THESIS ON POWER ENGINEERING,
ELECTRICAL ENGINEERING, MINING ENGINEERING D70

Development of Energy Reserve Optimization Methodology for Households with Renewable Power Systems

AIVAR AUVÄÄRT

TUT PRESS

TALLINN UNIVERSITY OF TECHNOLOGY
Faculty of Power Engineering
Department of Electrical Engineering

Dissertation was accepted for the commencement of the degree of Doctor of Philosophy on Power Engineering and Geotechnology

Supervisors: Senior Researcher Ph.D. Argo Rosin, Department of Electrical Engineering, Tallinn University of Technology

Professor D.Sc. Tõnu Lehtla, Department of Electrical Engineering, Tallinn University of Technology

Opponents: Dr.sc.ing Anna Mutule, Leading researcher, Laboratory of Power Systems Mathematical Modelling, Institute of Physical Energetics, Latvia and Associate Professor, Riga Technical University, Latvia

Professor D.Sc. Andres Annuk, Institute of Technology, Department of Energy Engineering, Estonian Univeristy of Life Sciences

Defense of the thesis: 21.08.2014

Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology, has not been submitted for doctoral or equivalent academic degree.

Aivar Auväärt...............................

Copyright: Aivar Auväärt, 2014
ISSN 1406-474X
ISBN 978-9949-23-664-0 (publication)
ISBN 978-9949-23-665-7 (PDF)

ENERGEETIKA. ELEKTROTEHNIKA. MÄENDUS D70

Taastuva energia allikatega kodumajapidamiste energiareservi optimeerimise metoodika väljatöötamine

AIVAR AUVÄÄRT

TTÜ
KIRJASTUS

CONTENTS

LIST OF PUBLICATIONS

The present doctoral thesis is based on the following publications, which are referred to in the text byRoman numbers I-VI:

[I] Rosin, A.; Auväärt, A.; Lebedev, D. (2012). Energy storage dimensioning and feasibility analysis for household consumption scheduling based on fluctuations of Nord Pool Spot price. Przeglad Elektrotechniczny, 88(1a), 37 - 40.

[II] Rosin, A.; Rosin, K.; Auväärt, A.; Strzelecki, R. (2012). Dimensioning of household electricity storage for PV-systems and load scheduling based on Nord Pool Spot prices. Przeglad Elektrotechniczny, 88(4b), 294 – 299.

[III] Rosin, A.; Auväärt, A.; Lebedev, D. (2012). Analysis of operation times and electrical storage dimensioning for energy consumption shifting and balancing in residential areas. Electronics and Electrical Engineering, 4 (120), 15 – 20.

[IV] Auväärt, A.; Rosin, A.; Belonogova, N.; Lebedev, D. (2011). Nord Pool Spot price pattern analysis for households energy management. *In: 7th International Conference-Workshop Compatibility and Power Electronics (CPE2011), Tallinn, Estonia, June 01-03, 2011:* IEEE, 2011, 103 - 106.

[V] Rosin, A.; Palu, I.; Rosin, K.; Auväärt, A. (2012) Dimensioning of Electricity Storage according to Small Wind Turbine Power Generation and Household Load Patterns. *In: 38th Annual Conference on IEEE Industrial Electronics Society (IECON), Montreal, Canada, 25 - 28 October, 2012: IEEE, 2012, 5155 – 5160.*

[VI] Aivar Auväärt, Argo Rosin, Kai Rosin, Imre Drovtar, Madis Lehtla. (2013) Comparison of Renewable Electricity Generation Options with Household Electrical Load Patterns. In: IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society, Vienna, Austria, 10 - 13 November, 2013: IEEE, 2013, 1553 - 1558

In Appendix 1, copies of publications I-VI are included.

Author’s Contribution to the Publications

The contribution by the author to the papers included in the thesis is as follows:

[I] Aivar Auväärt participated in writing the paper. He was responsible for data collection and some of the calculations. He had substantial role in writing.

[II] Aivar Auväärt participated in writing the paper. He was responsible for some of the calculations. He had substantial role in writing.

[III] Aivar Auväärt participated in writing the paper. He was responsible for data collection and some of the calculations. He had substantial role in writing.

[IV] Aivar Auväärt is the main author of the paper. He is responsible for literature review and data collection, and performed the calculations. He had a major role in writing. He made a presentation of the paper at 7th International Conference-Workshop Compatibility and Power Electronics (CPE2011), Tallinn, Estonia.

[V] Aivar Auväärt participated in writing the paper. He was responsible for data collection and some of the calculations. He had minor role in writing.

[VI] Aivar Auväärt is the main author of the paper. He is responsible for literature review and data collection, and performed some calculations. He had a major role in writing.

INTRODUCTION

Motivation

The deregulation of the electricity industry leads to global developments toward the commodization of electric energy [1, 2]. The liberalization and privatization of the electricity sector began in Chile in 1982 and the trend spread to Latin American countries and the rest of the world in the 1990s [3].

This tendency has intensified in Europe and North America, where market forces have pushed policymakers to begin removing artificial obstacles that have shielded electric utilities from competition.The price of electricity is far more volatile than that of other commodities normally noted for extreme volatility [2].

Relatively small changes in load or generation can cause large changes in price and all in a matter of hours (with real-time dynamic prices in seconds or minutes) [4].

Unlike in the financial markets, electricity is traded every hour of the year, but electricity cannot be stored efficiently. The balance between the generation and consumption must be kept every hour of a year [5].

However, electricity and other commodity markets are not similar. The wide variety of variable costs on the production side is the reason for a large difference. There is nearly no variable cost in hydro and wind generation and thus gas powered turbines are considered on a wide scale. To satisfy the demand for low cost power, a variety of generation sources are needed. Some power generation units are expensive to build but can be operational all year round [6]. Other types like combined heat and power are used mostly to cover wintertime heating and needs during high price periods. Gas powered turbines are used only for certain periods of high price and electricity demand because of their energy intensive nature [7].

Thesis objectives and tasks

The main objective of the thesis is to analyze the possibility to use electrical energy reserves for balancing of energy generation and consumption in households and to present some data for dimensioning the electrical energy reserve in real-time open market conditions using renewable energy generation on the example of photovoltaic panels and wind turbines.

This research is important because the open market price fluctuations in Estonia are scarcely studied and the market opened fully for all customers in 2013. Also, costs of energy storage and small-scale renewable sources are being reduced and subsidies are available for their installation at private houses. The use of a renewable energy source in conjunction with energy storage and open market prices could be beneficial also for smaller customers. Therefore the analysis of energy consumption in a smaller household is essential to acquire information for dimensioning the energy reserve.

Research tasks

Statistical analysis of the power generation of solar and wind power systems, load patterns and electricity price to design an energy reserve optimization methodology for grid connected households with integrated small-scale renewable systems, which includes

- Analysis of time-dependence of electricity consumption and Nord Pool Spot price fluctuations for household energy management to overcome peak times
- Analysis for the evaluation of electricity production in small-scale renewable power generation systems
- Development of an energy reserve optimization methodology for grid connected households with integrated small-scale renewable systems

Major results and novelty

The scientific contributions of the thesis, which are considered as new, can be summarized as the development of an energy reserve optimization methodology for grid connected households with integrated small-scale renewable systems, which includes analysis methods for the evaluation of

1. Nord Pool Spot price fluctuations
2. load patterns and time dependence of electricity consumption
3. spot price based load management possibilities
4. distributed/local renewable power generation
5. balance between distributed/local power generation and consumption

Thesis outline

The thesis is divided into three chapters, the introduction and conclusions.

Chapter 1 provides an overview of issues in the contemporary open electricity market, the Nord Pool Spot market and the storage systems suited for small-scale systems.

Chapter 2 covers the analysis of energy use of home users, the price formation in Nord Pool Spot Estonian area and introduction of a simplified method on the possible use of price fluctuations at households using a storage system.

Chapter 3 describes the electrical energy reserve optimization method for households using renewable power generation.

SYMBOLS

a – represents an Nord Pool Spot area
d_a – demand in the area a
D_a – demand function in the area a
s_a – supply in the area a
S_a – supply function in the area a
n_{nps} – number of areas
t – index for time
S – energy storage level
Δt – time step (h)
P_s – power output of energy storage
S – energy storage level
η_s – round-trip efficiency of energy storage
η_c – charging efficiency of energy storage
η_d – discharging efficiency of energy storage
E_{st} – minimum electrical storage capacitance
E_{hb} – high-tariff consumption before shifting of shiftable loads
E_{sh} – shifted energy
E_{ha} – high-tariff consumption after energy consumption shifting of shiftable loads
$E_{u,\Sigma}$ – energy of the under-consumption period
$E_{o,\Sigma}$ – energy the over-consumption period
$E_{o,max}$ – energy consumption at the highest over-consumption period
$E_{u,max}$ – energy consumption at the highest under-consumption period
E_i – energy amount at the moment i
$\overline{E}$ – average energy consumption
$E_{i,awh}$ – water heater energy consumption after shifting at time i
$E_{i,bwh}$ – water heater energy consumption before shifting at time i
$E_{i,b}$– total energy consumption before shifting at time i
E_{SE} – shortage of energy, which should be balanced by the electrical energy storage
X_i – price of electrical energy in the instance i
X_F – average area price
A_{pv} – PV-module area
k_{pr} – performance ratio
E_c – total daily electricity consumption
E_{pv} – daily electricity generation of a PV-system
E_s – global irradiance in Wh
η_{pv} – efficiency of a PV-system
$E_{pv,i}$ – generated electricity at the hour i
n – 24 hours a day
$\overline{E_{pv}}$ – average daily electricity generation
V_R – coefficient of variation

P– power of a turbine,
A – rotor area;
ρ – density of air;
η– efficiency;
d – diameter of rotor;
v – wind speed;
c_w – power coefficient;
E_g – electricity generation of a wind-turbine per day;
$P_{r,g}$ – rated power of a wind turbine;
$P_{r,c}$ – needed rated power of a wind turbine for covering daily electricity consumption.
E_{pp} – electricity generated by a generation system
E_{sp} – surplus of generated electricity
E_{los} – total losses
$E_{dir,c}$ – direct consumption of electricity generated by a generation system
$E_{res,c}$ – indirect consumption of electricity generated by a generation system
$E_{g,i}$ – electricity generated at the hour i
$E_{c,i}$ – electricity consumption at the hour i
E_{sp} – daily surplus of electricity
$E_{g,i}$ – electricity generated at the hour i
$E_{c,i}$ – electricity consumption at the hour i
$E_{g,i,m}$ – electricity generated at the month i
n_y – 12 months a year
$\bar{E}_g$ – average annual electricity generation.
E_{res} – daily demand for stored energy
$E_{res,i}$ – demand for stored energy at the hour i
k_{res} – relative daily demand for stored electricity compared to total demand (i.e. consumption)
E_{dir} –average daily directly consumed electricity
k_{dir} – relative direct coverage of load
x – first range of values (e.g. power generation) and
y – second range of values (e.g. power consumption)

ABBREVIATIONS

AC	Alternating current
CAES	Compressed air energy storage
CHP	Combined heat and power
CSP	Concentrated Solar Power energy storage.
DC	Direct current
DoD	Depth of discharge
EE	Nord Pool Spot Estonian area
ES	Electricity storage
HD	Weekend days
HY	Hybrid
kWh	Kilowatt hour
NPS	Nord Pool Spot
PG	Power generation
PHES	Pumped hydroelectric energy storage
PV	Photovoltaic
SESAM	Nord Pool Spot Trading System
SMES	Superconducting magnetic energy storage
SP1	Nord Pool Spot system area
WD	Working days
VRF	Vanadium redox flow
WT	Wind turbine

1. STATE OF THE ART AND RECENT ADVANCES IN OPEN ELECTRICITY MARKET AND DEMAND-SIDE MANAGEMENT POSSIBILITIES

1.1 Open electricity market

The process of deregulation of electricity market started in South America in 1982, slowly spreading around the world. In 1990, the privatization of the electricity industry in England and Wales triggered processes for the deregulation of electricity market in other Commonwealth of Nations countries and from there all over the world. Despite different deregulation processes, market concepts are relatively the same. Main tasks of a market are: to unbundle the competitive functions from the monopoly functions and to establish a free wholesale and retail electricity market.

In different jurisdictions, bulk system (or "grid") operators are termed in a different way: in Europe they are called transmission system operators (TSOs); in India - load dispatch centers; in the United States - regional transmission organizations (RTOs) or independent system operators (ISOs). Operators of the low-voltage level who reduce the voltage from the transmission lines and deliver power through the distribution lines also have different names, including distribution system operators (DSOs) in Europe and utilities in the United States. The load-serving entities (LSEs), such as utilities, competitive retailers, and the DSOs that sell electricity to retail consumers, purchase their power from the wholesale energy market [8].

Current literature points out three major models in use for electricity markets: the Bertrand model [9], the Cournot model [10], and the supply function equilibrium (SFE) model [11]. The SFE model applies very well to the market structure of many restructured electricity markets, such as New Zealand, Australia, Pennsylvania-New Jersey-Maryland Interconnection, California Power Exchange and Nord Pool Spot. In these markets, the bid format is precisely a supply function [12].

There are several open electricity markets worldwide that are mostly operating on regional basis. Some countries are also part of several electricity markets, like Germany (European Energy Exchange EEX, EPEX SPOT, Austria - EPEX SPOT, EXAA Energy Exchange; Hungary - Hungarian Power Exchange HUPX and PXE - Power Exchange Central Europe [13-17] and some larger countries have several electricity markets within the country mostly due to territorial reasons; Australia - Wholesale Electricity Market (WEM) for the South West interconnected system of Western Australia (SWIS), Australian Power Market Operator for other parts of Australia, and USA with ten different electricity markets [18-20].

1.2 Estonia in the open electricity market

The Estonian electricity market is a part of the physically interconnected Nordic market, which also includes Finland, Denmark, Norway, and Sweden. Nord Pool Spot offers both day-ahead and intraday markets to its participants. 370 companies from 20 countries trade on the Exchange. In 2011, the NPS group had a turnover of 316 TWh and in 2013 already 493 TWh [21].

The Estonian market has been open for large consumers since 2010. A large consumer is a company that uses more than 2 GWh of electricity a year through one connection point. The law provides a large consumer the right and the obligation to choose their own electricity seller. This can be done by purchasing directly or through a broker in the Nord Pool Spot's Estonia price area. The electricity market was opened fully for all consumers from 2013.

The main factors that influence the price of electricity in the open market are the availability of production capacity and connenction capacity that ensure electricity flow within the country and between neighboring countries. Nowadays, Estonia has electricity connections with Russia, Latvia and Finland. Connection to Finland is via the 350 MW sea cable EstLink 1. In 2014 the EstLink 2 sea cable between Estonia and Finland was opened, tripling the transmission capacity between the Baltic and Nordic countries. In addition to EstLink 2, NordBalt between Lithuania and Sweden (2016), a third line between Estonia and Latvia (2020) and LitPol between Lithuania and Poland (2020) are being planned [22].

The spot market at NPS is an auction-based exchange for the trading of physically delivered electricity. The spot market's key task is balancing the supply and demand in the power market. There is also a final balancing process for fine adjustments in the real time balancing market. The spot market receives bids, offers from producers and consumers alike, and calculates an hourly price that balances these opposing sides. NPS publishes a spot price for each hour of the coming day in order to balance supply and demand [23].

The SESAM calculation equation is based on an application of the social welfare criteria in combination with market rules. SESAM is maximizing the value of the objective function subject to physical constraints, like volume constraints, area balances, transmission and ramping constraints [24].

$$Max\sum_{n}\left\{\int_{0}^{d_a} D_a(x)dx - \int_{0}^{s_a} S_a(y)dy\right. , \tag{1.2.1}$$

where a – an area; d_a – demand in the area a; D_a – demand function in the area a; s_a – supply in the area a; S_a – supply function in the area a; and n – number of areas.

The system area price for each hour determined by the intersection of the aggregate supply and demand curves representing all bids is offered for the entire

Nordic region. In addition to the area price there is also an annual fixed fee and a variable trading fee for all market participants. In the political debate surrounding energy, this type of price formation is labeled a marginal price setting. However, this gives a false impression that the establishment of prices in the electricity market is different from the price formation process in other commodity markets. The only difference lies in the significantly higher requirements for the secure delivery of electricity because it must be delivered at the precise moment it is needed by the consumer. The inelasticity caused by the inability to store electricity is the reason of this difference [25].

1.3 Electricity storages for households

ES is a vital factor for distributed generation systems in order to fulfil power peaks, reduction of installed generation capacity and balancing missing long and short-term coincidence between power generation and demand [26].

Optimal dimensioning of electricity storage according to the energy production of micro-scale renewables (in residential areas and households) and electricity consumption are important topics in the development of micro- and smartGRID technologies to increase system reliability and to reduce the profitability time. Flourishing use of an electrical grid needs permanent online balancing of supply and demand, including grid losses. Correctly chosen electricity storage technologies will smooth out these surges and allow electricity to be dispatched later [27].

All the commercially available battery storage systems have a similar system design: batteries are connected to a power conversion system that converts a variable DC voltage of the battery to a 3-phase AC voltage of the utility [28].

The battery storage device is defined by its energy capacity, charging efficiency, discharging efficiency, charging power capacity, and discharging power capacity. The relationship between the storage content S and the power flow in/out of the storage P_s is as follows [29]:

$$\begin{matrix} (P_s(t) \geq 0) \\ (P_s(t) < 0) \end{matrix} \qquad S(t+1)) = \begin{cases} S(t) - \dfrac{1}{\eta_d} P_s(t)\Delta t \\ S(t) - \eta_c P_s(t)\Delta t \end{cases} \tag{1.3.1}$$

$$\begin{gathered} P_s^{\min} \leq P_s(t) \leq P_s^{\max} \\ S^{\min} \leq S(t) \leq S^{\max} \end{gathered} \tag{1.3.2}$$

where η_c and η_d - efficiencies of charging and discharging, respectively; t - index for time; S - energy storage level; Δt - time step; P_s - power output of energy storage; S - energy storage level. The round-trip efficiency of electricity storage is $\eta_s = \eta_c \cdot \eta_d$

Electricity can also be stored by converting it into another form such as potential, kinetic or chemical energy [30]. ES has a wide spectrum of use in different applications. It is mainly derived from their special storage capacities and energy power that can be received from various ranges of devices. Figure 1.3.1 shows a widely used approach for classifying electrical energy storages according to the energy form used [31].

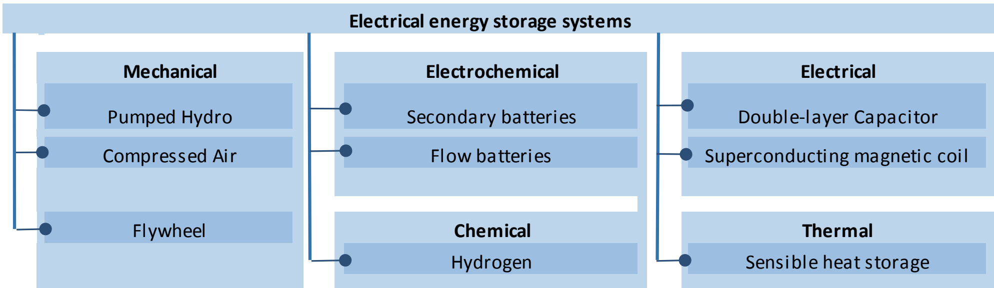

Figure 1.3.1. Classification of electrical energy storage systems according to the energy form

CAES and pumped hydro do not suit well for small-scale renewable energy systems due to the size and the costs of these systems and therefore havea wider use in utility scale installations. SMES and SCES are high-power devices that have very high efficiency and can withstand several cycles without substantial loss of energy storage capacity but they have high execution expenditures and the technology is in the stage of development [30, 32, 33].

