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Analysis of Operation Times and Electrical Storage Dimensioning for Energy Consumption Shifting and Balancing in Residential Areas

A. Rosin, A. Auvaart, D. Lebedev
Department of Electrical Drives and Power Electronics, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia, phone: +372 620 3708, e-mail: vagur@cc.ttu.ee

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Introduction

According to a report by the U.S. Department of Energy in 2008 [1], 74% of the nation's electricity consumption occurs in buildings. This represents 39% of the total energy consumption among all sectors. There are two general approaches for energy consumption management in buildings: reducing consumption and shifting consumption [2]. The former can be done through raising awareness among subscribers for more careful consumption patterns as well as constructing more energy efficient buildings [3].

In the household without energy generation units, the main cost reducing possibilities are shifting of loads and/or replacing the less efficient loads with more efficient ones. Profitability of load replacing depends on energy costs, consumption amount, investments (replacement costs), exploitation costs and lifetime of the device. The shifting profitability depends on load priorities and storage possibilities. The household consumption is not a homogenous group, different appliances have different regimes, priorities and roles [4]. P. Kadar has divided household electrical appliances to three groups: critical load, flexible load, and autonomous flexible intelligent load.

Energy storage systems play a key role in shifting critical (not shiftable) loads. Storages can be classified into heating and electrical ones. Heating energy storages are water or space heaters in residential buildings with electrical heating loads. Compared to total consumption, these loads have mainly high energy consumption, which is about 30%...50%. Energy consumption shifting and balancing with existing heating energy storage systems needs small investments, and their profitability is mostly less than one year.

Optimization of electrical energy storage capacitance, control models (including the charging/discharging cycles) are important research questions. The main objectives of customers are:

- To minimize their energy costs;
- To increse the power quality and comfort.

The main objectives of the following analysis are the analysis of operation times and electrical storage dimensioning for energy consumption:

- Shifting, depending on the two-tariff system price and on the Nord Pool Spot price;
- Balancing with and without water heater shifting.

Operation times of home appliances

The following analysis is based on four-week measurements (in February/March 2010). The object of the analysis was a 3-room (67.4 m2) apartment with four habitants (2 adults, 2 children). The object built in 2005 has a two-tariff energy measurement system. The high tariff period in the winter time is from 7 to 11 o'clock (in the summer time from 8 to 24 o'clock) on workdays. The rest is a low-tariff period, including the weekend. For energy consumption measurements 12 *Voltcraft Energy Logger 4000* devices were used. The total measurement error was less than 5% compared with the main energy meter. The total energy consumption by load is shown in Fig. 1.

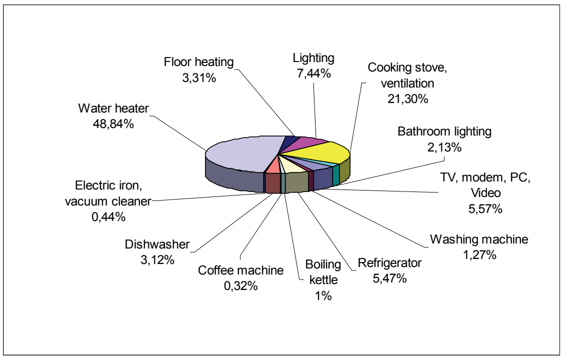

Fig. 1. Energy consumption of loads

By shift-ability, loads can be divided into three priority groups:

I (not shiftable) – cooking stoves, kitchen ventilation, coffee machines (without thermos), bathroom lighting and ventilation, TV sets, PCs with modem, home cinema and audio systems, and local lighting;

II (almost shiftable) – lighting, refrigerators, boiling kettles, coffee machines (with thermos), vacuum cleaners, electric irons, and floor heating for drying purposes;

III (shiftable) – water heaters, washing machines, dishwashers, and floor heating for heating purposes.

Based on the analysis of electricity consumption, the average workday consumption per hour is 0.9 kWh, and the average holiday consumption per hour is 1.4 kWh. Before the consumption shifting and reducing in the workday the average high-tariff consumption is 1.05 kWh/h and average low-tariff is 0.55 kWh/h. There are three peak hours for energy consumption [5]:

- The morning on the workday (from 7 to 8);
- The midday on the holiday (from 12 to 14);
- The evening on the workday or holiday (from 19 to 21).

