LAPPEENRANTA UNIVERSITY OF TECHNOLOGY

Faculty of Technology

Department of Electrical Engineering

APPLY OF ENERGY STORAGES IN ELECTRICITY DISTRIBUTION NETWORKS AND RESERVE CAPACITY APPLICATIONS

Master's thesis

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Supervisor: Professor, D.Sc. Jarmo Partanen

Instructor: Assistant, Jukka Lassila

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Author Iaroslav Boiko

ABSTRACT

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Iaroslav Boiko

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Keywords: Battery energy storage systems, Li-ion batteries, savings from outage costs, savings from peak cutting, storage costs.

The Thesis is dedicated to development of an operative tool to support decision making of battery energy storages implementation in distribution networks. The basics of various battery technologies, their perspectives and challenges are represented in the Thesis. Mathematical equations that describe economic effect from battery energy storage installation are offered. The main factors that influence profitability of battery settings have been explored and mathematically defined. Mathematical model and principal trends of battery storage profitability under an impact of the major factors are determined. The meaning of annual net value was introduced to show the difference between savings and required costs. The model gives a clear vision for dependencies between annual net value and main factors. Proposals for optimal network and battery characteristics are suggested.

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Iaroslav Boiko

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DC	Direct current
AC	Alternating current
PSH	Pumped storage hydroelectric
CAES	Compressed air energy storage
BESS	Battery energy storage system
EU	European Union
Li-ion	Lithium-ion
NaS	Sodium-Sulfur
ZnBr	Zinc-Bromine
DSO	Distribution system operator
TSO	Transmission system operator
EV	Electric vehicle

1. INTRODUCTION

Energy Storage Systems mostly based on lithium-ion and other types of battery technologies nowadays starting to play an important role in distribution networks along the world, e.g. short term power management and peak shaving. It can be declared that benefits of battery storage depend on type of the customer and its characteristics (value and duration of peak power, availability of solar, wind generation, etc.). Benefits of battery storage installation can be compared with outage costs, savings from peak shaving and ability to store electricity produced from solar panels, wind turbines for further sale to the grid during peak hours. Battery storage supports distribution system keeping stability in fault conditions and even to avert new investments or reinforcements into the grid. Industrial and domestic customers can profit from peak shaving, better quality of electricity supply and opportunity to sell their surplus energy to the grid on profitable terms.

In this paper various cases of peak shaving and short term power management amid industrial and domestic customers were regarded. Three main criteria were assumed as basic ones: savings from outage costs and from peak shaving and investment costs. The mathematical model was presented by assembling three major parameters (savings from outage costs, savings from peak cutting and investment costs). However, as it become seen from the model a lot of obscurities exist and for that purpose assumptions were implemented. Ergo, certain network type and power load curve were assumed as basic data. Firstly, the lengths of lines and average powers were defined and then used as initial information. Secondly, daily utilization time of the battery was set up at 2 hours and the amount of cycles of the BESS established at 100 cycles per year. Finally, network was supposed to contain either domestic customers only or 100% of industry. It was done to simplify calculations, besides better insight can be achieved while looking to the graphs; real situation is to be between boundaries of industrial and domestic curves. It should be also mentioned that savings from outage costs are not equal to factual outage costs because real powers are not considered in this paper but power difference is regarded. Power difference can present battery power and that fact might simplify calculations. It should be also noted that batteries are supposed to be mounted in distributive manner in the grid that means batteries are installed in each line of the network proportionally to the average powers.

The main goal of this paper is to present the economic effect of BESS implementation. So, for this purpose the net value was introduced, it shows the difference between savings from outage costs and from peak cutting and investment costs. Other words, net value is the difference between savings and expenses under battery implementation. When net value is positive it can be said about profitability of BESS, otherwise when net value is below zero installation of battery storages is disadvantageous. It should be also noticed that calculations for future periods were made and the results were compared with current outputs. It was done to show the trend and to try predict how BESS can be improved. Moreover, representatives from business were asked about BESS implementation, its perspectives, advantages and obstacles. Two DSO companies (Caruna, Finland and Western Power Distribution, UK) were interviewed about battery storages technology. Surprisingly, their visions and opinions about current situation and future perspectives differ significantly. Thus, Finnish company reckons that government should stimulate BESS implementation in the grids whilst English company thinks about BESS as an incentive for creating capacity market in UK. Besides, Caruna awaits of fast growing of battery storages in near future but there are no such expectations in Western Power Distribution. However, both companies noted the same obstacles and plans of using BESS. So, extremely high prices for batteries and obscurities with payments for BESS were declared. Moreover, both companies complain to lack of regulation and legislative barrier that consider BESS as generation, thus according to EU laws DSOs are not allowed to own any generation settings.

As the result of this paper optimal conditions of required battery storage characteristics were established. Crucial parameters that can affect the profitability of BESS installation were detected. The major ones are battery power capacity, battery prices and type of the customers. Besides, the length of lines, rates of switching and repair time, interest rate and payback period might influence significantly final results.

2. OVERVIEW OF BATTERY STORAGES, APPLICATIONS, TECHNOLOGIES AND PROGNOSIS

2.1 Different energy storage technologies

Energy storage can be an important part of distribution network. Nowadays a lot of various energy storage systems exist, depending on size, lifespan and type of application. Some of these applications can be used for load leveling, peak shaving or as backup reserves. In terms of battery storage utilization duration they can be classified into short term and long term applications. Short term applications find their place in improvement of system stability and frequency in the grid when it is needed. Long term storage systems can find their place for load leveling, peak shaving and renewables integration. In this paper long term application of BESS is considered.

There are diverse battery technologies for their utilization in large scale application. Applications for BESS locally installation for industrial customers and for grid interconnections are existed today. Currently there are two major types of batteries are investigated in power systems: cell (Lithium Ion, Sodium Sulfur, Lead Acid) and flow (Zinc Bromine, Vanadium Redox Battery) batteries. Both types have the same integration concept, the batteries are connected to power system through Direct current (DC) to Alternating current (AC) interface and transformer. The inverter converts the DC voltage of the battery to AC voltage that is connected to the grid via transformer (Adam R. Sparacino et al., 2012).

2.1.1 Lead-Acid batteries

The lead-acid battery was invented in the middle of 1800s and is known as the oldest type of rechargeable battery. They become most commonly used thanks to their ability to supply high surge currents. These characteristics and their low costs made lead-acid batteries attractive for using in motor vehicles, because automobile starters are required high currents. This type of batteries has a non-linear power output and their lifetime depend highly on charging/discharging rate, utilization and the number of deep discharging cycles. Lead-acid battery sales considered a half of the total battery sold worldwide and their prices hang upon the lead prices. The batteries historically are used as a backup sources and for power quality management (Adam R. Sparacino et al., 2012).

The working principle is based on electrochemical reactions of the lead and lead dioxide in the aqueous solution of sulfuric acid. During discharge recovery of lead dioxide occurs on the anode and the lead oxidation on the cathode. During the charge reaction flows back. When recharging the battery the electrolysis of water starts, after lead sulfate exhausting, wherein oxygen is emitted on the anode and hydrogen on the cathode.

Nowadays innovative materials and technologies are used to better life cycle and other exploitation characteristics. Some of these modernized batteries were created especially for transmission and distribution networks (D. Rastler, 2010).

While battery discharging sulfuric acid is spent from the electrolyte and the electrolyte density decreases as the concentration of the acid solution is reduced. Whereas charging the electrolyte density increases when sulfuric acid is emitted in the electrolyte solution. At the end of charge, when the amount of lead sulfate on the electrodes decreases below a certain critical value the process of water electrolysis begins. Hydrogen and oxygen are extracted from the electrolyte in the form of bubbles - the so-called "boiling" overcharge. This undesirable phenomenon while charging cycle, if possible, should be avoided, because of significant water consumption and the concentration and density of the electrolyte increase.

2.1.2 Lithium Ion batteries

Lithium-Ion battery – the type of electric battery which is widespread in modern consumer electronics and used as a backup device in electric vehicles and energy storage in power systems. The working principle of lithium-ion battery is the movement of lithium ions between anode and cathode producing a flow of current as the result of this displacement. First lithium-ion battery was successfully commercialized in 1991 by Sony Co. (Energy Storage Association, 2015). There are many configurations of lithium-ion batteries, different materials are used as positive electrodes and electrolytes. Major battery parameters, such as the voltage, energy density, lifespan and safety of lithium-ion battery can be changed dramatically depending on materials been used. Lithium-ion batteries are more expensive than the other types examined in this paper, however operate in wider temperature span and have greater energy density (Adam R. Sparacino et al., 2012).

Lithium – a light metal, it is twice lighter than water. Simultaneously, lithium has great electrochemical potential, which makes it one of the most active metals. This feature allows to create lithium-ion batteries with a high energy density, minimal size and weight. The other advantage of lithium-ion batteries is extremely low (comparing with other types of batteries) self-discharge current. This means the lithium-ion battery can keep charge while device is switched off for years longer than alkaline batteries. For electronics, this means that the batteries do not have to be periodically recharged, or have to do it much less (Antti Väyrynen et al., 2011). The main disadvantage of lithium-ion batteries is their relatively high costs, however the price dynamics is promising and some years later lithium-ion batteries will be competitive (EnergyTrend, 2015). According to McKinsey&Company, lithium-ion battery pack price could fall down by three times by 2020 (Russell Hensley, 2012).

Li-ion batteries are one of the fastest growing markets among the other types of battery energy storages. According to the U.S. Department of Energy, installed capacity of the lithium-ion batteries, used by transmission and distribution operators in United States is 54 MW (Adam R. Sparacino et al., 2012).

2.1.3 Sodium-Sulfur batteries

Sodium-sulfur battery is a secondary chemical current source, wherein the material of the negative electrode is molten sodium, the positive electrode is sodium sulfide solid and the electrolyte is a beta-alumina containing aluminum and sodium oxides. This battery operated at the temperature of about 300 degrees and has a high specific energy and power, and require special security measures. The main advantage of Sodium-Sulfur battery is its high specific energy: theoretical energy capacity is about 800 Wh/kg. It is almost an order of magnitude more capacious than the now widely used lead-acid batteries, and three times - the lithium-ion, which are currently at the peak of successful development. Sodium-Sulfur battery operates only at high temperatures of its components - the liquid anode and cathode. Since they are the sodium and sulfur, the elements need to be heated at the beginning of operation. However, the heating has to be significantly higher than their melting point, since this requires yet another important element of the design - the ceramic partition between the two molten components.

The high operating temperature is the danger of sodium ignition in the case of accident. A ceramic baffle plate serves as a filter which is at a temperature of 300-350 degrees skips sodium ions towards the cathode sulfur. Whereas sodium atoms cannot pass into the container with sulfur, as sulfur atoms and ions cannot penetrate into the volume occupied by the liquid sodium. Later during operating the temperature of the battery is kept by the warm from Sodium-Sulfur battery itself. Temperature resistant materials (e.g. asbestos) can be used for temperature preserving purposes. (Adam R. Sparacino et al., 2012).

Sodium-Sulfur batteries can find an application in different areas such as renewable integration, peak shaving, short term power management and reserve power. NaS batteries are also one of the most commercially successful and mature technologies. Moreover, there are a lot of working NaS battery systems in the world: Bob (big-old battery) in Presido, Texas, USA is one of the biggest with power of 4 MW and total cost twice lower than building a new line (Jeremy Hsu, 2010).

2.1.4 Zinc-Bromine batteries

Zinc-Bromine battery is the type of battery, where zinc is used as anode and bromine as cathode. Total energy storage capacity of that battery type depends on electrode area and electrolyte storage sizes. It is noticeable that anode electrolyte is water-based and organic amine compound is contained in the positive electrolyte to hold bromine in solute.While charging zinc is recovered on the zinc electrode in the form of dense nonporous sediment. Bromide ions are oxidized to elemental bromine on the opposite electrode. While discharging zinc oxidation and bromine recovery to bromine ions occur (Energy Storage Association, 2015).

The separation of positive and negative electrodes is extremely important issue in Zinc-Bromine battery. For this purpose porous separators, ion exchange membrane and gel electrolytes can be used. However, the most complicated methods of separation can reduce the loss of capacity only up to 50% in 50 hours of storage. There are some proposals to keep bromine separately in the insulated tanks and supply positive electrode with bromine while battery discharging.

There are several applications of Zinc-Bromine battery in the world. One of them was built by ZBB Energy, 50 kWh modules were made out of three parallel connected 60 battery packs. The life time of the batteries is expected about 2500 cycles. There are some advantages of Zinc-Bromine battery: higher energy density comparing with lead-acid ones, 100% depth of discharge capability. Besides, Zinc-Bromine batteries are more environmental friendly comparing with lead-acid batteries because of the lower content of toxic electrolytes. However, that type of batteries requires more researches and improvements. Zinc-bromine batteries have just a few working installations in the world. (Adam R. Sparacino et al., 2012).

2.2 Battery storage applications and prognosis

Nowadays renewable energy sources are more and more used in energy sector worldwide. In 2013, about 21% of global energy consumption was met from renewable energy sources with total installed capacity about 500 GW. However, wind and solar energy are interruptible and impermanent types of energy sources. Thus, measures for uninterruptible power supply are needed and one of them can be battery energy storage systems (BESS).

2.2.1 Pilot installations and economical aspects

Actually, storing energy in the network is not a new idea, several projects have been created and implemented since 1970s. Presently electricity is stored in different methods, such as pumped storage hydroelectric plants (PSH), compressed air energy storage (CAES) and various battery storage technologies. The main problem of PSH and CAES implementation that they require specified geographical conditions, thus they can not be used in the grid where storage plants need to be utilized. Moreover, PSH and CAES are not fast enough to respond adequately for swift demand changes, so they are not suit for frequency regulation. It can be said BESS is the future of network level energy storage because of two reasons. First is the limitation of areas where PSH and CAES can be build and second – new technologies and success of the BESS. Energy storage systems can provide solutions to: renewable sources integration, peak shaving and load shifting, power quality management, emergency backup power and capital investment savings (Thomas W. Overton, JD., 2014).

There are many battery storage technologies at the moment under various levels of development. These technologies can be classified for maturity from developed and commercialized to demo versions and pilot installations. These technologies include lithium-ion, sodium-sulfur, lead-acid, zinc-bromine, nickel/metal hydride, zinc-air, nickel-cadmium and other types of batteries. Each technology provides unique features and competitiveness comparing with other technologies upon the situation. Some storage technologies are regarded in Table 2.2.1 below (Adam R. Sparacino et al., 2012).

Table 2.1 Comparison of energy storage technologies

Storage technology	**Maturity**	**Power (MW)**	**Capacity (MWh)**	**% Efficiency (total cycles)**	**Total Cost (€/kWh)**	**Self-Discharge**	**Response Time**
PSH	mature	250-530	1680-5300	80-82 (>13 000)	125-325	negligible	min
CAES	commercial	135	1080	60-70	50-150	-	sec
Lead-Acid	commercial	50	300	85-90 (2200)	300	low	ms
Li-ion	commercial	1-100	0.25-25	87-92 (1000-2000)	450	medium	ms
NaS	commercial	2	7.2	75-85 (4500)	280	-	ms
ZnBr	demo	1	5	70-76 (3000)	665	-	ms

Today, a lot of battery energy storage systems have been installed already and operate fairly good. The first wind farm with BESS in the world was established in 2008, in Japan (Rokkasho). A Sodium-Sulfur batteries were used at this plant and the total installed power is 34 MW/245MWh. The batteries are utilized for peak shaving, load shifting, firm capacity and for selling electricity to the market during the high prices (Styczynski Z. A. et al., 2009). Lithium-ion batteries are starting to play important role in renewable integration and power quality management. According to U.S. Department of Energy there are 102 Li-ion battery settings in the world operating or under construction with total energy storage capacity about 175 MWh (Thomas W. Overton, JD., 2014). One of the leaders of BESS implementation and development, United States has a lot of existed battery energy storages, as well as under construction and pilot installations. The greatest Lithium-ion BESS will be installed in 2015, in California at the Tehachapi Wind Resource Area, one of the largest wind farms in the world. The Tehachapi BESS will test 32 MWh

(8MWx4hours) li-ion batteries and it will help to store energy from nearly 5000 wind turbines (U.S. Department of Energy, 2012). Nowadays, a lot of Lithium-ion battery energy storages operate perfectly, though they are pilot installations and technologies are not mature enough. Currently, Sodium-Sulfur batteries are the most mature and commercially successful technology. However, the Li-ion battery prices tend to decrease significantly over next decades and they can rival with present prosperous technologies.

2.2.2 Scenarios for renewable generation and storage capacity

Production of renewable energy, especially from wind and sun, increased mainly over the past 10 years. In 2013, with the exception of large hydroelectric power stations installed around the world capacity based on renewable sources is estimated at 560 GW (Christine Lins, 2014). They are mainly installed in Europe, North America and Asia-Pacific region. European Union (EU) will continue supporting the production of energy from renewable sources because of the problems of climate change and energy security. One of the targets is to increase generation from renewable sources to 20% of the energy in the EU mix in 2020. Also other countries such as USA and Canada are going to increase the production from renewable sources in the coming decades (Styczynski Z. A. et al., 2009).

Nowadays, a lot of storage technologies existed and in the process of development. Some of them are already mature and commercial successful, but some are just pilot projects and demonstrations. According to various prognosis Li-ion BESS will be the most attractive technology in the future. Table 2.2.2 summarizes the states of current storage technologies.

Table 2.2 The state of storage technologies (U.S. Department of Energy, 2013)

Technology	Primary Application	What we know currently	Challenges
PSH	· Energy management · Backup and seasonal reserves · Regulation service also available through variable speed pumps	· Developed and mature technology · Very high ramp rate · Currently most cost effective form of storage	· Geographically limited · Plant site · Environmental impacts · High overall project cost

CAES	· Energy management · Backup and seasonal reserves · Renewable integration	· Better ramp rates than gas turbine plants · Established technology in operation since the 1970's	· Geographically limited · Environmental impacts · Lower efficiency due to roundtrip conversion · Slower response time than batteries
Advanced Lead-Acid	· Load levelling and regulation · Grid stabilization	· Mature battery technology · Low cost · High recycled content · Good battery life	· Limited depth of discharge · Low energy density · Large footprint · Electrode corrosion limits useful life
NaS	· Power quality · Congestion relief · Renewable integration	· High energy density · Long discharge cycles · Swift response · Long life · Good scaling potential	· Operating temperature required between 250 and 300 C · Liquid containment issues
Li-ion	· Power quality · Frequency regulation	· High energy density · Good cycle life · High charge/discharge efficiency	· High production cost-scalability · Intolerance to deep discharges · Sensitive to over temperature, overcharge and internal pressure buildup

In order to design storage capacity specific parameters are needed, such as type of storage, its functionality and investment costs. To assess the overall capacity some kind of universal pattern can be used e.g. reservoir model and take specific storage parameters, such as charge/discharge efficiency, depth of charge/discharge and discharging gradients. Taking these parameters into consideration, storage capacity for various scenarios can be calculated.

