Abstract-This paper describes an analysis of battery energy storage technologies and possibilities of profitability attainment by these techniques in households.

I. INTRODUCTION

Increasing use of electric grids requires constant online balancing of supply and demand (including grid losses). Correctly chosen energy storage (ES) technologies will smooth out these surges and allow electricity to be dispatched when needed. An ES technology plays the main role in the scheduling of critical loads. The simplest definition of a storage device is specifically designed to store electricity from the grid, convert it into an energy form suitable for storage, subsequently convert it back into electricity and return it to the grid [1]. All energy storages are characterized by several parameters defined below.

The most significant parameter is energy storage capacity: it is the amount of electrical energy the device can store usually measured in kilowatt-hours (kWh) or megawatt-hours (MWh). Additionally ES is characterized by power capacity: it is the maximum instantaneous output that an energy storage device can provide, usually measured in kilowatts (kW) or megawatts (MW). The price of ES depends mainly on these two parameters. Efficiency parameter: it indicates the quantity of electricity which can be recovered as a percentage of the electricity used to charge the device. Round-trip efficiency: it indicates the quantity of electricity that can be recovered as a percentage of the electricity used to charge and discharge the device. The last main characteristic is response time. It shows the length of time it takes the storage device to start releasing power [2].

Owing to variable capacity and power combinations energy storages are used in a wide range of areas. Electrochemical energy storages will be further described in detail as the most appropriate ones for household use. Regarding to the relation of consumption and supply, there are two main load management features. The first one is load levelling: using off-peak power to charge the energy storage device and subsequently allowing it to discharge during the peak demand. As a result, the overall power production requirements become flatter and thus cheaper base load power production can be increased. Another feature is load following: energy storage device acts as a sink when the power required falls below production levels and acts as a source when the power required is above production levels [2].

As the power engineering community becomes more aware of ES systems, the benefits of such systems have to be balanced against their cost. That cost has to be justified against the alternatives, which could include, for example, doing nothing and living with power quality problems; increased use of peaking generators; or building a new transmission line. The normal tool for making these cost justifications is a life cycle costing (LCC) analysis, in which all costs associated with the alternative approaches are defined over a certain time period, often 10 or 20 years. In the same way, an LCC analysis can be used to differentiate between competing ES technologies. This is particularly the case for new technologies, which typically have a high cost when first introduced. Each technology will often have a particular advantage, such as cycling capability, energy efficiency, high performance, etc [10]. In order to make a comparison among competitive ES technologies for households, they must be grouped accordingly to the value of power and energy storage capacity. Theoretically three ES groups can be defined: ES group with light, medium and large energy capacity and power capacity. Light and medium groups are suitable for use in households and small businesses, respectively.

The next criterion for a group’s definition has three options based on the response time. Short-term response energy storage technology – technologies with high power density (MW/m3) and with the ability to respond in a short- time frame belong to this category. They are usually applied to improve power quality, particularly to maintain the voltage stability during transients (a few seconds or minutes). Long-term response energy storage technology - technologies for power system applications can usually absorb and supply electrical energy for minutes or hours. They are usually deployed to contribute to the energy management, frequency regulation and grid congestion management. Real long-term response energy storage technology – real long-term (days, weeks, or months) response energy storage technologies are usually applied to match supply and demand over 24 hours or longer response of ES for days, weeks, or months and are typically applied to fulfill demands over 24 hours or longer [3].

Consumption shifting in households requires usually some hours of energy storage usage. This means that long-term response technology will be the best solution in this case.

The main parameters, such as energy capacity, power and life time cycles mentioned above, will be considered below in the calculations of energy storages profitability.
III. ENERGY STORAGE TECHNOLOGIES

