three categories depending on their usual period of use, i.e. 1) appliances with constant time of use; 2) appliances with variable time of use; and 3) devices with variable energy and time of use, as described in detail in [28]. The first category covers appliances for which a change of use is not preferred and includes electric stoves, TVs, refrigerators with freezers etc. The second category encompasses appliances that could be used in various periods of the day like water heater, air conditioner, electric vehicle battery charger, etc. The third category includes appliances with shiftable time of use and energy use that changes over time. It includes devices such as washing machines, dishwashers and clothes drying machines. Eq. (1.3) - (1.5) introduce the user-defined constraints and are related to the three categories of devices mentioned above. The optimisation process consists of two parts: the first part, which optimises the use of the appliances from the second category (with variable time of use) based on the described LP optimisation and the second part, which aims to find the best period for the use of the devices from the third category, while achieving the least peak durations.

To solve the optimisation problem, a computational program was developed using standard MATLAB package. The input data includes total number of devices, number of devices per category, installed power of each device, and time of use each of the devices. The input file contains a matrix with 24 rows and eight columns. The rows refer to each hour of the day, while the columns represent the devices being considered in the household. Therefore, the number of columns may change for different households according to the number of observed appliances. The elements of the matrix show the state of the device, i.e., whether the device is turned on or not during the considered period. To simplify the optimisation and to reach the optimal solution faster, the elements of this matrix are 1 and 0 – where 1 indicates the devise is ‘on’ and 0 the device is ‘off’. In addition to this, information about the categories of the devices is obtained with the aim to show how many devices belong to each of the categories that were previously described. In a separate matrix column, the data for total engagement of a separate device during the day, installed power of each device as well as the minimum and maximum power of the device are provided, the latter referring devices with variable time and power of use are entered.

After reading the input data and placing it in appropriate variables, an optimisation function is called. The optimisation consists of two parts. The first time the program optimises the operation of devices with variable time of use and it is assumed that they can be turned on at any time of the day. This separation is made due to the specificity of devices with variable energy and time of use because their operation should not be interrupted. The optimisation approach of these devices is equal to shortest path algorithms whereby all possible combinations are considered and the combination that causes the minimum peak load is selected as a desirable solution.

2.2 Optimisation results

In this paper, the operation of the devices in a four-member household is optimised through the application of a DR program. The input data used for the devices are indicative, based on [28]. It is assumed that the air conditioning unit can be switched on in an economic mode (predefined temperature) during the day to keep a steady temperature in the household for inhabitants returning before 17 hours (usually school children older than 10 years) and it is placed in the second category of appliances. It could easily be switched to another category if the household members have other habits. This is valid for the other appliances as well – their use will depend on the habits of the household members and thus vary from one household to another.

The results are presented in Fig. 1 to Fig. 4. Fig. 1 shows the baseline scenario, without any optimisation. Fig. 2 presents the case after the optimisation is applied, showing that in the optimised solution the peak in the household consumption is significantly decreased. To broaden the analyses, additional cases have been considered. The sensitivity analyses applied on the proposed solution show how changes in user defined constraints influence the optimised solution. Fig. 3 shows the load curve if the devices from the second category are switched on only after 5 p.m., while Fig. 4 shows the load curve if a constraint on the number of devices switched on per hour is introduced (in this case, four devices may be simultaneously switched on). Further sensitivity analyses are presented in [29]. It is worth mentioning that this method places the appliances in the solution once a pre-defined condition is satisfied, which explains the occurrence of the peak in early morning hours or after 5 p.m. in the examples below.