For example, storage systems might be replaced by new power lines and vice versa, while scarcity of network transfer capacity more and more BESS need to be installed. Thus, economic benefits of battery storage implementation in the networks depend on many reasons: the investment strategy of transmission and distribution companies, the cost of batteries and storage expenses, the development of renewable sources. Nevertheless, some prognosis might be done now; EU energy policy aims to increase the renewables share in total electricity consumption and costs of the batteries are predicted reducing significantly (Russell Hensley, 2012).

3. MATHEMATICAL MODEL FOR BATTERY SELECTION

Formulation of the mathematical model for battery energy storage systems is a crucial part of this paper. Energy storages have a potential to increase the security of supply of the distribution network. They can provide electricity during outages and balance the grid during normal operation. The use of BESS might minimize the outage costs and better the quality of power supply. The other economic advantage of BESS realization is concluded in money savings from peak shaving and load shifting. DSOs can reduce their costs by installation conductors with lower cross-section. However, besides the positive economic and technical aspects there are some surplus expenditures such as investment or storage costs. The purpose of this paper is to assemble all the criteria and to evaluate the economic effect of BESS installation.

A mathematical model of the object has been developed for certain network type where reserve supply can be used in fault cases from all the edges of grid. Mostly, that supposition impacts the value of outage costs and real situation can be different. It should be noted that a lot of assumptions are needed to evaluate economic effect from battery implementation because there are too many uncertainties. All the assumptions made in this paper are considered below.

Three main parameters have been taken into account: the value of outage costs, savings from peak shaving and investment costs. Savings from peak shaving can be achieved by installation cables with lower cross-section and then it is economy in metal (copper or aluminum usually). Investment costs are truly always a significant part of the total expenditures. Since distribution companies do not possess huge amount of cash liquidity they use loan capital. Thus, interest rate and payoff time should be taken into account while investment costs being estimated. To execute peak shaving and to benefit from outage costs savings we need to store electricity in batteries. The outage costs consist of expenditures from non-supplying during the repair time and supplying interruption expenses while switching time. It can be said that the value of outage cost depends on total length of the grid, network configuration and the amount of consumed power in considered area. The value of outage cost can be derived from equation (3.1).

$$C_{out} = \lambda \cdot \sum(l_n \cdot P_n) \cdot \left(C_{fp} + C_{fe} \cdot t_{rep} + C_{pp} + C_{pe} \cdot t_{rep}\right) + \lambda \cdot \sum_{n=1}^{m}[(l - l_n) \cdot (P - P_n)] \cdot (C_{fp} + C_{fe} \cdot t_{sw} + C_{pp} + C_{pe} \cdot t_{sw}) \quad (3.1)$$

where

λ	= fault rates per kilometer of the line per year
l	= the total length of lines
l_n	= the length of the line where fault occurred
P	= average power in the chosen part of network
P_n	= average power in the line where fault occurred
C_{fp}	= outage cost per kW in case of fault interruption
C_{fe}	= outage cost per kWh in case of fault interruption
C_{pp}	= outage cost per kW in case of planned interruption
C_{pe}	= outage cost per kWh in case of planned interruption
t_{rep}	= repair time, needed for fault elimination
t_{sw}	= switching time, needed for separating the fault
m	= the number of lines in the network

As it can be seen from equation (3.1) too many variables are regarded in formula. Thus, to avoid uncertainties given configuration of network with lengths and average powers is considered. The configuration of network, lengths and average powers can be found on Fig.3.1. It can also be seen that the network has reserve supplying from all the edges. This assumption was made to simplify outage costs calculations and obtain truly results. Furthermore, savings from outage costs are considered in this paper thus, second part of the equation (3.1) is calculated only. Whilst the fault is occurred in certain line there are no possibilities to deliver electricity by this line even we have BESS connected to the line.

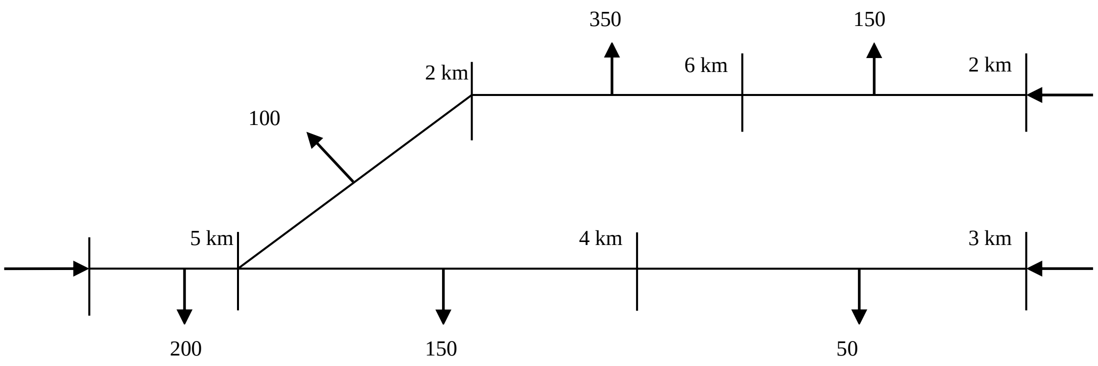

Fig. 3.1 Configuration of the network

Average powers and lengths are demonstrated on figure 3.1. The total average power of network is 1000 kW and the length is 22 km. It should be noticed that the powers and lengths will be increased proportionally in further calculations.

Savings from peak shaving for distribution companies might be achieved by investment costs reducing. That means distribution company may benefit from load shifting by installation cables or wires with lower cross-section. However, there are a lot of uncertainties related to load shifting and peak shaving. The value of savings from peak shaving depends on how much we can reduce peak power and retrench on wires. It can be added that definite load profile is needed to avoid obscurities. The load profile with various levels of battery level (i.e. the value of peak shaved power) can be found on Fig.3.2.

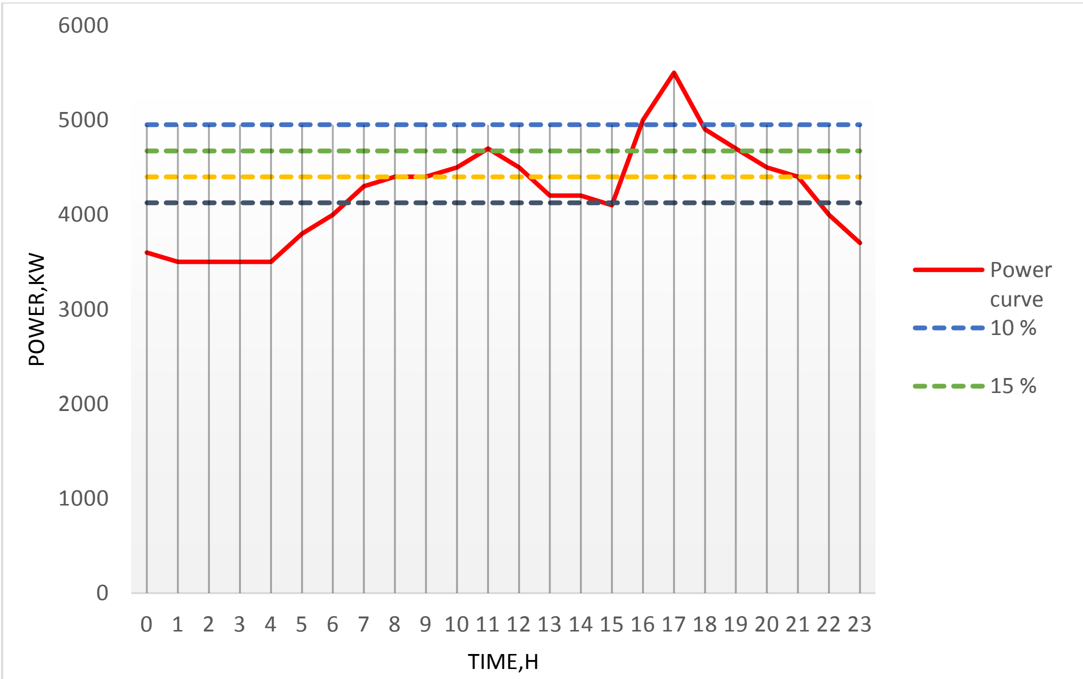

Fig.3.2 Load profile and peak shaving levels

To calculate the savings from peak shaving the cross section values of cables and current levels are needed. The value of current can be found from equation (3.2) and the value of cable/wire cross section is defined from equation (3.3)

$$I = \frac{P}{\sqrt{3} \cdot U \cdot cos\varphi} \tag{3.2}$$

P = peak power

U = voltage of the network

cosφ = power factor

$$s = \frac{I}{j} \tag{3.3}$$

j = the economic density of current

After calculation of the cross section value it is needed to select next standard cross section value ($s_{st} \geq s$). It can be assumed that insulation costs might be neglected because their proportion in total price of cable is low and metal part is taken into account only in this paper. Costs of copper of the line can be determined from equation (3.4)

$$S_1 = s_{st} \cdot l \cdot C_{cop} \tag{3.4}$$

s_{st} = next standard cable or wire cross section

C_{cop} = the price of copper, eur/mm^2

To evaluate the savings of peak power shifting we need to subtract the value of shifted power. Thus, it is necessary to recalculate the value of cross section of the line – equation (3.5). The value of savings from load shifting can be derived from equations (3.6) and (3.7).

$$s = \frac{P - \Delta P}{\sqrt{3} \cdot U \cdot cos\varphi \cdot j} \tag{3.5}$$

$$S_{sav} = (s_{st1} - s_{st2}) \cdot l \cdot C_{cop} \tag{3.6}$$

$$S_{sav} = \frac{\Delta P}{\sqrt{3} \cdot U \cdot cos\varphi \cdot j} \cdot l \cdot C_{cop} \tag{3.7}$$

s_{st1} = standard conductor cross section before peak shaving

s_{st2} = standard conductor cross section after peak shaving

According to equation (3.7) savings from peak shaving depend on shifted power (the same value as the power of BESS), length of lines and copper prices. Voltage level and power factor are assumed to be constant, because these parameters cannot be easily altered.

Investment costs are truly always a significant part of the total expenditures. Since distribution companies do not possess huge amount of cash liquidity they use loan capital. Thus, interest rate and payoff time should be taken into account while investment costs being estimated. Annual investment costs can be found from equation (3.9). The formula of annuity coefficient is presented on equation (3.8).

$$\varepsilon = \frac{\frac{p}{100}}{1-(1+\frac{1}{\frac{p}{100}})^{t}} \quad (3.8)$$

p = interest rate

t = investment lifetime in years

$$S_{inv} = C_{bat} \cdot P \cdot \varepsilon \cdot t_b \quad (3.9)$$

C_{bat} = battery cost per kWh

t_b = average time of battery utilization per day

Investment costs depend on interest rate, payoff period, daily time of battery usage and battery prices per unit. Of course, power also affects these expenditures significantly, however decreasing the amount of power will reflect the reducing of outage costs and savings from peak shaving. Thus, declining of the installed power is not the right way for cost savings.

To execute peak shaving and to benefit from outage costs savings we need to store electricity in batteries. However, it is not uncostly, moreover energy storage prices are much higher than the price of electricity production. The value of storage costs can clearly show the effect of battery storages, because it presents the price of stored electricity per kWh and easily might be compared with electricity prices on spot markets. To find storage cost total energy of the battery and battery capacity (daily BESS energy) are needed, they can be derived from equations (3.10, 3.11). Storage costs can be detected from equation (3.12)

$$W_{bat} = P \cdot t_b \quad (3.10)$$

$$W_{total} = P \cdot t_b \cdot n \quad (3.11)$$

$$C_{st} = \frac{W_{bat} \cdot C_{bat}}{W_{total}} \quad (3.12)$$

n = the amount of battery cycles per year

Storage costs depend proportionally on amount of cycles of the battery per year and battery price per kWh. It can be said that currently the storage costs per kWh are higher than the price of generated power and there are two ways of storage costs reduction: battery price decreasing or rising up lifespan of the battery.

Committing the investment decision all above mentioned parameters should be taken into account. If the sum of outage costs and savings from peak shaving is larger than the sum of investment the installation of BESS is profitable and recommended. Otherwise, when investment exceed the possible economic effect from batteries implementation, improvements and reinforcements in the grids are preferable. The condition of BESS profitability can be derived from inequality (3.13).

$$C_{out} + S_{sav} > S_{inv} \quad (3.13)$$

It is better to transform the inequality (3.13) into equation and introduce the net value. Net value is the difference between savings from BESS usage and storage, investment costs. Net value can be found from equation (3.14).

$$S_{nv} = C_{out} + S_{sav} - S_{inv} \quad (3.14)$$

or,

$$S_{nv} = \sum_{n=1}^{m} [(l - l_n) \cdot (P - P_n)] \cdot \lambda \cdot (C_{fp} + C_{fe} \cdot t_{sw}) + \frac{\Delta P}{\sqrt{3} \cdot U \cdot cos\varphi \cdot j} \cdot l \cdot C_{cop} -$$
$$- C_{bat} \cdot P \cdot \varepsilon \cdot t_b \quad (3.15)$$

Net value clearly shows the effect of BESS installation. When it is negative the utilization of battery storages is unprofitable, whereas positive Net value demonstrates the advantages of BESS settings. However, it is rather complicated to calculate net value that is why it is solved by parts (each variable is defined in its own chapter) and then all the solutions are assembled together.

3.1 Assumptions

Some assumptions were made for the calculations to avoid obscurities:

- the total energy reserved for peak shaving is used in 100 cycles per year, BESS is utilized in wintertime 1.11 – 31.3 (5 months, 20 days)
- power factor (cosφ) is 0.8
- BESS value is divided for 20 years (payoff time is 20 years)
- service and maintenance costs were neglected
- power losses in BESS and lines with their effects were neglected
- the costs of cables insulation were neglected
- fault rates in case of fault and planned interruptions are equal
- the economic density of current is 3.5 (j=3.5 for copper three phase conductor)
- average powers and lengths are increased proportionally
- the value of fault rates is 0.05 per km, a
- switching time is 0.5 hours
- battery price is 450 euro/kWh at present and 280 euro/kWh in 2030
- the configuration of regarded network is shown on Figure 3.1
- reserve supplying is performed from all the ends of network
- the voltage of considered network is 10 kV

3.2 Estimation of the value of savings from peak shaving

Savings from peak shaving for distribution companies might be achieved by investment costs reducing. That means distribution company may benefit from load shifting by installation cables or wires with lower cross-section. However, nowadays a lot of conductor types exist, thus it is rather complicate to match the benefits and drawbacks. It is easier to calculate the price of copper conductor per mm^2 per one meter, whilst the costs of insulation can be neglected. To estimate the savings from load shifting in practical way next computations were done:

Firstly, we can evaluate the volume of conductor, see equation (3.16) and then it is possible to calculate the mass of conductor (3 phases + neutral phase), see equation (3.17). It can be supposed that our conductor is a cylinder with 1 mm diameter and one meter length.

$$V = \frac{1}{4} \cdot \pi \cdot d^2 \cdot h \tag{3.16}$$

where,

d = the diameter of conductor cross section

h = the length of conductor

$$m = 4 \cdot V \cdot \rho \tag{3.17}$$

ρ = the density of copper

The cost of copper conductor with cross section one square mm and one meter length can be found from equation (3.18).

$$C_{cop} = C_{cop,kg} \cdot m \tag{3.18}$$

$C_{cop,kg}$ = the price of copper per kilogram

The density of copper is 8.96 g/cm^3

According to London Metal Exchange the price of copper is nearly 6 euro per kg

Thus, C_{cop} = 0.17 euro per mm^2 per meter of copper conductor

It can be noticed that six types of load curves are regarded to show savings from peak shaving, these power curves can be found on Fig.3.3. Various load curves are considered to present better vision of peak cutting opportunities. The levels of peak shaving are calculated on relation of peak power for each load curve. Thus, it can be said that absolute value of slashed peak power is various among these load curves whereas relative value of shaved power is permanently the same (10, 15, 20, and 25 %). It can be declared that the deeper the peak shaving level the sleeker the peak form. Thus, the depth of peak slashing mostly impacts on peak shape, whereas peak power influences on the size of battery. The level of peak cutting depth also affects to battery capacity, because of changing the form of peak. However, the effects of load curve type and peak shaving depth are diverse. Impacts of various power curves and peak cutting depth levels can be observed in table (3.6).

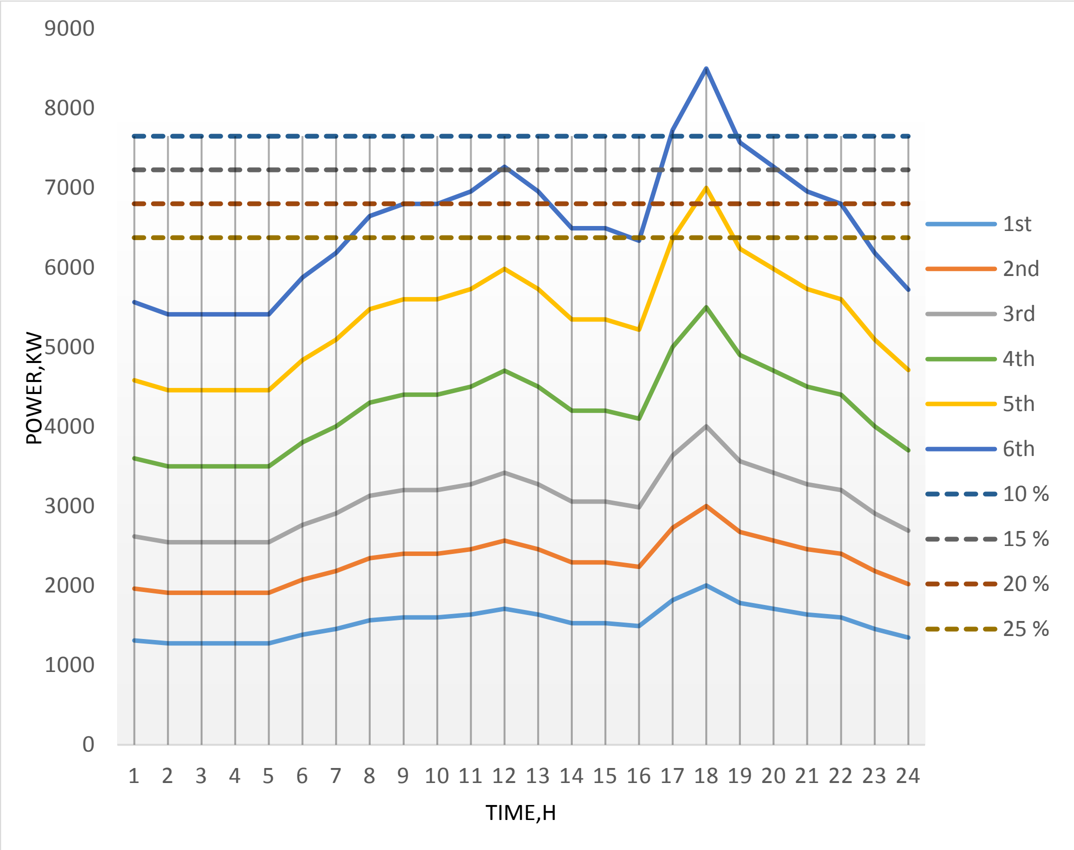

Fig.3.3 Various types of load power curves

Assumptions mentioned in chapter 3.1 are implemented for the calculations of peak cutting savings and network configuration presented on Fig.3.1 is used for further calculations. It should be stated that total length of the network is examined 22 km, as it stated on Fig.3.1 and the length remains stable whatever the load curve or depth of peak cutting are. The effect of slashed peak power configuration can be observed by using formulas (3.2-3.7) in next tables (3.1-3.6). To represent the effect of load shifting four cases of the depth of peak shaving are considered (10%, 15%, 20% and 25%) for each type of load curve. By comparing the results of the depth of peak cutting we can find an optimal peak configuration (sharp or smooth peak). Battery power capacity equals to slashed peak power and shaved peak power can be found as square bounded with load curve and line of peak cutting level. Collating the results for each power curve it is possible to derive an optimal battery size. All of them are compared with primary case, the information of which is shown on table 3.1.