In the technology description, the ES group with light and medium energy storage capacities will be considered. This group includes two types of batteries: Battery Energy Storage (BES) and Flow Battery Energy Storage (FBES). The oldest and the most common technology in BES is a Lead Acid (LA) battery. It has low cost and fast response time. Lead acid batteries are divided into two types: flooded lead acid (FLA) and valve regulated lead acid (VRLA) batteries. FLA batteries consist of two lead plates, electrodes, which are immersed in a solution of sulphuric acid (35%) and water (65%). Principles of operation of VRLA and FLA batteries are the same; the only difference is that VRLA batteries are sealed with a pressure-regulating valve [2]. The second type in the BES group is a Nickel Cadmium (NiCd) battery. The main elements of a usual construction (vented or sealed designs) are a positive plate with nickel oxyhydroxide as the active material and a negative plate with an electrode composed of metallic cadmium. At the stage of charging a Nickel Cadmium battery hydrogen will be generated at the negative electrode and oxygen will be generated at the positive electrode. NiCd storages have very quick response time (within milliseconds) and can be applied from TV-set remote control up to diesel engine starters. They have relatively long life time, but the limited number of charge/discharge cycles has also an impact on the life time. The last type of batteries in the BES group is a Sodium Sulphur (NaS) Battery. The structure of these batteries is more complicated than with LA. It has a cylindrical electrochemical cell that contains a molten-sodium negative electrode and a molten-sulphur positive electrode. The solid β-alumina is used as an electrolyte [2]. During discharging, sodium ions pass through the β-alumina electrolyte where they react at the positive electrode with the sulphur to form sodium polysulfide. During charging, the reaction is reversed so that the sodium polysulfide decomposes, and the sodium ions are converted to sodium at the positive electrode [2]. This ES has relatively higher efficiency and a longer lifetime than analogous solutions in LA or NiCd. This storage technology is good for power quality management due to the characteristic of the discharging curve.

The next group of batteries is FBES and the first type is a Vanadium Redox (VR) Flow Battery. VR batteries save energy by using vanadium redox couples stored in gelatin sulphuric acid solutions (electrolytes). While charge/discharge cycles take place, H+ ions are swapped between the two electrolyte tanks through the hydrogen-ion permeable polymer membrane. VR batteries have a wide versatility, relatively high energy power capacity (up to 5 MWh) and efficiency 85%. The next type of battery in FBES is a Polysulfide Bromide (PSB) Flow Battery [3]. The working structure of the battery is based on the same principles and components as in the previous type VR. The electrolytes used within batteries are sodium bromide as the positive electrolyte and sodium polysulfide as the negative electrolyte. While discharging, the two electrolytes flow from their containers to the cell where the reaction goes at a polymer membrane that allows sodium ions to go through. As compared to a FBES battery, a PSB has lower efficiency (up to 75%), but a faster response time (within 20 milliseconds) PSB also has different applications. The last type in the FBES group is a Zinc Bromine (ZnBr) Flow Battery. Despite the fact that the components of ZnBr are similar to the previous two types, the principle of work is slightly different. Thus, during discharge, Zn and Br are being combined into zinc bromide, generating 1.8 volts within each cell. This will increase the Zn2+ and Br- ion density in both electrolyte tanks. During charge, metallic zinc will be deposited (plated) as a thin film on one side of the carbon-plastic composite electrode. ZnBr batteries have high energy density with relatively compact design (in comparison to other battery types). This type is able to provide load management of UPS as well as frequency control on wind farms or solar panels. It means that the share of ZnBr ES on the renewable energy market will obviously grow.

IV. STORAGE DIMENSIONING FOR TWO-TARIFF PRICE BASED ENERGY CONSUMPTION

Control and optimization of electricity consumption by applying ES are the prime objectives to minimize energy cost. The following investigation was conducted to find ES dimensions for use in a two-tariff energy measurement system (Estonian region energy system). The analysis was 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 high tariff period in the winter time in Estonia on a workday is from 7 to 23 o’clock (in the summer time from 8 to 24 o’clock). The rest is a low tariff period, including the weekend. Based on electricity consumption analysis, an average weekday consumption per hour is 0.9 kW, and average consumption per hour on the weekend is 1.4 kW. Before the shifting and reducing of energy consumption on the workday the average high tariff consumption was 1.05 kWh and low tariff consumption was 0.55 kWh. Figure 1 shows energy consumption before and after load shifting on weekdays. There are three peak hours for energy consumption:

- Morning on the workday (from 7 to 8 o’clock);
- Midday on the holiday (from 12 to 14 o’clock);
- Evening on the workday or holiday (from 19 to 21 o’clock).