Kinetic energy storage systems [32, 34, 35] mostly based on flywheel technology are used for short duration, high-power discharges and are therefore widely used in the uninterruptable power source market. The main disadvantage is the friction losses [34, 36] and therefore they have a rather high cost for set-up and care [32]. Flow battery characteristics include high power and low self-discharge as compared to other forms of storage technologies [37, 38]. Flywheels and fuel cells are not yet suitable for integration at households but the batteries with their high energy density, well-known technology and simplicity of relative usage are a much better option [30].

Effects of demand response on the end-customer distribution fee and experiences from spot-market based price response of residential customers are reviewed in [39, 40]. Opening of the electricity market gives new opportunities to optimize micro grid topologies, including surface and storage capacity of a PV system. Optimization of renewable systems (including HY renewable systems and WT or PV systems with ES) has been studied thoroughly, but analysis about the optimization of electricity reserve and renewable systems according to open electricity market prices (e.g. NPS) is scarce.

2. ENERGY MANAGEMENT ANALYSIS IN HOUSEHOLDS

This chapter is a compedium of articles [I], [III] and [IV] and takes into consideration the issues described in the previous chapter. It covers the household consumption patterns and storage considerations according to the operational times of home appliances and considers open electricity market "Nord Pool Spot" price fluctuations as a possibility of retrenchment of electricity cost at households.

The total primary energy consumption of U.S. residential and commercial buildings is around 73% of the total US electricity consumption, which includes also the construction sector [41, 42]. U.S. building sector includes single- and multi-family residences and commercial buildings use 41% of the primary energy in the United States of America.

Consumption of electricity at households in Estonia is nearly 35% of the total national energy consumption, and in this respect is one of the largest in the European Union [43].

Energy consumption management in buildings has only two generally known approaches, one is consumption reduction and the other is consumption shifting [44]. The anterior is enabled by raising awareness among users and building more energy efficient buildings [45]. There are some demand-side management systems in which management takes place on the basis of priority [46-48], although the feasibility of these systems is questionable. For feasible consumption shifting management, the consumption patterns must be analyzed beforehand.

Multi-tariff systems with large tariff differences could be the major factor in changing the customer behavior. The inquiries of household owners and energy consumption analysis have shown low awareness about the energy consumption, consumption shifting possibilities and feasibility. About 80% of household owners know that using compact fluorescent lamps and consumption shifting to the low tariff period reduces the costs. Less than 20% of people are unaware of consumption distribution between the loads like lighting, water heating etc.; high and low tariff consumption distribution by loads; and investments feasibility of energy consumption shifting or energy saving devices [49].

Households without power generation ability have only two cost reduction methods: a) reduction of consumption or b) time-shifting loads. The profitability of time-shifting depends on load priorities and possibility to use energy storage. The household consumption is not uniform, different appliances have different regimes, priorities and roles [50]. Energy storage systems play a key role in shifting critical (not shiftable) loads. Storages can be classified into heating and electrical ones. Heating energy storages are water or space heaters in residential buildings with electrical heating loads. In terms of total consumption, these loads have mainly high-energy consumption, which is about 30%...50%. Energy consumption shifting and balancing with existing heating energy storage systems needs small investments, and their profitability is mostly less than one year.

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

- to minimize their energy costs
- to increase the power quality and comfort

Authors' [49] position is that consumption priorities can be divided into three main groups:

- non-shiftable (a),
- almost shiftable (b),
- shiftable (c).

Shiftable loads can be defined as loads that can be shifted from a high tariff period to a low tariff period without any investments to additional electrical or thermal ES systems. Shiftability is closely related to customer's needs or convenience and depends on the functional possibilities of the loads, technical characteristics and surrounding environment (including building construction).

2.1 Load taxonomy and analysis of electrical energy consumption patterns

Consumer loads in US are studied by the US Department of Energy. The result is shown in Figure 2.1.1 [42] where wet cleaning incorporates washing machines and dryers as well as dishwashers; adjust to SEDS is the US Energy Information Administration's adjustment to reconcile supply-side.

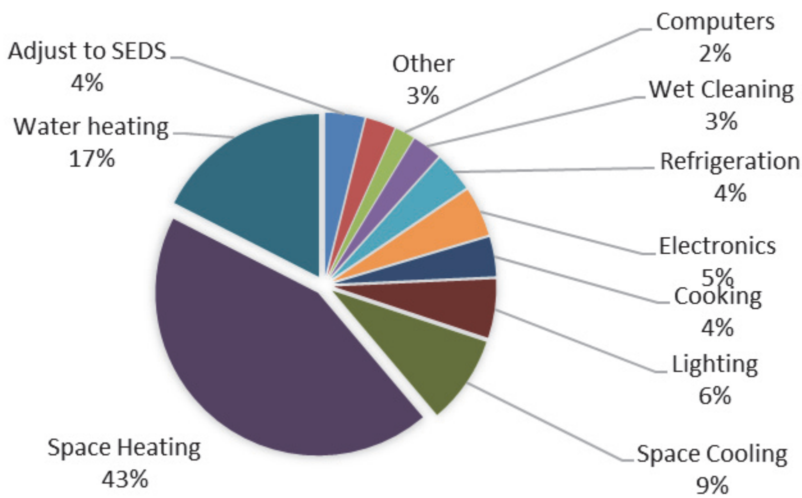

Figure 2.1.1 Residential energy use in US in 2011 [42]

The authors' [49] analysis is based on four-week measurements (in February/March 2012). They chose an average Estonian household as an object of analysis. The entire energy consumption by load in that apartment is shown in Figure 2.1.2. Similarities with energy use in US households are quite evident.

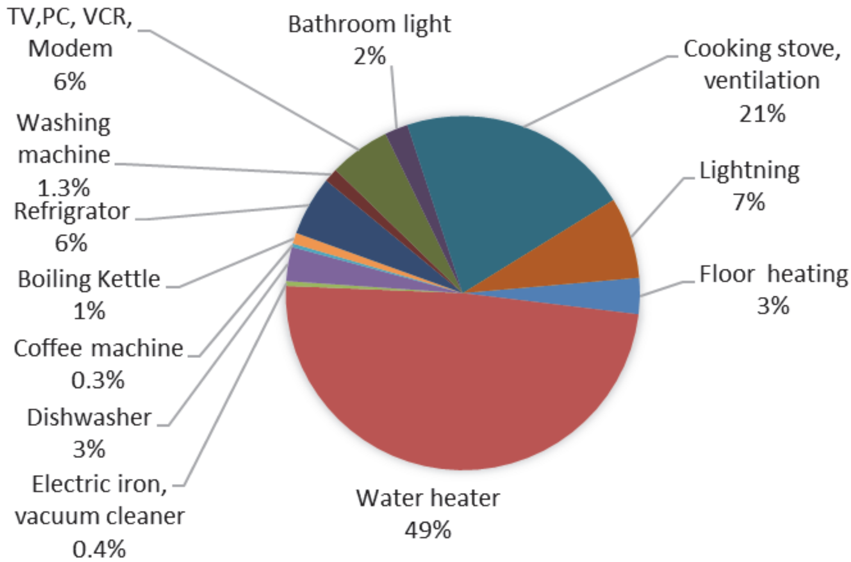

Figure 2.1.2. Load distribution of household appliances [49]

Analysis on the customer behavior and the real consumption preferences can be classified according to [50].

1. Shiftable loads are electrical water heaters, dishwashers and washing machines - about 54% from the total consumption.
2. Nearly shiftable loads are refrigerators, boiling kettles, coffee machines, floor heating, irons, and vacuum cleaners - about 10% from the total consumption.
3. Non-shiftable loads are TV sets, PCs with a modem, home cinema and music centers, cooking stoves, kitchen ventilation, bathroom lighting and ventilation - about 36 % from the total consumption [49].

2.2 Time-dependence of energy consumption

Based on the analysis of electricity consumption [Ibid], the average workday consumption per hour is 0.9 kWh, and the average holiday consumption per hour is 1.4 kWh. Before the consumption shifting and reducing in the workday, the average high-tariff consumption is 1.05 kWh/h and average low-tariff is 0.55 kWh/h. Three peak hours were discovered: a couple of hours on the workday morning, noon on holiday and evening on workday and holiday. Main load: in the morning, noon and evening is the water heater; at noon and in the evening - the cooking stove. The lighting influences only consumption in the evening.

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

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

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

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

2.3 Energy reserve dimensioning for consumption shifting in a two-tariff system

If the consumption of all freely shiftable loads (water heater, dishwasher, washing machine) is time-shifted to the low-tariff time and regular lighting bulbs are replaced with compact fluorescent or light emitting diode bulbs, the 6.5...7 kWh of almost- and non-shiftable energy consumption stays in the high-tariff period. After consumption scheduling and using of compact fluorescent lamps, the average high-tariff energy consumption is 0.43 kWh/h.

In the high-tariff period, two high and low consumption periods with a difference of about 7.4 times can be identified. The low energy consumption period is between 7...17 and 21...23 o'clock - with the average energy consumption of 0.165 kWh/h. The high energy consumption period is between 17...21 o'clock with the average energy consumption of 1.22 kWh/h. [III]

Two different choices are available for electrical energy reserve calculation. First, reserve should cover energy need for the whole high-tariff period. Using a simplified formula (2.3.1), reserve capacitance of about 6.9 kWh can be calculated:

$$E_{st} = E_{hb} - E_{sh} = E_{ha}, \tag{2.3.1}$$

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

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

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

2.4 Reserve dimensioning for consumption balancing

In the following analysis the consumption of a water heater, dishwasher and washing machine will be shifted with the electrical energy reserve system. To balance electricity consumption it is important to define average electricity consumption and deviation of electricity consumption. The simplified formulas (2.4.1) and (2.4.2) for the calculation of maximum over- and under-consumption amounts are described as follows:

$$E_i > \overline{E} \Rightarrow \begin{cases} E_{u,\Sigma} = 0 \\ E_{o,\Sigma} = \sum_{i=1}^{n} (E_i - \overline{E}) \\ E_{o,\max} < E_{o,\Sigma} \Rightarrow E_{o,\max} = E_{o,\Sigma} \end{cases}, \qquad (2.4.1)$$

$$E_i < \overline{E} \Rightarrow \begin{cases} E_{o,\Sigma} = 0 \\ E_{u,\Sigma} = \sum_{i=1}^{n} (E_i - \overline{E}) \\ E_{u,\max} > E_{u,\Sigma} \Rightarrow E_{u,\max} = E_{u,\Sigma} \end{cases}, \qquad (2.4.2)$$

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

The average daily electricity consumption is 1 kWh per hour [III]. It is shown in Figure 2.4.1 that at WD two over- and two under-consumption periods occur. Over-consumption periods are from 7 to 10 o'clock and from 17 to 1 o'clock with an energy amount of 2 kWh and 5.4 kWh, respectively. Under-consumption periods are from 1 to 7 o'clock and from 10 to 17 o'clock with an energy amount of 3.5 kWh and 3.9 kWh, respectively.

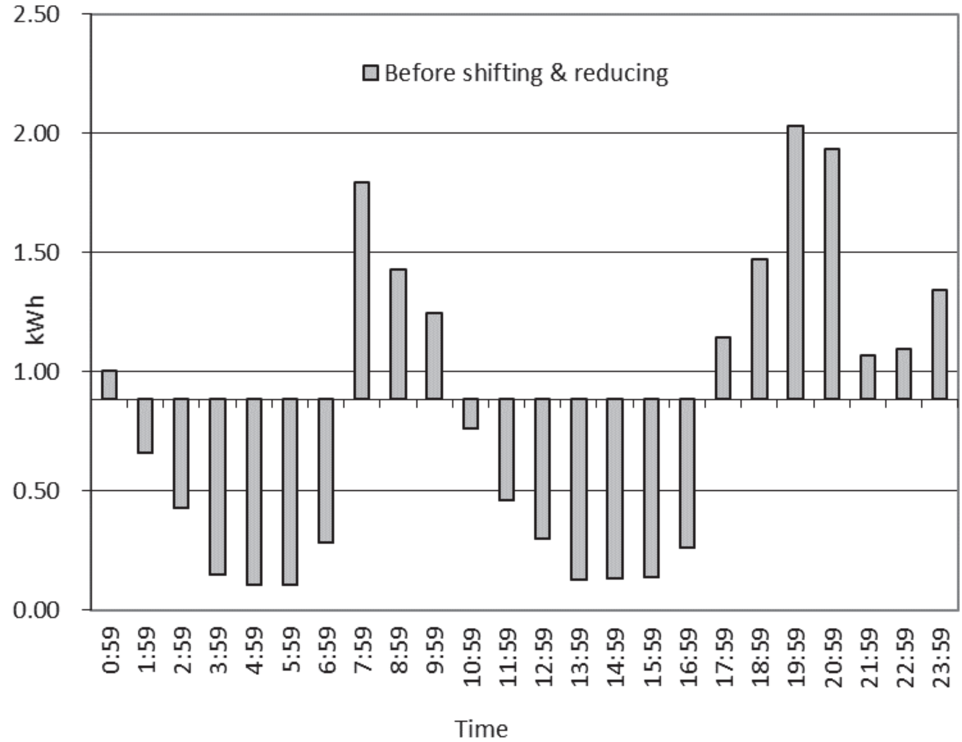

Figure 2.4.1. Average WD electricity consumption before shiftable loads scheduling

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

If all shiftable loads on WD are “switched on“ under average price, then at least 1.1 kWh reserve system is needed for shifting of energy consumption.

If all shiftable loads on HD are “switched on“ under average price, then at least 11.8 kWh of energy consumption should be supplied from the reserve system (Figure 2.4.2). If an average price deviation is allowed (43.05 - 29.76)*10% = 1.33€ (10 % from maximum and minimum price difference), then 4.83 kWh should be supplied from the electrical energy reserve.

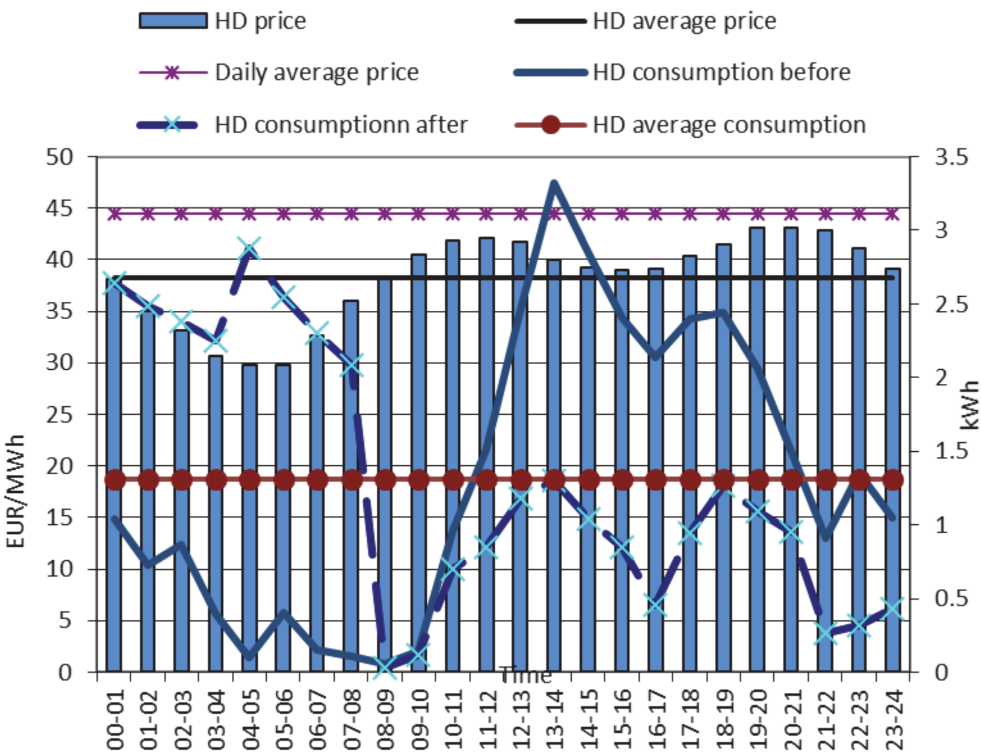

Figure 2.4.2 Average holiday price fluctuation compared to electricity consumption before and after scheduling of shiftable loads

2.5 Consumption balancing with water heater consumption shifting

This section analyzes the use of a water heater for electricity consumption balancing in a two-tariff system. Using a simplified formula (2.5.1) the consumption pattern of a new water heater for balancing is calculated

$$E_{i,awh} = E_{i,bwh} - (E_{i,b} - \overline{E})$$
$$E_{i,awh} < 0 \Rightarrow E_{SE} = \left|\sum_{i=1}^{n} E_{i,awh}\right|, \qquad (2.5.1)$$

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

Figure 2.5.1 shows that consumption scheduling with a water heater can balance electricity consumption on holiday. Also, no problems are encountered in consumption balancing with water heater scheduling at workday from 0 to 17 and 21 to 24 o'clock.

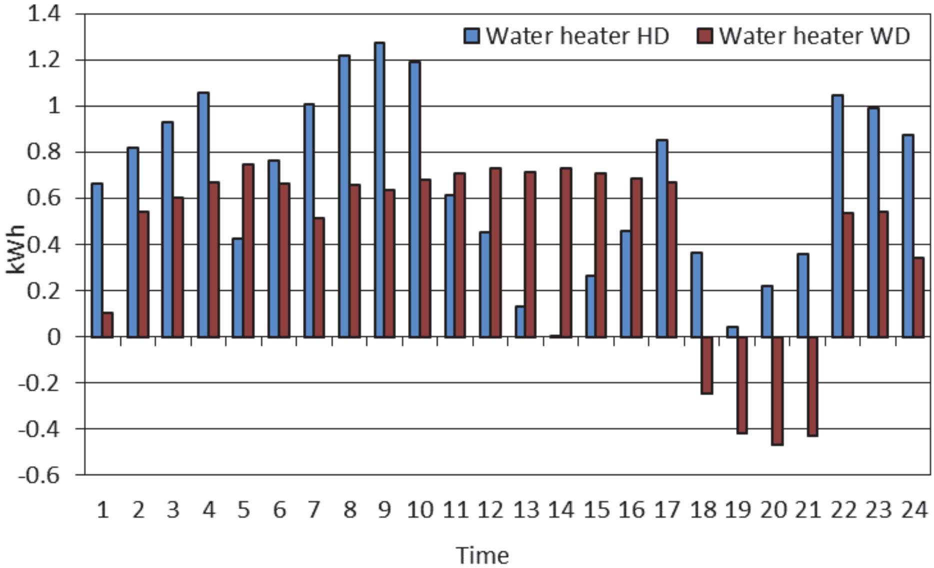

Figure 2.5.1. New consumption pattern for water heater HD and WD consumption

As shown in Figure 2.5.1, it impossible to balance consumption between 17 and 21 o'clock with a water heater. At the same time another high consumption unit, the cooking stove, is used. During that period the shortage of energy is about 1.6 kWh (0.4 kWh per hour), which should be supplied by an additional electrical energy storage system or energy source. An alternative is to reduce the comfort level by shifting or reducing of other non-shiftable loads.

2.6 Reserve dimensioning considering the Nord Pool Spot average daily price

Energy consumption in households in the UK is reported in [51] and in Estonia in [49]. Peak hours for UK households are from 06-08 and 13-18. Main peak hours for Estonian average households are at 07-08 and 19-21 on workdays and 12-14 and 19-21 at weekends. It is quite easy to see the possible use of energy reserve to smoothen the loads at morning or midday use and even the evening use at weekends.

To find the possibilities for consumption scheduling, an average day from the actual data from the NPS trading system was constructed. A period of seven months starting in April 2010 was studied. Average price was calculated with the well-known formula of a generalized mean:

$$\bar{x} = \sqrt[m]{\frac{\sum_{i=1}^{n} x_i^m}{n}} , \qquad (2.6.1)$$

where X_i – price of electrical energy at the time *i*.
The smallest time interval in these calculations is one hour, because on the NPS spot electricity trading prices are set constant for one hour. According to the analysis, fluctuations in the system area are smaller (around 11.00 €/MWh) than in the EE area (the amplitude of the price during the day is much higher at 26.35 €/MWh) [IV]. The high price amplitude in the local market enables consumption scheduling models to be used in residential areas to gain economy.