Main loads which affect the local extremums are: in the morning – water heater; in the midday – water heater and cooking stove; in the evening – water heater, cooking stove and lighting.

Before the consumption shifting and reducing the average ON time period is 4 hours and 36 minutes. The average ON time in the high-tariff period is 2 hours and 10 minutes.

The operation times of home appliances can be divided into three groups:

- Long operation period (3 hours and more): refrigerator, TV, modem, PC, video, lighting, water heater, floor heating;
- Average operation period (between 1 to 3 hours): bathroom lighting, cooking stove & ventilation, iron, vacuum cleaner, dishwasher;
- Short operation period (up to 1 hour): washing machine, coffee machine, boiling kettle, toaster.

Appliances with a long operation period like water heaters, floor heating and refrigerators have an energy storage capability (Table 1). Energy consumption scheduling of about 200-liter water heater and floor heating energy up to six hours does not affect the customers comfort. Control for scheduling of a small water heater (up to 50 liters) and a refrigerator must be reasonable and take into consideration vacancy of the apartment. Water heaters and refrigerators are rarely used on workdays between 9 and 15 o'clock, which makes it possible to shift small water heaters and refrigerators electricity consumption for one to three hours.

Table 1. Operation times and energy consumption of home appliances

Load name(s)	ON-time per day	ON-time/day, %	ON time in high-tariff period	ON time in low-tariff period	Max continuous ON time	Total consumption by loads, %	High tariff consumption, %
Refrigerator	15 h 36 min	65	7 h 24 min	8 h 11 min	17 h 30 min	5.5	47.50
TV, modem, PC, Video	12 h 42 min	53	7 h 5 min	5 h 37 min	16 h	5.6	55.76
Lighting	7 h 58 min	33	4 h 40 min	3 h 17 min	8 h	7.4	58.68
Water heater	5 h 46 min	24	2 h 52 min	2 h 54 min	5 h 30 min	48.7	49.66
Floor heating	4 h 5 min	17	1 h 10 min	2 h 54 min	15 h 30 min	3.3	28.79
Bathroom lighting	2 h 57 min	12	1 h 31 min	1 h 26 min	5 h	2.1	51.35
Cooking stove, ventilation	2 h 12 min	9	1 h 8 min	1 h 4 min	3 h	21.3	51.35
Iron, vacuum cleaner	2 h 2 min	8	0 h 11 min	1 h 50 min	50 min	0.4	9.41
Dishwasher	1 h 7 min	5	0 h 2 min	1 h 4 min	1 h 45 min	3.1	4.36
Washing machine	32 min	2	0 h 0 min	0 h 32 min	1 h	1.3	0.28
Coffee machine	10 min	0,7	0 h 1 min	0 h 8 min	1 h	0.3	12.49
Boiling kettle	7 min	0,55	0 h 4 min	0 h 3 min	7 min	1	61.96

Energy storage dimensioning for consumption shifting in a two-tariff system

If the consumption of all freely shiftable loads (water heater, dishwasher, washing machine) is shifted to the low-tariff period and lighting bulbs are replaced with economy bulbs, the 6.5...7 kWh of almost- and not-shiftable energy consumption stays in the high-tariff period. After consumption scheduling and using of saving bulbs (compact fluorescent lamp) the average high-tariff energy consumption is 0.43 kWh/h.

Fig. 2 shows that at the high-tariff period two high and low consumption periods with a difference of about 7.4 times can be identified. The low energy consumption period is between 7...17 and 21...23 o'clock - with the average energy consumption of 0.165 kWh/h. The high energy consumption period is between 17...21 with the average energy consumption of 1.22 kWh/h.

Two different choices are available for electrical energy storage calculation. First, storage should store energy for the whole high-tariff period. Using a simplified formula (1), storage capacitance of about 6.9 kWh can be calculated

$$E_{st} = E_{hb} - E_{sh} = E_{ha}, \qquad (1)$$

where E_{st} – minimum electrical storage capacitance, E_{hb} – high-tariff consumption before shifting of shiftable loads, E_{sh} - shifted energy (energy consumption of shiftables loads), E_{ha} – high-tariff consumption after energy consumption shifting of shiftable loads.