The simplest method of electrical ES calculation is as follows: the storage should store energy for the whole high tariff period. This method will enable the estimation of the required maximum value of an initial energy storage capacity. By help of following formula (1) storage capacitance of about 6.9 kWh can be calculated without considering energy losses in the scheduling process and system self-consumption [4].

\[ E_{st} = E_{hb} - E_{sh} = E_{ha} \]

where \( E_{st} \) - minimum storage capacitance; \( E_{hb} \) - high tariff consumption before shifting; \( E_{sh} \) - shifted energy; \( E_{ha} \) - high tariff consumption after shifting.
V. STORAGE DIMENSIONING FOR NPS PRICE BASED ENERGY CONSUMPTION

Nord Pool Spot (NPS) is the largest market of electrical energy in the world, offering over day and intraday markets to its participants. NPS provides a market place to producers, energy companies and large consumers for buying or selling electrical energy. It is the central reseller in all trades, guaranteeing settlement for trade. In spite of continuously changing prices, it is possible to monitor tendencies in average price trends and patterns of different regions, i.e. Estonia. The monitoring was made during April/November 2010. The first fact is that the price curves are not similar on weekdays and on weekends. The maximum price on weekends is 65.93€/MWh and the minimum is 33.35€/MWh, which are higher than on the weekends 43.05€/MWh and 29.76€/MWh, respectively. Average price below the Estonian area average (44.50€/MWh) is 38.02€/MWh (-14.55%) on the workdays and 38.256€/MWh (-14.03%) on the weekends. Average price above the Estonian area average is 53.49€/MWh (20.22%) on the workdays and does not exceed the average on the weekends. If all shiftable loads on a workday (WD) are switched on under average price, then 1.1 kWh of energy consumption should be covered by storage system (Fig. 1). If all shiftable loads on a holiday (HD) are switched on under average price, then 11.8 kWh of energy consumption should be supplied from the storage system [5].

The average price trends and calculations enable a pattern to be created for beneficial energy consumption, which will be similar to the curve “WD consumption after” in Figure 1. According to NPS average price fluctuations and household electricity consumption, the minimum value of energy storage capacity must be 12 kWh.

VI. ENERGY STORAGE FEASIBILITY FOR HOUSEHOLDS

Today batteries as ES are the best solution for consumption shifting in an average apartment. Their feasibility for households can be estimated by the system cost and profit calculation. Further, the consumption pattern based on a two-tariff energy measurement system will be provided. However, in the case of batteries it is usually complicated to achieve profitability. For example, an LA type battery provides cheap kWh cost but a costly recycle process. Furthermore, there are many operational drawbacks during service of an LA battery. To find a profitable ES, it is necessary to analyze parameters and costs described in Table I [7][8].

The parameter of self-discharge rate is a measure of how quickly a cell will lose its energy while unused due to unwanted chemical actions within the cell. The rate depends on the cell chemistry and the temperature. Specific energy is the energy output per unit weight of a battery. Specific power is the power output per unit weight of a battery.

Energy density is the amount of energy stored in a battery. It is expressed as the amount of energy stored per unit volume or per unit weight (Wh/L or Wh/kg). Power density is the amount of power available from a battery. It is expressed as the power available per unit volume or per unit weight (W/L or W/kg) [11]. ES system cost is the overnight capital cost of the storage device itself, and is typically given in two parts: power capacity cost ($/kW) and energy capacity cost ($/kWh). By dividing the cost this way, there is an inherent assumption that the energy capacity and power capacity are independent, which is not true for all systems. For example, this assumption is true for flow batteries and pumped hydroelectric storage, but not true for traditional secondary batteries and flywheels. However, since most systems can be scaled up by interconnecting multiple units in series/parallel combinations, it will be assumed that this methodology correctly approximates the system costs [8]. The kWh cost is based on the system capital cost per one unit of the rated energy capacity, as measured by duration (hours) at the rated power (kW). Power conversion system costs (PCS) ($/kW) consist of all components between the storage device and the utility grid including power conditioning equipment, control systems, power lines, transformers, system isolation equipment, and safety sensors.

Balance of plant costs (BOP) ($/kW) encompass construction costs and engineering, land, access routes, taxes, permits, and fees [8].

Operation and maintenance (O&M) fixed costs ($/kW-yr) include annual costs for the routine maintenance required to keep the system operational. The units for these costs are dollars per kW of installed capacity, per years of operation (so Fixed OM costs of 5$/kW-yr for a 1kW system would cost 5$/year) [8].