Figure 2.6.1 shows the deviation calculated by the simple formula (2.6.2) from the average price to analyze possibilities to use off-peak hours to store energy or shift the load to off-peak hours. We needed an assurance of off-peak hours available to recharge the batteries or other storage equipment. We found that the average duration of peaks that are higher than the average area price is 9.59 hours and the average duration of off-peaks is 13.48 hours. That means there is plenty of time to recharge storage equipment during the off-peak time.

Deviation from an average price is higher at peak hours, but peak hours last shorter than off-peak hours. It is most profitable to save energy between 23...06 o'clock when the price is lower than 10% compared to average. It is also possible to save energy between 16...19 o'clock when the price is about 2-3% lower than average.

$$S = \frac{\sum_{n=1}^{k} \frac{x_i}{n} - X_F}{X_F} , \qquad (2.6.2)$$

where X_i - the price of electrical energy in the instance *i* (from 0-24 hours) and X_F - the average area price.

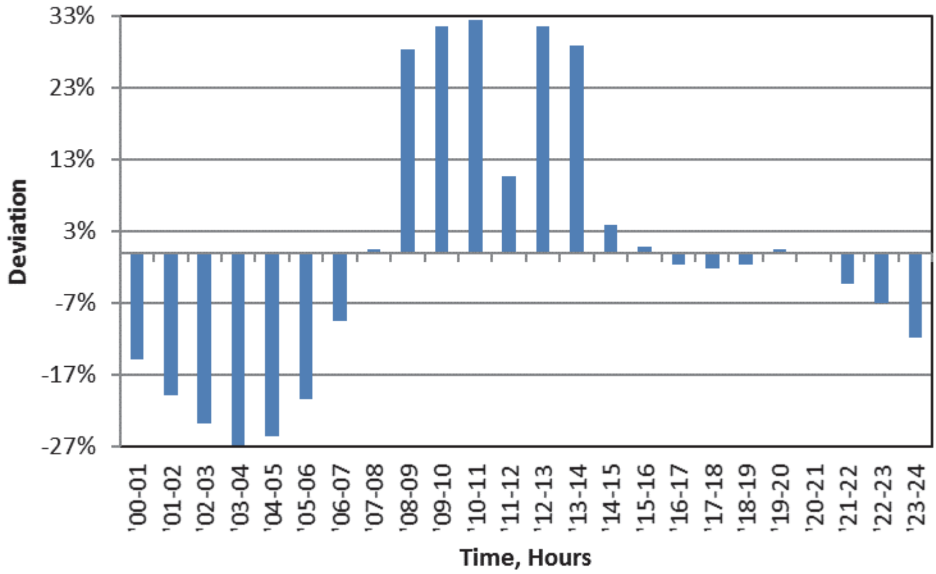

Figure 2.6.1 Average EE area price deviation

The volatility of electricity price has a cyclical character. The daily and weekly seasonality is illustrated by the intra weekly plot of mean absolute hourly price changes in [IV]. Volatility patterns are in correlation with the on-peak/off-peak specification on the NPS market. The lowermost volatility is detected at the weekends and during night. The huge increase of price within hours 33-39 is a result of emergency shutdown of the thermal power plant section in the EE. A strong seven day dependence for electricity spot price returns is easily detectable. It is also surprising that this dependence lasts almost forever [52].

Another seasonal phenomenon was observed on a yearly basis as a result of comparison of NPS SP1 prices in 2009. The price is much higher in the winter season but remains nearly the same in other seasons, as plotted in Figure 2.6.2. The price curve in the summertime for the EE in 2010 is quite similar to trends observed in the SP1 in the summertime.

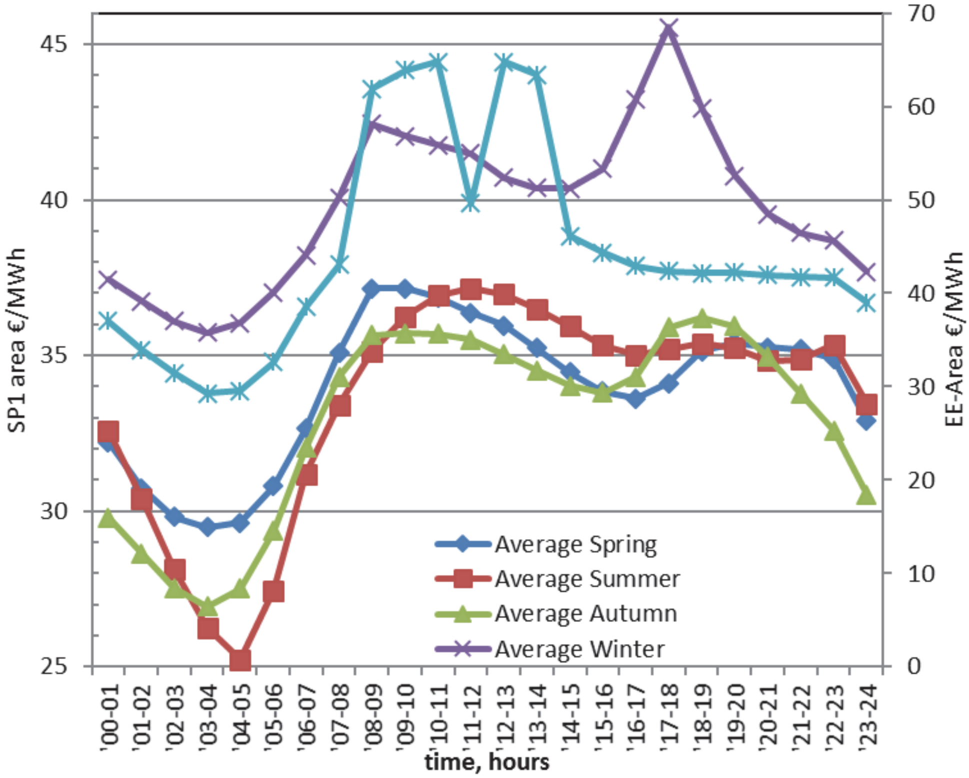

Figure 2.6.2 Average daily price at the SP1 on the seasonal scale compared to the EE price in the summertime

As seen in Figure 2.6.3, the distribution of prices is symmetric and leptokurtic. With the leptokurtic distribution, the price will have a relatively low amount of variance because return values are close to the mean. This could mean that energy producers will not try to invest to storage facilities, as there could be quite small return on investment. This area needs further research with focus on the profitability of using energy storing and shifting on the demand side.

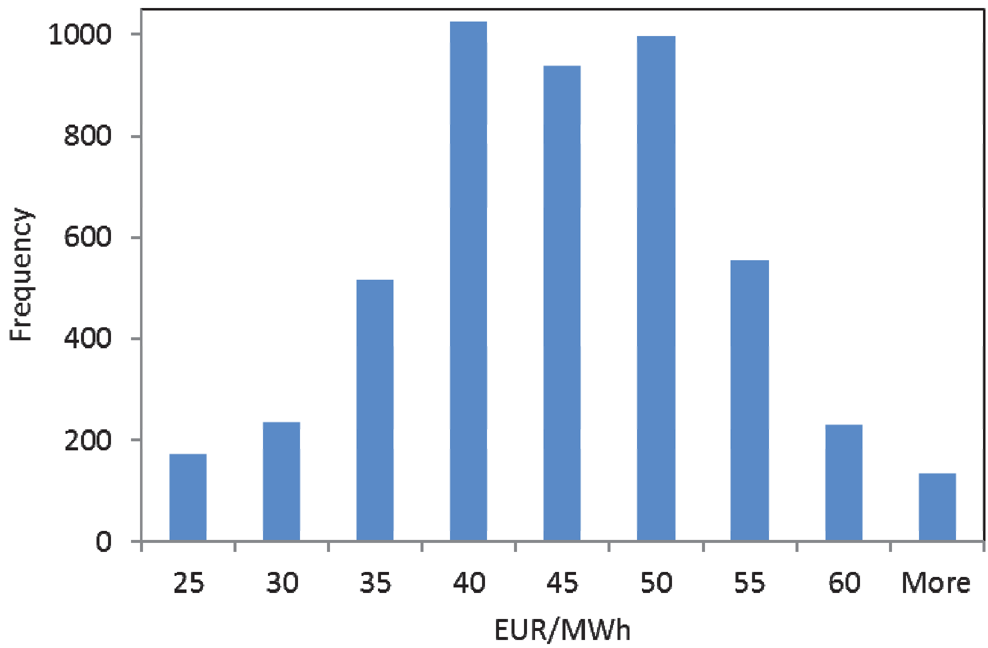

Figure 2.6.3 Distribution of price range in the EE area

To understand the possibilities for actualprofit earning from using electrical energy storage, a simple method for demand side control was introduced. For the calculations, the NPS data for the Estonian area within one year were used.

Storage is charged at the lowest price during the regular off-peak time from 02-05 o'clock in the morning. Storage is discharged at the three consecutive peak hours during the next 24 hours (2.6.3).

$$y^d = \begin{cases} p_i^h = p_d^{\max} \wedge soc > X_e^{\max}, 1 \\ p_i^h \neq P_d^{\max} \vee soc = X_e^{\min}, 0 \end{cases}$$
$$y^c = \begin{cases} p_i^h = p_d^{\min} \wedge soc > X_e^{\max}, 1 \\ p_i^h \neq p_d^{\min} \vee soc = X_e^{\min}, 0 \end{cases}, \tag{2.6.3}$$
$$\left. \begin{matrix} p_d^{\min} > p_i^h \\ i = 1..24 \end{matrix} \right\} p_d^{\min} = p_i^h$$

This method gives us theoretically 365 charging/discharging cycles per year. The analysis shows that the cycle lifetime in most commonly used chemical storage devices is between 1000–15,000 with 80% DoD [53, 54].

Lead acid batteries have a cycle life of 1200–1800 cycles, with a round trip efficiency of 75–80% and with a lifetime of 5–15 years [55]. Low self-discharge rate at less than <0.1% per day makes lead acid batteries suitable for long period energy storages [56].

The Ni–Cd battery's cycle life is predicted around 3500 cycles with low maintenance costs, using high DoD [57, 58]. Even 50,000 cycles is possible at 10% of DoD but has also a major disadvantage of poisonous heavy metal cadmium use.

The energy density and the energy efficiency of NaS batteries are very high, also very low self-discharge, low maintenance and excellent recyclability [59]. NaS battery's main problem is a working temperature of typically 350 °C and the battery needs to be heated even in standby mode, which reduces its total efficiency. [28]

The system life for VRF is around 15 years, with net energy efficiency of 0.72 [60, 63], it can handle over 1000 cycles at 100% of DoD [38, 61], but needs maintenance as the separator membrane has to be replaced every 5 years [62]. Nevertheless, VRF is well suitable for low cost, long time energy storage.

It has been taken into consideration that the cost per cycle which is from 0.385 € in NaS batteries to 8.39 € in lead acid batteries [64]. Considering the self-discharge rate of 0-20% of typical chemical batteries, NaS batteries have been reported as having the lowest price per cycle and nearly no self-discharge as beta alumina has nearly zero conductivity; therefore nearly 100% charge efficiency could be attained [65].

Even if the device allows us to use it for 5-20 years, the outcome is most likely not profitable; therefore some calculations were made on its possible profitability. Calculations are considering 24 kW/h consumption per day and storage cost is calculated using NaS batteries. According to the calculations, a 47% yearly total saving can be achieved. Considering also the storage cost, the calculated savings will be reduced at least by 50%. This storaging principle in combination with PV panels and wind turbine can increase the profit as PVs are most efficient at peak-time and most of wind generator production is also at the peak time. A surplus of energy occurs at peak time that can be sold to the open market at a profitable price.

3. ENERGY RESERVE OPTIMIZATION METHOD FOR GRID CONNECTED HOUSEHOLDS WITH INTEGRATED SMALL-SCALE RENEWABLE SYSTEMS

3.1 Dimensioning of distributed renewable systems for load coverage

The following calculations are based on the analysis of electrical energy consumption in households described in the previous chapter and in Articles [II] and [V].

PV System Dimensioning for Typical Estonian Households

The following calculations (3.1.1-3.1.2) are simplified and do not take into account the PV system performance ratio, including system losses, and the temperature coefficient of module efficiency. Solar modules based on crystalline cells can even reach a performance ratio of 85 - 95% [66].

$$A_{pv} = \frac{1}{k_{pr}} \cdot \frac{E_c}{E_{pv}} = \frac{1}{k_{pr}} \cdot \frac{1}{\eta_{pv}} \cdot \frac{E_c}{E_s}, \qquad (3.1.1)$$

$$A_{pv,ideal} = \frac{E_c}{E_{pv}} = \frac{1}{\eta_{pv}} \cdot \frac{E_c}{E_s}, \qquad (3.1.2)$$

where A_{pv} – PV module area; k_{pr} – performance ratio; E_c – electricity consumption per day; E_{pv} – electricity generation of a PV system per day; E_s – global irradiance in Wh; η_{pv} – efficiency of a PV system.

In different seasons of the northern regions, the deviation of global solar irradiation and PV system generated energy is relatively high. The coefficient of variation V_R of monthly generation is 72% (3.1.3).

$$V_R = \frac{\sum_{i=1}^{n} \left| E_{pv,i} - \overline{E_{pv}} \right|}{n \cdot \overline{E_{pv}}}, \qquad (3.1.3)$$

where $E_{pv,i}$ – generated electricity at the hour i; n – 24 hours a day; $\overline{E_{pv}}$ – average daily electricity generation.

High variations in annual electricity generation are the main problem to define an optimal PV system and electricity reserves for an energy storage system for load coverage.

Wind Turbine Dimensioning for Typical Estonian Households

The following calculations (3.1.4-3.1.5) are simplified and do not take into account the wind-turbine performance ratio, including system losses and efficiency of power electronics.

$$P = \frac{\pi \cdot \eta \cdot \rho \cdot d^2 \cdot v^3}{8} = c_w \cdot \frac{1}{2} \cdot \rho \cdot A \cdot v^3, \qquad (3.1.4)$$

$$P_{r,c} = P_{r,g} \cdot \frac{E_c}{E_g}, \qquad (3.1.5)$$

where P- power of a turbine; A – rotor area; ρ - density of air; η - efficiency; d - diameter of the rotor; v - wind speed; c_w - power coefficient; E_c – electricity consumption per day; E_g – electricity generation of a wind-turbine per day; $P_{r,g}$ – rated power of a wind turbine; $P_{r,c}$ – needed rated power of a wind turbine for covering daily electricity consumption.

The following analysis compares three micro-generation systems using the dimensioning methodology described in [II, IV]:

- PV system with an area of 34 m^2 and optimal efficiency of 20% [II];
- WT system – with a rated power of 10 kW [IV];
- HY that consists of a PV system with an area of 18 m^2 and efficiency of 20%, and WT system – with a rated power of 5 kW.

The efficiency of 20% corresponds to that of recent best PV panels on the market. Efficiencies of generation units are important for generation system dimensioning but affect less the correlation between the load and generation than the dimensions of the energy storage system. For example, by increasing the PV system efficiency up to 40%, the capacitance of the energy reserve could be decreased only up to 10%.

3.2 Electricity generation and load balance

Energy balance of an electricity system can be described according to the following simplified formula:

$$E_{pp} = E_c + E_{sp} + E_{los} \quad E_{pp} = \underbrace{E_{dir,c} + E_{res,c}}_{E_c} + E_{sp} + E_{los}, \qquad (3.2.1)$$

where E_{pp} – electricity generated by a generation system; E_c – electricity consumption; E_{sp} – surplus of generated electricity; E_{los} – total losses; $E_{dir,c}$ – direct consumption of electricity generated by a generation system; $E_{res,c}$ – indirect consumption of electricity generated by a generation system (stored energy reserve of generated energy).

In the calculation system losses are not taken into account (E_{los} = 0).

First, the diversity of power generation was analyzed with the load on an average day of each month. Since the workday and weekend have different consumption patterns, the analysis was made separately for both periods. Energy balance $E_{bal,i}$ at the hour *i* can be calculated using equation (3.2.2):

$$E_{bal,i} = E_{c,i} - E_{g,i}, \qquad (3.2.2)$$

where $E_{g,i}$ – electricity generated at the hour *i*; $E_{c,i}$ – electricity consumption at the hour *i*.

According to the calculations at the WD, the average surplus of the generated energy is the highest at midday when the load is trivial compared to the evening. Load maximum prevails in the evening from 16 to 21 o'clock. This means that the generated energy should be stored for the evening period (Figure. 3.2.1).

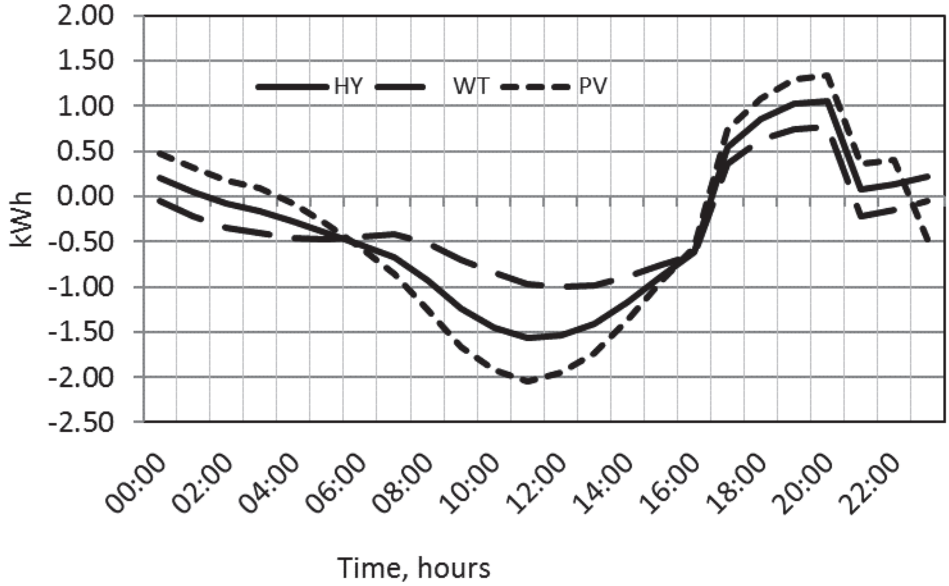

Figure. 3.2.1. Balance of WD consumption and generation

Solutions should be found for more efficient utilization of this generated electricity surplus. On the HD the direct load coverage from all renewable energy sources is better than on the WD [VI]. Surplus energy of the WD or HD could be stored in the energy storage or used by controllable (shiftable) loads, such as a refrigerator, a water heater or a washing machine proposed in the ECOGRID project [67].

3.3 Electricity surplus and shortage

According to the seasonal analysis, the PV system has the highest electricity surplus during the summer season (from April to September) and the highest shortage during the winter season (from October to March). The analysis indicated that the WT system is most optimal in particular houshold conditions. The result revealed a minor shortage during the HD in the summer season, which could be easily solved by proper load management. The analysis also showed that electricity consumption over the summer season is at least 15% smaller than in winter (Figure. 3.3.1). If the electricity supply system has a grid connection, then zero-generation hours can be covered with cheaper off-peak electricity from the electricity market.

The main disadvantage of a hybrid system is its higher initial system cost and shortage in power generation during winter holidays.