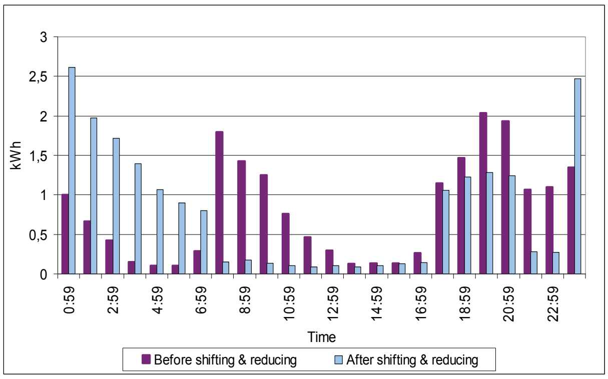

Fig. 2. Electricity consumption before and after load scheduling and power reducing on workdays

Naturally it is important to take into consideration also all energy losses in the scheduling process and system self-consumption.

Second, the storage should store only energy of the high energy consumption period, which means a storage capacitance of about 4.9kWh (about 29% less than described before). In both cases the peak power of the storage system should be approximately between 1.2 and 1.5 kW.

Storage dimensioning for consumption scheduling based on the Nord Pool Spot (NPS) average daily price

Energy consumption in households in the UK is reported in [6] and in Estonia in [7]. Peak hours for UK households are from 06-08 and 13-18. Main peak hours for Estonian average households are at 7-8 and 19-21 on workdays and 12-14 and 19-21 at weekends. It is quite easy to see the possible use of energy storage to smoothen the loads at morning or midday use and even the evening use at weekends. However, some exact calculations are needed in terms of the possibilities to conserve energy at low price before evening peak hours on workdays.

Average NPS price during the measured period in the Estonia (EE) area is calculated as 44.50€/MWh. The NPS price curve is not similar on workdays and at weekends. The maximum price on workdays is 65.93€/MWh and the minimum is 33.35€/MWh. At weekends the maximum and minimum prices are 43.05€/MWh and 29.76€/MWh, respectively. Average price below the EE area average (44.50€/MWh) is 38.02€/MWh (-14.55%) on workdays and 38.26€/MWh (-14.03%) at weekends. Average price above the EE area average is 53.50 €/MWh (20.22%) on workdays and does not exceed the average at weekends.

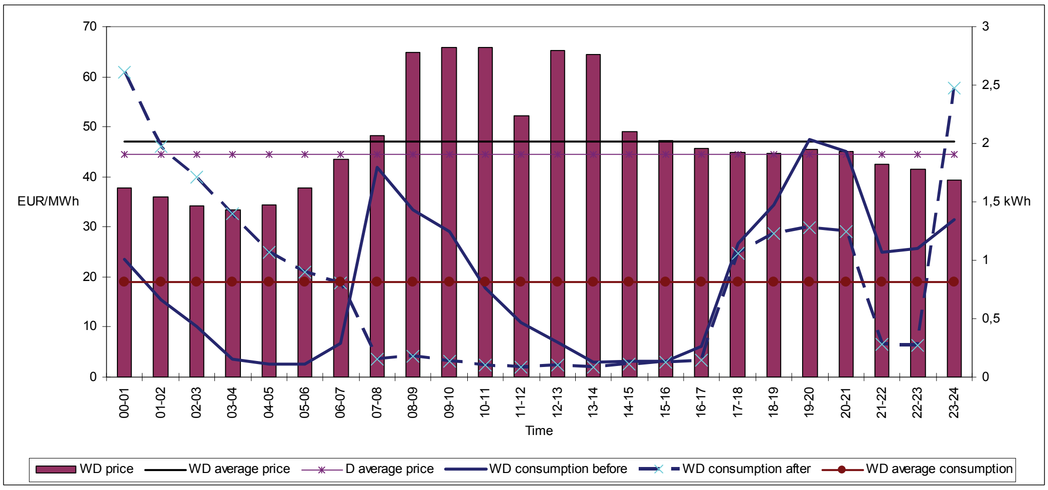

Fig. 3. Average workday price fluctuation compared to electricity consumption before and after scheduling of shiftable loads