The total capital costs of the system $C_{tot}$ can be computed by help of (2) by multiplying the power capacity value of the system by the sum of the BOP, PCS, power capacity costs and adding the system energy capacity multiplied by the energy capacity cost.

$$C_{tot} = P_{max} \cdot (C_{BOP} + C_{PCS} + C_{ES} + C_{OM} \cdot E_{max} \cdot E_{EC} \cdot (2)$$

where $C_{PC}$ - power capacity costs ($$/kW); $C_{EC}$ - energy capacity costs ($$/kWh); $C_{PCS}$ - power conversion system costs ($$/kW); $C_{BOP}$ - balance of plant costs ($$/kw); $C_{OM}$ - operations and maintenance fixed costs ($$/kW-yr) multiplied by the amount of expected years and the discount rate %; $P_{max}$ - power capacity of the system (kW) and $E_{max}$ - energy capacity of the system to shift consumption with a particular depth of discharge (kWh).
### Table I: Cost/Life Cycle Characteristics of Storage Technologies

<table>
<thead>
<tr>
<th>Technical Parameters</th>
<th>NaS</th>
<th>LA</th>
<th>NiCd</th>
<th>Li-Ion</th>
<th>ZnBr</th>
<th>PSB</th>
<th>VR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roundtrip Efficiency (%)</td>
<td>70-90</td>
<td>70-82</td>
<td>60-70</td>
<td>85-98</td>
<td>60-75</td>
<td>57-75</td>
<td>60-85</td>
</tr>
<tr>
<td>Self-discharge (%Engy/day)</td>
<td>0.05-20</td>
<td>0.033-0.3</td>
<td>0.067-0.6</td>
<td>0.1-0.3</td>
<td>0.24</td>
<td>-0</td>
<td>0.2</td>
</tr>
<tr>
<td>Cycle Lifetime (cycles)</td>
<td>2.500-10000</td>
<td>100-2000</td>
<td>800-3500</td>
<td>1000-10000</td>
<td>2000</td>
<td>2000</td>
<td>000-14000</td>
</tr>
<tr>
<td>Expected Lifetime (Years)</td>
<td>5-15</td>
<td>3-20</td>
<td>5-20</td>
<td>5-15</td>
<td>5-10</td>
<td>10-15</td>
<td>5-15</td>
</tr>
<tr>
<td>Specific Energy (Wh/kg)</td>
<td>150-240</td>
<td>30-50</td>
<td>50-75</td>
<td>75-200</td>
<td>30-50</td>
<td>10-50</td>
<td>10-30</td>
</tr>
<tr>
<td>Specific Power (W/kg)</td>
<td>150-230</td>
<td>75-300</td>
<td>150-300</td>
<td>150-315</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Energy Density (Wh/L)</td>
<td>150-250</td>
<td>50-80</td>
<td>60-150</td>
<td>200-500</td>
<td>30-60</td>
<td>16-60</td>
<td>16-33</td>
</tr>
<tr>
<td>Power Density (W/L)</td>
<td>0</td>
<td>10-400</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Power Cost ($/kW)</td>
<td>150-3000</td>
<td>175-600</td>
<td>150-1500</td>
<td>175-4000</td>
<td>175-2500</td>
<td>330-250</td>
<td>0</td>
</tr>
<tr>
<td>Energy Cost ($/kWh)</td>
<td>250-500</td>
<td>150-400</td>
<td>600-1500</td>
<td>500-2500</td>
<td>150-1000</td>
<td>120-1000</td>
<td>150-1000</td>
</tr>
<tr>
<td>BOP Cost ($/kW)</td>
<td>120-600</td>
<td>120-600</td>
<td>120-600</td>
<td>120-600</td>
<td>120-600</td>
<td>120-600</td>
<td>120-610</td>
</tr>
<tr>
<td>PCS Cost ($/kW)</td>
<td>0-120</td>
<td>58-180</td>
<td>58-180</td>
<td>0</td>
<td>0-120</td>
<td>60-120</td>
<td>36-120</td>
</tr>
<tr>
<td>O&amp;M Fixed Cost ($/kW-y)</td>
<td>23-61</td>
<td>1.8-52</td>
<td>6-32</td>
<td>12-30</td>
<td>15-47</td>
<td>18-96</td>
<td>24-65</td>
</tr>
</tbody>
</table>

Results of (2) are shown in Table III. Large scale group members PHES (Pump Hydroelectric Energy Storage), Underground PHES and CAES (Compressed Air Energy Storage) strongly depend on the availability of suitable terrains and practically cannot be applied in households. Therefore, they will not be shown in this table and in further figures. Due to the low values of energy density of SCES (Supercapacitor ES) and SMES (Superconducting ES), they will not be calculated. Furthermore, FES (Flywheel ES) will not be considered, because of relatively short discharge time. The consumption pattern of the two-tariff energy system for an average apartment shows the required maximum limit of energy storage capacity, 7 kWh. But this amount of energy can be released only with 100% storage discharge. In real conditions the depth of discharge (DoD) of ES should be less than 100% and both system life cycles and the required energy capacity limit will be increased. The new maximum life cycle number of ES can be found from figures shown below.