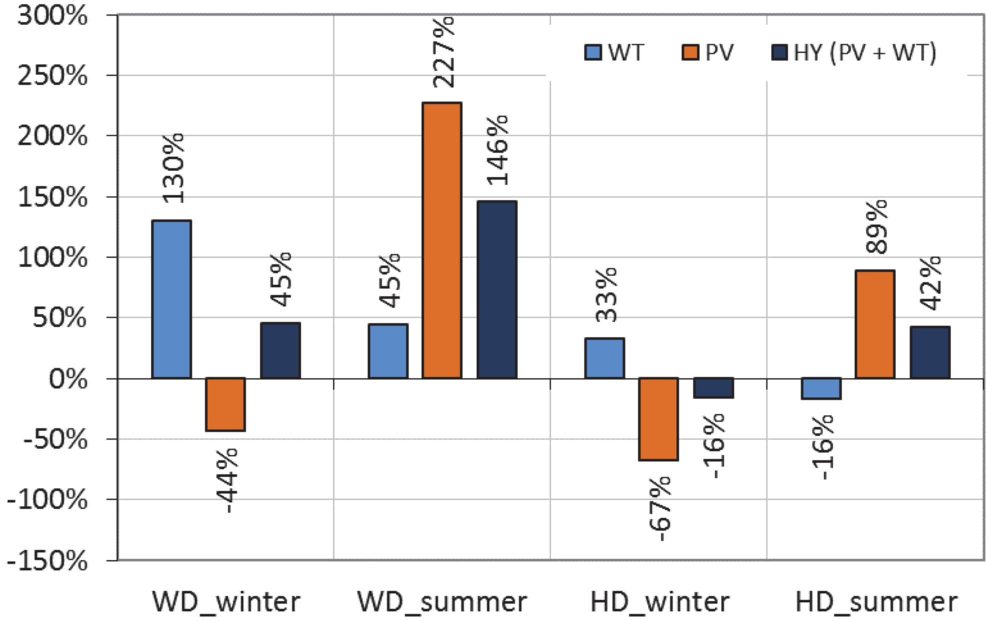

Figure. 3.3.1. Seasonal electricity surplus/shortage of the three systems

According to the monthly analysis, the wind energy system and hybrid energy systems could theoretically cover the average WD electricity consumption during the entire year. The wind energy system has a higher surplus from October to February when electricity consumption is the highest. This is an advantage compared to the other systems [VI]. The relative electricity surplus coefficient k_{sp} can be calculated using equation (3.3.1):

$$k_{sp} = \frac{E_{sp}}{E_c} = \frac{\sum_{i=1}^{n}(E_{g,i} - E_{c,i})}{\sum_{i=1}^{n} E_{c,i}} , \qquad (3.3.1)$$

where E_{sp} – daily surplus of electricity; E_c – total daily electricity consumption; $E_{g,i}$ – electricity generated at the hour i; n – 24 hours a day; $E_{c,i}$ – electricity consumption at the hour i.

The monthly energy balance analysis shows that all the three described systems have trouble covering the average HD electricity consumption during the entire year (Figure. 3.3.2).

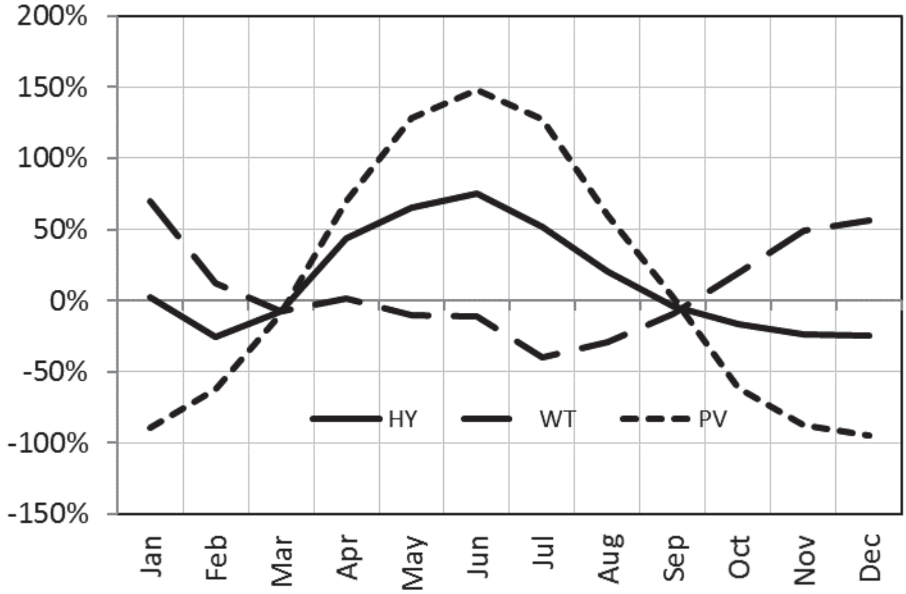

Figure. 3.3.2. Relative electricity surplus and shortage of an average HD of a month

The coefficient of variation V_R of the monthly power generation of WT is 25% (for a PV system - 72%, and a HY system - 28%) (3.3.2).

$$V_R = \frac{\sum_{i=1}^{n_y} \left| E_{g,i,m} - \overline{E_g} \right|}{n_y \cdot \overline{E_g}}, \qquad (3.3.2)$$

where $E_{g,i,m}$ – electricity generated at the month i; n_y – 12 months a year; $\overline{E}_g$ – average annual electricity generation.

WT or a HY system has an advantage of lower variations in annual electricity generation over a PV system (Figure. 3.3.3).

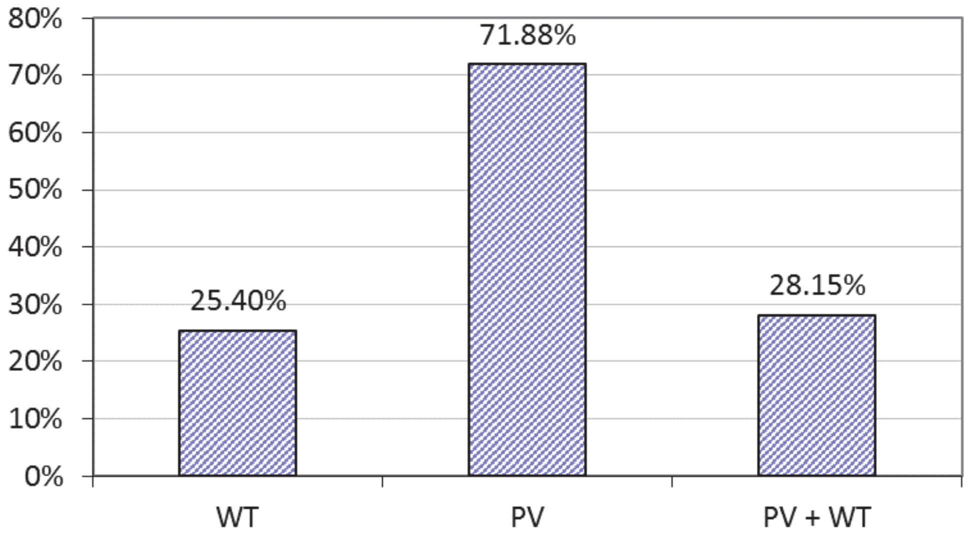

Figure. 3.3.3. Variation of monthly power generation

3.4 Demand for stored energy to cover household electrical power consumption on an average day

The demand for stored energy (3.4.1) to cover household power consumption from ES (during low power generation hour) in the WD and the HD during summer months (from May to August) is almost equal for all three analyzed systems. The highest differences in the requirements were detected from November to January. Figure 3.4.1 shows that the hybrid system has the smallest variation between the seasons during workdays.

$$E_{g,i} \leq E_{c,i} \Rightarrow E_{res} = \sum_{i=1}^{n} (E_{c,i} - E_{g,i}) = \sum_{i=1}^{n} \left| E_{g,i} - E_{c,i} \right|, \qquad (3.4.1)$$

where E_{res} – daily demand for stored energy; $E_{res,i}$ – demand for stored energy at the hour i; $E_{g,i}$ – electricity generated at the hour i; n – 24 hours a day.

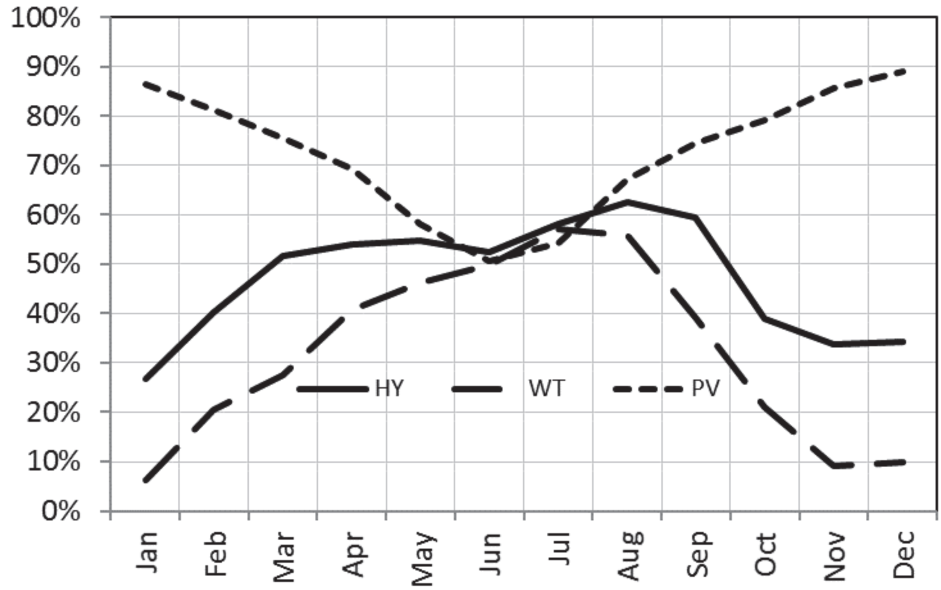

Figure. 3.4.1. Relative demand for stored electricity compared to total demand on an average WD of a month

To describe the relative daily demand for stored electricity compared to the total demand (i.e. consumption), the coefficient k_{res} (3.4.2) can be used.

$$k_{res} = \frac{E_{res}}{E_c} = \frac{\sum\limits_{E_{g,i} < E_{c,i}} (E_{c,i} - E_{g,i})}{\sum E_{c,i}}, \tag{3.4.2}$$

where k_{res} – relative daily demand for stored electricity compared to the total demand (i.e. consumption); $E_{c,i}$ – electricity consumption at the hour i; $E_{g,i}$ – electricity generated at the hour i.

At an average WD, the household with the wind energy system had the lowest maximum stored electricity demand (about 5.2 kWh). The household with the hybrid system had the second lowest maximum stored electricity demand, i.e. about 12% higher demand than that of the wind energy system (Figure. 3.4.2).

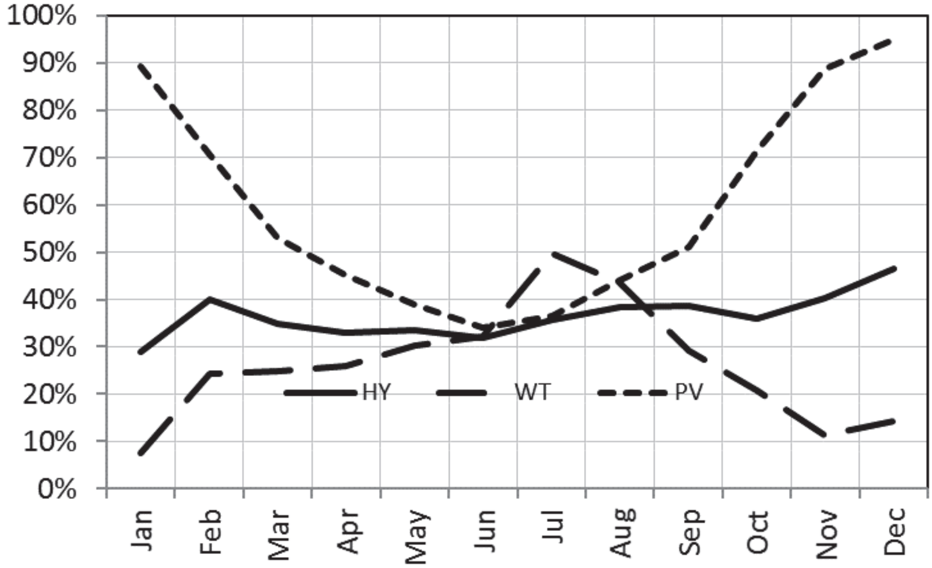

Figure. 3.4.2. Relative demand for stored electricity compared to the total demand on an average HD of a month

At an average HD, the household with the hybrid energy system had the lowest maximum stored electricity demand in December (about 7.4 kWh). The wind energy system had the second lowest maximum stored electricity demand, about 8% higher than that of the hybrid energy system [VI]. Generation systems should be oversized according to Figures 3.5.1-3.5.2 to cover loads in the winter season.

3.5 Direct coverage of household electrical loads from renewable energy sources

Figures 3.4.1-3.4.2 illustrate how the energy consumption can be directly covered by different systems. No differences exist between the three systems during workdays, meaning that about 50% of energy consumption can be covered directly from the renewable energy source (Figure. 3.5.1).

The main difference in the Nordic region turned out to be during the winter season, when WT and HY systems have significant advantages over PV systems. The WT and HY system can cover respectively about 90% and 70% of energy consumption directly during the coldest three months in winter (from November to January). Electricity directly consumed (E_{dir}) from a WT, PV or HY can be calculated as in (3.5.1, 3.5.2):

$$E_{dir} = \sum E_{c,i} - \underbrace{\sum_{E_{g,i} \le E_{c,i}} (E_{c,i} - E_{g,i})}_{E_{res,i}} = \sum_{E_{g,i} \le E_{c,i}} E_{g,i} + \sum_{E_{g,i} > E_{c,i}} E_{c,i}, \quad (3.5.1) \qquad k_{dir} = \frac{E_{dir}}{E_c}, \quad (3.5.2)$$

where E_{dir} – average daily directly consumed electricity; E_c – daily total energy consumption; k_{dir} – relative direct coverage of load.

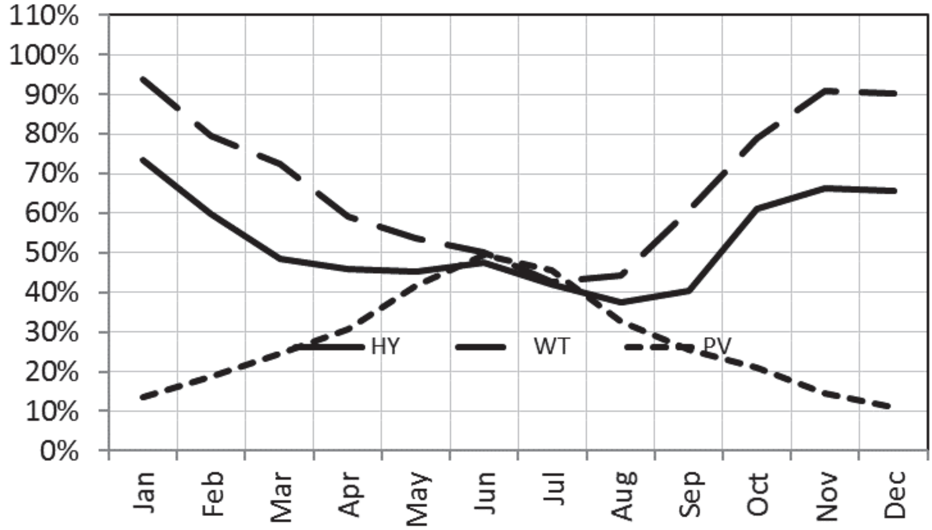

Figure. 3.5.1. Relative direct coverage of the household load on an average WD of a month

The HD consumption pattern had the highest impact on the direct consumption coverage in a PV and a HY system and the lowest in a WT system (Figure. 3.5.2). Annual average direct load coverage in a HD is 10-13% higher than on a WD. The same indicator for a WT system is about 5%. These numbers show clearly that generation curves of the PV and HY systems are more similar to power consumption curves on weekends.

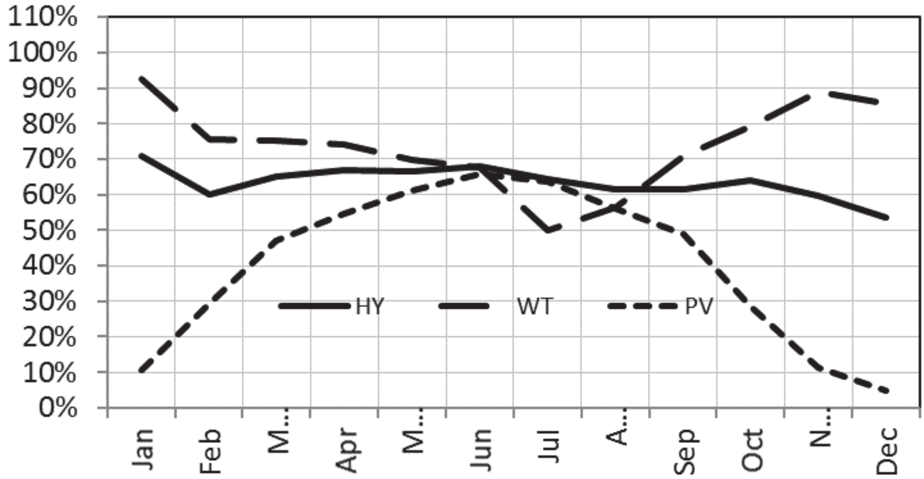

Figure. 3.5.2. Relative direct coverage of the household load on an average HD of a month

3.6 Demand for stored energy according to zero generation periods

Comparison of the three systems reveals that in hybrid systems 90% of periods without power generation are shorter than 12 hours. In a PV and a WT system, these numbers are 18 and 22 hours, respectively (Figure. 3.6.1).

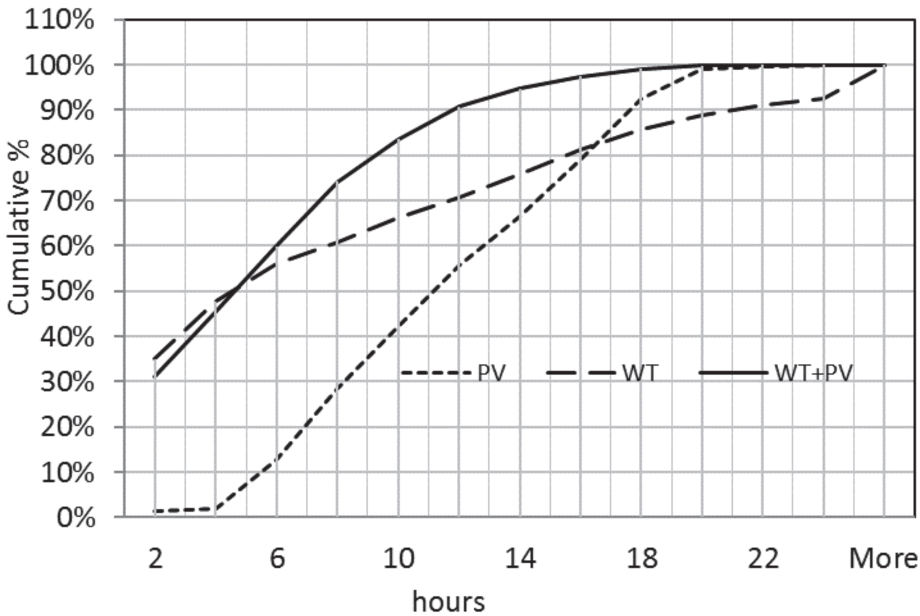

Figure. 3.6.1. Histogram of periods without power generation (2005-2009)

Compared to a PV and a WT system, the periods without PG can be reduced with a hybrid system by 33% and 45%, accordingly. In addition, the demand for stored electricity to cover the 90% of periods without PG could be also proportionally smaller. In hybrid systems, the average monthly periods without power generation are shorter than in the PV or WT systems. For a HY, a PV and a WT system, the annual average periods without PG are 6, 12 and 10, respectively (Figure. 3.6.2).

Figure 3.6.3 illustrates the average maximum periods without power generation over the year (according to the weather analysis from 2005 to 2009).