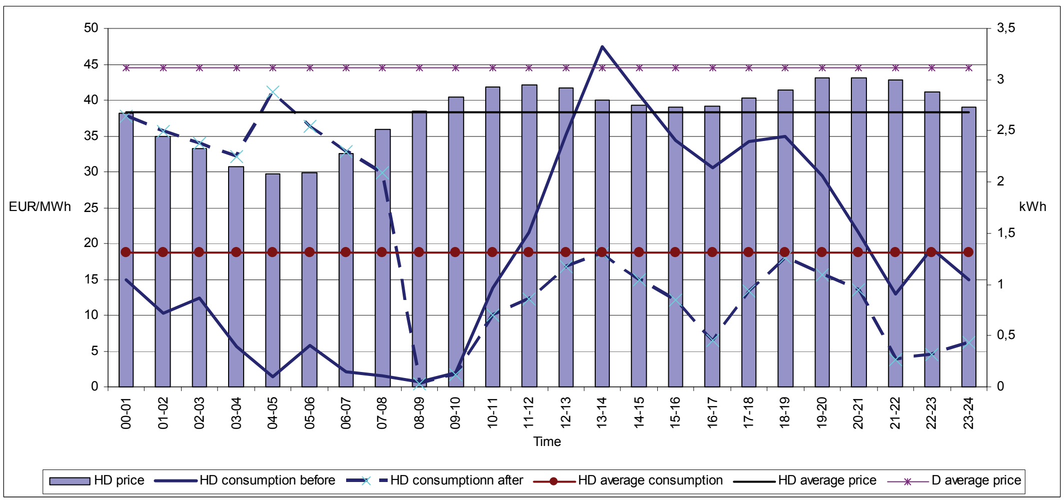

Fig. 4. Average holiday price fluctuation compared to electricity consumption before and after scheduling of shiftable loads

If all shiftable loads on workday (WD) are "switched on" under average price, then at least 1.1 kWh storage system is needed for shifting of energy consumption (Fig. 3).

If all shiftable loads on holiday (HD) are "switched on" under average price, then at least 11.8 kWh of energy consumption should be supplied from the storage system (Fig. 4). If an average price deviation is allowed (43.05 - 29.76)*10% = 1.33€ (10 % from maximum and minimum price difference), then 4.83 kWh should be supplied from the electrical energy storage.

Storage dimensioning for consumption balancing

In the following analysis the consumption of a water heater, dishwasher and washing machine will be shifted with the electrical energy storage system.

To balance electricity consumption it is important to define average electricity consumption and deviation of electricity consumption. The simplified formulas (2) and (3) for the calculation of maximum over- and under-consumption amounts are described as follows:

$$E_i > \overline{E} \Rightarrow \begin{cases} E_{u,\Sigma} = 0, \\ E_{o,\Sigma} = \sum_{i=1}^{n}(E_i - \overline{E}), \\ E_{o,\max} < E_{o,\Sigma} \Rightarrow E_{o,\max} = E_{o,\Sigma}, \end{cases} \tag{2}$$

$$E_i < \overline{E} \Rightarrow \begin{cases} E_{o,\Sigma} = 0, \\ E_{u,\Sigma} = \sum_{i=1}^{n}(E_i - \overline{E}), \\ E_{u,\max} > E_{u,\Sigma} \Rightarrow E_{u,\max} = E_{u,\Sigma}, \end{cases} \tag{3}$$

where $E_{u,\Sigma}$ – energy of the under-consumption period; $E_{o,\Sigma}$ – energy the over-consumption period; $E_{o,max}$ – energy consumption at the highest over-consumption period; $E_{u,max}$ – energy consumption at the highest under-consumption period; E_i – energy amount at the moment i; $\overline{E}$ – average energy consumption.

The average daily electricity consumption is 1 kWh per hour. In Fig. 5 two important periods: over and under consumption period are shown for storage system dimensioning. The largest over consumption period is from 17 to 1 o'clock and the under-consumption period is from 1 to 7 o'clock with energy amounts of 4.5 kWh and 4 kWh, respectively.