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**Fig. 2.** Life cycles and depth of discharge of batteries.

Figure 2 depicts curves of different battery types with life cycles dependent on DoD [9]. All curves have trend lines with equations, that allows DoD calculations for any number of cycles.

**Fig. 3.** DoD equation of Li-Ion, NiCd and NaS type of batteries.

**Fig. 4.** DoD equation of LA, ZnBr and VR type of batteries.

Figures 3 and 4 shows the dependence between life cycles and DoD of batteries.

DoD equations can be used in the calculation of constant cycles number, e.g. 10-year usage of ES will give approximately 3650 cycles. Nevertheless, in the case of constant DoD value, the required energy capacity may be different from an initial energy capacity. The simple formula
The analysis was made on the basis of six different types of batteries. In compliance with the consumption pattern for a two-tariff energy measurement system, the most suitable capacity value of ES for households is 7 – 12 kWh and the peak power of about 7 kW. The total cost of different storages varies from 4270$ for ZnBr to 10738$ for NiCd battery ES. Nevertheless, it is not an old product on the market and its cost will be reduced after an increase in the production of competitors. NaS battery storage includes two techniques. The first one is the production of useful energy with transmission through a grid or directly on a consumer’s site. The second technique is to stabilize electricity voltage or system frequency [7]. The main difficulty is that developing companies generally target this technology for utility-scale (>1000 kW) stationary applications. Developments in NaS system solutions for small consumers and apartment houses can bring this type of storages to the residential market.

VII. CONCLUSION

The last column of Table III is the multiplying factor of tariff difference. It shows the need for an increase in current difference price between tariffs for ES recoupment. As we can see none of battery storages are able to return the investment and make profit within current lifetime. It means there are only two opportunities to achieve profitability. First, it can be achieved by reducing the total cost of the energy storage system (cheaper components, cheaper maintenance). This should provide for the return of investment in a limited period of time, i.e. 7 – 10 years. The second method is increasing the lifetime of ES (more cycles, higher efficiency). As a result, an investment can be returned in about 20 – 30 years, before it fails or breaks down.

Table III shows that a Sodium Sulphur (NaS) Battery is a more perspective ES with limited lifetime cycles. It is the most universal type of ES. It has medium energy capacity cost and slightly expensive power capacity cost (up to 500$ /kW). Nevertheless, it is not an old product on the market and its cost will be reduced after an increase in the production of competitors. NaS battery storage includes two techniques. The first one is the production of useful energy with transmission through a grid or directly on a consumer’s site. The second technique is to stabilize electricity voltage or system frequency [7]. The main difficulty is that developing companies generally target this technology for utility-scale (>1000 kW) stationary applications. Developments in NaS system solutions for small consumers and apartment houses can bring this type of storages to the residential market.

VII. CONCLUSION

The analysis was made on the basis of six different types of batteries. In compliance with the consumption pattern for a two-tariff energy measurement system, the most suitable capacity value of ES for households is 7 – 12 kWh and the peak power of about 7 kW. The total cost of different storages varies from 4270$ for ZnBr to 10738$ for NiCd battery ES. Lifetime cycles fluctuate from 100 for LA to 14000 for VR. However, an important aspect to be considered is the depth of the discharge factor characteristic of a battery.
Previous calculations for the two-tariff price based energy system show that every work cycle (charge/discharge) of a storage system enables an economy of 0.42$. Nevertheless, due to the total price of energy storage, the cheapest work cycle cost is 0.56$ (Table III). Today it means that there is no ES solution for a household that would return total initial investments and make a profit in a lifetime period. With current battery lifetimes and current DoDs, battery storages will bring profit only with the difference growing between tariff prices of the electrical grid by 1.3 for NaS as a minimum and by 28.8 for LA as a maximum one.

Adequate cycle numbers from Table III highlight the NaS energy storage system as a leader for battery ES payback and profitability. Everyday work of a NaS battery with 50 % DoD should return an investment if technology developments amplify battery lifetime period by 1.32 times or price difference between high and low tariff will increase.

All calculations made with the two-tariff system will be continued for NPS price based system. According to EE area NPS costs, NaS batteries can be profitable too. Nevertheless, this open energy market system needs additional investigations. Calculations for large commercial and industrial objects are also required.

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REFERENCES