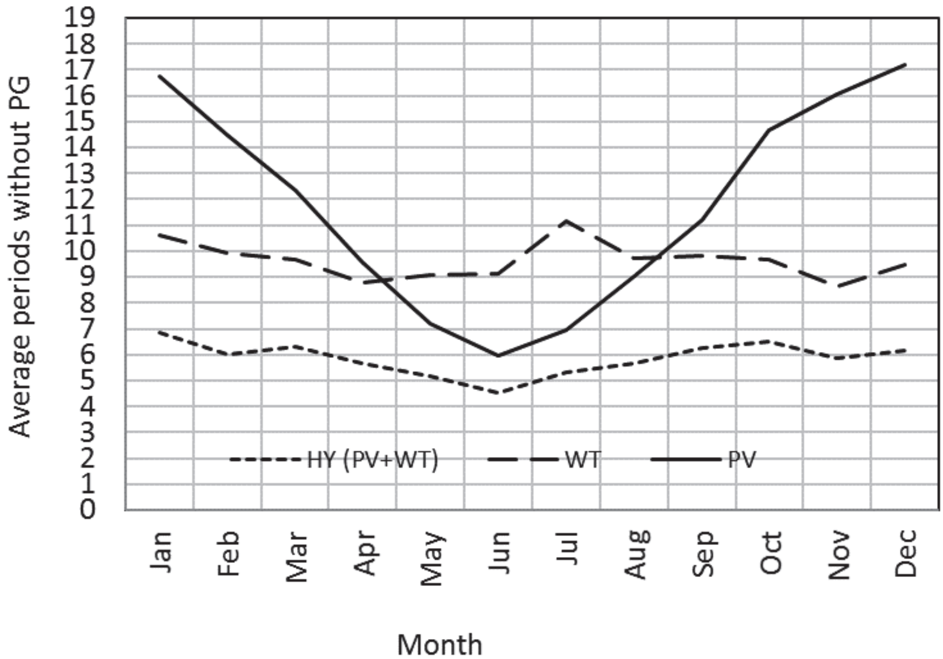

Figure. 3.6.2. Average periods without power generation (2005-2009)

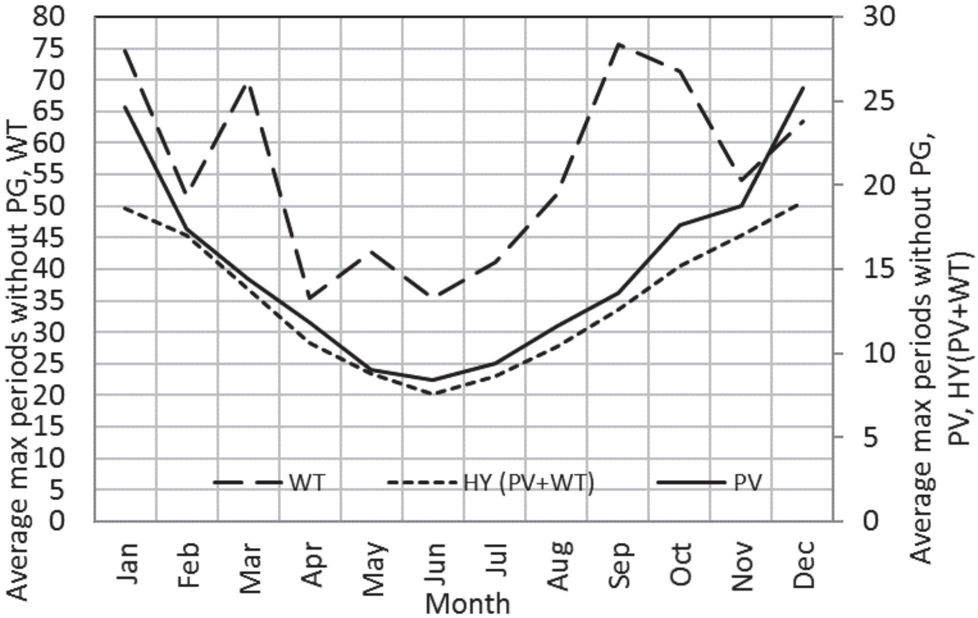

Figure. 3.6.3. Average maximum periods without power generation

In the Nordic regions, the average maximum periods without power generation in December are two times longer than in June. According to the presented curve of hybrid systems, the demand for an additional energy source in winter is higher than in the summer season, but the duration of periods is approximately three times shorter than in the WT system. In hybrid systems, during winter seasons the wind turbines have the highest impact on the power generation, while the power generation of a PV system in December is 20 times lower than in June. An additional energy source is anyway needed to cover long wind-lulls, because power generation from PV panels is very low in the winter season - approximately 15% from the annual production. In WT- and PV-based household systems, about 50% of hours should be covered from storage or an additional power generation unit. In a hybrid system, it is 25%.

3.7 Correlation between distributed power generation, load and spot price

The correlation analysis of power generation and consumption shows that the WT system is most suitable for Nordic countries in coastal areas. However, a disadvantage of all the systems is the poor correlation between the workday load and power generation (Table 3.7.1).

$$Cor(x,y)=\frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2\sum(y-\bar{y})^2}}, \quad (3.7.1)$$

where x is the first range of values (e.g. power generation) and y is the second range of values (e.g. power consumption).

AL in Table 3.7.1 corresponds to an average load. Negative correlation values refer to possible difficulties when covering household loads from these renewable sources on WDs.

TABLE 3.7.1 Correlation between average power generation and consumption

	PV	**WT**	**WT+PV**
AL	-14%	5%	-11%
WD	-49%	-40%	-48%
HD	24%	49%	28%

According to the data of electricity spot price from 2011 to 2012 (a year after opening of the electricity market in Estonia), all the described renewable power generation systems are in good correlation with the spot price at the electricity market. The most suitable PG solution seems to be a hybrid or a PV system 83.9% and 83.6%, accordingly. This means that excess of energy could be sold with the best spot price. The correlation between the average power consumption and the spot prices is worse at the weekend while the correlation coefficient is the highest at 72.5%. [VI]

4. CONCLUSIONS AND FUTURE WORK

This thesis focuses on the concurrent analysis of the energy usage pattern of the households, open market price fluctuations and solar and wind power generation and market price fluctuations. The main outcomes of statistical analysis are as follows:

- The minimum energy reserves that an electrical energy storage system should have for household energy consumption:
  - shifting based on the two-tariff system - 19-27% of daily consumption;
  - shifting based on the NPS average daily price - 19-47% of daily consumption;
  - balancing if shiftable loads consumption is not separately shifted - 22-40% of daily consumption; balancing if shiftable loads consumption is separately shifted - 6% of daily consumption.
- If shiftable loads like water heaters, dish washers and other similar appliances are not included, then the minimum energy reserves for household power consumption shifting stay between 75....100%.
- Compared to a PV and a WT system, the periods without power generation can be reduced with a hybrid system by 33% and 45%, accordingly. In addition, the demand for stored electricity to cover 90% of periods without PG. could be also proportionally smaller. Comparison of the three systems reveals that in hybrid systems 90% of the periods without power generation are shorter than 12 hours. In a PV and a WT system these numbers respectively are 18 and 22 hours. In WT- and PV-based household systems about 50% of hours should be covered from storage or an additional power generation unit. In a hybrid system it is 25%.
- An increase in the efficiency of a PV system will reduce the area of PV panels, but it has a relatively small impact on the storage system capacity. Double efficiency of a PV system will decrease the reserve system capacity only up to 10%.
- According to seasonal electricity surplus/shortage of generation units and correlation with energy consumption, a wind turbine system suits properly as it covers the seasonal and daily demand best. On coastal areas, the hybrid or windpower systems are more feasible in autonomous power generation systems where the correlation between power consumption and generation is better. On the inland the PVs and hybrid systems are more feasible.

In off-grid household the electricity reserve should be at least 645% of daily consumption if only WT is installed. If PV is added to the system, the reserve can be reduced but not significantly as the longest periods without WT power generation occur in January and October when it is the lowest PV power generation period. In an on-grid household, the electricity reserve is more dependent on the consumption pattern and the current price plan and generally the needed reserve is smaller than daily electricity consumption.

Further research into the issues discussed continues. Currently, historical recorded data were used, but as there are already several distributed generation installations, real information could be included to correspond to more realistic situations. Future research will address the actual distributed generation environment**.**

The main scientific result of the thesis is the energy reserve optimization methodology for grid connected households with integrated small-scale renewable systems, which includes the following steps:

1. Analysis of load patterns and time-dependence of power consumption to determine
    a. load taxonomy including amount of shiftable and non-shiftable loads
    b. load shifting possibilities, depending on the two-tariff system price and on the Nord Pool Spot price
    c. load balancing possibilities
2. Analysis of power generation of distributed renewable systems to define
    a. prospective seasonal and daily power generation
    b. seasonal electricity surplus and shortage including load coverage
    c. period without power generation
3. Analysis of daily balance between electricity distributed power generation and consumption to define
    a. direct coverage of loads from renewable energy sources
    b. daily demand for energy reserve to cover power consumption
    c. correlation between power generation and consumption
4. Analysis of electricity Nord Pool Spot price to define
    a. daily demand for energy reserve to cover possible zero-generation periods of renewable systems
    b. correlation between price, power generation and consumption
5. Theoretical outcomes and recommendation for dimensioning of small-scale renewables systems and possible energy reserves

Practical value of the thesis is as follows:

1. Developed methodology was/is already used by other research group members in the following research projects:
    a. Analysis of Large Electricity Consumers Demand Profiles to Determine Implementation of Demand-Side Management Measures, Lep12121
    b. Analysis of Local Energy Production Possibilities for Office Building, Lep12154
    c. Design consultation and technical support for Suur-Ameerika Street 1 office building, Lep12012
    d. Energy resources and their using and storing potentiality in Pakri EG, stage 1, Lep12176
2. In the Baltic countries proper analysis for small-scale renewable systems is scarce. Some results described in the thesis were used also for the preparation of measures for financial support of new renewable systems for small- and middle- scale consumers.

Future research areas

- Price prediction methodologies for mid-range price prediction to help to change the price plan in a household.
- Economical use of real-time tariff in the demand-side using available renewable energy sources.
- Feasible usage of electric car batteries as an energy reserve in households.

REFERENCES

[1] Strecker S, Weinhardt C.; Electronic OTC Trading in the German Wholesale Electricity Market, Lecture Notes in Computer Science, 2000, Volume 1875/2000, 280-290.

[2] Rafal Weron Energy price risk management Physica A 285 (2000) 127{134.

[3] Hiroaki Nagayama, Effects of regulatory reforms in the electricity supply industry on electricity prices in developing countries, Energy Policy, Volume 35, Issue 6, June 2007, Pages 3440-3462.

[4] R. Weron, Pricing derivatives in electricity markets, International Conference on Stochastic Finance, 2004.

[5] R. Weron, Beata Przybylowicz, Hurst analysis of electricity price Dynamics, Physica A 283 (2000) 462{468.

[6] Alenka Kavkler, Sebastijan Repina and Mejra Festić (2012). A Comparison of Electricity Generation Reference Costs for Different Technologies of Renewable Energy Sources, Energy Efficiency - A Bridge to Low Carbon Economy, Dr. Zoran Morvaj (Ed.), ISBN: 978-953-51-0340-0.

[7] Price formation in NPS http://www.nordpoolspot.com/How-does-it-work/Day-ahead-market-Elspot-/Price-formation-in-Nord-Pool-Spot/ (2014)

[8] Federal Energy Regulatory Commision http://www.ferc.gov/industries/electric/indus-act/rto.asp.

[9] J. Bertrand, "Theorie mathematique de la richesse sociale," *J. Savants*, vol. 45, pp. 499–508, 1883

[10] A. Cournot*, Recherches sur les Principes Mathematiques de la Theorie des Richesses* (in English) Transl.: Translation by N. T. Bacon Publisher in Economic Classics [Macmillan, 1897] and reprinted in 1960 by Augustus M. Kelly. Paris, France: Hachette, 1838

[11] R. Green and D. M. Newbery, "Competition in the British electricity spot market," *J. Political Econ.*, vol. 100, no. 5, pp. 929–953, Oct. 1992

[12] Ruibal, C.M.; Mazumdar, M.;, "Forecasting the Mean and the Variance of Electricity Prices in Deregulated Markets," *Power Systems, IEEE Transactions on* , vol.23, no.1, pp.25-32, Feb. 2008

[13] European Energy Exchange EEX http://www.eex.com/en

[14] EPEX SPOT http://www.epexspot.com/en

[15] EXAA Energy Exchange http://en.exaa.at/

[16] Hungarian Power Exchange HUPX http://www.hupx.hu/home/index

[17] PXE - Power Exchange Central Europe http://www.pxe.cz/

[18] Western Australia (SWIS) http://www.imowa.com.au/home,

[19] Australian Power Market Operator forother parts of Australia http://www.aemo.com.au/

[20] USA electricity markets http://www.ferc.gov/market-oversight/mkt-electric/overview.asp

[21] NPS market news http://www.nordpoolspot.com/Message-center-container/Exchange-list/ (2014)

[22] Elering homepage www.elering.ee (2012).

[23] The Nordic Electricity Exchange and the Nordic model for a liberized electricity market http://nordpoolspot.com/Global/Download%20Center/Rules-and-regulations/The-Nordic-Electricity-Exchange-and-the-Nordic-model-for-a-liberalized-electricity-market.pdf (2012)

[24] Price calculation principles in NPS http://www.nordpoolspot.com/How-does-it-work/Day-ahead-market-Elspot-/Price-calculation/Price-calculation-principles/ (2014)

[25] Price calculation in NPS http://www.nordpoolspot.com/How-does-it-work/Day-ahead-market-Elspot-/Price-calculation/ (2014).

[26] Matics, J.; Krost, G.;, "Intelligent Design of PV based Home Supply using a Versatile Simulation Tool," Intelligent Systems Application to Power Systems, 2005. Proceedings of the 13th International Conference on, vol., no., pp.61-66, 6-10 Nov. 2005

[27] Masaud, T.M.; Keun Lee; Sen, P.K., An overview of energy storage technologies in electric power systems: What is the future?, North American Power Symposium (NAPS), 2010, 26-28 Sept. 2010, IEEE

[28] A. Oudalov, D. Chartouni, C. Ohler, and G. Linhofer, “Value analysis of battery energy storage applications in power systems,” in *Proc. 2nd IEEE PES Power Syst. Conf. Expo.*, 2006, pp. 2206–2211.

[29] M. Korpaas, Arne T. Holen, Ragne Hildrum, Operation and sizing of energy storage for wind power plants in a market system, International Journal of Electrical Power & Energy Systems (10.2003) Elsevier

[30] Nirmal-Kumar C. Nair, Niraj Garimella Battery energy storage systems: Assessment for small-scale renewable energy integration Energy and Buildings 42 (2010) 2124–2130

[31] International Electrotechnical Commission, White Paper on Electrical Energy Storages www.iec.ch/whitepaper/ (2011)

[32] P.J. Hall, E.J. Bain, Energy-storage technologies and electricity generation, Energy Policy 36 (12) (2008) 4352–4355

[33] P.F. Ribeiro, et al., Energy storage systems for advanced power applications, Proceedings of the IEEE 89 (12) (2001) 1744–1756. 36 (12) (2008) 4368–4373.

[34] J. Baker, Newtechnology and possible advances in energy storage, Energy Policy

[35] “Electricity energy storage technology options: A white paper primer on applications, costs, and benefits,” Tech. Rep. 1020676, Electric Power Research Institute (EPRI), Palo Alto, CA, December 2010.

[36] H. Ibrahim, A. Ilinca, J. Perron, Energy storage systems—characteristics and comparisons, Renewable and Sustainable Energy Reviews 12 (5) (2008) 1221–1250.

[37] K.C. Divya, J. Ųstergaard, Battery energy storage technology for power systems- An overview, Electric Power Systems Research 79 (4) (2009) 511–520

[38] K. Emura, Recent Progress in VRB Battery, Proceedings of EESAT Conference, 2003.

[39] Belonogova N, Lassila J, Partanen J, „Effects of Demand response on the end-customer distribution fee“, CIRED Workshop Lyon 7-8 June 2010, Paper 0081.

[40] Koponen P., Kärkkäinen S., Experiences from spot-market based price response of residential customers, CIRED 2007 Vienna, 21-24 May 2007. Page 33 July 14, 2008

[41] U.S. Department of Energy, 2008 Buildings Energy Data Book. Energy Efficiency and Renewable Energy, Mar. 2009.

[42] U.S. Department of Energy, 2011 Buildings Energy Data Book. March 2012

[43] Energy consumption in households, Rita Raudjärv, Ljudmilla Kuskova, 1/13. Quarterly Bulletin of Statistics Estonia

[44] Energy Conservation Committee Report and Recommendations, Reducing Electricity Consumption in Houses. Ontario Home Builders' Association, May 2006.

[45] Amir-Hamed Mohsenian-Rad, Vincent W.S. Wong, Juri Jatskevich, Robert Schober. Optimal and Autonomous Incentive-based- Energy Consumption Scheduling Algorothm for Smart Grid. Innovative Smart Grid Technologies (ISGT), 2010. 19-21 Jan. 2010 On page(s): 1 - 6.

[46] Handa, T.; Oda, A.; Tachikawa, T.; Watanabe, Y.; Ichimura, J.; Nishi,H.; Table-based scheduling method for distributed demand side management, Industrial Electronics, 2008. IECON 2008. 34th Annual Conference of IEEE 10-13 Nov. 2008 Page(s):2748 - 2753.

[47] Giuseppe MAURI, Diana MONETA, Paolo GRAMATICA; Automation systems to support smart energy behaviour of small customers, CIRED Seminar 2008 SmartGrids for Distribution, Frankfurt 23-24 June 2008.

[48] Majid, M.S.; Rahman, H.A.; Hassan, M.Y.; Ooi, C.A.; Demand Side Management Using Direct Load Control for Residential Research and Development, 2006. SCOReD 2006. 4th Student Conference on 27-28 June 2006, Page(s): 241 - 245.

[49] Rosin, A., Möller,T., Lehtla, M., Hõimoja, H., Analysis of household electricity consumption patterns and economy of water heating shifting and saving bulbs, Scientific Journal of Riga Technical University. Power and Electrical Engineering, 27, 15 - 20.

[50] Kadar, P. ZigBee controls the household appliances // Intelligent Engineering Systems, 2009. INES 2009. International Conference on Publication Year: 2009, Page(s): 189 - 192.

[51] Firth S., Lomas K., Wright A., Wall R. Identifying trends in the use of domestic appliances from household electricity consumption measurements, Energy and Buildings 40 (2008) 926–936.

[52] F.J. Nogales, J. Contreras, A.J. Conejo, R. Esp´ınola, Forecasting next-day electricity prices by time series models, IEEE Trans. Power Syst. 17 (2) (2002) 342–348.]

[53] K. Bradbury, “Energy Storage Technology Review”, Duke University, August 22 2010, pp. 1-34.

[54] F. Díaz-González, Andreas Sumper, Oriol Gomis-Bellmunt, Roberto Villafáfila-Robles, Renewable and Sustainable Energy Reviews *16 (2012)* 2154–217

[55] Greenblatt JB, Succar S, Denkenberger DC, Williams RH, Socolow RH. Baseload wind energy: modeling the competition between gas turbines and compressed air energy storage for supplemental generation. Energy Policy 2007; 35:1474–92.

[56] IEEE Power & Energy Society. IEEE Recommended practice for the characterization and evaluation of emerging energy storage technologies in stationary applications. IEEE Std 1679-2010, 2010.

[57] Broussely M, Pistoia G. Industrial applications of batteries. From cars to aerospace and energy storage. Elsevier B.V; 2007.

[58] McDowall J. Integrating energy storage with wind power in weak electricity grids. Journal of Power Sources 2006; 162:959–64.

[59] T. Kousksou,P. Bruel,A. Jamil,T. El Rhafiki,Y. Zeraouli, Energy storage: Applications and challenges, Solar EnergyMaterials&SolarCells120(2014)59–80

[60] Rydh CJ, Sandén BA. Energy analysis of batteries in photovoltaic systems. Part II: Energy return factors and overall battery efficiencies. Energy Conversion and Management 2005; 46:1980–2000.