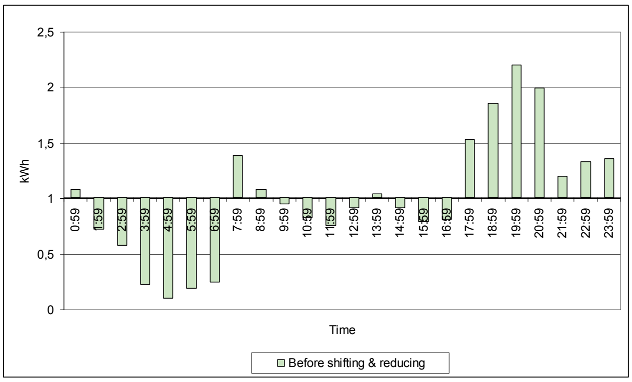

Fig. 5. Average daily electricity consumption before shiftable loads scheduling

To obtain a more precise overview holiday and workday consumption should be analyzed separately. Fig. 6 shows that at holiday one large over- and under-consumption period occurs. The largest over-consumption period is from 11 to 21 o'clock with an energy amount of 10 kWh. The largest under-consumption period is from 23 to 11 o'clock with an energy amount of 9.7 kWh. By an average consumption deviation of 25%, over- and under-consumption energy amounts are about 7 kWh and 5.7 kWh, respectively.

It is shown in Fig. 7 that at workdays two over- and two under-consumption periods occur. Over-consumption periods are from 7 to 10 o'clock and from 17 to 1 o'clock with an energy amount of 2 kWh and 5.4 kWh, respectively. Under-consumption periods are from 1 to 7 o'clock and from 10 to 17 o'clock with an energy amount of 3.5 kWh and 3.9 kWh, respectively.

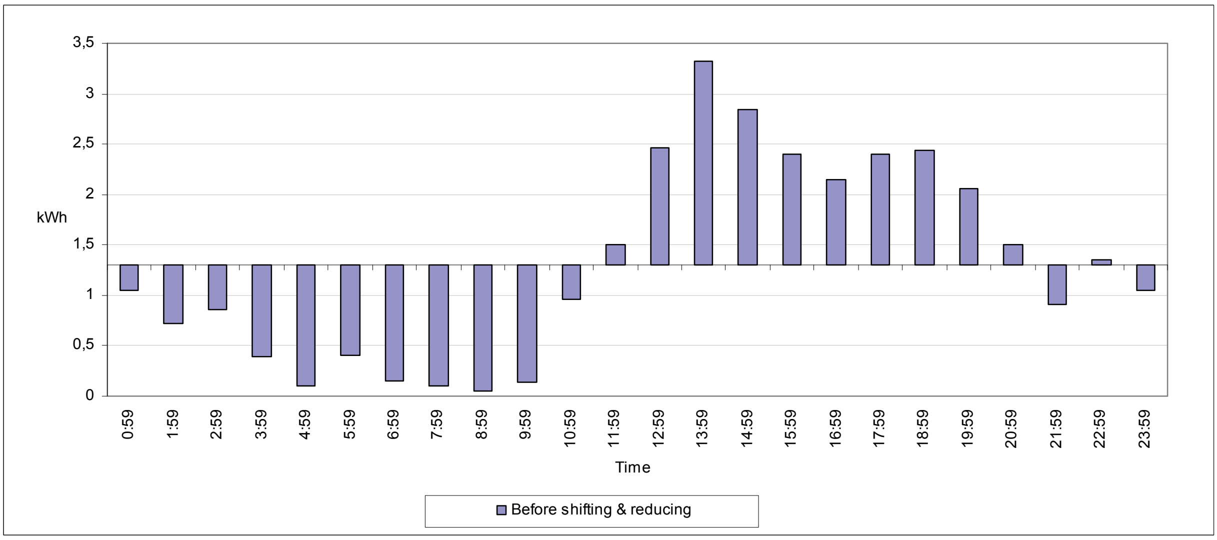

Fig. 6. Average holiday electricity consumption before shiftable loads scheduling