Table 3.1 The prices of conductors before peak shaving

Load curve number	**Peak power**	**Current**	**Cross section**	**Standard cross section**	**Price per km**	**Total price**
	P, kW	I,A	s,mm^2	s_{st}, mm^2	euro	euro
1st	2000	144,337	41,239	50	7 011	154 235
2nd	3000	216,506	61,858	70	10 516	231 353
3rd	4000	288,675	82,478	95	14 021	308 470
4th	5500	396,928	113,408	120	19 279	424 146
5th	7000	505,181	144,337	150	24 537	539 823
6th	8500	613,434	175,267	185	29 795	655 499

The data presented in table 3.1 is used as initial one for comparisons when peak cutting is implemented. Calculations were done according to equations (3.2)-(3.7). However, for definite presentation of peak shaving impact calculated cross sections are used instead of standard ones, equation (3.6). That assumption is done because standard cross sections can be much greater than calculated one and the effect of peak shaving sometimes can be invisible. Standard cross section scale might have long intervals, e.g. 120 mm^2 and next is 150 mm^2, thus for observing a peak cutting significant peak power reduction is needed. Moreover, all the parameters in this paper are equaled to annual values, thus for this purpose the value of annual savings from peak shaving is introduced, it can be found from equation (3.17).

$$S_{sav,a} = S_{sav} \cdot \varepsilon \tag{3.17}$$

According to table 3.2 dependency between battery capacity and annual savings might be perceived however, it is not linear. When battery capacity is increased by four times annual savings rise up only twice, but investment costs are proportional to battery capacity. So, smaller battery installation is more profitable according to given data.

Table 3.2 The prices of conductors and savings after 10% peak shaving

Load curve number	**New peak power**	**New cross section**	**New total price**	**Total savings**	**Battery power capacity, kWh**	**Annual savings**
1st	1800	37,115	138 812	15 424	200	1 345
2nd	2700	55,673	208 217	23 135	300	2 017
3rd	3600	74,230	277 623	30 847	400	2 689
4th	4950	102,067	381 732	42 415	550	3 698
5th	6300	129,903	485 840	53 982	700	4 706
6th	7650	157,743	589 949	65 550	850	5 715

Table 3.3 The prices of conductors and savings after 15% peak shaving

Load curve number	**New peak power**	**New cross section**	**New total price**	**Total savings**	**Battery power capacity, kWh**	**Annual savings**
1st	1700	35,053	131 100	23 135	500	2 017
2nd	2550	52,580	196 650	34 703	750	3 026
3rd	3400	70,106	262 200	46 271	1 000	4 034
4th	4675	96,396	360 524	63 622	1 400	5 547
5th	5950	122,688	458 849	80 973	1 750	7 060
6th	7225	148,977	557 174	98 325	2 125	8 572

Comparing results in table 3.3 the same derivations as for latter table can be observed. Thus, bigger battery capacity setting drives to larger investment costs whilst benefits from peak power savings are nonlinear and cannot cover all the losses related with battery purchasing prices. The comparison of tables 3.2 and 3.3 provides us with important results. When battery capacity for each load curve is grown by 2.5 times annual savings increase slightly (even no more than 1.5 times). Thus, it can be said the deeper peak slashed level is the greater losses are.

Table 3.4 The prices of conductors and savings after 20% peak shaving

Load curve number	**New peak power**	**New cross section**	**New total price**	**Total savings**	**Battery power capacity, kWh**	**Annual savings**
1st	1600	32,991	123 388	30 847	1000	2 689
2nd	2400	49,487	185 082	46 271	1 500	4 034
3rd	3200	65,982	246 776	61 694	2 000	5 379
4th	4400	90,726	339 317	84 829	2 750	7 396
5th	5600	115,470	431 858	107 965	3 500	9 413
6th	6800	140,213	524 399	131 100	4 250	11 430

Table 3.5 The prices of conductors and savings after 25% peak shaving

Load curve number	**New peak power**	**New cross section**	**New total price**	**Total savings**	**Battery power capacity, kWh**	**Annual savings**
1st	1500	30,929	115 676	38 559	2150	3 362
2nd	2250	46,394	173 514	57 838	3325	5 043
3rd	3000	61,858	231 353	77 118	4300	6 723
4th	4125	85,056	318 110	106 037	5900	9 245
5th	5250	108,252	404 867	134 956	7500	11 766
6th	6375	131,450	491 624	163 875	9 100	14 287

According to above stated data the economic efficiency of battery energy storages installation can be observed. All the data are assembled in table 3.6, where economic effect from load shifting can be recognized for each power curve by rows.

Table 3.6 Annual savings from peak shaving

Load curve number		Depth of peak shaving			
		10 %	15 %	20 %	25 %
1st	Battery power capacity, kWh	200	500	1000	2150
	Annual savings, eur	1 345	2 017	2 689	3 362
	Annual Investment costs, eur	7 830	19 575	39 150	84 173
	Total annual savings, eur	**-6 485**	**-17 558**	**-36 461**	**-80 811**
2nd	Battery power capacity, kWh	300	750	1500	3325
	Annual savings, eur	2 017	3 026	4 034	5 043
	Annual Investment costs, eur	11 745	29 363	58 725	130 174
	Total annual savings, eur	**-9 728**	**-26 337**	**-54 691**	**-125 131**
3rd	Battery power capacity, kWh	400	1000	2000	4300
	Annual savings, eur	2 689	4 034	5 379	6 723
	Annual Investment costs, eur	15 660	39 150	78 300	168 345
	Total annual savings, eur	**-12 971**	**-35 116**	**-72 921**	**-161 622**
4th	Battery power capacity, kWh	550	1 400	2 750	5900
	Annual savings, eur	3 698	5 547	7 396	9 245
	Annual Investment costs, eur	21 533	53 831	107 663	230 985
	Total annual savings, eur	**-17 835**	**-48 284**	**-100 267**	**-221 740**
5th	Battery power capacity, kWh	700	1750	3500	7500
	Annual savings, eur	4 706	7 060	9 413	11 766
	Annual Investment costs, eur	27 405	68 513	137 025	293 625
	Total annual savings, eur	**-22 699**	**-61 453**	**-127 612**	**-281 859**
6th	Battery power capacity, kWh	850	2125	4250	9100
	Annual savings, eur	5 715	8 572	11 430	14 287
	Annual Investment costs, eur	33 278	83 194	166 388	356 265
	Total annual savings, eur	**-27 563**	**-74 621**	**-154 958**	**-341 978**

It can be noted that load curves with greater peak power are more sensitive for peak shaving. It can be seen from table 3.6, annual savings for 6th load curve are almost doubled whilst savings for 1st one are increased 1.5 times (comparison for 10% and 25% depth of peak cutting). However, savings from peak shaving are nonlinear, it can be perceived from table 3.6 by collating battery power capacity and annual savings. For clear understanding of the mechanism and impact of peak power cutting investment costs should be regarded. Investment costs are in linear proportion to battery capacity, it can be seen from table 3.6 by comparing annual investment costs and battery power capacity. Therefore, investment costs cross out benefits from peak shaving in most cases, because they rise rapidly with battery capacity and savings from peak slashing lag behind. It can be concluded that installation of smaller battery and shaving sharp peaks are more preferable. Thus, it was proved that savings from peak shaving are in dependence with peak power and peak shaving depth. Fig.3.4 represents dependence between peak power (i.e. load curve type in our case) and annual savings and fig.3.5 clearly demonstrates relation between annual savings and depth of peak saving.

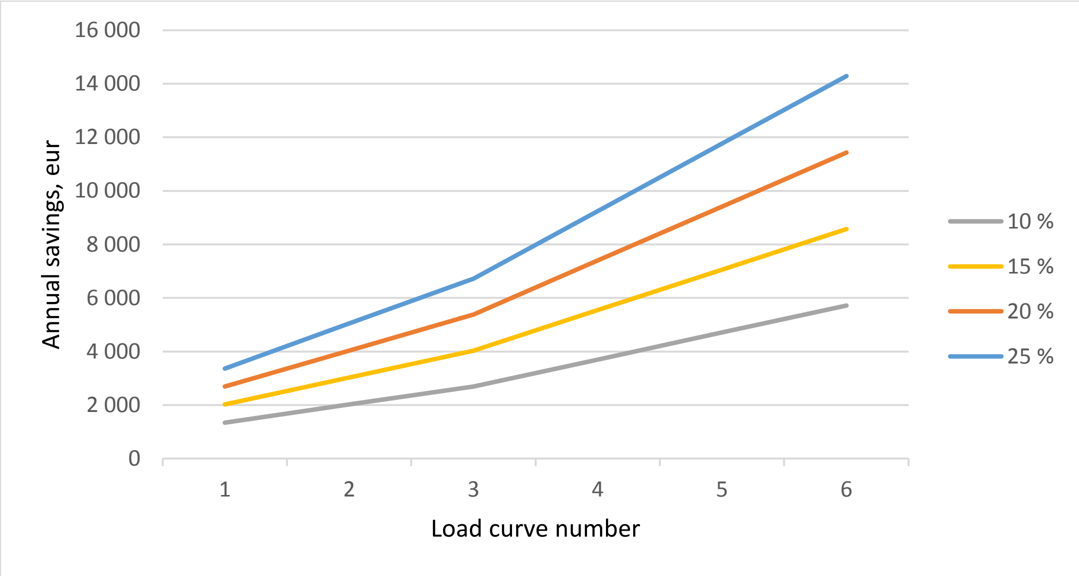

Fig.3.4 Relation between load curve type and annual savings

It is seen that annual savings are proportional to load curve (Fig.3.4) and correlation is nonlinear. Therefore, while rising the peak power battery installed capacity is also increased, thus economic impact is not absolutely clear and other components (investment costs, outage costs) should be taken into account to reveal useful or not battery energy storages. However, there are a lot uncertainties calculating outage costs, that is why they are not considered in this chapter, but the influence of investment costs can be extracted from table 3.6. It should also be added that type of load curve affects more on battery power and the value of peak cutting depth influences more to daily duration of battery utilization. As it was stated above sharp peak configuration is prefer then there is no need for deep peak shaving. Nowadays, battery prices are rather high, thus installation of smaller capacity can significantly reduce losses. Economic effect of BESS installation under various parameters might be observed from Fig.3.5.

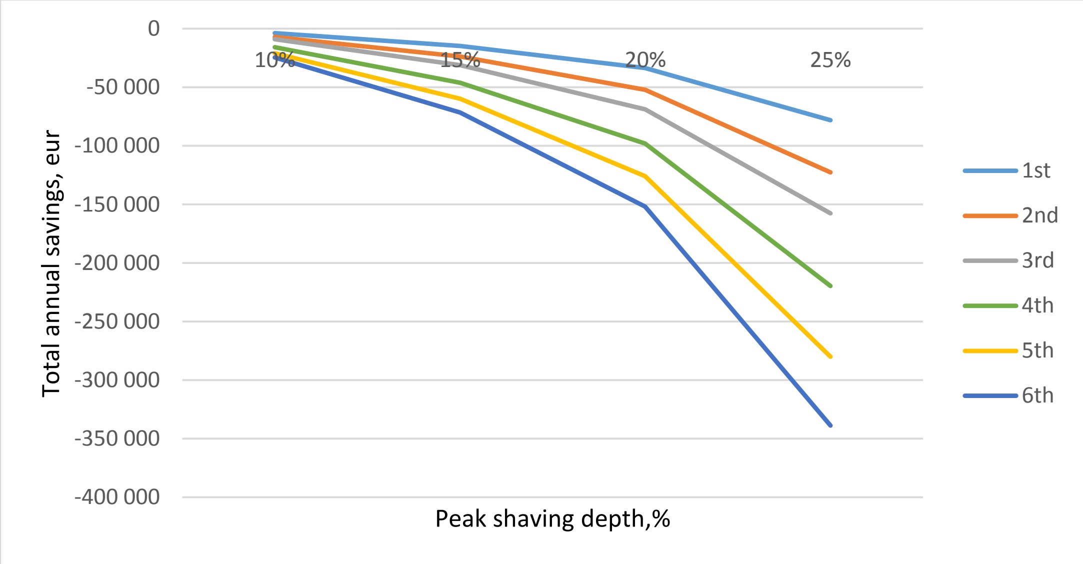

Fig.3.5 Economic effect from peak shaving for different power curves

3.3 Estimation of the value of savings from outage costs

The outage costs consist of expenditures from non-supplying during the repair time and supplying interruption expenses while switching time. According to equation (3.1) it can be said that the value of outage cost depends on total length of the grid, network configuration, customers' type and the amount of consumed power in considered area. Of course, the value of outage costs depends on times needed for fault elimination and switching time, but these values are regulated by energy authorities, thus the impact of switching time changing is theoretical and presented for better understanding in this paper.

The main variables affected significantly to the value of outage costs are: power, repair time, switching time, total length of the lines, customers' type and the configuration of network. However, the values of outage costs per kW and kWh mentioned in formula (3.1) are not still explained. These values differ from one customer type to another and they are mounted for each type of the customer for both fault and planned interruption cases. Outage costs per kW and per kWh by different types of customer are presented on table 3.7, these values are established by the authorities.

Calculating the values of outage costs some initial parameters are required, e.g. repair time, switching time and using time of the battery. According to Finnish regulations average switching time is 0.5 hour and average repair time is 2.5 hours. Average time of battery utilization is considered to be 2 hours per day.

Table 3.7 Outage costs parameters for different electricity consumer groups

Customer type	**Fault interruption**		**Planned interruption**		**High-speed automatic reclosing €/kW**	**Delayed automatic reclosing €/kW**
	A €/kW	B €/kWh	A €/kW	B €/kWh		
Domestic	0.36	4.29	0.19	2.21	0.11	0.48
Industry	3.52	24.45	1.38	11.47	2.19	2.87
Service	2.65	29.89	0.22	22.82	1.31	2.44

It can be noticed that service and industry type of customer is more preferable for BESS installation, because of higher rates for outages in fault and planned interruptions. However, there are no distribution networks with only service customer load. Therefore, it is unrealistic to regard network with 100% of service type customer. Whilst considering network with domestic or industrial customers only is rather possible and proper.

Thus, outage costs for industrial and domestic clients are regarded in this paper and since neither pure industry nor clear domestic grids exist, then these cases can be examined as boundaries. That means practical situation is disposed inside the bounds, thus the effect of BESS installation can be seen. It should be added that under the meaning of outage costs the difference of outage costs is implied and it is simplified for better understanding. It signifies savings from outage costs calculated in this paper, and they are not equal to factual outage costs. We are confident doing it because economic calculations (i.e. savings) are interested for us and there is no necessity for calculation real outage costs. It can be also pointed that battery power and real average power in network are not equal. It follows from the supposition of fact that actual outage costs are not considered, so the powers stated in this paper are the difference of power or battery power. The one chapter where real values of power and battery power capacity are compared is the estimation of savings from peak shaving.

As it can be seen from equation (3.1) finding the value of outage costs is rather complicated deal and a lot of uncertainties occur while calculating. Thus, several assumptions were added to perform calculations of savings from outage costs and build distinct dependencies. It should be noted that the major obscurity is network and its configuration. Network showed on Fig.3.1 and all the parameters presented on it (lines lengths and average powers) are decided to be the pattern for next computations. The second issue is BESS time utilization per day, in this chapter major time is viewed 2 hours. Switching time is 0.5 hours and fault rate is 0.05 per km, a. Finally annuity coefficient is needed to calculate investment costs and then collate them with savings from outage costs. According to equation (3.8) interest rate and payback period are necessary, ergo interest rate is chosen to be 6% and payoff period is 20 years. Battery price is 450 euro per kWh (see chapter 3.1 Assumptions). The important announcement that BESS is considered to being installed distributive along all the lines in given grid. The dependence between outage costs for domestic and industrial customers and battery power capacity is presented on Fig.3.6 and dependency between battery power capacity and total savings (savings from outage costs minus investment costs) can be found on Fig.3.7.