[61] Beck F, Ruëtschi P. Rechargeable batteries with aqueous electrolytes. Electrochimica Acta 2000; 45:2467–82.

[62] Rydh CJ. Environmental assessment of vanadium redox and lead-acid batteries for stationary energy storage. Journal of Power Sources 1999; 80: 21–9.

[63] Huang K-L, Li X-G, Liu S-Q, Tan N, Chen L-Q. Research progress of vanadium redox flow battery for energy storage in China. Renewable Energy 2008; 33:186–92.

[64] J. Jacobi and S. Wilson, “Fast Response Energy Storage Devices, Technology descriptions and overview”, ScottMaden Inc., 2009, pp. 1-26.

[65] Zhaoyin Wen, Jiadi Cao, Zhonghua Gu, Xiaohe Xu, Fuli Zhang, Zuxiang Lin, Research on sodium sulfur battery for energy storage, Solid State Ionics, Volume 179, Issues 27–32, 30 September 2008, Pages 1697-1701

[66] Quaschning, Volker. Regenerative Energiesysteme, Technologie − Berechnung − Simulation. 6., neu bearbeitete und erweiterte Auflage. Hanser Verlag München. 2009. 397 s. ISBN 978-3-446-42151-6.

[67] Aleixo, L.; Rosin, A.; Saele, H.; Morch Z. A.; Grande, S. O.; Palu, I. (2013). Ecogrid EU Project – Real Time Price Based Load Control and Economic Benefits in a Wind Production Based System. CIRED 22 International Conference on Electricity Distribution, 10-13 June 2013, Stockholm, Sweden. Paper 1474.

LIST OF PUBLICATIONS

[I] Rosin, A.; Auväärt, A.; Lebedev, D. (2012). Energy storage dimensioning and feasibility analysis for household consumption scheduling based on fluctuations of Nord Pool Spot price. *Przeglad Elektrotechniczny, 88(1a), 37 - 40.*

[II] Rosin, A.; Rosin, K.; Auväärt, A.; Strzelecki, R. (2012). Dimensioning of household electricity storage for PV-systems and load scheduling based on Nord Pool Spot prices. *Przeglad Elektrotechniczny, 88(4b), 294 – 299.*

[III] Rosin, A.; Auväärt, A.; Lebedev, D. (2012). Analysis of operation times and electrical storage dimensioning for energy consumption shifting and balancing in residential areas. *Electronics and Electrical Engineering, 4 (120), 15 – 20.*

[IV] Auväärt, A.; Rosin, A.; Belonogova, N.; Lebedev, D. (2011). Nord Pool Spot price pattern analysis for households energy management. *In: 7th International Conference-Workshop Compatibility and Power Electronics (CPE2011), Tallinn, Estonia, June 01-03, 2011:* IEEE, 2011, 103 - 106.

[V] Rosin, A., Palu, I., Rosin, K:, Aivar Auväärt (2012) Dimensioning of Electricity Storage according to Small Wind Turbine Power Generation and Household Load Patterns.*In: 38th Annual Conference of the IEEE Industrial Electronics Society (IECON-2012) Montreal, October 25-28, 2012*

[VI] Aivar Auväärt, Argo Rosin, Kai Rosin, Imre Drovtar, Madis Lehtla. (2013) Comparison of Renewable Electricity Generation Options with Household Electrical Load Patterns. In: *IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society, Vienna, Austria, 10 - 13 November, 2013: IEEE, 2013, 1553 - 1558*

[VII] Vodovozov, V.; Pettai, E.; Auväärt, A. (2008). Design and Modelling of Electric Drive in Database Environment. *2008 IEEE International Symposium on Industrial Electronics, Cambridge, UK, 30 June-2 July, 2008. (Toim.) IEEE. United Kingdom: IEEE, 2008.*

[VIII] Roasto, I.; Vinnikov, D.; Lehtla, T.; Auväärt, A. (2008). A Simplified Peak Current Mode Control Algorithm for Special Purpose High Voltage IGBT Converters. *In: BEC 2008 : 2008 International Biennial Baltic Electronics Conference : Proceedings: 11th Biennial Baltic Electronics Conference, Tallinn University of Technology, October 6-8, 2008, Tallinn, Estonia. Tallinn: Tallinn University of Technology, 2008, 305 - 308.*

[IX] Auväärt, A.; Rosin, A.; Müür, M.; Lebedev, D. (2011). Nord Pool Spot price fluctuation analysis for energy management of household appliances. *In: 10th*

International Symposium ""Topical Problems in the Field of Electrical and Power Engineering", Doctoral School of Energy and Geotechnology. Pärnu, Estonia, January 10-15: (Toim.) R. Lahtmets. Tallinn, Estonia: Estonian Society of Moritz Hermann Jacobi, 2011, 91 - 94.

[X] Auväärt, A.; Lehtla, T. (2007). Energy efficient trajectory planning of industrial robots. *In: 8th International Workshop on Research and Education in Mechatronics 2007: 8th International Workshop on Research and Education in Mechatronics 2007, REM-2007, Tallinn, Estonia, 14-15 June 2007.* Tallinn: Tallinn University of Technology Press, 2007, 89 - 92.

Acknowledgements

I would like to express my sincere gratitude to my supervisor, Senior Researcher Argo Rosin, for his very skilful guidance, encouragement, and unbelievable patience during this work. I also thank my other supervisor Professor Tõnu Lehtla for keeping up the faith and directing the goal.

I want to express my gratitude to the deceased Professor Juhan Laugis who gave me the opprtunity to be involved in research in the field of electrical engineering.

Many thanks to all my closest colleagues from TUT who have supported me withmy mission all these years.

My deepest gratitude, however, goes to my wife, my daughter and my mother for showingsupport, patience and encouragement throughout the writing of this thesis.

ABSTRACT

Current thesis explores reductions of the total expenditure of the households derived from the possibility that from 2013 households can make use of the real-time electricity tariffs and access the benefits of linking the electricity price fluctuations in the free market to the generation of electricity on the demand side. The goal is to find economically feasible dimensions of electricity reserves without changing consumption characteristics. Topicality of the study lies in the fact that in a short term, entire households must transfer to the new tariff systems across Europe to purchase electricity from the free market. Free market with price volatility provides several options on how to keep the price level lower on the demand side. Although the real-time tariff has its own advantages, the current household automation is not following new trends and profitable usage of price volatility at the households is not yet a simple action. The renewable energy sources have also been significantly reduced in price. Solar panel and wind generator prices are decreasing each year.

Chapter 1 describes the formation of the free electricity market and principles of behavior of the free market, the status of Estonia in the free electricity market, and the options of energy storages in the households.

Chapter 2 evaluates consumers' electricity usage patterns and consumption time dependence. It also provides guidelines for the calculation of the consumption of the reserves in relation to the market price movements.

In the final chapter the usability of renewable energy sources in Estonia and dimensioning relevant systems on the basis of wind speed and sunshine and usage patterns of the consumers in relation with Nord Pool Spot prices are assessed. In addition, the sample solar module, wind generator and hybrid system capabilities for covering household loads in Estonian households are analyzed.

KOKKUVÕTE

Antud doktoritöös uuritakse võimalust kodumajapidamistes kulutusi kokku hoida arvestades võimalust alates 2013 aastast kasutada elektrienergia tunnipõhiseid tariife ning sidudes elektribörsi hinnakõikumisi taastuvenergiaallikatest saadava elektrienergiaga. Töö üldeesmärgiks on leida majanduslikult otstarbekas elektrienergia reservide vajadus kulude kokkuhoiuks ilma tarbimiskarakteristikuid muutmata. Töö teema on aktuaalne seoses sellega, et ka kodumajapidamised peavad lähiajal kogu Europas üle minema uutele tariifisüsteemidele, kuna on kohustatud ostma elektrienergiat vabaturu tingimustes. Vabaturg oma hinnavolatiilsusega annab mitmeid võimalusi, kuidas hinnataset tarbijapoolel madalamal hoida. Kuigi reaalajahinnal on omi eeliseid pole sellega kaasa jõudnud kodumajapidamiste automaatika ning hinnakõikumis ärakasutamine pole veel lihtne tegevus. Samuti on oluliselt arenenud tasuvamaks ka taastuvenergeetika tootmisallikad. Nii päikesepaneelid kui ka tuulegeneraatorid odavnevad iga aastaga.

Töö esimeses peatükis on kirjeldatud vabaturu teket ning vaba elektrituru käitumispõhimõtteid, Eesti seisundit vabaturul ning energiasalvestuse võimalusi tarkvõrkudes.

Teises peatükis hinnatakse ja klassifitseeritakse tarbijate kasutusmustreid ning tarbimise ajasõltuvust. Samuti antakse esmased juhised reservide arvutamiseks lähtuvalt tarbimisest ja arvestades turuhinna liikumisi.

Viimases peatükis hinnatakse taastuvenergeetikavahendite kasutusvõmalusi Eestis ning vastavate süsteemide dimensioneerimist lähtuvalt nii tuulest, päikesepaistest ja tarbijate kasutusmustrist samuti lähtudes ka Nord Pool spot börsihinnast. Lisaks on analüüsitud täpsustatud suurusega päikesepaneeli, konkreetse võimsusega tuulegeneraatori ning nendest kombineeritud hübriidsüsteemi võimekust tagada energiavarustus kodumajapidamises Eesti tingimustes.

APPENDIX 1 ELULOOKIRJELDUS

1. Isikuandmed

   Ees- ja perekonnanimi: Aivar Auväärt
   Sünniaeg ja -koht: 31.10.1974, Tallinn, Eesti
   Kodakondsus: Eesti

2. Kontaktandmed

   Aadress: Kiini 10, Tallinn, Eesti
   Telefon: +372 5213 831
   E-posti aadress: aivar.auvaart@eesti.ee

3. Hariduskäik

Õppeasutus (nimetus lõpetamise ajal)	Lõpetamise aeg	Haridus (eriala/kraad)
Tallinna Tehnikaülikool	2006	Tootearendus/ tehnikateaduste magistri kraad
Eesti-Ameerika Ärikolledž	2004	Ärijuhtimine/ rakenduskõrgharidus
Tallinna Tehnikaülikool	2003	Tootmistehnika/ tehnikateaduste bakalaureuse kraad
Tallinna 13. Keskkool	1993	Keskharidus

4. Keelteoskus (alg-, kesk- või kõrgtase)

Keel	Tase
Eesti keel	Emakeel
Inglise keel	Kõrgtase
Soome keel	Kesktase
Vene keel	Kesktase

5. Teenistuskäik

Töötamise aeg	Tööandja nimetus	Ametikoht
2013-	Tallinna Tehnikaülikool	Osakonna juhataja aseäitja
2013-	Tallinna Tehnikaülikool	Nõukogu liige
2011-	Collectum Consulting OÜ	Juhatuse liige
2010-2014	CONORT Engineering OÜ	Juhataja
2009-	Kesk-Eesti Hoiu-laenuühistu	Juhatuse liige
2008-2013	Navigator Consulting OÜ	Juhatuse liige
2006-2013	Tallinna Tehnikaülikool	Projektijuht
2004-2006	Ettevõtluse Arendamise Sihtasutus	Arenduskonsultant
2002-2004	Almaren OÜ	Juhataja
2002	Starman AS	Teenindusjuht
2000-2002	Tele2 Eesti AS	Tootejuht
1998-2000	Datel AS	Projektijuht
1997-1998	Mainor AS	Müügijuht

6. Teadustegevus

Projekt ETF7572 Võimsad kõrgsagedusliku vahelüliga alalispingemuundurid, põhitäitja
Projekt SF0140009s08 Säästev ja jätkusuutlik elektroenergeetika, põhitäitja
Projekt BF95 rahvussvahelise sümpoosioni Topical Problems in the Field of Electrical and Power Engineering ettevalmistamine
Projekt F12006 Radioaktiivse kiirguse mõõtmise meetodi rakendamine, põhitäitja
Projekt Lep11050 Puidukahjurite neutraliseerimine ülikõrgsagedusliku elektromagnetvälja abil, põhitäitja
Projekt F10133 Elektrit mittejuhtivate materjalide kuivatamine ülikõrgsagedusliku magnetvälja abil, põhitäitja
Projekt IN576 Energia ja geotehnika doktorikool, vastutav täitja

7. Kaitstud lõputööd

Magistritöö: Elektropneumaatilise õppestendi arendusprojekt, 2006 juhendajad dotsent Tauno Otto ja Martins Sarkans, Tallinna Tehnikaülikool
Bakalaureusetöö: Toote elutsükli juhtimine õppetöö näitel, 2003, juhendaja dotsent Andres Kimmel, Tallinna Tehnikaülikool
Diplomitöö: Avalik arvamus äris ja selle kujundamise viisid, 2004, juhendaja Žanna Aronstam, Eesti-Ameerika Ärikolledž

8. Teadustöö põhisuunad
   Reaalajatariif, tarkvõrgud

9. Teised uurimisprojektid
   Ülikõrgsagedusliku kiirguse kasutusalad

APPENDIX 2 CURRICULUM VITAE

1. Personal data

    Name: Aivar Auväärt
    Date and place of birth: 31th October 1974, Tallinn, Estonia

2. Contact information

    Address Kiini 10, Tallinn
    Phone + 3725213831
    E-mail: aivar.auvaart@eesti.ee

3. Education

Educational institution	Graduation year	Education (field of study/degree)
Tallinn University of Technology	2006	Product Development/MSc
Estonian-American Business College	2004	Business Management/ college diploma
Tallinn University of Technology	2003	Production Engineering/ BSc
Tallinn Secondary school no 13	1993	Secondary Education

4. Language competence/skills (fluent; average, basic skills)

Language	Level
Estonian	Mother tongue
English	Fluent
Finnish	Average
Russian	Average

5. Professional Employment

Period	Organization	Position
2013-	Tallinn University of Technology	Deputy Head of Office
2013-	Tallinn University of Technology	Member of Council
2011-	Collectum Consulting OÜ	Member of Executive Board
2010-2014	CONORT Engineering OÜ	CEO
2009-	Kesk-Eesti Hoiu-laenuühistu	Member of Executive Board
2008-2013	Navigator Consulting OÜ	Member of Executive Board
2006-	Tallinn University of Technology	Project Manager
2004-2006	Enterprise Estonia	Business Development Consultant
2002-2004	Almaren OÜ	CEO
2002	Starman AS	Service Manager
2000-2002	Tele2 Eesti AS	Marketing Manager
1998-2000	Datel AS	Project Manager
1997-1998	Mainor AS	Sales Manager

6. Scientific work

Project ETF7572 High power DC voltage converters with high frequency transformer link, research staff

Project SF0140009s08 Energy saving and sustainable electrical power engineering, research staff

Project BF95 Preparation for the international symposium Topical Problems in the Field of Electrical and Power Engineering, research staff

Project F12006 New method for detecting radioactive decay, research staff

Project Lep11050 Elimination of timber pests with ultra-high frequency electromagnetic field, research staff

Project F10133 Drying of non-conductive materials using high intensity magnetic fields, research staff

Projekt IN576 Doctoral School of energy and geotechnology, principal investigator

7. Defended theses

MSc: Development project for electro-pneumatic training stand, 2006 Supervisors Ass. Prof. Tauno Otto and Martins Sarkans, Tallinn University of Technology

BSc: Product lifecycle management in basis of studies, 2003, supervisor Ass. Prof Andres Kimmel, Tallinn University of Technology
Diploma: Formation of public opinion in business, 2004, supervisor Žanna Aronstam, Estonian-American Business College

8. Main areas of scientific work/Current research topics
   Real-time tariff, distributed generation

9. Other research projects
   Usage of ultra-high frequency electromagnetic radiation

PAPER I

Rosin, A.; Auväärt, A.; Lebedev, D. (2012). Energy storage dimensioning and feasibility analysis for household consumption scheduling based on fluctuations of Nord Pool Spot price. Przeglad Elektrotechniczny, 88(1a), 37 - 40.

Argo ROSIN[1], Aivar AUVÄÄRT[1], Denis LEBEDEV[1]

Tallinn University of Technology (1)

Energy storage dimensioning and feasibility analysis for household consumption scheduling based on fluctuations of Nord Pool Spot price

***Abstract**. This paper describes the analysis of price fluctuations in the Nord Pool Spot (NPS) Estonia (EE) area. Also the electrical energy storage dimensioning and feasibility analysis for consumption scheduling on the basis of the NPS EE area price is discussed.*

***Streszczenie.** W artykule przedstawiono analizę fluktuacji cen na obszarze objętym przez Nord Pool Spot (NPS) Estonia. Dodatkowo zaprezentowano metody wymiarowania oraz analizę wykonalności układów magazynowania energii na podstawie danych dotyczących zużycia energii w systemie NPS EE. (**Wymiarowanie i analiza wykonalności magazynów energii dla obiektów mieszkalnych na podstawie fluktuacji cen w Nord Pool Spot**).*

Keywords: consumption scheduling; household; Nord Pool Spot; energy storage dimensioning; feasibility.
Słowa kluczowe: in the case of foreign Authors in this line the Editor inserts Polish translation of keywords.

Introduction

The deregulation of electricity industry is giving way to global trends toward the commodization of electric energy. [1][2]. This trend has intensified in Europe and North America, where market forces have pushed legislators to begin removing artificial barriers that have shielded electric utilities from competition. The price of electricity is far more volatile than that of other commodities normally noted for extreme volatility. Relatively small changes in load or generation can cause large changes in price and all in a matter of hours (with real-time dynamic prices in seconds or minutes). Unlike in the financial markets, electricity is traded every hour of the year - including nights, weekends and holidays. Unlike other commodities, electricity cannot be stored efficiently. Therefore, delicate balance must be maintained between the generation and consumption for 8760 hours a year.

There is, however, a great difference between electricity and the other energy (and commodity) markets in that the variable costs of production vary so greatly between different types of installation – Wind and Hydropower with a virtual nil cost at one extreme and Gas Turbines at the other end of the scale. In order to satisfy fluctuating consumer demand at the lowest cost, a broad variety of generating techniques are required. Some installations are capital intensive but can be run year round and are relatively fuel efficient (hydro, nuclear, coal-fired). Other units such as co-production of heat and power are used less frequently to cover winter heating demand at times of higher prices. Whilst energy intensive units such as Gas Fired Turbines are used for brief periods of very high price and demand.

Although the principle of generation electricity is simple, generating electricity for an area as large as Europe means a complex balancing process. One of the biggest problems faced by the system operator is congestion. When congestion occurs, zonal prices supersede power exchange’s market clearing price, which is based on the aggregated energy supply and demand curve intersection point for each hour [3]. In such a case, electricity prices can increase or decrease dramatically. The primary role of a market price is to establish equilibrium between supply and demand. This task is especially important in the power markets because of the inability to store electricity efficiently and the high costs associated with any supply failure. NPS runs the largest market for electrical energy in the world, offering both day-ahead and intraday markets to its participants. 330 companies from 20 countries trade on the Exchange. In 2009 the NPS group had a turnover of 288TWh [4]. The spot market at NPS is an auction based exchange for the trading of prompt physically delivered electricity. The spot market carries out the key task of balancing supply and demand in the power market with a certain scope for forward planning. In addition to this, there is a final balancing process for fine adjustments in the real time balancing market. The spot market receives bids and offers from producers and consumers alike and calculates an hourly price which balances these opposing sides. NPS publishes a spot price for each hour of the coming day in order to synthetically balance supply and demand. Every morning Nord Pool participants post their orders to the auction for the coming day. Each order specifies the volume in MWh/h that a participant is willing to buy or sell at specific price levels (€/MWh) for each individual hour in the following day. The SESAM (Elspot trading system) calculation equation (1) is based on an application of the social welfare criteria in combination with market rules. SESAM is maximizing the value of the objective function subject to physical constraints; like volume constraints, area balances, transmission and ramping constraints.

$$Max \sum_{n} \left\{ \int_{0}^{d^a} D^a(x)dx - \int_{0}^{s^a} S^a(y)dy \right. \tag{1}$$

where a – represents an area, d^a – demand in the area a, and D^a – demand function in the area a, s^a – supply in the area a, S^a – supply function in the area a, and n – number of areas.