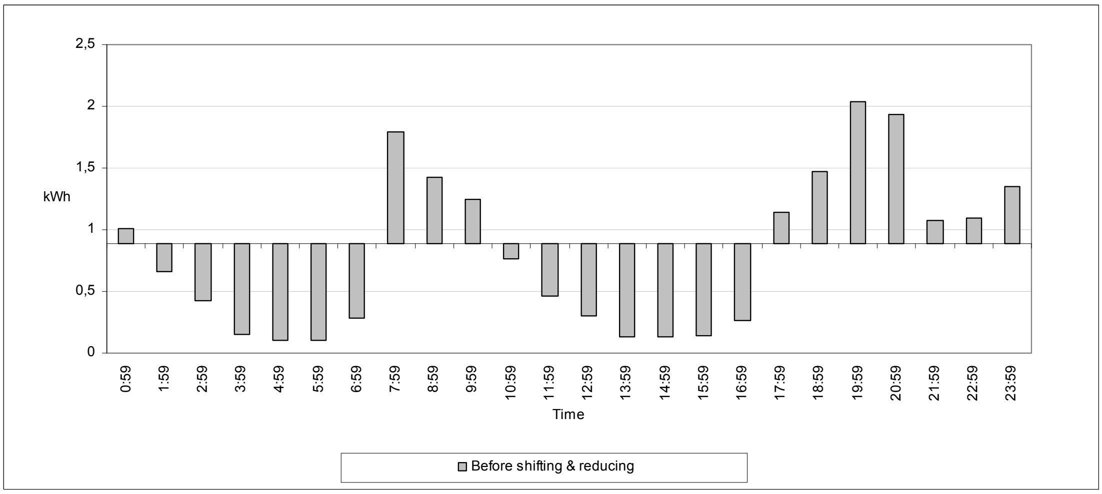

Fig. 7. Average workday electricity consumption before shiftable loads scheduling

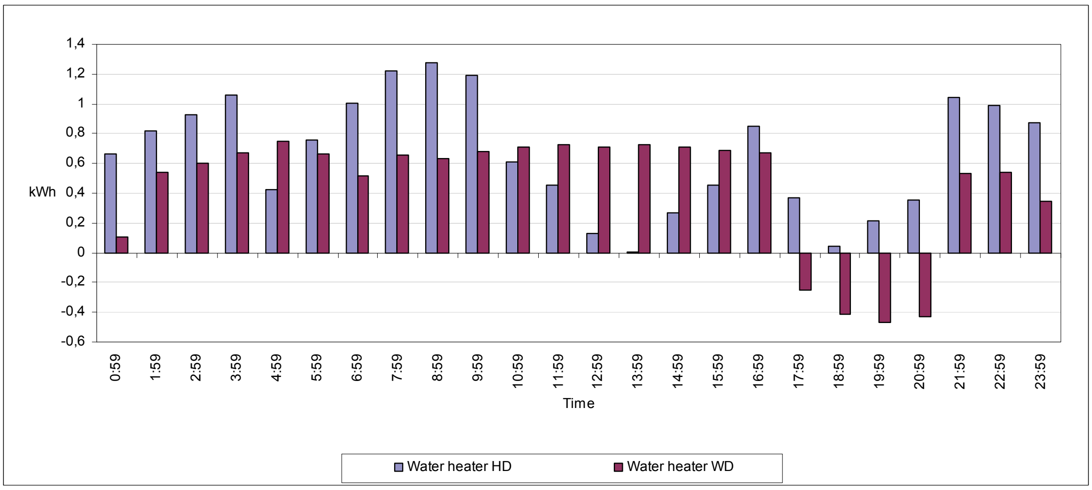

Fig. 8. New consumption pattern for water heater HD and WD consumption

Electrical energy storage capacitance should be greater than or equal to the highest energy consumption period. Comparing the energy consumption of a workday, holiday and average day, the maximum energy demand for balancing is about 7 kWh.