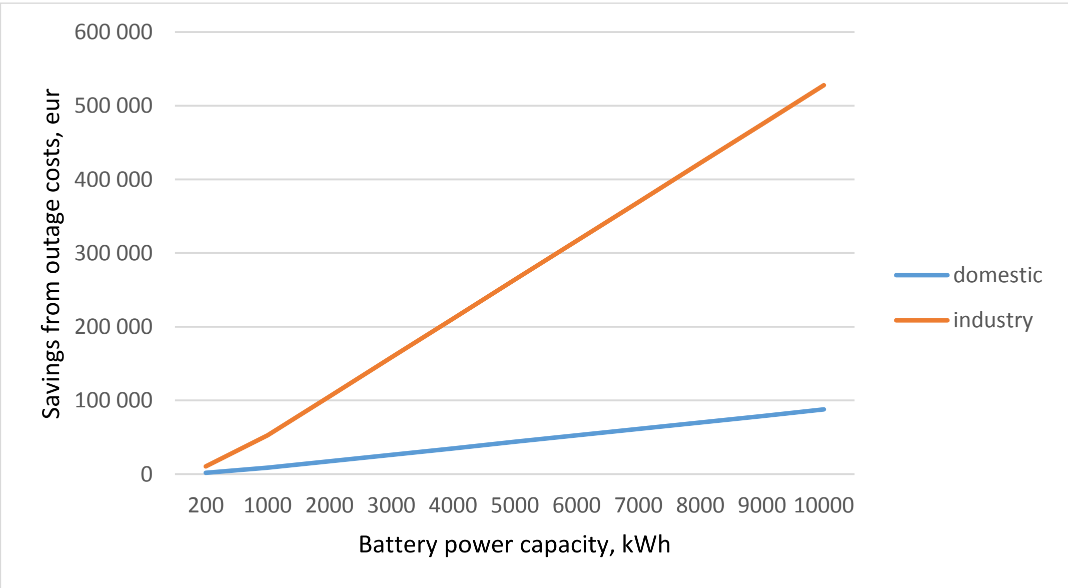

Fig. 3.6 Dependency between savings from outage costs and the battery power capacity (2 hours of BESS utilization per day)

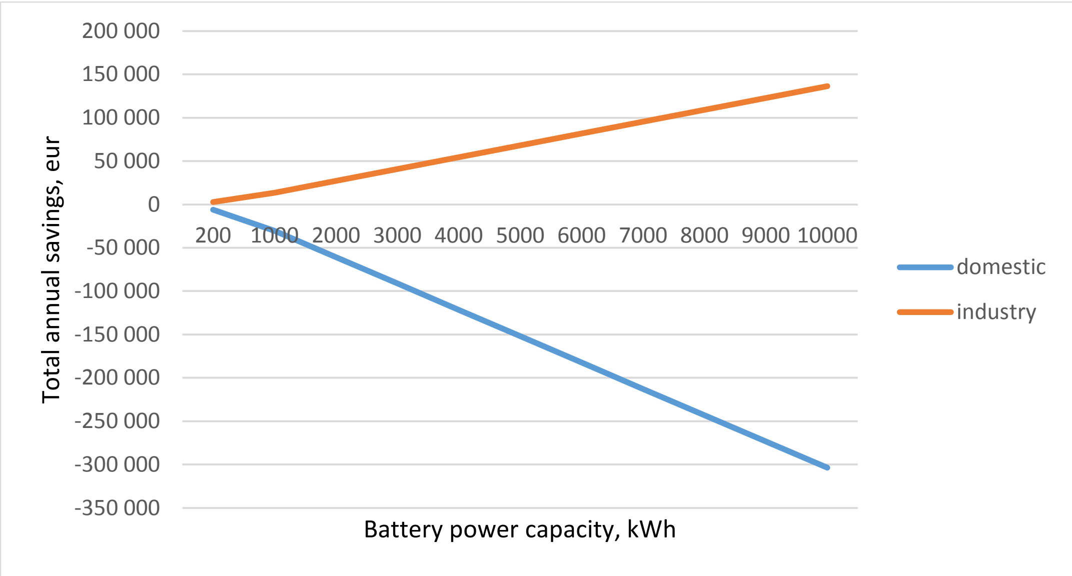

Fig. 3.7 Dependency between total annual savings and the battery power capacity (2 hours of BESS utilization per day)

According to the Fig.3.6 it is clearly seen that outage costs are proportional to the load power. It is definitely represented that industrial customers are more sensitive to power supply interruptions thus, higher outage cost rates are performed for them. Nevertheless, distribution grids are made in a way where domestic and industrial customers are mixed. So, it is not correct to speak about only two forms of networks and being oriented on industry curve. Real situation is situated between domestic and industry curves and that square should be always mentioned. The situation is changed absolutely when investment are taken into account, see Fig.3.7. The curve of domestics varies trend line and unprofitability of battery storages is evidently presented. Industrial customers look better and BESS settings might be recommended for installation in networks with better part of industries. However, curves on Fig.3.7 are not completely correct because daily BESS utilization time is always considered 2 hours. Actually, to keep constant daily use and increase battery power capacity we need to change the load profile. So, Fig.3.7 demonstrates the dependency between battery capacity and annual savings for different power curves.

Moreover, for better vision of advantages and drawbacks of BESS other parameters are considered as variables: switching time and lines length. It can be said that all above mentioned suppositions are examined here, such as network configuration, lengths of lines and average powers. Network showed on Fig.3.1 and all the parameters presented on it (lines lengths and average powers) are decided to be the pattern for next computations. The second issue is BESS time utilization per day, in this chapter major time is viewed 2 hours. Switching time is 0.5 hours and fault rate is 0.05 per km, a. Fig.3.8 and 3.9 are presented for above mentioned parameters and battery capacity 500 kWh. (table 3.6, 4^{th} curve number and 10% peak cutting depth). The dependence of savings from outage costs and switching time can be found from Fig.3.8.

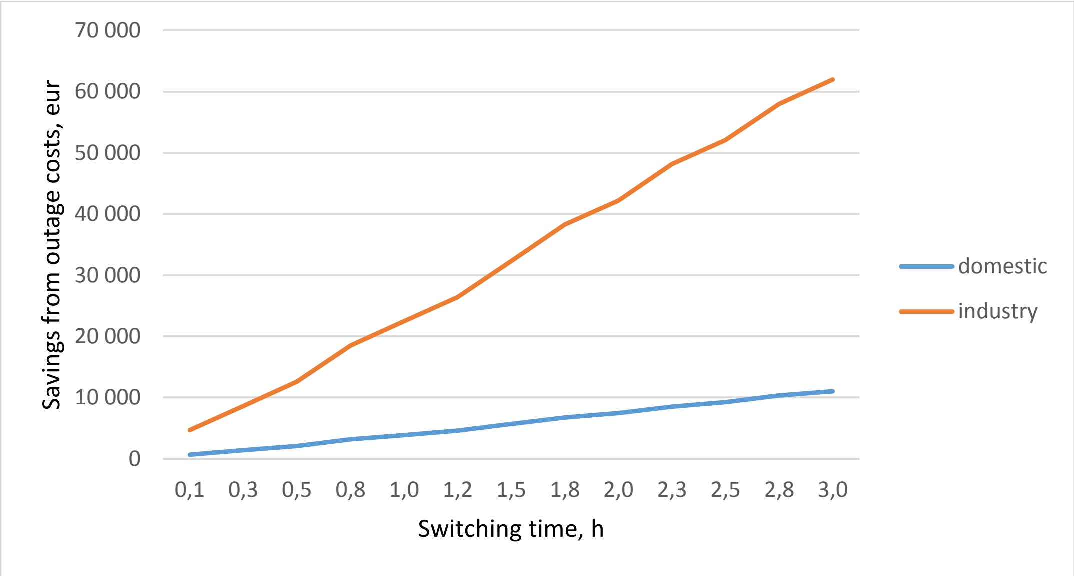

Fig.3.8 Dependency between savings from outage costs and switching time (battery capacity 500 kWh)

According to Fig.3.8 switching time impacts significantly to the value of savings from outage costs. The explanation is next switching time affects to the entire network (except the fault line). Thus, even small growth of switching time can cause great savings from outage costs for distribution companies. It can be declared that switching time plays more important role in network management than repair time. It is partially true because outage costs are not only in dependence with time parameters but also in relation with customer type, average power, network configuration and the total length of grid. It is fairly complicated to show the dependence between savings from outage costs and network configuration, but it is achievable to prove it with total length. It should be said that configuration of grid is not changed but the lengths of lines vary proportionally to original one and all the average powers remain stable as they are presented on Fig.3.1. Relation between savings from outage costs and total length of the network is presented on Fig.3.9.

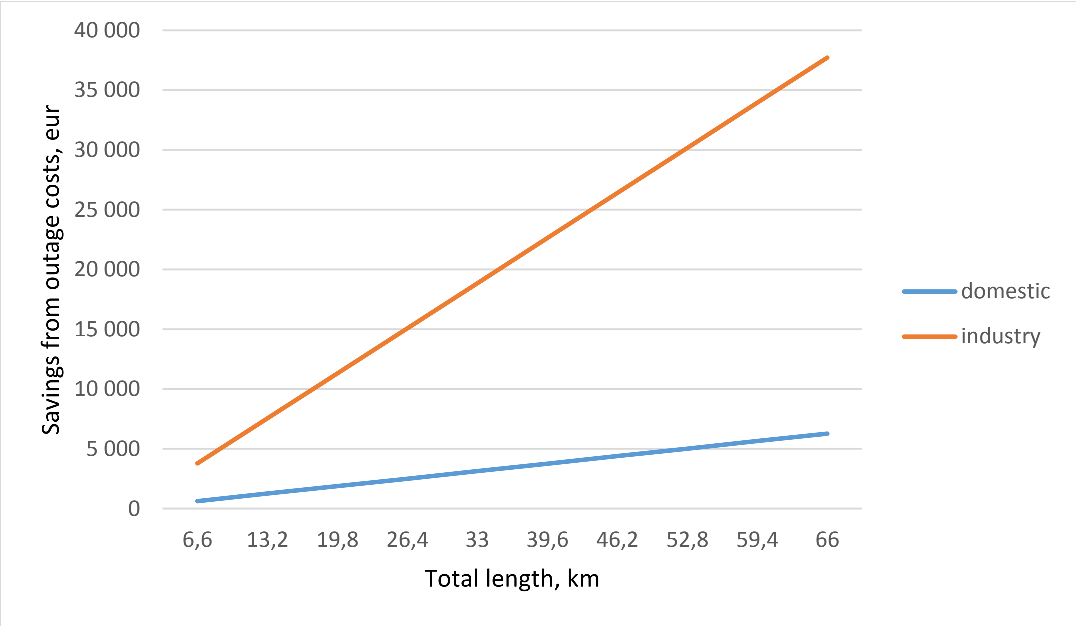

Fig.3.9 Dependency between savings from outage costs and total length (battery capacity 500 kWh)

According to Fig.3.9 the proportional dependence of outage costs and total lines length can be observed. It is definitely represented that industrial customers are more sensitive to power supply interruptions thus, higher outage cost rates are performed for them. It is noticeable that the character of power curves is rather same as presented on Fig.3.6. However, the length of lines have much less impact to savings from outage costs than battery power capacity. Although, savings from outage costs are substantial, regarding investment costs reduce them significantly and they are assumed to be around 20 000 euro for 500 kWh batteries distributed along the network. So, regarding total savings from outage costs (with investment costs) networks with only domestic clients are not profitable whatever the length of grid. Networks with industrial customers become profitable when the length of the grid is about 35 km. However, distribution grids with lengths exceeding 35 km are rareness and generally they are not commonly used. The other issue connecting with length that long distribution lines are used mostly by domestic customers, but they have lower savings from outage costs. Thus, it is a complicated question – what characteristics should be considered as major ones. Nonetheless, some obvious recommendations can be suggested to increase savings from outage costs: the share of industrial customers in network should be greater than domestic ones and the length of lines in grid should be as long as it possible.

3.4 Estimation of the value of investments costs

Investment costs depend on interest rate, the length of study period and battery prices per unit, see equations (3.8, 3.9). Of course, power also affects these expenditures significantly, however decreasing the amount of power will reflect the reducing of outage costs and savings from peak shaving. The impact of battery capacity size was presented in previous chapter, see Fig.3.7. Thus, investment costs influence significantly to final decision of BESS implementation and even can cross out all the benefits from outage costs and peak shaving savings. However, there are a lot of uncertainties and calculations for various battery sizes under different interest rates or payback periods are fairly cumbrous. That is why all the calculations and graphs in this chapter are done for the one variant of battery power capacity (500 kWh), see table 3.6. Network is presented on Fig.3.1 and power curve on Fig.3.2, basic parameters of interest rate is 6% and payback period is 20 years. The other substantial variable of investment costs is battery price; observations of Li-ion prices over last ten years show us remarkable results – prices per unit were reducing rather rapidly. We recognized present price of Li-ion battery at 450 euro per kWh. Nevertheless, it should be declared that battery prices per unit cannot being changed immediately thus, interest rate and the length of study period will affect substantially to annual investment costs. So, the impact of interest rate and payback periods are considered in this chapter. Fig.3.10 represents a relation between interest rate and annual investment costs (Li-ion and NaS batteries) under various payback periods (10, 20 and 30 years). The choice of NaS battery type can be explained by the maturity and innovativeness. So, sodium-sulfur batteries might exemplify well the outlooks and edges of Lithium-ion batteries.

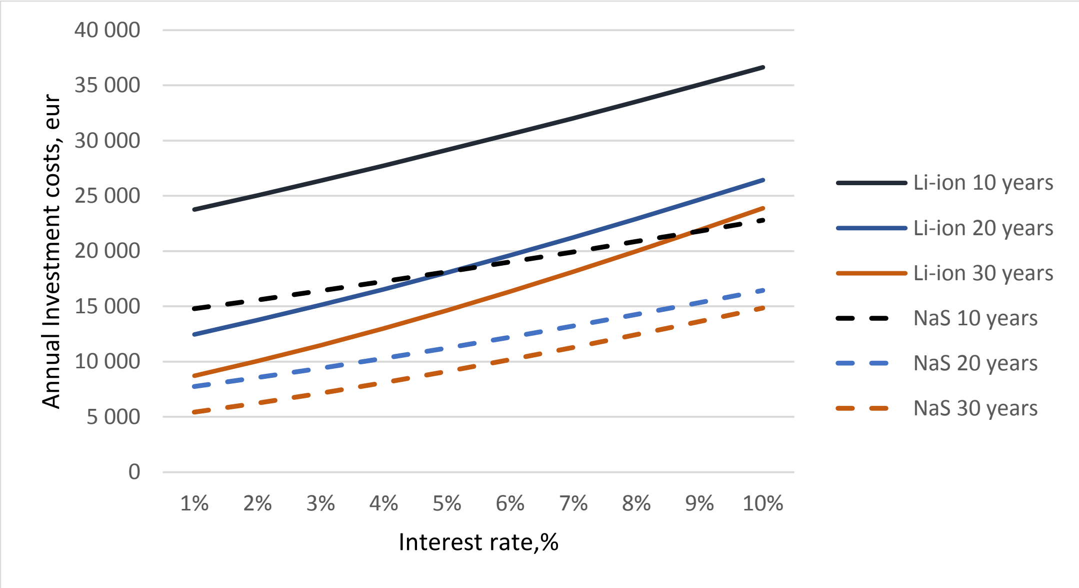

Fig.3.10 Interest rate and annual investment costs relation (battery capacity 500 kWh)

As it could be predicted annual investment costs is in a proportional ratio with interest rate. Sodium-Sulfur batteries have lower annual investment costs because of cheaper battery prices per unit. Moreover, NaS batteries might have shorter payback period, because of lower price per battery unit (see table 2.1). So, price of the battery influence significantly the payoff period, it can be observed from Fig.3.10. It means that installation of Sodium-Sulfur battery with payoff period 10 years can lead to almost the same annual investment costs setting Li-ion type of the battery with 20 or 30 years. Thus, in this case utilization of NaS battery energy storages is more attractive and preferable. It should be noted that annual investment costs with 20 and 30 years payoff time are almost equal whatever the type of the battery thus, it can be reasonable in some cases to decrease payback period. Reducing payoff period can positively reflect to financial statement of the company and help to save money. Payback period affects substantially to the annual investment expenses. It can be stated that the longer payoff period is the lower annual investment expenses are. However, it is not always better to increase payoff period at least payback period should not exceed the lifespan of the battery. Nowadays Li-ion battery lifetime is about 2 000 cycles and it has to be decided how often BESS should be used to minimize losses. On the Fig.3.11 dependency between the length of study period and annual investment costs is demonstrated among Li-ion and NaS battery types.

For better understanding calculations were done under different interest rates (1%, 6% and 10%).

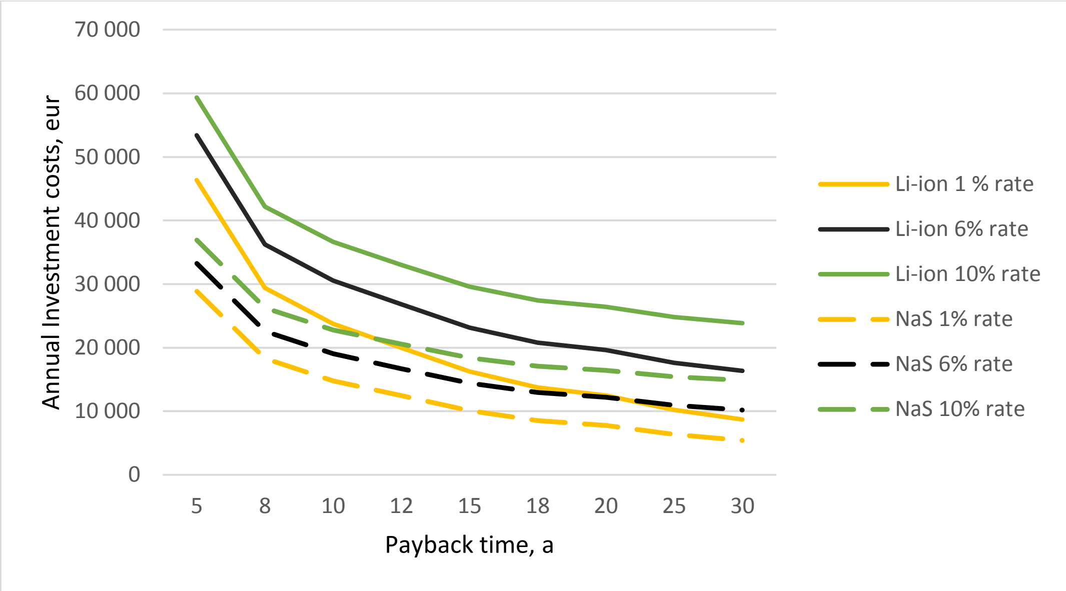

Fig.3.11 Dependency between payback period and annual investment costs (battery capacity 500 kWh)

Whilst interest rate is in direct proportion with annual investment costs, the length of study period is inversely proportional to them. Utilization of NaS batteries provides a client with lower annual investment costs comparing to Li-ion BESS, that is also because of less price per kWh. Despite of seemed supremacy of Sodium-Sulfur batteries under Lithium-ion BESS latter has better working requirements and perspectives. Sodium-Sulfur batteries operate under high temperatures and that causes additional expenditures for fire safety. However, there are still a lot of uncertainties operating Li-ion batteries, because that technology is rather new and under development. Fig.3.11 shows us what payback time we should choose if annual savings are known, annual savings can be compared with annual investment costs and payback time might be selected.

3.5 Estimation of the value of storage costs

Storage costs are needed for better understanding of nature of BESS settings. Storage costs can be found from equation (3.12) and they present how much money spent for storage one kWh of electricity. Thus, the value of storage cost can be easily compared with current electricity prices and the primary conclusion might be done immediately. According to equation (3.12) storage costs depend proportionally on power, the amount of cycles of the battery per year and battery price per unit. It can be said that currently the storage costs per kWh are higher than the price of generated power. However, storage costs are awaited to decline by four times by 2030 (Russell Hensley, 2012). For calculation of storage costs some assumptions done, because there are a lot of uncertainties. We assumed that battery utilization will be 100 cycles per year (20 weeks by 5 days in wintertime) and the lifecycle of Li-ion battery nowadays is 2 000 cycles. The time of battery utilization is supposed to be 2 hours per day. Of course, all the calculations made here for the same network (see Fig.3.1), although grid configuration parameters are not taken into account in storage costs computations.

It is decided to use battery 100 times per year because of its lifespan and optimal payback period, thus 2 000 cycles divided by 20 years of payoff period. Besides, increasing annual amount of cycles of the battery storage costs are increased and because of payback period shortening annual investment expenses also rising up. It should be noted that investment and storage costs are rather relative conceptions. However, the idea of investment cost is better for detailed economic calculations, because it contains interest rate and payback variables. Whilst, the value of storage costs gives general vision and intended for primary computations. Furthermore, investment costs are higher than storage expenses, because loan resources are taken into account. Annual storage costs and battery power capacity dependence in different years are clearly presented on Fig.3.12.