The system price (SP1) for each hour is determined by the intersection of the aggregate supply and demand curves which are representing all bids and offers for the entire Nordic region [4]. In addition to area price there is also an annual fixed fee and a variable trading fee for all market participants. In the political debate surrounding energy, this type of price formation is labeled a marginal price setting. This gives a false impression that the establishment of prices in the electricity market is different from the price formation process in other commodity markets. The only difference lies in the significantly higher requirements for the secure delivery of electricity because it must be delivered at the precise moment it is needed by the consumer. The inelasticity caused by the inability to store electricity is the reason of this difference.

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

To find the possibilities for consumption scheduling it was constructed an average day from actual data from the NPS trading system. It was studied a period of seven months starting in April 2010. Average price was calculated with the well-known formula of a generalized mean.

$$\bar{x} = \sqrt[m]{\frac{\sum_{i=1}^{n} x_i^m}{n}} \tag{2}$$

where X_i – price of electrical energy at time i

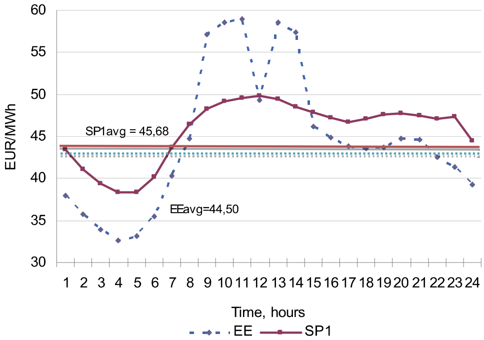

Fig. 1. Average daily price at the EE area and SP1 area

One hour is the smallest time interval when prices can change, because on spot electricity trading prices are set constant for delivery of power during a certain hour. Analysis shows that fluctuations in the system area are smaller (around 11.00€/MWh) than in the EE area (the amplitude of the price during the day is much higher at 26.35€/MWh) (Fig. 1). The high price amplitude in the local market provides opportunities to use consumption scheduling models in residential areas to gain economy.

Energy consumption in households in the UK is reported in [5] and in Estonia in [6]. Peak hours for UK households are from 06-08 and 13-18. Main peak hours for Estonian average households are at 7-8 and 19-21 on workdays (WD) and 12-14 and 19-21 at weekends (HD). It is quite easy to see the possible use of energy storage to smoothen the loads at morning or midday use and even the evening use at weekends. However, some exact calculations are needed in terms of the possibilities to conserve energy at low price before evening peak hours on workdays [7].

According to equation 2 the average NPS price during the measured period (April 2010 to October 2010) in the Estonia (EE) area is calculated as 44.50€/MWh. The NPS price curve is not similar on workdays and at weekends. The maximum price on workdays is 65.93€/MWh and the minimum is 33.35€/MWh. At weekends the maximum and minimum prices are 43.05€/MWh and 29.76€/MWh, respectively. Average price below the EE area average (44.50€/MWh) is 38.02€/MWh (-14.55%) on workdays and 38.26€/MWh (-14.03%) at weekends. Average price above the EE area average is 53.50 €/MWh (20.22%) on workdays and does not exceed the average at weekends.

If all shiftable loads on workday (WD) are "switched on" under average price, then at least 1.1 kWh storage system is needed for shifting of energy consumption (Fig. 2).

If all shiftable loads on holiday (HD) are "switched on" under average price, then at least 11.8 kWh of energy consumption should be supplied from the storage system (Fig. 3). If an average price deviation is allowed (43.05 - 29.76)*10% = 1.33€ (10 % from maximum and minimum price difference), then 4.83 kWh should be supplied from the electrical energy storage.

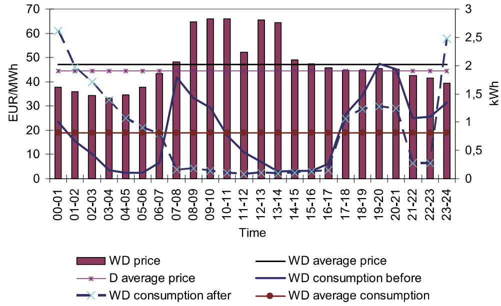

Fig. 2. Average workday price fluctuation compared to electricity consumption before and after scheduling of shiftable loads

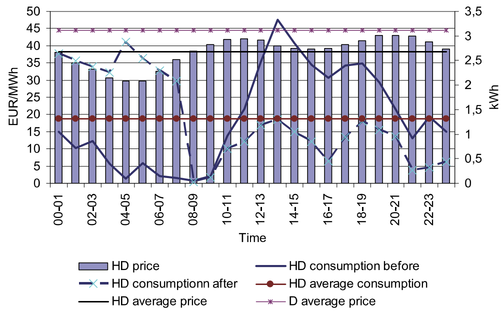

Fig. 3. Average holiday price fluctuation compared to electricity consumption before and after scheduling of shiftable loads

Average price deviation and distribution of price range

As shown on figure 4, the deviation calculated by the simple formula (3) from the average price to analyze possibilities to use off-peak hours to store energy or shift the load to off-peak hours. We needed an assurance of off-peak hours available to recharge the batteries or other storage equipment. We found that the average duration of peaks that are higher than the average area price is 9.59 hours and the average duration of off-peaks is 13.48 hours. That means there is plenty of time to recharge storage equipment during the off-peak time.

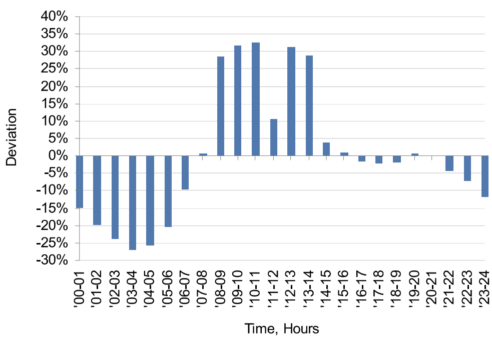

Fig. 4. Average EE area price deviation

Deviation from an average price is higher at peak hours, but peak hours last less than off-peak hours. It is most profitable to save energy between the 23...06 o'clock, then the price is lower than 10% compared to average. There is also a possibility to save energy between 16...19 o'clock when the price is about 2-3% lower than average.

$$S = \frac{\sum_{n=1}^{k} \frac{x_i}{n} - X_F}{X_F} \quad (3)$$

where X_i – price of electrical energy in the instance i (from 0-24 hours), and X_F – average area price.

As seen in fig. 5 the distribution of prices is symmetric and leptokurtic. With the leptokurtic distribution, the price will have a relatively low amount of variance, because return values are close to the mean. This could mean that energy producers will not try to invest to storage facilities as there could be quite small return on investment. This gives us an opportunity to continue our research on the profitability of using energy storing and shifting on the demand side.

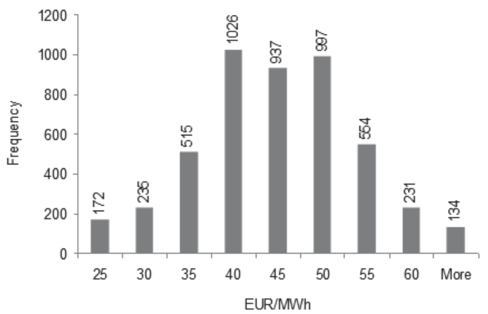

Fig. 5. Distribution of price range in the EE area

Feasibility analysis

Today batteries could be the best solution for consumption shifting in an average apartment [6]. Their feasibility for households can be estimated by the system cost and profit calculation. To find a profitable ES, it is necessary to take into account parameters and costs described in papers [8] and [9]. In current analysis are described Lead-Acid (LA), Nickel Cadmium (NiCd), Lithium Ion (LiIon), Sodium Sulphur(NaS), Vanadium Redox Flow(VR), Polysulfide Bromide Flow (PSB) and Zinc Bromide (ZnBr) batteries.

10 year usage of energy storage (1 charge/discharge cycle per day) will give approximately 3650 cycles then charging takes place in the low price period at night and discharge takes place in the high price period during daytime. In case of constant Depth of Discharge (DoD) value, the required energy capacity is different from initial energy capacity. The simple equation 4 establishes the final required energy capacity for consumption scheduling with particular DoD.

$$E_{1,\max} = \frac{E_I}{DoD} \quad (4)$$

Where $E_{1,max}$ – required maximum energy capacity, and E_I – initial required energy capacity.

Table 1 shows the result of DoD and energy capacity calculation with 3650 cycles for different batteries with 7 and 12 kWh of Initial Required Energy Capacity (IREC). It shows that highest discharge depth can be applied in case of NaS battery, which reduces the final required energy capacity until 7.68 kWh. Thus, daily maximum load shifting to low price involves one charging/discharging cycle of ES with 7 kWh of energy capacity. Daily cost savings C_{cyc} for one charge/discharge cycle with estimated price deviation are shown in (5).

$$C_{cyc} = E_{2,\max} \cdot \Delta x \quad (5)$$

where E_{2max} – ES maximum energy capacity for financial saving, Δx – amplitude of price during the day (26.35€/MWh).

Table 1. DoD and energy capacity calculation with 3650 cycles

	Li-Ion	LA	NiCd	ZnBr	VR	NaS
DoD, %	72,76	14,58	43,63	45,62	76,66	91,10
IREC 7 (kWh)	9,62	48,02	16,04	15,34	9,13	7,68
IREC 7 (kWh)	16,49	82,32	27,50	26,31	15,65	13,17

The result of equation 5 is 0.186 € (7 kWh x 0.0264 €/kWh). It means that one charging/discharging cycle of ES for investigated apartment will save 0.19€

Table 2 demonstrates ES total cost calculated for initial required energy capacity of 7 kWh and peak power 7 kW. There are columns with calculated number of cycles for investment return and costs per 1 cycle. The last column of table 2 is price difference multiplying factor. It shows by how many times current price difference must be increased for ES recoupment. As we can see none of batteries storages is able to return the investment and make profit within current life-time (cycles). It means, with current price differences, there are only two opportunities to achieve profitability. The first one is reducing the total cost of energy storage system (cheaper components, cheaper maintenance), which should give possibility to return investment in limited period of time i.e. 7 – 10 years. The second method is increasing lifetime of ES (more cycles, higher efficiency), which should give possibility to return investment in period of time about 20 – 30 years, before it fails or breaks down.

According to table 2 the most prospective ES is Sodium Sulphur (NaS) Battery. It has medium energy capacity cost and slightly expensive power capacity cost (up to 380€ / kW). While it is quite new product on the market, the cost could be reduced. Today, the main difficulty is that developing companies generally target this technology for utility-scale (>1000 kW) stationary applications. Developing of NaS system solutions for small consumers can bring this type of storages to households market.

The increasing usage of renewable energy sources (and/or increasing production of renewable sources) on the market could increase price differences and profitability of ES systems. Also, introduction of full real-time dynamic pricing system (e.g. price changing period is 5 minutes or less), with increased amplitude of price, could reduce profitability time of electrical ES systems for households.

Table 2. Investments return calculation for battery energy storages

Battery type	Energy storage cost €	Cost per cycle €	Amount of required cycles to return the investment	ES actual lifetime cycles with DoD 50%	Price difference multiplying factor to return investments with lifetime cycles
NaS	4109	0,41	21625	10000	2,2
LA	3399	8,94	17889	380	47,1
NiCd	7948	2,65	41833	3000	13,9
Li-Ion	6772	0,97	35642	7000	5,1
ZnBr	3161	0,93	16635	3400	4,9
PSB	3979	0,99	20944	4000	5,2
VR	3394	0,64	17862	5300	3,4

Conclusion

We observed the EE area price during 4802 hours starting from 1 April 2010 when Estonia entered the NPS market. During that time an average hourly price for the EE price area was 44.5€/MWh and it is slightly lower than the price in the system area. The price curve is similar on weekdays and at weekends. At weekends the average hourly price remains under an average area price. An average off-peak time lasts for 13.48 hours, which is long enough to store energy with cheaper storage equipment or shift the power usage to a less expensive time period without losing customer's comfort requirement. The minimum energy reserves that an electrical energy storage system should have for described household energy consumption shifting, based on the Nord Pool Spot (NPS) average daily price should be between 4.83....11.8 kWh (average about 7 kWh).

Described analysis shows that there is no ES solution for a household which would return total initial investments and make a profit in a lifetime period. With current battery lifetimes and current DoDs, battery storages will bring profit only with the difference growing between energy prices by 2.2 for NaS as a minimum and by 47.1 for LA as a maximum one. Nevertheless, the similarity of the calculated parameters of household energy storage with the parameters of existing hybrid electric vehicle batteries makes the technology used in vehicles attractive for residential areas. Today, the most feasible solution is load shifting with simple scheduling systems (without electrical energy storage). Profitability time of investments for simple scheduling systems is up to 2 years. For example, investment for the shifting equipment of water heater is less than 1 year.

Authors thank the Estonian Ministry of Education and Research (Project SF0140016s11) and Estonian Archimedes Foundation (Project "Doctoral School of Energy and Geotechnology II") for financial support of this study.

REFERENCES

[1] Strecker S, Weinhardt C, ;Electronic OTC Trading in the German Wholesale Electricity Market, Lecture Notes in Computer Science, 2000 Volume 1875/2000, 280-290.
[2] S. Green, Power Eng. Int. 7 (4) (1999) 45.
[3] Rafal Weron, Energy price risk management, Physica A: Statistical Mechanics and its Applications, Volume 285, Issues 1-2, 15 September 2000, Pages 127-134, ISSN 0378-4371, 10.1016/S0378-4371(00)00276-4.
[4] NPS homepage; www.nordpoolspot.com (2010).
[5] S. Firth, K. Lomas, A. Wright, R. Wall, Identifying trends in the use of domestic appliances from household electricity consumption measurements, Energy and Buildings, Volume 40, Issue 5, 2008, Pages 926-936, ISSN 0378-7788, 10.1016/j.enbuild.2007.07.005.
[6] Rosin, A.; Hõimoja, H.; Möller, T.; Lehtla, M.; , "Residential electricity consumption and loads pattern analysis," Electric Power Quality and Supply Reliability Conference (PQ), 2010 , vol., no., pp.111-116, 16-18 June 2010, 10.1109/PQ.2010.5550009
[7] Auvaart, A.; Rosin, A.; Belonogova, N.; Lebedev, D.; , "NordPoolSpot price pattern analysis for households energy management," *Compatibility and Power Electronics (CPE), 2011 7th International Conference-Workshop*, pp.103-106, 1-3 June 2011, 10.1109/CPE.2011.5942215
[8] J. Jacobi and S. Wilson, "Fast Response Energy Storage Devices, Technology descriptions and overview", ScottMaden Inc.,2009, pp.1-26.
[9] K. Bradbury, "Energy Storage Technology Review", Duke University, August 22 2010, pp. 1-34.

***Authors**: D. Sc. Eng. Argo Rosin, Department of Electrical Drives and Power Electronics, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, E-mail: vagur@cc.ttu.ee; Ph.D. student Aivar Auväärt, Department of Electrical Drives and Power Electronics, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, E-mail: aivar.auvaart@ttu.ee; Ph.D. student Denis Lebedev, Department of Electrical Drives and Power Electronics, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, E-mail: denis.lebedev@saksa-automaatika.ee.*

PAPER II

Rosin, A.; Rosin, K.; Auväärt, A.; Strzelecki, R. (2012). Dimensioning of household electricity storage for PV-systems and load scheduling based on Nord Pool Spot prices. Przeglad Elektrotechniczny, 88(4b), 294 – 299.

Argo ROSIN[1], Kai ROSIN[1], Aivar AUVÄÄRT[1], Ryszard STRZELECKI[2]

Tallinn University of Technology (1), Electrotechnical Institute/Gdynia Maritime University (2)

Dimensioning of household electricity storage for PV-systems and load scheduling based on Nord Pool Spot prices

***Abstract**. This paper analyzes global irradiance data measured in the Tallinn-Harku Aerological Station (Estonia). Dimensioning of a PV-panel area and electricity storage for a typical household is discussed. The final part describes electricity storage dimensioning based on a combination of Nord Pool Spot (NPS) prices and a grid connected household PV-system generation.*

***Streszczenie.** W artykule są analizowane całościowe dane pomiarowe oświetlenia słonecznego na stacji metrologicznej Tallinn-Harku. Na tej podstawie jest dyskutowany dobór paneli PV i zasobnika energii w warunkach typowego gospodarstwa domowego. Końcowa części opisuje wymiarowanie zasobnika energii elektrycznej, w oparciu o ceny dystrybutora energii i połączonego z siecią domowego systemu PV. (**Wymiarowanie zasobnika energii elektrycznej w gospodarstwach domowych dla systemów PV i planowanie obciążeń w oparciu o ceny Nord Pool Spot**).*

Keywords: Solar energy; global radiation; photovoltaics; dimensioning of electricity storage, electricity balance.
Słowa kluczowe: in the case of foreign Authors in this line the Editor inserts Polish translation of keywords.

Introduction

Energy storage (ES) is crucial component of distributed generation systems in order to comply with power peaks, to reduce installed generation capacity and to balance missing long and short term coincidence between power generation and demand [1]. Variable nature of solar radiation makes it impossible to deliver energy from a photovoltaic (PV) system at a constant power level, and energy backup and torage are always needed [2]. As described by B. S. Borowy and Z. M. Salameh the optimum mix of PV modules and batteries depend on the particular site, load profile, and the desired reliability of the hybrid system [3].

Optimal dimensioning of electricity storage according to the energy production of micro-scale renewables (in residential areas and households) and electricity consumption are important topics in the development of micro- and smartGRID technologies to increase system reliability and to reduce the profitability time. Flourishing use of an electric grid needs permanent online balancing of supply and demand, including grid losses. Correctly chosen electricity storage technologies will smooth out these surges and allow electricity to be dispatched at a later time.

Good overview about effects of demand response on the end-customer distribution fee and experiences from spot-market based price response of residential customers is described in [4, 5]. Opening of electricity market gives new opportunities to optimize microgrids topologies, including surface and storage capacity of PV-system. Optimization of renewable systems (including hybrid renewable systems and PV-systems with energy storages) is well analyzed research topic, but it can be found only few analysis about optimization of energy storages and PV-systems according to open electricity market prices (e.g. Nord Pool Spot)

Solar Radiation Analysis in North Estonia

Solar surface irradiance depends first of all on astronomical factors, but is greatly modified by cloudiness, atmospheric transparency and snow cover. The latter factors show significant spatial and temporal variability, which is reflected in the variability of solar fluxes [6]. Detailed long-term global irradiance data about Estonia is described in [7]. The analysis below is based on global irradiance data measured in the Tallinn-Harku Aerological Station (latitude N 59°23´53´´; longitude E 24°36´10´´, height above sea level 33 m), and average household energy consumption data described in [8]. As a result of the global radiation analysis, the global radiation of an average day in June compared to December is up to 50 times higher. In June at peak hour (11 o'clock) the total radiation is up to 18 times higher than in December. About 85% of the resource is concentrated on the summer season from April until September, when energy generation is over average (Fig. 1).