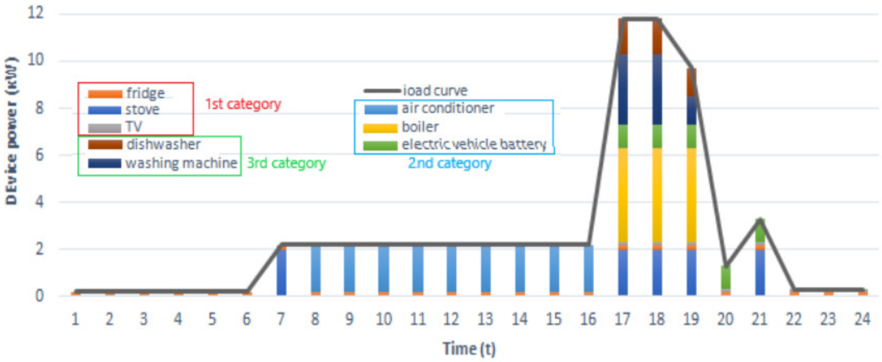

Figure 1: *Baseline scenario - without optimisation*

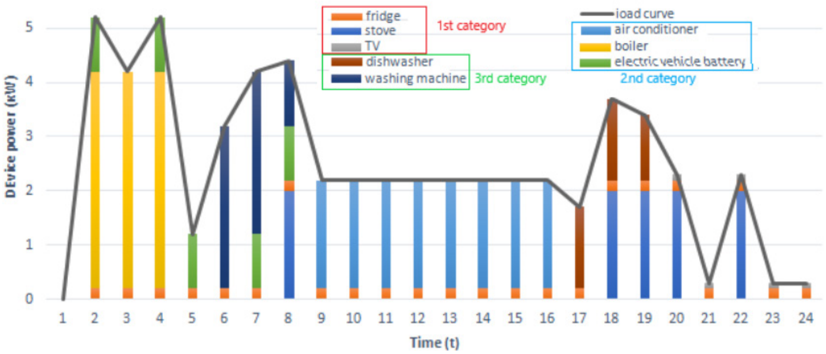

Figure 2: *Optimised use of the considered devices*

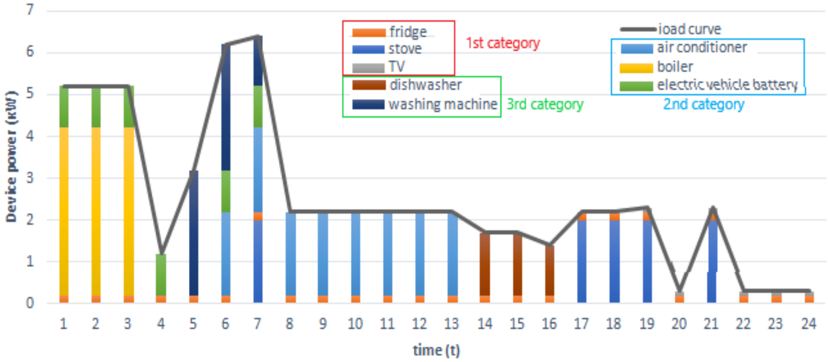

Figure 3: *Category 2 devices are switched on after 5 p.m.*

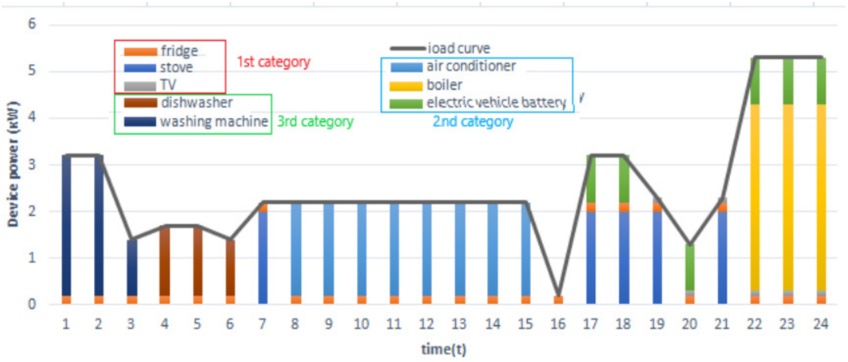

Figure 4: *Load curve with a limited number of switched devices per hour*

2.3 Financial Impact of Implementation of DSM programs

The practical implementation of a DSM program is plausible if both sides – suppliers (aggregators) and customers are expecting to obtain benefits. It is reasonable that the financial compensation (or financial benefit) is the main motivation for both parties to participate in DSM programs. To valorise the expected benefits for the customers, the examples described in the previous subsection are compared to the baseline scenario, considering existing prices of electricity for each case. The performed calculations show the amount of money spent by the household to cover the electricity costs per day if the household appliances are used as in the baseline scenario and as in the scenarios depicted in Fig. 2 to Fig. 4 (the optimised distribution of use of the devices). The calculations are performed considering the current electricity prices for households in the Republic of North Macedonia [30], i.e. low tariff of 1.3183 denars/kWh for the period between 10 pm and 7 am and first block tariff of 4,7257 denars/kWh for the rest of the day (for monthly usage of up to 200 kWh). The prices are for energy only and costs for transmission and distribution of electricity are not included.