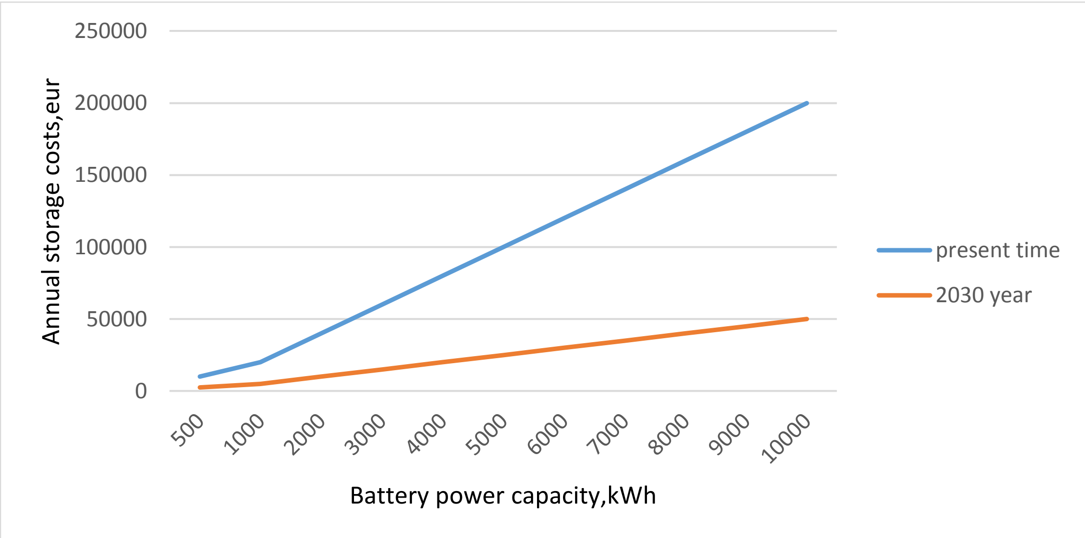

Fig.3.12 The relation of annual storage costs and battery power capacity

According to the Fig.3.12 proportional dependence between storage costs and battery power can be observed. As it was stated above storage costs declined by four times in 2030 in accordance with storage prices per kWh.

3.6 Estimation of net value

Net value is a parameter introduced in this paper especially to make distinct visible the economic effect of BESS implementation. Net value clearly shows the effect of BESS installation. When it is negative the utilization of battery storages is unprofitable, whereas positive Net value demonstrates the advantages of BESS settings. Net value is a difference between savings (i.e. savings from peak shavings and outage costs) and costs (investment expenditures) equated to annual values. Annual investment costs are irresponsive to average switching and repair times, total length and configuration of the grid, but they sensitive to battery power capacity and investment expenses per unit. The value of saving from peak slashing is receptive to shaved power (i.e. battery power), depth of peak cutting, conductor prices and lines length, but impervious to average switching and repair times. It should be noted that instead of conductor prices the costs of copper were regarded, thus insulation expenses were neglected. Besides, the value of outage costs are susceptible to switching and repair times, total length and configuration of network, battery power capacity and customer type. However, outage costs are irresponsive to conductor and investment prices.

Net value is an essential and important indicator of BESS installation. Firstly it presents in plain manner the profitability of battery storage possible implementation. Secondly, it contains all the crucial parameters, as battery power capacity, customers' type, the amount of battery utilization cycles per year and battery prices. Finally, it is universal and can be executed for other network and load curves types.

The dependencies between annual net value and power capacity of the battery, average switching time and total length of the network are represented in this chapter. Annual net value can be defined from equation (3.15), however a lot of obscurities occurred while net value deriving. Therefore, a lot of assumptions were performed to obtain affordable outcomes. The initial data mentioned above is used for net value calculations, see chapter 3.1. Furthermore, network (Fig.3.1) and load curve (Fig.3.2) were used as given arguments. Besides, the lengths of lines and average powers stated on Fig.3.1 are used for net value computations. Fault rate is 0.05 per km,a and switching time is 0.5 hours, other values see from chapter 3.1 Assumptions. Outage costs parameters can be extracted from table 3.7. It should be mentioned that the length of study period is considered 20 years and interest rate 6%. Certain power curve is used (table 3.6, 4th load curve number). However, for presenting correlation between battery power capacity and annual net value different BESS power capacities were examined. Dependencies between net value and battery power capacities for NaS and Li-ion battery types are represented on Fig.3.13.

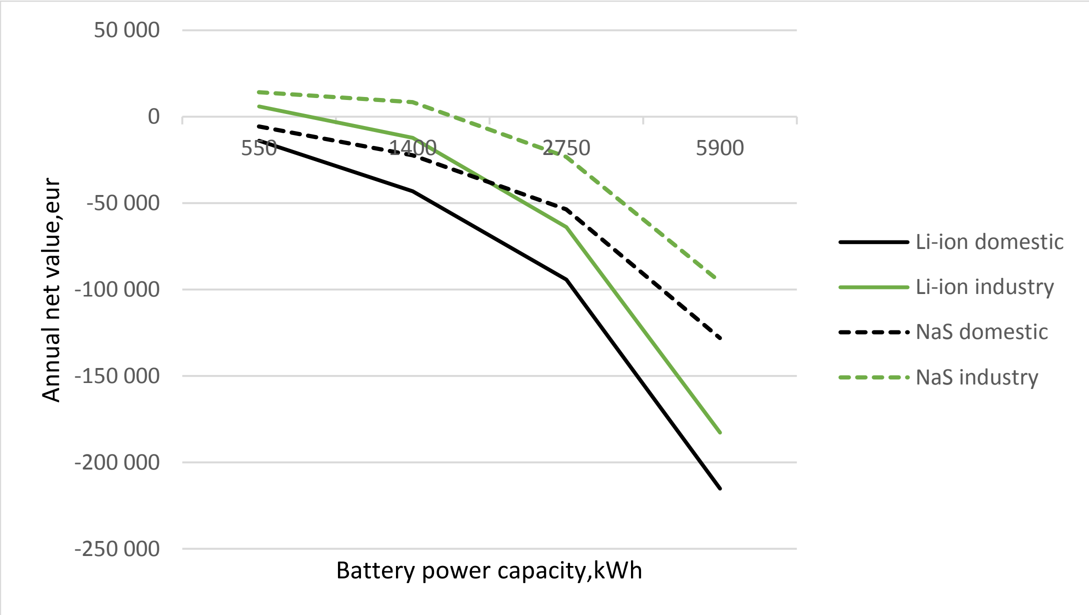

Fig.3.13 Dependency of annual net value and battery power capacity

According to Fig.3.13 economic effect from BESS installation can be observed. Li-ion batteries are not profitable for high capacities and that battery type shows negative dynamics. However, it is profitable to install batteries with power capacity less than 550 kWh. Sodium-Sulfur batteries show better results than Li-ion ones, but there are a lot of issues concerning maintenance, construction and safety of NaS batteries. Thus, additional expenses are required for NaS battery settings, which are not considered in this paper. It can be said that even today Li-ion batteries can be profitable under specific network parameters. Besides, distribution networks basically contain both industrial and domestic customers, so real situation will be between two lines (households and industries) and affirmative results are predicted to being annulled and disregarded. For better understanding the influence of customers' types on net value let us calculate minimal share of industrial customers in the grid to achieve rentability of BESS setting. We assumed that economic effect of industrial and domestic clients might compensate each other at certain proportion and of course, that ratio cannot exceed 100%, see equation (3.18). Then we can substitute one variable by another, in our cases y was replaced and transform former equation to new one (3.19).

$$S_{nv,ind} \cdot x = S_{nv,dom} \cdot y \tag{3.18}$$

where,

$S_{nv,ind}$ = annual net value for industrial customers only

$S_{nv,dom}$ = annual net value for domestic customers only

x = minimal share of industrial customers

y = maximal share of domestic customers

$$x = \frac{S_{nv,dom}}{S_{nv,dom} - S_{nv,ind}} \tag{3.19}$$

Using the data presented on Fig.3.13 it is possible to find out the required minimum of industrial customers in each case. However, too many assumptions were done and calculations for factual situations can differ significantly and even some positive outcomes may be achieved. So, the results from Fig.3.13 should not being taken on belief, because they were calculated for definite parameters and certain network configuration. The idea is to present common concept of BESS utilization via introducing battery storages implementation under given characteristics.

The impact of battery power capacity and type of the customer was examined rather detail, but there are a lot of other features able to reduce or increase annual net value. Battery power capacity and customer type decisively influence to annual net value however, it is not the one parameter that can affect to final effect of BESS installation. Switching time exerts considerably to outage costs, see fig.3.8 and since saving from outage costs is important part of net value then this time should effect also significantly to annual net value. The relation of switching time to annual net value can also provide us with substantial results. Network presented on Fig.3.1 and power curve on Fig.3.2 are used to execute calculations. Fault rate is 0.05per km,a, battery power capacity is 500 kWh, other parameters can be found from chapter 3.1

Assumptions. Dependency between annual net value and switching time can be observed on Fig.3.14.

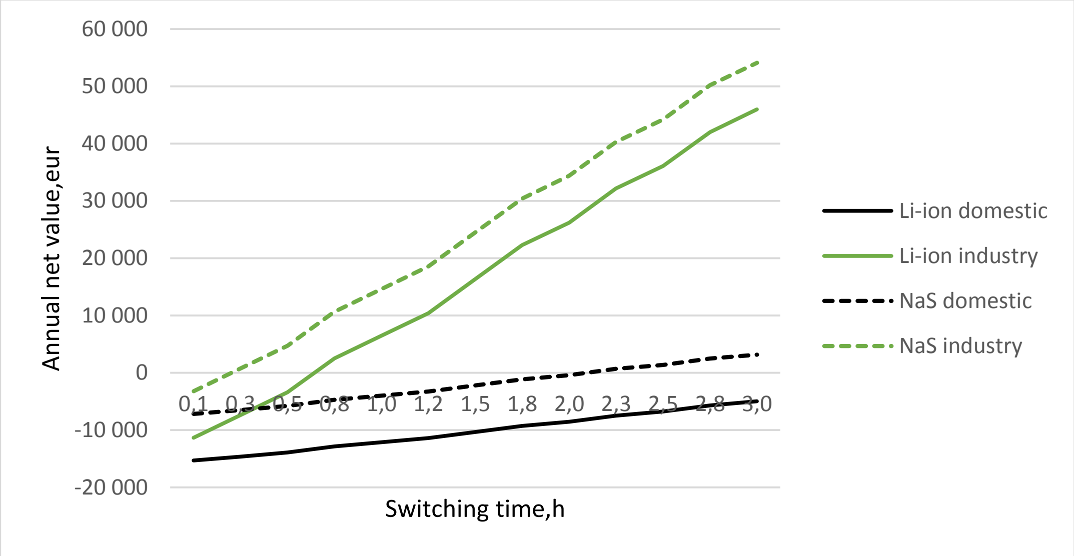

Fig.3.14 Relation between annual net value and switching time (battery capacity 500 kWh)

Switching time affects substantial to annual net value and that might be observed from Fig.3.14. It can be interpreted next way: switching time is used for outage costs calculation of entire network (except fault line). It should be noted that industrial customers are more sensitive to the changes of switching time. Especially it is demonstrated on Fig.3.14, the higher outage costs per kW and kWh are the explanation for that phenomenon. It can be concluded that savings from outage costs are variable in cases of dependency between annual net value and switching time. According to Fig.3.14 an optimal switching time from an economic point of view is 0.2 hours for NaS battery and 0.6 hours for Li-ion one. Since normal switching time is 0.5 hours, Sodium-Sulfur battery has good perspectives to be installed under these parameters because optimal switching time for NaS battery is lower than normal one. For better understanding and vision dependency between annual net value and length of lines in network should be represented. All the above mentioned parameters, i.e. battery power capacity 500 kWh, network configuration and load curve type are applicable for dependency between net value and length of lines and it can be observed on Fig.3.15.

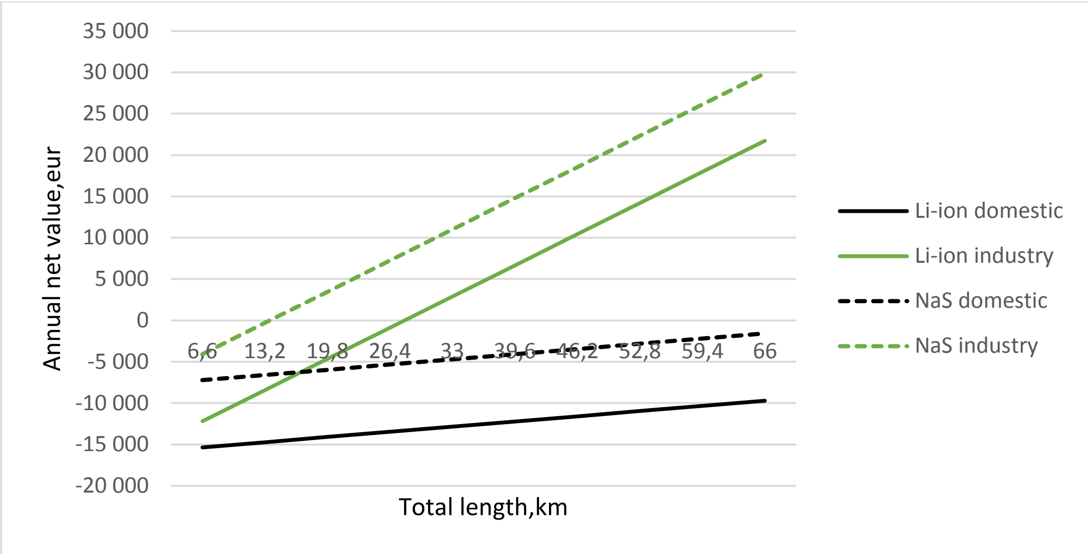

Fig.3.15 Dependency of annual net value and total length of lines in the grid (battery capacity 500 kWh)

Annual net value differs substantially for industrial and domestic customers among changing the length of lines in network. Whatever the length networks with households only do not achieve any rentability. However, as it was referred a lot of times singular customer type grids do not exist. Thus, actual effect should be observed from square between two boundaries of industrial and domestic lines. It can be said that some positive outcomes might be for the networks with long distance lines. It is possible to have staid net value from battery energy storage systems installation not altering recommended parameters of distribution network. In our case an optimal distance of the entire grid is about 13 km for NaS type of battery and 26 km for Lithium-ion type. According to Fig.3.15 implementation of BESS is profitable in networks with long distances between customers. However, actual medium voltage distribution systems are short even in rural areas where long distances between loads. That is reasonable because power losses are the function of the square of current and currents in medium voltage power systems are rather high. Besides, power losses depend on the length of line. Ergo, power losses increase rapidly if long distances are used in distribution grids. That is why the implementation of long lines in medium voltage power systems is inexpedient. So, basing on real situation and parameters the positive impact from BESS utilization is limited.

4. BESS TECHNOLOGY DEVELOPMENT BY 2030

According to data in above stated chapters it can be declared that installation of BESS currently is unprofitable. Nevertheless, Li-ion battery prices dropped dramatically over last years and lessening trend is still observed on markets. It can be noted that significant price fall per unit of Li-ion battery and storage costs is awaited by 2030. It is predicted to storage costs declining by four times because of fast development of energy storages and technology enhancements. There are several reasons why soon growth of BESS technology is expected. Firstly, EVs are predicted to overrun the automobile market and boosting on battery prices, since Li-ion batteries are most attractive for EV then the most considerable price drop is awaited for Li-ion batteries. Secondly, swift growth of renewable energy sources drives to necessity of power imbalances management between consumed and generated electricity. Finally, the implementation of BESS might enhance security of energy supply and used as backup during fault cases. All these reasons can be the proofs of superior outlooks of Li-ion batteries.

It is rather difficult to assume how outage costs and conductors' prices will be transformed in 2030, because outage costs mainly depend on energy policy of the government whereas conductors (primarily copper and aluminum) are stock commodities. Thus, outage costs and savings from peak shaving are supposed being the same as nowadays in this paper. Conductor prices were taken from London Metal Exchange on current dates because it is impossible to predict copper prices in long term period. So, in this chapter investment costs and net value changes are considered only, the results of savings from outage costs and peak cutting can be found in chapters 3.2 and 3.3. Storage costs are recalculated for 2030 year and they can be observed from Fig.3.13.

Significant price drop is awaited for Li-ion batteries by 2030 according to various companies and agencies. So, the most considerable change for BESS in 2030 will be the reduction of investment costs. Investment costs depend on interest rate, the length of study period and battery prices per unit. Of course, power also affects these expenditures significantly, however decreasing the amount of power will reflect the reducing of outage costs and savings from peak shaving. We supposed a battery price for Li-ion at 280 euros per kWh in future and that is 60% from current prices, see chapter 3.4. Thus, investment change significantly and proportionally.

In previous calculations of annual investment costs two types of the battery were examined and in this chapter results for the one battery type are presented. We decided not to show outcomes for Sodium-Sulfur batteries because their outlooks are obscure and breakthrough is not expected for that technology. Moreover, NaS prices are not going to being decreased sharply, thus their economic effect will be almost the same as nowadays. This action can be explained by limited sphere of NaS battery utilization. Sodium-Sulfur batteries require special maintenance and service, besides they are fire hazardous because they operate under high temperatures. Thus, that type of the battery can be used as stationary setting only whilst Li-ion batteries might be used for both stationary and mobile installations. On the Fig.4.1 dependency between the length of study period and annual investment costs is demonstrated. Network presented on Fig.3.1, load curve on Fig.3.2 and parameters regarded in chapter 3.1 Assumptions are used for calculations.

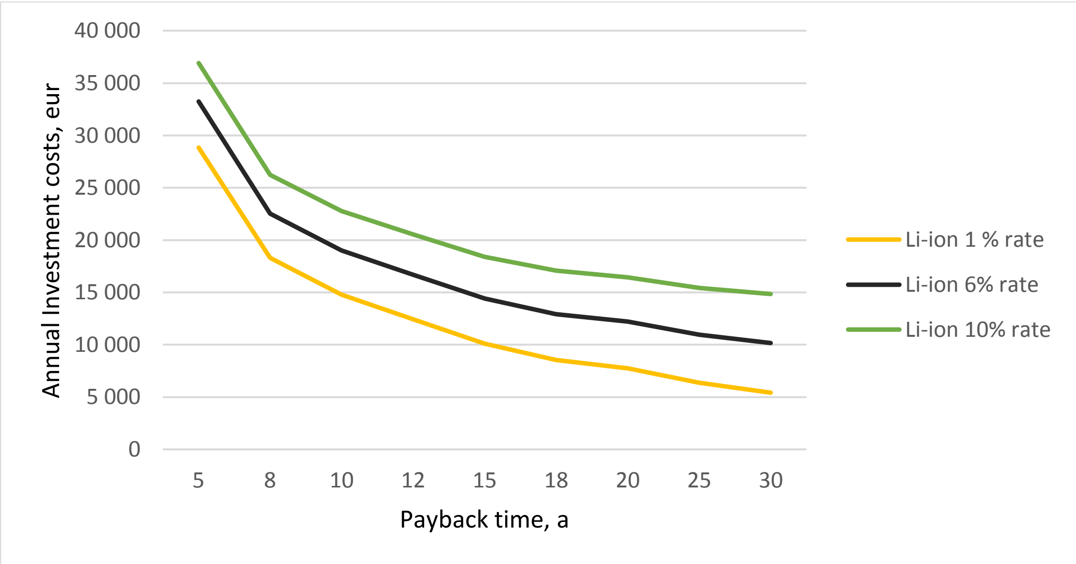

Fig.4.1 Dependency between payback period and annual investment costs (battery capacity 500 kWh)

The relation of annual investment costs and payback period is presented on Fig.4.1. The length of study period is inversely proportional to annual investment costs. It should be noted that the difference of annual investment costs between 20 and 30 years are slight thus it might be expediently to shorten payoff time. Besides, payoff time cannot exceed the lifespan of equipment and it is considered that average durability of Li-ion battery is 20 years (2 000 cycles totally). However, there are still a lot of uncertainties operating Li-ion batteries, because that technology is rather new and under development. Nevertheless, payback impacts identically to annual investment costs whatever the interest rate. Apparently, reducing the interest rate and increasing payback period may decline annual investment costs considerably. The dependencies between net value and power of the battery, average switching time and total length of the network are represented for 2030 year in this chapter.