Consumption balancing with water heater consumption shifting

This section analyzes the use of a water heater for electricity consumption balancing in a two-tariff system. Using a simplified formula (4) the consumption pattern of a new water heater for balancing is calculated:

$$E_{i,awh} = E_{i,bwh} - (E_{i,b} - \overline{E});\ \ E_{i,awh} < 0 \Rightarrow E_{SE} = \left|\sum_{i=1}^{n} E_{i,awh}\right|, \quad (4)$$

where $E_{i,awh}$ – water heater energy consumption after shifting at time i; $E_{i,bwh}$ – water heater energy consumption before shifting at time i; $E_{i,b}$– total energy consumption before shifting at time i; $\overline{E}$ – average energy consumption; E_{SE} - shortage of energy, which should be balanced by the electrical energy storage.

Fig. 8 shows that consumption scheduling with water heater can balance electricity consumption on holiday. Also, no problems are encountered in consumption balancing with water heater scheduling at workday from 0 to 17 and 21 to 24 o'clock.

As shown in Fig. 8, it is not possible to balance consumption between 17 and 21 o'clock with a water heater. At the same time another high consumption unit, the cooking stove, is used. During that period the shortage of energy is about 1.6 kWh (0.4kWh per hour), which should be supplied by an additional electrical energy storage system or energy source. An alternative is to reduce comfort level by shifting or reducing of other non-shiftable loads consumption.

Conclusions

The minimum energy reserves that an electrical energy storage system should have for described household energy consumption:

- Shifting, based on the two-tariff system, 4.9...6.9 kWh;
- Shifting, based on the Nord Pool Spot (NPS) average daily price, 4.83....11.8 kWh;
- Balancing, if shiftable loads consumption is not separately shifted, 5.4...10 kWh;
- Balancing, if shiftable loads consumption is separately shifted, 1.6 kWh.

As described above, an electrical energy storage system should have energy reserves of approximately 5 to 10 kWh. The peak-power of an electrical energy storage system should be chosen in most cases between 2 to 7 kW, depending on functionality and consumption patterns. Electrical energy storage with such parameters can be used in most energy consumption balancing and shifting cases.

Similarity of the calculated parameters of household energy storage with the parameters of existing hybrid electric vehicle batteries makes the technology used in vehicles attractive for residential areas. Profitability of DSM (demand-side management) systems for loads priority based scheduling [8][9], using an electrical energy storage, is questionable.

The feasibility of investment to different control systems and models depends on customers habits. For small customers/households often very simple and fast profitable energy consumption costs reduction (for example in household device integrated scheduling functionality) solutions exists.

Optimization of electrical energy storage charging/discharging cycles according to realtime dynamic prices is an important topic for further research. Dimensioning of electricity storage according to production of micro-scale renewables (in residential area and housholds) is another important topic for furher research.

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This article describes operation times of home appliances and energy consumption based electrical energy storage dimensioning analyses for residential areas. The analysis is based on an object in Estonia. The electrical energy storage dimensioning for consumption scheduling in the two-tariff system and on the basis of the Nord Pool Spot (NPS) price is discussed. Additionally, in the storage dimensioning part, consumption balancing using of electrical energy storage and water heater consumption shifting is analyzed. Optimization of electrical energy storage charging/discharging cycles according to realtime dynamic prices is an important topic for further research. Ill. 8, bibl. 9, tabl. 1 (in English; abstracts in English and Lithuanian).

A. Rosin, A. Auvaart, D. Lebedev. Elektros energijos talpyklų eksploatacijos trukmių parametrizavimo analizė siekiant subalansuoti elektros suvartojimą gyvenamosiose vietovėse // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2012. – Nr. 4(120). – P. 15–20.

Pateikti buitinės technikos eksploatacijos trukmių ir energijos suvartojimo analizės rezultatai. Aptartas elektros energijos talpyklos parametrizavimas suvartojimui planuoti dviejų tarifų sistemoje. Analizuojamas vartojimo subalansavimas naudojant elektros energijos talpyklą ir kaitinimui sunaudoto vandens postūmį. Elektros energijos talpyklos įkrovimo ir iškrovimo ciklų optimizavimas, atsižvelgiant į kainų kitimą, yra tolesnių tyrimų sritis. Il. 8, bibl. 9, lent. 1 (anglų kalba; santraukos anglų ir lietuvių k.).