The results of the calculations are presented in Table 1 below. The period T1 represents the period of the day between 7 am and 10 pm and the period T2 represents the period between 10 pm and 7am. Although the tariff system in place considers 4 tariff blocks, the calculations are done considering the tariff for the first block only. It is a reasonable approach as the optimisation should maximise the use of shiftable appliances in the off-peak period, leading to a situation where the customer monthly consumption would not exceed the limit of the first block. This is valid in the cases where electricity is not the major source for household heating. Furthermore, the calculations are only done once per day, to relate to the simulation results of the previous section.

Table 1: *Costs for energy for the baseline and optimised scenarios*

	Baseline scenario (Fig. 1)		Optimised scenario (Fig. 2)		Optimised scenario (Fig. 3)		Optimised scenario (Fig. 4)	
Time of day	T1	T2	T1	T2	T1	T2	T1	T2
Energy (kWh)	58	1.8	31.6	28.2	33.2	27.6	35.4	25.4
MKD	274.1	2.37	149.3	37.18	156.9	36.4	167.3	33.5
Total (MKD)	276.5		186.5		193.3		200.8	
Total (EUR)	4.5		3		3.14		3.3	

As can be noted from the results presented in Table 1, the redistribution of the use of the appliances to periods with lower electricity price could significantly decrease the electricity bill. The optimisation presented in Fig. 2 results with the least energy costs, which is achieved in accordance with the customer's constrains, i.e. without considerable changes of their habits. Relieving customer's constraints would lead to achieving higher savings. Fig. 5 gives a graphical presentation of the possible reduction of costs relative to the baseline scenario.

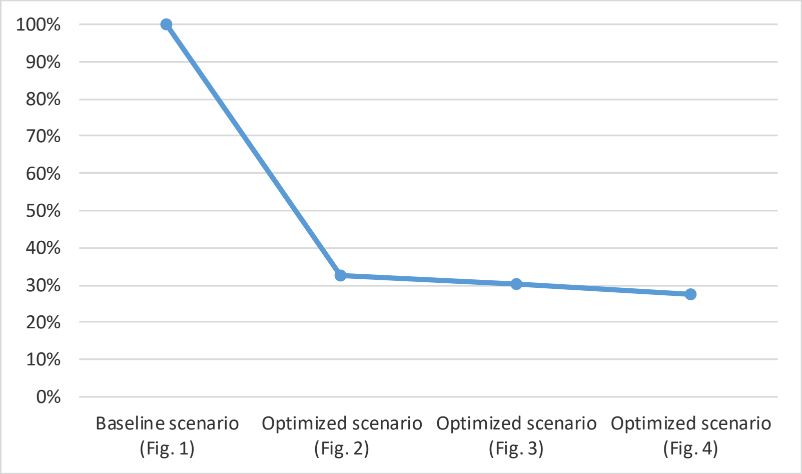

***Figure 5**: Reduction of costs for the analysed scenarios*

The described example presents the possible household savings on electricity if a specific DR program is in place, with pre-defined time periods and tariffs per periods. In such case, the implementation of the described LP method would allow the customer to use the shiftable household appliances in periods with low tariff following a schedule derived from the LP solution. Further analyses are required to valorise the benefits for customers in the case of dynamic prices.

3 CONCLUSIONS

This paper shows how the implementation of simple optimisation solutions can ease the implementation of DSM programs in households. By introducing user-defined constraints, solutions can be tailored towards the consumer, but without the need to implement complex algorithms and advanced technologies. Both the system operators and the consumers benefit from the optimisation of the household flexibility. The presented analyses confirm a decrease in the household peaks, something which benefits the distribution system operation. Furthermore, the distribution of the appliances following the described LP optimisation will lead to decrease of household electricity costs. The savings will depend on the constraints introduced by the customers and their willingness to slightly change their living habits.

It is worth mentioning that the implementation of such solutions requires certain behavioural changes, something which are often hard to change. Reduction of electricity costs may be perceived as a strong motivation factor, especially in periods of crisis and high prices, especially in developing economies. However, to maintain implementation, it is also important to raise public awareness on the costs related to electricity production, transmission and distribution and to promote energy efficiency as a priority measure for both public and private sectors. It could be assumed that the benefits of such programs would be higher if households became prosumers and even had their own storage systems. Further analyses are required to confirm and quantify this assumption.

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