Annual net value can be defined from equation (3.15), however a lot of obscurities occurred while net value deriving. Therefore, a lot of assumptions were performed to obtain affordable outcomes. The initial data mentioned above is used for net value calculations, see chapter 3.1. Furthermore, network (Fig.3.1) and load curve (Fig.3.2) were used as given arguments. Besides, the lengths of lines and average powers stated on Fig.3.1 are used for net value computations. It should be mentioned that the length of study period is considered 20 years and interest rate 6%. However, for presenting correlation between battery power capacity and annual net value different BESS power capacities were examined. Dependency between net value and battery power capacity is represented on Fig.4.2

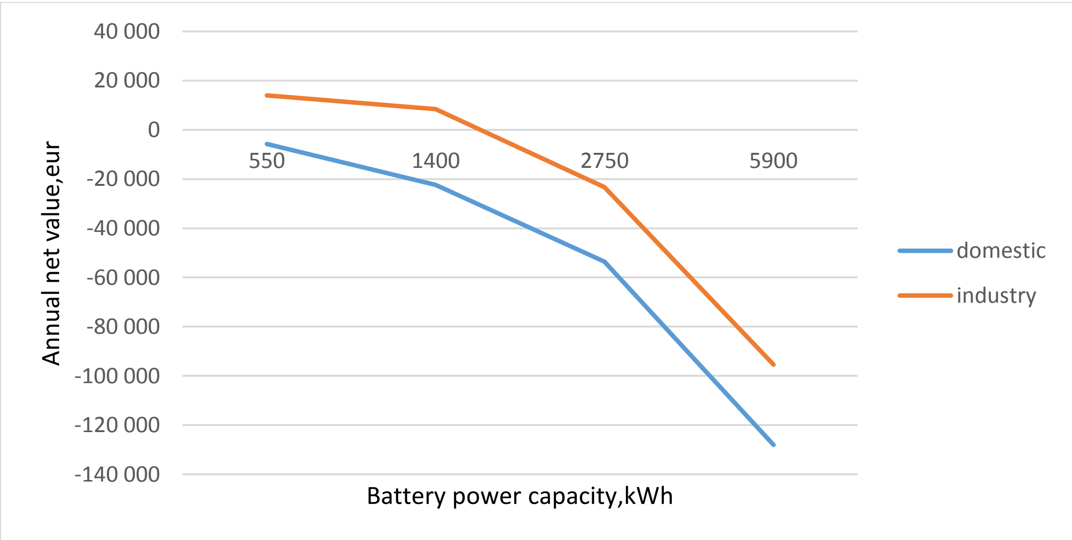

Fig.4.2 Dependency of annual net value and battery power capacity

According to Fig.4.2 economic effect can be observed from BESS installation for both domestic and industrial customers. BESS can be profitable if small battery is installed and it is located among industrial clients. However, that result is calculated for certain network type and power curve thus, some affirmative may be achievable for other network types. Distribution networks basically contain both industrial and domestic customers, so real situation will be between two lines (households and industries). Besides, the major problem is about legislation, at present DSOs cannot operate or own any large scale storage capacity. Thus, independent energy storage providers are required in that case and that will drive to costs rising. However, comparing Fig.4.2 and Fig.3.13 better situation is observed in the future, thus BESS implementation based on Li-ion technology have great potential.

The impact of battery power capacity and type of the customer was examined rather detail, but there are a lot of other features able to reduce or increase annual net value. Battery power capacity and customer type decisively influence to annual net value however, it is not the one parameter that can affect to final effect of BESS installation. Switching time exerts considerably to outage costs and since saving from outage costs is important part of net value then these times should effect also significantly to annual net value. The relation of switching time to annual net value can also provide us with substantial results. On the Fig.4.3 dependency between the length of study period and annual investment costs is demonstrated. Network presented on Fig.3.1, load curve on Fig.3.2 and parameters regarded in chapter 3.1 Assumptions are used for calculations. Dependency between annual net value and switching time can be observed on Fig.4.3.

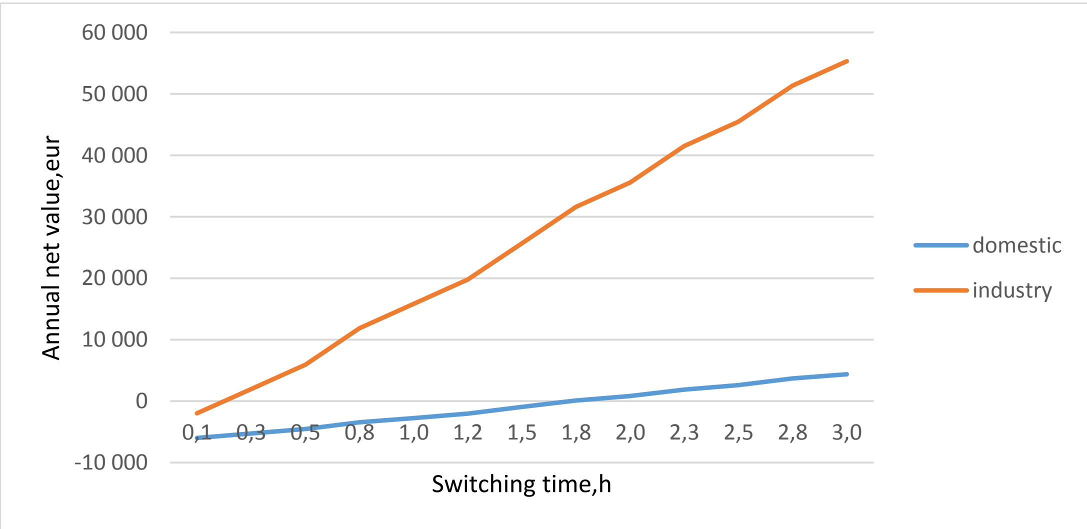

Fig.4.3 Relation between annual net value and switching time (battery capacity 500 kWh)

Switching time affects substantially to annual net value and that might be observed from Fig.4.3. It can be interpreted next way: switching time is used for outage costs calculation of entire network, except fault line. It should be noted that industrial customers are more sensitive to the changes switching time. Especially it is demonstrated on Fig.4.3, the higher outage costs per kW and kWh are the explanation for that phenomenon. It can be concluded that savings from outage costs are variable in cases of dependency between annual net value and switching time. According to Fig.4.3 an optimal switching time from an economic point of view is 0.2 hours for network with industrial customers and about 2 hours for grid full of households. Since normal switching time is 0.5 hours, battery installation amid industries has good perspectives to be mounted under these parameters because optimal switching time for battery is lower than normal one. For better understanding and vision dependency between annual net value and length of lines in network should be represented and it can be observed on Fig.4.4. On the Fig.4.4 dependency between the length of study period and annual investment costs is demonstrated. Network presented on Fig.3.1, load curve on Fig.3.2 and parameters regarded in chapter 3.1 Assumptions are used for calculations.

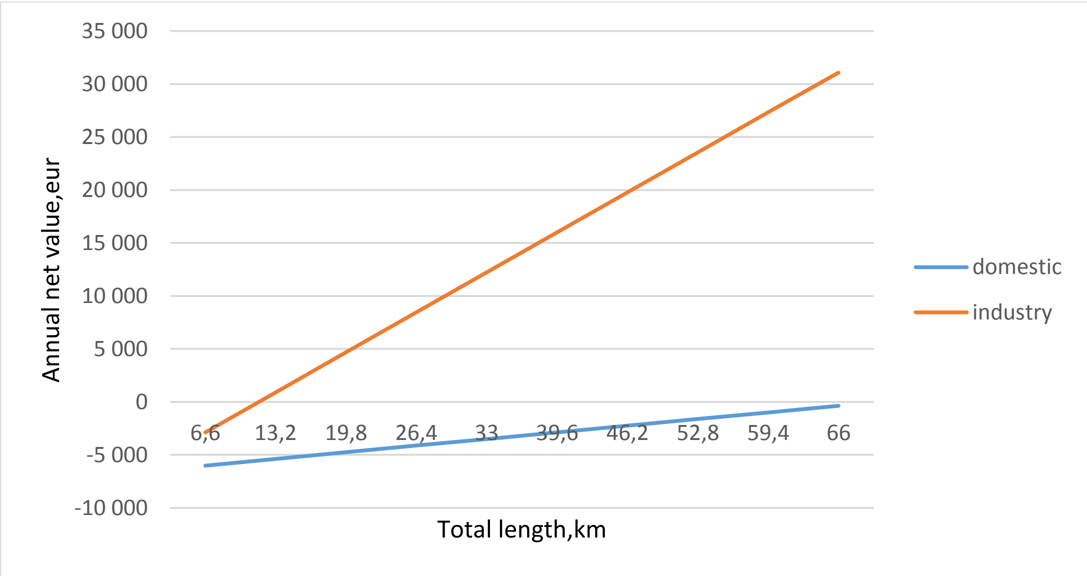

Fig.4.4 Dependency of annual net value and total length of lines in the grid (battery capacity 500 kWh)

Annual net value differs substantially for industrial and domestic customers among changing the length of lines in network. Whatever the length networks with households only do not achieve any profitability. However, as it was referred a lot of times singular customer type grids do not exist. Thus, actual effect should be observed from square between two boundaries of industrial and domestic lines. It can be said that some positive outcomes might be for the networks with long distance lines. It is possible to have staid net value from battery energy storage systems installation not altering recommended parameters of distribution network. In our case an optimal distance of the entire grid is about 10 km for Lithium-ion type of the battery. However, there are no networks with one client type thus actual minimum of total length required being BESS profitable is higher. According to Fig.4.4 implementation of BESS is profitable in networks with long distances between customers. However, actual medium voltage distribution systems are short even in rural areas where long distances between loads. That is reasonable because power losses are the function of the square of current and currents in medium voltage power systems are rather high. Besides, power losses depend on the length of line. Ergo, power losses increase rapidly if long distances are used in distribution grids. That is why the implementation of long lines in medium voltage power systems is inexpedient. So, basing on real situation and parameters the positive impact from BESS utilization is limited.

Assuming all the results from this chapter we can find that implementation of BESS will be more profitable in 2030. Besides, there might be added some features which improve BESS rentability such as set up of Li-ion battery storages in networks with high share of industrial customers. Comparing the outcomes for 2030 with current annual net value we can observe that BESS based on Li-ion technology has great potential. Strict limitations for battery can be weakened and then more networks types with various characteristics will be suitable for BESS realization.

5. THE LOCATION OF BESS IN GIVEN GRID

In previous chapters it was supposed that BESS are distributed proportionally to average powers along the grid. However, it is needed to show how battery storage can affect the net value in case of several settings installation in the network. Obviously distributive location of the BESS was a good decision but it is needed to explain why we opted to locate batteries along the network. In this chapter two cases of BESS position are examined. First variant presents single battery installation in any one line and second option shows BESS fitting in two lines. Thus, we can compare the impact of BESS installation and what is an optimal way to introduce batteries into the grid. First location is assumed to be in line with greatest power, i.e. line number 5 with average power 350 kW. Second option is to mount two battery packs in two different lines, it was decided to set up batteries in lines number 6 and 3 with total average power of the lines 200 kW. It should be noted that total power should be provided with battery is 1 000 kW in both cases. Since battery is used during switching time and it is 0.5 hours then we can select battery power capacity 500 kWh. That was done to equal battery power capacity and then we can declare that investment costs are the same for both cases and they can be neglected. Thus, savings only (from peak cutting and from outage costs) should be compared in this chapter.

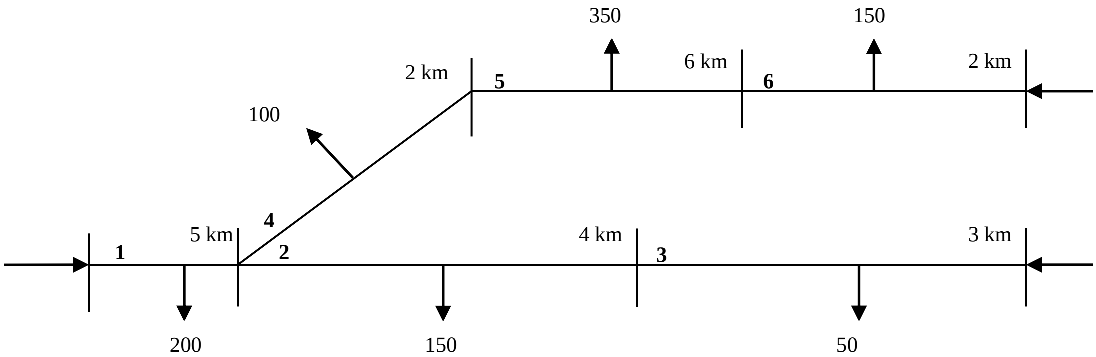

Fig.5.1 Given network and its parameters

It should be added that average powers presented on Fig.5.1 are not actual powers of lines but they are considered to be the power that can be substituted by battery sources. It was done for better understanding and vision, besides that assumption simplifies computations of savings from outage costs. Real powers of the network are needed only to calculate savings from peak cutting and they are considered in relative tables below.

The network with installed battery can be seen from Fig.5.2. Savings from outage costs are calculated with formula (5.1) and numerical values can be found below. It should be said that battery is not full used all the time, e.g. when the fault occurs in line number 4, battery cannot supply second and third lines during switching time. Besides, when fault occurs in line 5 where BESS is installed there are no opportunities to supply the rest lines in the grid during required switching. Thus, effectiveness of large battery is doubtful.

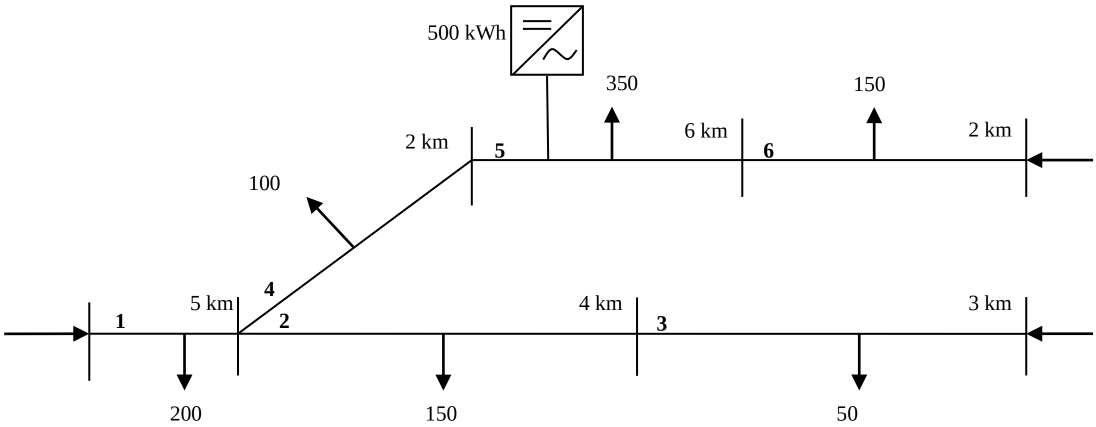

Fig.5.2 First variant of BESS installation

$$C_{out,a} = \lambda \cdot \sum_{n=1}^{m} [(l - l_n) \cdot (P - P_n)] \cdot (C_{fp} + C_{fe} \cdot t_{sw} + C_{pp} + C_{pe} \cdot t_{sw}) \quad (5.1)$$

To calculate annual savings from outage costs we can use parameters of switching time from chapter 3.3 and characteristics of outage costs per kW and kWh from table 3.7. Fault rate is 0.05 per km,a and switching time is 0.5 hours. We assumed that all the customers are industries in present grid.

Savings from outage costs for first variant:

When the fault occurs in lines 5, 6, 2 and 3 there is no effect from battery implementation to savings from outage costs. When line number four is fault then fifth and sixth lines are supplied by battery and total energy is 250 kWh (500 kW by 0.5 hours). When the fault occurs in first line then battery should supply the rest part of network with total energy 400 kWh (800 kW by 0.5 hours).

For line number 5: $C_{out,a} = 0.05 \cdot 17600 \cdot (3.52 + 24.45 \cdot 0.5 + 1.38 + 11.47 \cdot 0.5) = 20\ 117$ euro, a

The network with installed two batteries can be seen from Fig.5.3. Savings from outage costs are calculated with formula (5.1) and numerical values can be found below. It should be said that battery is not full used all the time, e.g. when fault occurs in lines 3 or 6 there are no opportunities to supply that lines during required switching. When fault occurs in second line then there is no electricity supply in lines number 1 and 4 during switching time because of power scarcity of the battery. After replacing values into equation (5.1) numerical value of savings from outage costs can be found.

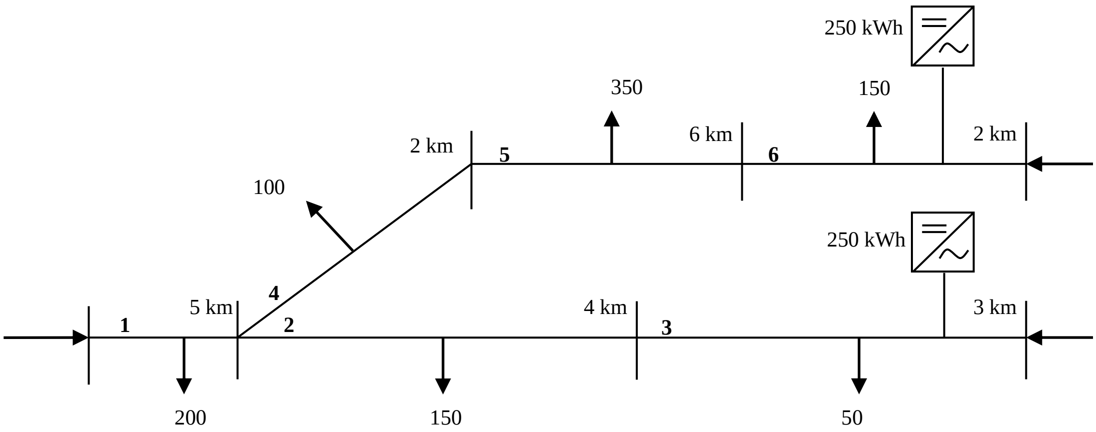

Fig.5.3 Second variant of BESS installation

Savings from outage costs for second variant:

When the fault occurs in lines number 3 and 6 there is no effect from battery utilization because batteries are connected with defect line. During the fault in second line battery can supply third line (25 kWh), when fifth line is out another battery can deliver electricity to sixth line (75 kWh). When fault occurs on line number 4 fifth and sixth lines can be supplied and battery is full used in that case (250 kWh). Fault on first line leads to use of 400 kWh from the batteries during switching time.

For lines number 3 and 6: $C_{out,a} = 0.05 \cdot 18050 \cdot (3.52 + 24.45 \cdot 0.5 + 1.38 + +11.47 \cdot 0.5) = 20\ 631$ euro, a

As it can be seen from the results of savings from outage costs it is a bit more profitable to install two smaller batteries than one large. Comparing the results with outcome for distributive located batteries (Fig.3.6) we can observe that batteries in each line increase savings from outage costs. Annual savings from outage costs for latter is around 26 500 euro and it has to be noticed again that investment costs are equal in each case 500 kWh (250 kW by 2 hours daily utilization). Thus, right location and distribution of the battery can enhance profitability and security of supply dramatically. It can be concluded that installation of small batteries along the network is more profitable because more lines might be provided with electricity in different fault cases during switching time.

Nevertheless, savings from outage costs is not the one characteristic taken into account savings from peak shaving are expected to play significant role in total outcome. Therefore, for objective presentation of the results savings from peak shaving should be considered. It is useful to apply former principle of savings from peak cutting calculation that is given in chapter 3.2. Firstly, it is needed to calculate prices of conductors for non-peak shaved network and then find out new prices for peak slashed grid, derived difference is the saving from peak cutting. Some assumptions were done to execute computations: copper prices are regarded instead of conductor prices. It is done to simplify calculations because too many conductor types exist nowadays besides, insulation costs are small part of total wire cost and they can be neglected. Additional supposition was done about cross section selection. Actually standard cross section is used for conductor selection but we used calculated cross sections. It was done for better understanding of savings from peak cutting mechanism. Sometimes intervals between standard cross sections are large and decreasing of found cross section can be in that interval thus, standard cross section is not changed in that case. We reckon the peak power is 5 000 kW and the depth of peak cutting is 10% (500 kW), the price of copper can be found from chapter 3.2. We can use equation (3.7) for savings from peak cutting calculation. The price of copper conductors can be extracted from table 5.1.

Table 5.1 The price of conductors before peak cutting

Peak power	**Current**	**Cross section**	**Standard cross section**	**Price per km**	**Total price**
P, kW	I,A	s,mm^2	s_{st}, mm^2	euro	euro
5 000	360,845	103,093	120	17 527	385 588

So, data stated in table 5.1 is used as initial one for further calculations. It should be mentioned that total length of lines in the network is considered 22 kilometers and voltage level is 10 kV. Calculations about conductor prices after peak cutting can be found from table 5.2. When one large BESS is mounted then large power flow occurs in line number 4, see fig.5.2 and it causes growth of the value of peak power in that line whilst the levels of peak powers in rest lines are reduced. Thus, there is no effect from peak cutting for 4th line. When two smaller battery packs are installed (option 2) decreasing of peak power can be observed in each line. As it can be seen from table 5.2 annual savings from peak shaving for second variant are higher but first option also demonstrates good results. So, it can be declared that first and second options present almost equal outcomes about saving from peak cutting.

Table 5.2 The prices of conductors after peak shaving

Option	**New peak power**	**New cross section**	**New total price**	**Total savings**	**Battery power capacity, kWh**	**Annual savings**
1st variant	4 750	97,943	380 330	5 258	500	458
2nd variant	4 750	97,943	375 072	10 516	500	917

Comparing the results of savings from peak slashing and savings from outage costs the latter much lower than annual savings from outage costs. It can be said annual savings from peak shaving are rather low comparing to savings from outage costs and they play insignificant role. To evaluate two options we need to summarize the effects from peak cutting and outage costs savings. Besides we can add the value of investment costs to show a net value, see equation (5.2).

$$S_{sav,total} = C_{out} + S_{sav} - S_{inv} \tag{5.2}$$

For first variant: $S_{nv,1} = 20\ 117 + 458 - 19\ 575 = 1\ 000$ euro, a

For second variant: $S_{nv,2} = 20\ 631 + 917 - 19\ 575 = 1\ 973$ euro, a

It should be added that the value of investment cost is calculated for 6% interest rate, payback period of 20 years and 500 kWh battery capacity, see equation (3.9). It can be stated that installation of two small batteries is more profitable solution, moreover the implementation of BESS in each grid leads to higher savings from outage costs and relatively increase total profitability of BESS. Although, the installation of 500 kWh battery is profitable in both cases but rentability can be increased by setting some small batteries instead of one large.

6. END USERS AND RETAIL COMPANIES BENEFITS FROM BESS UTILIZATION

End-users, retail and distribution network operators play different and distinctive roles on energy market. They cannot combine roles because of European electricity market decoupling. Thus, the impact of BESS installation is different for various types of market participants. The effect of battery implementation for distribution system operator was considered above and BESS influence for consumers is being regarded in this chapter. It can be declared that BESS installation is less profitable for consumers because they cannot obtain money from outage costs savings, although the security of supply is increased. So, all the same expenses (investment or storage costs) are kept, whilst savings from outage costs are vanished and the calculation method for savings from peak shaving is changed. Annual investment costs and storage expenses are the same as for DSO, thus they are not regarded detail here. The economic advantage of BESS realization is concluded in money savings from peak shaving (the battery is charged during the night time when electricity prices are low and discharging takes place whiles the peak load, thereby smoothing the power curve results). So, the main benefit for end-users and retail companies is peak shaving, but the calculation principle is basically different. The value of peak savings can be found from equation (6.1).

$$S_{sav} = C_{sav} \cdot n \cdot P \cdot t_b \tag{6.1}$$

where

C_{sav} = price difference between day and night tariffs

t_b = average time of battery utilization per day

n = the amount of battery cycles per year

P = shaved peak power

According to equation (6.1) the value of savings from peak shaving depends on power, the amount of charge/discharge cycles of the battery per year and the electricity price difference between day and night tariffs. Changing annual amount of charge/discharge cycles of the battery is rather difficult because of BESS durability and economic sides. Power is variable and one of the aim of this paper –

finding out the optimal power, thus power can not be used as the constant value. Obviously, detecting the price difference between day and night tariffs is the most proper way in this case. Furthermore, to achieve affirmative results from BESS installation the value of savings should be higher than investment costs and that can be seen from inequality (6.2). The value of annual investment costs can be found from equation (3.9).

$$S_{sav} > S_{inv} \tag{6.2}$$

However, to simplify the calculations the value of storage costs can be used instead of investment costs. So, we can compare price difference between day and night tariffs and storage costs, besides to attain positive results from battery implementation the value of storage cost should be less than price difference between day and night tariffs that can be observed from inequality (6.3). The value of storage costs can be found from equation (3.12).

$$C_{sav} > C_{st} \tag{6.3}$$

According to formula (3.12) it can be said that storage costs depend on current battery prices and battery lifespan. So, storage costs can be considered as constant value because Li-ion battery prices are decreasing slightly and durability of that battery type is tried being enhanced. Nowadays, lifespan of Li-ion battery is around 2 000 cycles and it costs 450 euro per kWh of installed power capacity. Put into the equation (3.12) the parameters of lifespan and battery price we can derive the value of storage cost and storing the electricity costs 22 cents per kWh. It should be noted that end-users and retail companies acquire electricity under different conditions, former purchases power mainly from fixed term contracts where electricity prices are invariable, latter can obtain electricity from spot markets and fixed term contracts. Thus, two main variants are going to be considered to estimate the correct value of price difference between day and night tariffs: for end-users from fixed term contracts and for retail companies from spot market.

6.1 End users benefits

Fixed-term price contracts are usually used by domestic, small industrial and service customers. These contracts are simple to understand, the price formation is clear and the electricity prices are invariable. Fixed-term contracts can be two types:

one tariff and double tariff. Apparently, one tariff price formation does not correspond with the idea of savings from peak shaving. Therefore, double tariff price formation will be regarded here. Several electricity providers were examined to get correct outcomes and reduce calculation error. The table 6.1 demonstrates the prices of different distribution retail companies in Finland.

Table 6.1 Comparison of electricity prices by distribution companies (Energiavirasto,2015)

The name of the distribution retail company	**Day tariff price (cents per kWh)**	**Night tariff price (cents per kWh)**	**Price difference (day tariff – night tariff), (cents per kWh)**
Vaasan Sähkö Oy	5.70	4.90	0.80
Energiapolar Oy	5.59	4.62	0.97
Kokkolan Energia Oy	6.10	5.17	0.93
Kymenlaakson Sähkö Oy	6.30	5.30	1.00
Savon Voima Oy	6.51	5.45	1.06
Pohjois-Karjalan Sähkö Oy	6.71	5.39	1.32
Pori Energia Oy	6.76	5.27	1.49
Vantaan Energia Oy	6.94	5.58	1.36
Lappeenrannan Energia Oy	7.20	5.80	1.40
Lahti Energia Oy	8.20	6.32	1.88

The table 6.1 is formed by Finnish website (http://www.sahkonhinta.fi) where customers can look out the electricity supplier and the prices for fixed-term contracts. According to the table 6.1 (ten randomly selected offers) average price difference between day and night tariffs can be derived from equation (6.4).

$$\Delta C_{av} = \sum_{n=1}^{10} \Delta C_n / 10 \qquad (6.4)$$

where,

ΔC_n = the price difference of certain company

$\Delta C_{av} = 1.22$ cents per kWh

It can be concluded that price difference between day and night tariffs for the customers, using fixed-term price contracts on the average is 1.22 cents per kWh. Comparing that result with storage cost (22 cents per kWh) we can observe that

BESS installation is unprofitable for customers using fixed term contracts. Thus, there is no need to calculate annual investment costs and savings from peak cutting because the result is obvious – storage costs much higher than possible effect from peak shaving and load shifting.

6.2 Retail companies' benefits

There are several types of the customers which can trade on spot markets: large-scale industry, medium-scale industry and retail companies. Nord Pool Spot is the market where almost all the Finnish electricity can be sold or purchased. Marginal cost principle is the main one in price formation on Nordic Energy market. That means each market participant (generators and consumers) makes its own bids for every delivery hour. Hydro power and nuclear power plants have the lowest marginal cost, thus they are utilized all the time. However, electricity demand fluctuates rapidly and substantially, the power capacities of hydro and nuclear plants are limited. Gradually increasing of the demand causes electricity price rising and so, switching on the installations with higher marginal costs (CHP, coal and gas power settings). Thereby, additional power plants with higher marginal cost becoming involved into the market. That is why electricity prices rise up during the time of high power demand. It can be noticed that marginal costs of different power plant types vary significantly thus the fluctuations of electricity price on Spot market are truly high. The value of price variation on Nord Pool Spot market is shown at Fig.6.1. According to Fig.6.1 huge variations of electricity prices during the day can be observed. Besides, prices can be dissimilar for various days, thus there are some risks for companies trading on spot markets. Nevertheless, it is obvious that electricity prices are higher in wintertime because of higher energy consumption so, it can be supposed BESS is better to be utilized in wintertime.

As it was decided before BESS is recommended being used in wintertime, besides electricity prices should be higher on weekdays ergo it is better to utilize battery storages 5 days per week. However, there are too many factors affecting electricity spot prices, such as availability of power transmission capacity, weather, windy days or water levels in reservoirs. Hour by hour electricity prices for various time periods are presented in Appendix I. The selections from Elspot data base were done for six months (October, November, December, January, February and March) and we chose one week from each month. That selection was made to enhance correctness of results and to reduce possible calculation error.

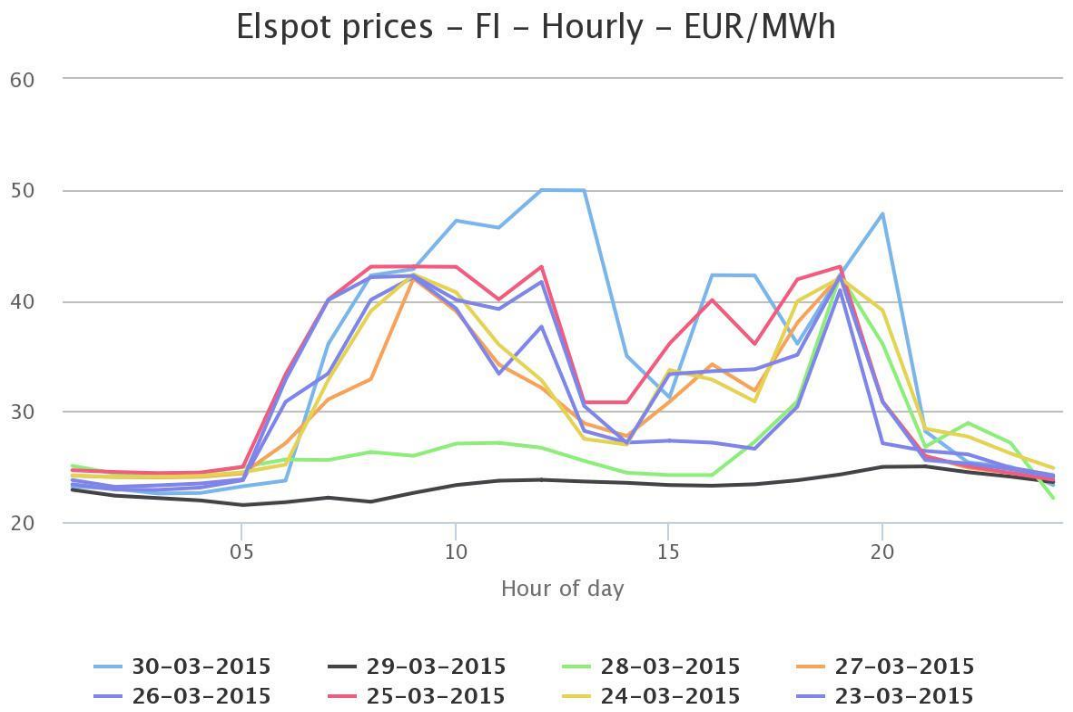

Fig.6.1 Electricity price fluctuations on Nord Pool Spot (Nord Pool Spot, 2015)

The calculation of average price between day and night tariffs is based on tables from Appendix I and can be found from equation (6.5). The average price difference between peak and non-peak hours is about 19.5 eur/MWh or 1.95 cents per kWh. That is a bit higher than customers under fixed-price contracts can acquire.

$$\Delta C_{av} = \sum_{n=1}^{6} C_{n,day} - C_{n,night}/6$$

(6.5)

$$\Delta C_{av} = 1.95 \text{ cents per kWh}$$

It can be concluded that price difference between day and night tariffs for the customers, under spot price contracts on the average is 1.95 cents per kWh. Comparing that result with storage cost (22 cents per kWh) we can observe that BESS installation is unprofitable for customers using spot contracts. Thus, there is no need to calculate annual investment costs and savings from peak cutting because the result is obvious – storage costs much higher than possible effect from peak shaving and load shifting.

It can be inferred that price difference between day and night time tariffs is higher on spot market. However, that option is not available for all the customers, because of the trading fees. Thus, greater discount is accessible to the clients with significant consumed power (retail companies, large-scale industry). Evidently, the installation of BESS is more profitable for retail companies than for households, at least this decision can be based on the price difference between peak and non-peak hours. Nevertheless, the price difference between day and night time tariffs and the value of savings from peak shaving is not the one feature for expediency of the BESS utilization.

7. CONCLUSION

Battery Energy Storage Systems have enormous potential on changing the way clients can be supplied with electricity, even it might become an inviting choice to power lines. Benefits of battery storage installation can be compared with outage costs, savings from peak shaving and ability to store electricity produced from solar panels, wind turbines for further sale to the grid during peak hours. Battery storage supports distribution system keeping stability in fault conditions and even to avert new investments or reinforcements into the grid. Distribution system operators can benefit from reduction of outage costs and peak cutting (avoiding reinforcements of the lines or using lower cable cross section). Customers can profit from peak shaving and load levelling, better quality of electricity supply and opportunity to sell their surplus energy to the grid on profitable terms.

The Thesis illustrates the conditions and parameters that have to be taken into account while BESS selection and installation. Such key issues as savings from outage costs, savings from peak shaving and net economic affect from battery setting are explored in the Thesis.

Installation of the BESS can significantly reduce costs. Additionally, it can act as a replacement for the spinning reserve, with power immediately available for the dispatch during certain times, e.g. frequency control. According to Caruna representative BESS has a tremendous ability on changing the way electricity will be delivered in future. It may become an attractive alternative to power lines, should the technology develop further to allow storing energy in large quantities at a competitive price. It should be also added that according European legislation DSOs and TSOs are not allowed to own or operate large-scale BESS, because BESS are considered as generation and due to market decoupling networks operators can not possess any electricity generating settings.

As the result of this paper optimal conditions of required battery storage characteristics are established. Crucial parameters that can affect the profitability of BESS installation were detected. The major ones are battery power capacity, battery prices and type of the customers. Besides, the length of lines, switching time, interest rate and payback period might influence significantly final results.

In the Thesis required parameters are established for better battery introduction into the grid: the configuration of network, the form of peak (i.e. sharpness of the peak), minimal share of industrial customers and optimal length of the grid. Firstly, we need to consider configuration of the network. In this paper specific network type is examined with reserve supplying from all the edges of network. Thus, while fault occurs in the beginning of the grid (i.e. feeding point) electricity is started to be delivered from the other sides of the network after switching time. In that case battery supplies customers with electricity during switching time only. When network is connected to electricity sources from one end only (i.e. no reserve supply) then battery can be used also during repair time. Let us consider the fault occurs in the beginning of the grid, ergo all the customers need to be supplied during repair time. As it can be seen absolutely different battery capacities should be selected in various network types. Furthermore, economic results of battery installation can be totally diverse. It is rather complicated to say exactly which network configuration type is more preferable because larger battery capacity leads to higher savings from outage costs as well as higher investment costs.

Secondly, the sharpness of the peak power affects significantly to the result of battery implementation. In the Thesis various peak forms are regarded: from 10% to 25% depth of peak shaving (see Fig.3.3). Obviously, the sharper the peak the higher savings can be reached. DSOs can avoid expensive line reinforcements by installation the battery. Besides, while planning to build new lines battery utilization can be examined and that may lead to installation conductors with smaller cross section. However, savings from outage costs should be also considered and after that final decision can be done. Thirdly, the share of industrial and service customers need to be taken into account. Domestic customers have low outage rates per kW and kWh thus, savings from outage costs are low for that customer types. Apparently, networks with high rates of industrial and service consumers are preferable because higher savings from outage costs can be achieved.

Finally, the length of network can considerably impact to the final decision of BESS implementation. In the thesis dependence between annual net value and total lines distance is examined. It can be observed that the longer lines the higher savings from outage costs. Besides, longer lines can also increase economic effect from peak shaving, we can save on conductor cross section. However, some issues can occur with long lines. There are not so many networks with long lines in distribution grids. It can be said that long lines are used in rural areas but mostly households are consumers in rural areas. So, it is difficult to find out right solution in that case. Besides, switching time can influence to annual net value but it is regulated by authorities and cannot be increased.

Additionally, the location of the battery in the network is also crucial parameter. In the Thesis three cases of BESS situation are examined. First one is location of several batteries (the amount of batteries equals to the number of lines) along the network in distributive manner. Second variant is installation of one large battery in certain line (see chapter 5) and third option is two battery packs mounted in two lines. It has to be noted that battery power capacity is equal in all the cases. It is done to even investment costs and for clearer presentation of the results. So, the best outcome is when batteries are installed in each line. Second and third options demonstrate almost the same results but latter one is a bit more profitable. It can be concluded that all the above parameters are connected with each other and change the one leads to correctives in the others. Nevertheless, general characteristics of BESS profitability are regarded in this paper and they should work under different conditions such as configuration type, the form of peak and customer type.

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Implementation of BESS and their perspectives according to Caruna company. (interview questions)

1. Does your company utilize any battery energy storage systems? If yes which types of the batteries are used, their power capacity, life span and the amount of charging/discharging cycles per year? Besides, what are the aims of BESS installation and are there any positive results of battery settings for your company?
2. Does company have any strategy for BESS implementation? According to you what are the best places (areas) for BESS installation in your distribution area? What types of the batteries are going to be used in your projects?
3. Do you think should the authorities stimulate battery energy storage systems implementation (e.g. feeding tariffs) in your country?
4. Does your company await fast growth of BESS installation in distribution network in near future? How battery storages can affect electricity prices in Nordic countries generally and in Finland particularly? How BESS can influence to the operation of the grids?
5. Are there any restrictions and limitations of BESS utilization in distribution networks? What are the major obstacles for battery storages using nowadays?
6. What is your vision about perspectives of the BESS implementation in your country?

Appendix I

Hour	20.10 .2014	19.10. 2014	18.10. 2014	17.10. 2014	16.10. 2014	15.10. 2014	14.10. 2014	13.10. 2014	Average price
00-01	20,59	30,43	31,02	31,05	30,54	31,1	31,78	31,04	29,69
01-02	18,1	30,2	30,8	30,8	30,25	30,75	31,24	30,94	29,14
02-03	16,37	25,89	30,7	30,53	30,09	30,55	31,07	30,71	28,24
03-04	10,05	25,34	30,67	30,65	30,18	30,51	31,07	30,82	27,41
04-05	18,38	30,2	30,63	30,83	30,67	31,01	31,37	31,2	29,29
05-06	39,11	30,21	30,67	32,41	39,13	32,9	33,12	35,3	34,11
06-07	48,8	29,01	31,52	42,95	50,73	37,16	36,13	37,92	39,28
07-08	60,02	27,32	37,13	46,79	53,11	38,8	37,72	40,95	42,73
08-09	60,02	30,27	38,8	50,72	49,28	40,35	39,38	43,83	44,08
09-10	60,02	33,98	39,74	50,24	47,92	40,5	39,06	43,31	44,35
10-11	60,02	35,17	39,72	48,43	48,01	40,09	38,81	43,84	44,26
11-12	53,08	36,08	39,14	46,87	47,94	40,89	40,03	42,74	43,35
12-13	38,46	35,32	39,18	36,58	39,08	37,58	37,07	39,13	37,80
13-14	37,43	33,9	39,18	35,33	38,24	37,47	36,6	38,92	37,13
14-15	35,59	33,85	37,49	34,97	37,7	37,18	36	37,9	36,34
15-16	45,02	34,57	36,83	42,68	39,75	38,03	37,49	37,72	39,01
16-17	46,17	36,86	39,12	43,9	39,56	38,13	37,78	37,39	39,86
17-18	60,03	42,62	59,09	54,78	43,61	43,26	39,22	40,37	47,87
18-19	60,02	47,59	65,01	60,06	70,8	64,74	44,62	44,66	57,19
19-20	42,42	42,69	60,09	36,53	40,53	37,92	37,82	40,39	42,30
20-21	33,86	38,27	41,89	34,5	37,11	36,04	36,39	36,98	36,88
21-22	33,56	37,85	44,97	34,22	35,78	35,3	35,82	35,47	36,62
22-23	32,29	36,44	34,36	33,45	33,59	34,35	34,71	34,22	34,18
23-00	30,11	31,27	32,54	31,9	32,11	32,08	32,26	33,23	31,94

$$C_{1,day} = (44.35 + 44.26 + 47.87 + 57.19)/4 = 48.41$$

$$C_{1,night} = (29.69 + 29.14 + 28.24 + 27.41 + 29.29 + 31.94)/6 = 29.28$$

Hour	17.11. 2014	16.11. 2014	15.11. 2014	14.11. 2014	13.11. 2014	12.11. 2014	11.11. 2014	10.11. 2014	Average price
00-01	26,46	26,65	27,39	29,39	28,7	25,14	25,97	24,61	26,79
01-02	24,61	24,07	26,02	27,93	28,11	23,88	25,48	24,08	25,52
02-03	24,57	23,83	25,56	26,34	26,88	23,74	25,42	24,26	25,08
03-04	25,06	23,52	24,59	25,97	24,95	23,7	25,28	23,91	24,62
04-05	26,3	23,07	24,89	26,94	26,55	24,85	25,44	24,08	25,27
05-06	29,01	23,59	25,96	29,32	28,41	27,79	27,98	25,63	27,21
06-07	43,43	25,33	27,22	44	37,68	35,25	31,29	31,93	34,52
07-08	45,99	26,73	28,23	62,48	55,31	41,34	35,22	41,93	42,15
08-09	45,72	27,22	29,79	73,78	58,51	41,61	34,97	48,5	45,01
09-10	65,2	28,05	30,86	64,28	45,13	50,15	39,03	48,04	46,34
10-11	36,57	29,75	31,12	40,5	33,97	33,11	33,26	32,25	33,82
11-12	35,48	30,5	31,23	37,54	33,12	32,91	33,22	32,16	33,27
12-13	33,6	30,66	30,83	37,06	32,78	32,76	32,82	32,26	32,85
13-14	33,26	29,36	30,75	35,73	32,87	32,55	32,65	32,34	32,44
14-15	67,36	28,7	30,67	45,68	74,32	39,82	36,64	37,33	45,07
15-16	74,33	29,3	31,1	73,02	79,73	57,96	52,55	51,27	56,16
16-17	74,31	30,72	32	73,93	76,51	70,58	74,37	65,04	62,18
17-18	74,31	31,79	32,26	70,95	80,07	63,2	63,42	51,99	58,50
18-19	71,23	32,01	32,11	67,54	74,38	52,8	54,09	38,06	52,78
19-20	33,09	31,2	31,22	36,32	35,99	36,02	32,52	31,83	33,52
20-21	31,82	30,73	30,63	30,93	32,27	32,09	31,63	31	31,39
21-22	31,2	30,23	30,33	30,91	32,29	31,52	30,87	30,7	31,01
22-23	30,74	29,03	29,64	29,89	31,29	30,63	29,76	29,98	30,12
23-00	29,96	28,03	27,94	28,2	29,85	27,84	25,74	27,46	28,13

$$C_{2,\mathrm{day}} = (56.16 + 62.18 + 58.5 + 52.78)/4 = 57.41$$

$$C_{2,\mathrm{night}} = (26.79 + 25.52 + 25.08 + 24.62 + 25.27 + 27.21 + 28.13)/7 = 26.09$$

Hour	20.12. 2014	19.12. 2014	18.12. 2014	17.12. 2014	16.12. 2014	15.12. 2014	14.12. 2014	13.12. 2014	Average price
00-01	28,69	29,54	29,72	29,35	29,86	27,23	30,42	29,64	29,31
01-02	27,91	29,15	29,53	28,53	29,66	25,65	30,02	29,39	28,73
02-03	27,3	28,89	29,1	28,12	29,56	25	29,72	29,04	28,34
03-04	26,38	28,56	29,05	28,25	29,55	25,51	29,46	28,87	28,20
04-05	26,45	28,35	29,36	28,51	29,72	26,91	29,88	29,05	28,53
05-06	27,42	29,32	32,11	29,75	30,07	28,41	29,91	29,34	29,54
06-07	28,22	31,58	46,88	31,84	31,28	32,32	29,74	29,84	32,71
07-08	28,98	46,78	67,7	50,03	44,58	51,11	29,96	30,15	43,66
08-09	29,57	44,9	62,07	48,08	35,61	37,69	30,58	30,72	39,90
09-10	29,78	34,9	46,9	34,98	36,41	44,03	31,05	31,24	36,16
10-11	29,94	31,86	33,59	33,02	32,92	31,53	31,49	31,39	31,97
11-12	29,97	31,53	32,84	33,29	32,43	31,44	31,29	31,49	31,79
12-13	29,92	31,68	32,56	32,8	32,32	31,4	30,83	31,12	31,58
13-14	29,85	31,04	32,5	33,5	32,55	31,54	30,74	31,06	31,60
14-15	29,93	39,43	64,06	64,03	44,31	54,08	30,73	31,3	44,73
15-16	30,36	46,77	64,1	64,02	61,94	65,03	31,13	34,36	49,71
16-17	31,55	38,02	66,73	62,08	44,94	58,74	31,53	38,42	46,50
17-18	31,39	34,98	46,87	50,01	34,01	35,78	31,49	35,72	37,53
18-19	30,34	31,92	46,87	58,01	33,77	36,27	31,1	32,91	37,65
19-20	30,05	30,7	35,48	34,7	32,36	31,67	30,91	31,51	32,17
20-21	29,88	30,16	31,12	33,43	31,28	30,99	30,49	31,05	31,05
21-22	29,8	30,14	30,43	32,54	30,96	30,93	30,2	30,89	30,74
22-23	29,65	29,76	30,04	30,98	30,45	30,66	30,02	30,74	30,29
23-00	29,06	29,07	29,37	29,88	29,88	30,1	28,99	30,37	29,59

$$C_{3,\mathrm{day}} = (43.66 + 44.73 + 49.71 + 46.5)/4 = 46.15$$

$$C_{3,\mathrm{night}} = (29.31 + 28.73 + 28.34 + 28.2 + 28.53 + 30.29 + 29.59)/7 = 29$$

Hour	30.01. 2015	29.01. 2015	28.01. 2015	27.01. 2015	26.01. 2015	25.01. 2015	24.01. 2015	23.01. 2015	Average price
00-01	26,6	23,97	26,97	25,79	26,93	26,94	28,48	30,08	26,97
01-02	26,23	23,13	26,59	25,32	26,13	26,49	27,06	29,25	26,28
02-03	26,42	23,04	25,93	25,15	25,54	26,29	26,46	28,86	25,96
03-04	26,29	23,08	25,27	25,23	25,41	26,18	26,25	28,78	25,81
04-05	26,72	24,4	25,75	25,9	25,81	26,29	26,36	29,39	26,33
05-06	28,84	28,62	29,15	29,73	31,12	26,7	26,71	31,88	29,09
06-07	36,39	33,19	42,2	39,05	45,08	27,04	27,16	45,08	36,90
07-08	42,91	43,34	42,6	64,01	54,46	27,39	28,69	54,28	44,71
08-09	39,92	39,91	39,3	55,08	50,07	27,98	29,37	53,56	41,90
09-10	35,87	35,8	36,19	56,21	50,05	28,71	29,01	57,68	41,19
10-11	34,96	35,71	35,18	55,05	43,75	29,26	29,3	56,97	40,02
11-12	35,81	35,23	34,99	50,09	49,9	29,97	29,33	54,41	39,97
12-13	36,63	34,78	33,51	50,67	39,44	29,74	29,3	48,09	37,77
13-14	35,9	33,08	33,47	45,29	36,24	29,25	29,25	43,89	35,80
14-15	36,85	32,44	33,94	45,28	38,58	29,13	29,34	42,43	36,00
15-16	42,73	36,66	35,88	61,04	49,64	29,26	30,1	45,08	41,30
16-17	43,39	41,62	39,99	65,02	50,04	30,29	34,19	44,72	43,66
17-18	40,66	38,91	37,35	64,04	50,02	33,07	34,92	48,06	43,38
18-19	38,87	38,17	39,56	45,29	45,08	32,64	31,06	43,54	39,28
19-20	30,62	29,16	29,94	31,08	31,79	31,26	30,06	34,49	31,05
20-21	29,53	28,67	27,56	29,87	29,61	30,25	29,35	31,47	29,54
21-22	29,06	28,39	27,1	29,34	28,69	29,47	28,66	31,17	28,99
22-23	28,79	28,05	26,18	28,89	28,01	29,2	28,11	30,17	28,43
23-00	27,67	26,48	24,92	27,8	26,51	28,07	27,72	29,1	27,28

$$C_{4,\text{day}} = (44.71 + 41.9 + 43.66 + 43.38)/4 = 43.41$$

$$C_{4,\text{night}} = (26.97 + 26.28 + 25.96 + 25.81 + 27.28)/5 = 26.46$$

Hour	28.02. 2015	27.02. 2015	26.02. 2015	25.02. 2015	24.02. 2015	23.02. 2015	22.02. 2015	21.02. 2015	Average price
00-01	21,24	25,64	23,51	24,98	23,66	25,32	25,46	22,61	24,05
01-02	21,88	25,26	23,12	24,64	22,35	25,03	25,11	22,15	23,69
02-03	21,98	25,07	22,99	23,9	22,13	24,81	25,09	22,09	23,51
03-04	23,04	25,08	23,26	24	22,2	24,72	24,94	22,52	23,72
04-05	24,24	25,55	24,19	24,91	22,58	24,76	24,96	23,48	24,33
05-06	29,68	26,2	26,35	45,21	26,83	24,98	24,88	37,68	30,23
06-07	39,42	31,02	31,34	45,05	34,02	25,13	25,08	44,09	34,39
07-08	38,39	33,94	35,56	40,05	32,25	25,33	25,69	44,1	34,41
08-09	44,26	34,24	45,03	46,05	32,12	25,88	26,06	39,98	36,70
09-10	44,25	31,43	39,96	46,01	31,06	26,11	26,38	44,1	36,16
10-11	43,97	31,08	39,98	46,01	31,07	26,22	26,7	44,09	36,14
11-12	27,38	26,94	27,31	29,5	31,02	26,18	26,67	28,15	27,89
12-13	26,64	26,46	27,22	26,94	29,59	25,84	26,17	28,48	27,17
13-14	26,55	26,34	27,11	28,92	27,18	25,52	25,98	27,13	26,84
14-15	29,51	28,93	31,01	36,5	26,96	25,31	25,97	32	29,52
15-16	30,03	30,53	30,02	31,07	26,64	25,05	26,19	31,95	28,94
16-17	33,04	32,92	32,57	36,42	27,16	26,16	30,97	39,95	32,40
17-18	42,71	45,06	44,49	48	31,06	31,02	44,01	45,03	41,42
18-19	44,27	45,05	44,5	46,03	31,05	31,02	33,19	44,09	39,90
19-20	27,1	27,14	28,14	28,29	30,39	27,5	28,97	30,76	28,54
20-21	26,19	25,99	27,14	26,17	26,55	26,07	26,25	26,39	26,34
21-22	26,08	25,62	26,82	25,92	26,38	26,62	26,34	26,2	26,25
22-23	25,73	25,14	26,44	25,37	26,1	26,5	26,17	25,98	25,93
23-00	25,29	24,03	25,96	24,6	24,93	25,07	25,35	25,55	25,10

$$C_{5,\mathrm{day}} = (36.7 + 41.42 + 39.9)/3 = 39.34$$

$$C_{5,\mathrm{night}} = (24.05 + 23.69 + 23.51 + 23.72 + 24.33 + 25.93 + 25.1)/7 = 24.33$$

Hour	30.03. 2015	29.03. 2015	28.03. 2015	27.03. 2015	26.03. 2015	25.03. 2015	24.03. 2015	23.03. 2015	Average price
00-01	23,21	22,9	25,06	24,17	23,4	24,67	24,21	23,78	23,93
01-02	23,02	22,37	24,37	24,05	22,92	24,51	24,05	23,17	23,56
02-03	22,56	23,61	24,34	24,01	22,89	24,41	24,07	23,3	23,65
03-04	22,61	21,94	24,39	24,07	23,1	24,46	24,15	23,47	23,52
04-05	23,22	21,52	24,96	24,38	23,77	24,98	24,49	23,84	23,90
05-06	23,73	21,78	25,64	27,11	30,85	33,33	25,17	32,84	27,56
06-07	36,07	22,19	25,59	31,07	33,4	40,07	32,82	40,03	32,66
07-08	42,25	21,82	26,31	32,89	40,06	43,05	39,04	42,09	35,94
08-09	42,83	22,62	25,97	41,98	42,11	43,06	42,35	42,22	37,89
09-10	47,2	23,33	27,07	39,02	39,26	43,03	40,73	40,05	37,46
10-11	46,56	23,72	27,14	34,21	33,38	40,09	36,01	39,22	35,04
11-12	49,96	23,8	26,7	32,11	37,63	43,04	32,8	41,67	35,96
12-13	49,93	23,65	25,51	28,91	28,22	30,8	27,5	30,47	30,62
13-14	34,98	23,53	24,44	27,76	27,16	30,8	26,98	27,14	27,85
14-15	31,25	23,33	24,23	30,84	27,33	36,09	33,72	33,34	30,02
15-16	42,28	23,27	24,23	34,23	27,16	40,03	32,85	33,61	32,21
16-17	42,25	23,4	27,24	31,85	26,61	36,07	30,88	33,78	31,51
17-18	36,09	23,76	30,89	37,99	30,41	41,9	39,94	35,09	34,51
18-19	42,29	24,28	42,23	42,22	40,92	43,05	42,03	42,21	39,90
19-20	47,82	24,97	36,07	30,86	27,1	30,86	39,1	30,83	33,45
20-21	28,18	25,01	26,79	25,96	26,41	25,92	28,41	25,59	26,53
21-22	25,38	24,49	28,93	24,9	26,1	25,03	27,71	25,28	25,98
22-23	24,97	24,09	27,14	24,42	24,9	24,42	26,18	24,77	25,11
23-00	23,33	23,6	22,16	24,08	24,22	23,81	24,87	24,1	23,77

$$C_{6,\mathrm{day}} = (37.89 + 37.46 + 39.9)/3 = 38.42$$

$$C_{6,\mathrm{night}} = (23.93 + 23.56 + 23.65 + 23.52 + 23.9 + 23.77)/6 = 23.72$$