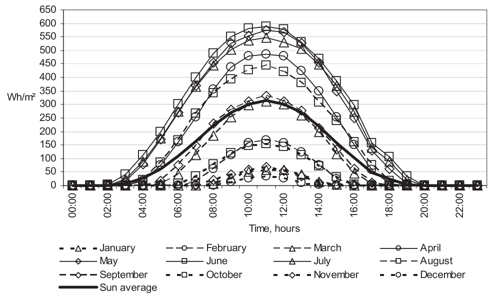

Fig. 1. Average daily radiation by months (Harku 2005-2009)

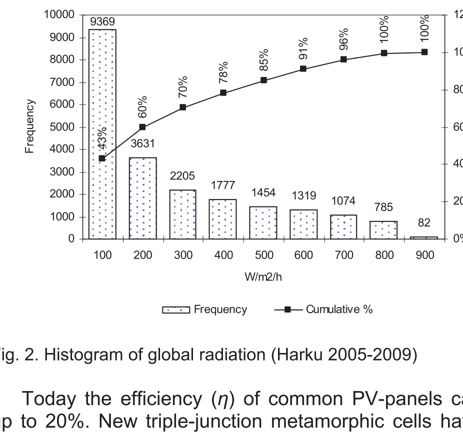

Fig. 2. Histogram of global radiation (Harku 2005-2009)

Today the efficiency (η) of common PV-panels can be up to 20%. New triple-junction metamorphic cells have an efficiency of about 40% (laboratory tested). Commonly the high efficiency solar cells are used in concentrating photovoltaic systems for solar power stations in the countries with a large fraction of direct solar radiation. In Estonia due to the high share of diffuse radiation, concentrators are not feasible and only flat plate collectors (PV-modules) can be recommended [9]. Also, the high share of diffuse radiation means a lower rate of radiation. As shown in Figure 2, during the last five years about 60% of sunset hours solar radiation was above 200 W/m^2/h.

Using of a 2-axis solar tracking system (2ASTS) in the winter season, it is very important to take into account apparent altitude of the sun (α_{aas}). In December the 2ASTS system produces approximately up to 2.5 times more energy than a horizontal system, but apparent amplitude of the sun is lower and shadows are longer. For example, if an apparent altitude of the sun is 10° (December), the shadow is five times longer than the object length (1).

$$l_{shw} = l_{obj} \cdot \frac{\sin(90 - \alpha_{aas})}{\sin(\alpha_{aas})}, \tag{1}$$

where l_{shw} – length of a shadow; l_{obj} – height of an object; α_{aas} – apparent altitude of the sun.

In June the difference of energy generation of ASTS and horizontal systems is 1.5 times. Using a 2-axis tracking system, the difference found between energy generation in June and December is about 20 times. Using a horizontal PV-system, the difference between energy generation in these months is about 50 times.

PV-System Dimensioning for Typical Estonian Households

The following calculations (2-3) are simplified and do not take into account the PV-system performance ratio, including system losses, and temperature coefficient of module efficiency. Solar modules based on crystalline cells can even reach a performance ratio of 85 - 95 % [10].

$$A_{pv} = \frac{1}{k_{pr}} \cdot \frac{E_c}{E_{pv}} = \frac{1}{k_{pr}} \cdot \frac{1}{\eta_{pv}} \cdot \frac{E_c}{E_s} \tag{2}$$

$$A_{pv,ideal} = \frac{E_c}{E_{pv}} = \frac{1}{\eta_{pv}} \cdot \frac{E_c}{E_s}, \tag{3}$$

where A_{pv} – PV-module area; k_{pr} – performance ratio; E_c – electricity consumption; E_{pv} – electricity generation of a PV-system; E_s – global irradiance in Wh; η_{pv} – efficiency of a PV-system.

Average electricity consumption (about 0.5 kWh per hour) [8], without consumption of an electrical water heater, in June can be covered by flat PV-panels with an area of 10.4 m^2 (η = 0.2). To cover an average electricity consumption (A) in December, PV-panels with an area up to 524 m^2 should be installed. Based on annual electricity generation and household consumption, the area of PV panels should be approximately 24 m^2. This calculation does not take into account the huge surplus in the summer season and the shortage in the winter season. At least the calculations should be based on average day data of solar radiation and electricity consumption for a month. A PV area calculation for an on-grid system is based on average daily electricity generation and the highest consumption day in the lowest global solar radiation month (in the summer season). As described, about 85% of the resource is concentrated on the summer season from April until September. To use this resource efficiently, during that period the highest consumption day should be found. For a PV area, calculations an average holiday (HD) and workday (WD) electricity consumption (accordingly 0.66 kWh/h and 0.38 kWh/h) should be compared. If the holiday total electricity consumption is greater or equal to the workday electricity consumption, then the PV area calculation is based on the holiday data, otherwise on the workday data (4).

$$E_c = \begin{cases} E_h, E_h \geq E_w \\ E_w, E_h < E_w \end{cases} \tag{4}$$

where E_h – total electricity consumption of a holiday; E_w – total electricity consumption of a workday;

Here the total electricity consumption of an average holiday is the sum of electricity consumption of 24 hours. Total irradiance of an average day is the sum of each hour in a day.

The largest average electricity consumption is on holidays. The smallest electricity generation in the summer season is in September. Based on these data the largest area of PV-panels in the summer season should be approximately 34 m^2 (holiday in September) (Fig. 3).

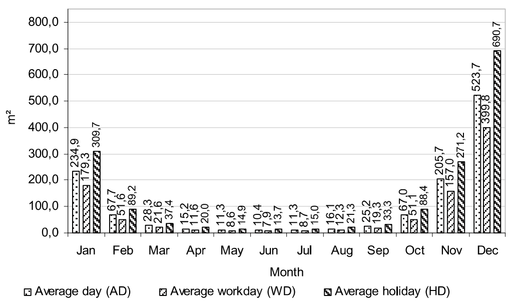

Fig. 3. Area of horizontal PV-panels

Based on the formula (3), a PV system with an area of 34 m^2 and efficiency of 20% will have theoretically the maximum total day generation of 54 kWh (June) and the minimum 0.1 kWh (December).

In different seasons of the northern regions the deviation of global solar irradiation and PV-system generated energy is relatively high. The coefficient of variation V_R of monthly generation is 72% (5).

$$V_R = \frac{\sum_{i=1}^{n} \left| E_{pv,i} - \overline{E_{pv}} \right|}{n \cdot \overline{E_{pv}}}. \tag{5}$$

where $E_{pv,i}$ – generated electricity at the hour i; n – 24 hours in a day; $\overline{E_{pv}}$ – average daily electricity generation.

High variations in annual electricity generation are the main problem to define an optimal PV-system and electricity reserves for an energy storage system for load coverage.

In Northern regions it is not reasonable to plan PV-systems because of the lowest global radiation. If a horizontal PV-system is used, the difference of the calculated areas for September and December is 20 times. Even, if 2ASTS is used, the difference of the calculated areas is 8-10 times. In an OFF-grid system for load coverage in the winter season, it is reasonable to use a PV system with a micro-CHP or a wind turbine. Average wind speed in the winter season is higher than in the summer season, and this can compensate the shortage of energy caused by lower solar radiation. Micro-CHP produces additional thermal energy, which can be fully used in the winter season. In an ON-grid system, in the winter season covering the shortage of electricity with low-tariff energy stored in the PV-system energy storage is a suitable solution. Next, energy balance of a household PV-system and energy reserve dimensioning for a storage system are analyzed. Also, it should give an answer to the question: "Is it possible to use electricity storage of a PV-system for Nord Pool Spot price based consumption scheduling or *vice versa*?"

Electricity Reserve Dimensioning of a Household PV-system for Load Coverage

Energy balance of a PV-system can be described according to the following simplified formula:

$$(6)\quad E_{pv} = E_c + E_{sp} + E_{los} \quad E_{pv} = \underbrace{E_{dir} + E_{res}}_{E_c} + E_{sp} + E_{los},$$

where E_{pv} – electricity generated by a PV system; E_c – electricity consumption; E_{sp} – surplus of generated electricity; E_{los} – total losses; E_{dir} – direct consumption of electricity generated by a PV system; E_{res} – indirect consumption of electricity generated by a PV system (stored energy reserve of PV generated energy).

In the calculations system losses are not taken into account (E_{los} = 0).

Balance between generation and load

The first step to define the dimensions needed for electricity reserve for load coverage of a household PV-system is the analysis of balance between PV generation and load consumption on an average day of each month (7). While the WD and HD have different consumption curves the analysis should be made separately for both days.

$$(7)\qquad E_{bal,i} = E_{c,i} - E_{pv,i},$$

where $E_{bal,i}$ – energy balance at the hour i.

According to calculations (7) at WD the surplus of generated energy is very high on midday, when the load is trivial. Load maximum prevails in the evening. This means that direct load coverage is very low and on midday generated energy should be stored for the evening period (Fig. 4).

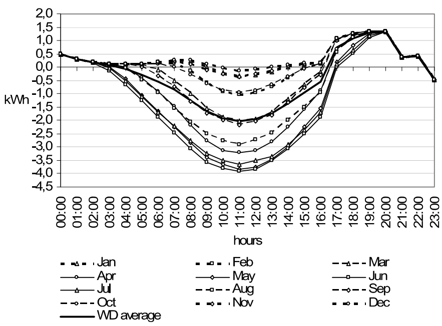

Fig. 4. Balance of WD consumption and generation

Measures should be taken to solve this huge surplus problem. At HD the direct load coverage is better than at WD. Balance between generation and load is better. In the summer season also energy reserves are similar to the reserves used in WD. In the winter season main problems are shortage and higher needs for energy reserves (Fig. 5).

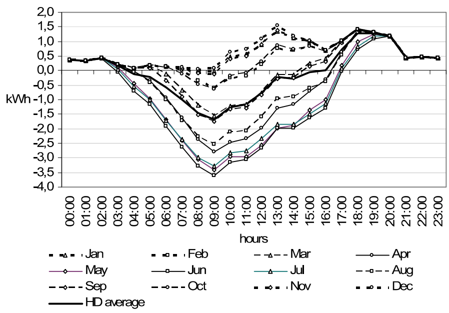

Fig. 5. Balance of HD consumption and generation

Electricity surplus and shortage

The analysis (8) below shows that PV-systems with an area of 34 m^2 can cover electricity consumption from April to September (Fig. 6).

$$(8)\qquad k_{sp} = \frac{E_{sp}}{E_c} = \frac{\sum_{i=1}^{n}(E_{pv,i} - E_{c,i})}{\sum_{i=1}^{n} E_{c,i}};\, n = 24,$$

where $E_{pv,i}$ – generated electricity at the hour i; n – 24 hours in a day; $E_{c,i}$ – electricity consumption at the hour i.

In the winter season theoretically about 43 % of an average consumption can be covered by a PV-system. In workdays and holidays these numbers are 56% and 33%, respectively. With a 2-axis solar tracking system theoretically up to 95% of electricity consumption in the winter season can be covered.

Without losses the average annual surplus of electricity generation of a PV-system in holidays and workdays is 11% and 92%, accordingly. In the summer season an average surplus is 150%, at WD and HD accordingly 227% and 89%. In the winter season the average shortage is 57%, at WD and HD accordingly 44% and 67%.

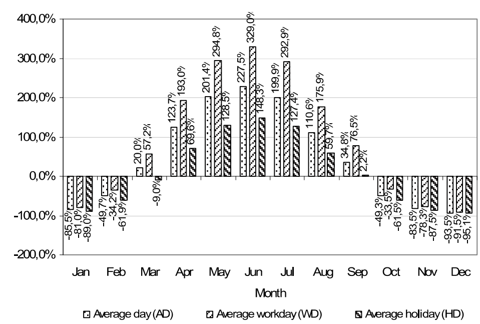

Fig. 6. Surplus/shortage of an average day of a month

Dimensioning of electricity reserve

Approximately 17% of PV-generated energy can be directly used in workdays and 50% in holidays. This is about 32% of a workday and 56 % of a holiday total electricity consumption (9-11).

(9) $$E_{dir} = \sum E_{c,i} - \underbrace{\sum_{E_{pv,i} \le E_{c,i}} (E_{c,i} - E_{pv,i})}_{E_{res,i}}$$

(10) $$E_{dir} = \sum_{E_{pv,i} \le E_{c,i}} E_{pv,i} + \sum_{E_{pv,i} > E_{c,i}} E_{c,i} ,$$

where E_{dir} – directly from PV-system consumed electricity.

(11) $$k_{dir} = \frac{E_{dir}}{E_c}$$

About 30% of an annual average PV generated energy is used directly, which makes approximately 44% of the annual average consumption.

The easiest way to calculate needed energy reserve (storage capacitance) for indirect load coverage is based on the difference of average hourly electricity generation and consumption (12 - 13).

(12) $$E_{pv,i} \le E_{c,i} , \quad \Downarrow$$

(13) $$E_{res} = \sum_{i=1}^{n} E_{res,i} = \sum_{i=1}^{n} (E_{c,i} - E_{pv,i}) = \sum_{i=1}^{n} \left| E_{pv,i} - E_{c,i} \right| ,$$

where $E_{res,i}$ – needed energy reserve at the hour i; E_{res} – needed average daily energy reserve.

Depending on the consumption pattern, about 35 to 40 % of the generated energy should be stored for the darkness period, making up 44 to 68 % of the consumption. In WD, if horizontally installed PV-panels are used, the highest energy reserve is needed in December (8.23 kWh) and the lowest in June (4.67 kWh) (Fig. 7).

In holidays in turn, the highest energy reserve needed is 15.17 kWh and the lowest is 5.44 kWh (Fig. 8). Use of panels with an optimal inclination or 2ASTS, the calculated energy reserve can be reduced up to 10%. The reduction of an energy reserve depends directly on the daylight time and consumption pattern.

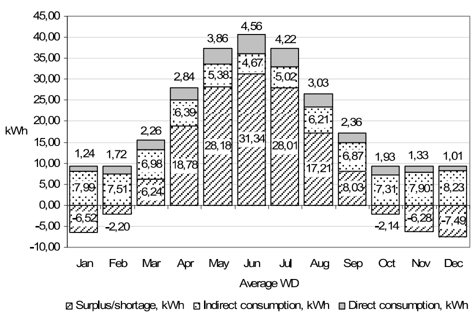

Fig. 7. Direct and indirect load coverage of an average WD of a month

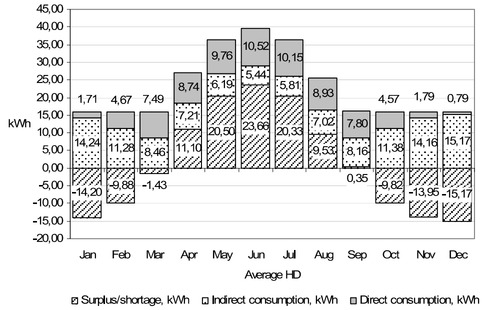

Fig. 8. Direct and indirect load coverage of an average HD of a month

Another calculation method of the energy reserve but rarely used is based on the analysis of the frequency of the duration of darkness hours and average electricity consumption. The following histogram (Fig. 9) shows that 99% of darkness periods are shorter than 20 hours. In the winter season the longest period without generation is about 18 to 22 hours (in December). Based on an average daily (0.5kWh/h), workday and holiday consumption (without electrical water heater) [8], the calculated energy reserves for the darkness period in December on an average day should be accordingly 10, 8 and 13 kWh. An error between the described calculation method of the energy reserves based and formula (13) depends on the difference of the consumption and the generation pattern. For example, as compared to workdays the calculation error of energy reserves in holidays is greater. The error of the calculated energy reserves for December is ≤ 15 %. Rough calculations show that energy reserve for 20 darkness hours can cover about 90% of the total energy consumption. The longest average darkness period is 17 hours in December and the shortest one is 5 hours in June.

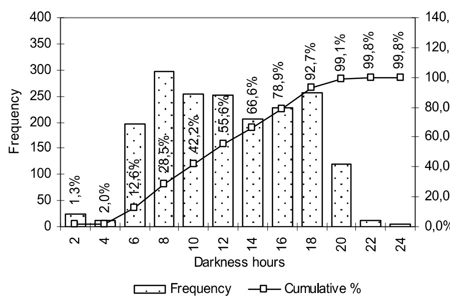

Fig. 9. Histogram of darkness hours

Electricity Reserve Dimensioning Based on NPS price and Grid connected Household PV-System generation

Average NPS (Nord Pool Spot) price during the measured period (April 2010 to March 2011) in the EE (Estonia) area was calculated as 46.30€/MWh. The NPS price curve is similar on workdays and at weekends. The average price of workdays is 47.81 €/MWh and that of weekends is 42.62€/MWh (Fig. 10). The main difference of WD and HD curves is higher midday peak on WD and higher evening peak on HD (Fig. 11, Fig.12). More detailed analysis of first half year is described in [11].

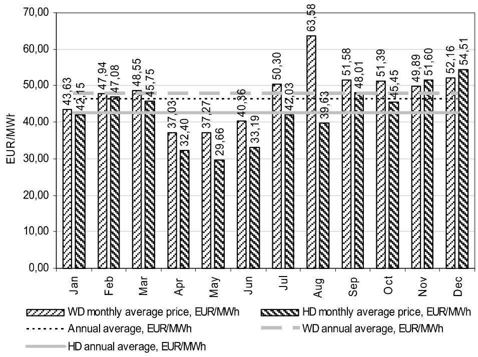

Fig. 10. NPS average day prices of months

The highest average price is in December, caused by weather conditions in Estonia. The lowest average prices are from April to June. In the summer season price fluctuations between night and day are higher; this makes the use of a PV-system during this period more feasible. High WD peak in August last year was caused by failures in the Estonian Power Plant (Fig. 11).

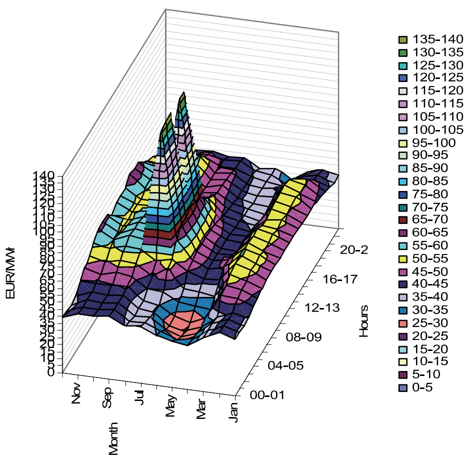

Fig. 11. NPS price fluctuations of WD

An advantage of a PV system on workdays is the similarity of NPS price and electricity generation dynamics. Energy surplus on workdays is relatively high on the peak time of NPS price. A disadvantage of a residential area PV-system is a relatively low local consumption of solar energy on the peak time of NPS WD price. High surplus of electricity generation at the peak time of price should be stored for the consumption peak-time. An advantage of a PV system on holidays is the similarity in the NPS price and electricity generation dynamics at midday (Fig.1 and Fig.12).

Also, energy surplus is relatively high at the first peak time of the NPS price at midday. The first disadvantage is energy deficit in the evening, when generation does not coincide with consumption and the NPS price has the second peak. The second disadvantage is very low energy generation in the winter season at the highest electricity consumption level.

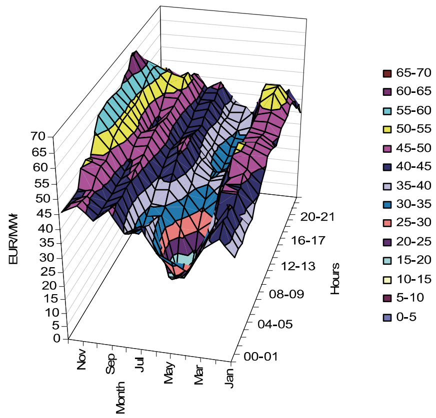

Fig. 12. NPS price fluctuations of HD

The following electricity reserve calculations are based on hourly prices of an average day in months (14). If the hourly price is lower than the average WD or HD price of the month, the electricity consumption and storage charging are covered from the grid. If the hourly price is over the average WD or HD price of the month, the electricity consumption is covered by the PV-system and electricity storage. Based on the described calculations the highest needed energy reserve is needed on holidays in December, which is 12.1 kWh (Fig. 13). On workdays in July and August there is no need for an energy reserve (Fig. 12).

$$p_{m,i} > \overline{p_m} \Rightarrow E_{pv,i} \le E_{c,i} \Rightarrow E_{res} = \sum_{i=1}^{n} (E_{c,i} - E_{pv,i}), \quad (14)$$

where $p_{m,i}$ – average price of the hour i in a month m, $\overline{p_m}$ – average price of a month m

According to the presented energy reserve calculations (Fig. 13, Fig.14), by the combined control of solar irradiance and NPS price based storage control, the storage capacity can be reduced. As compared to the control of PV generation and load balancing, at an annual average WD and HD, combined control allows the energy reserve capacity to be reduced by 46% and 26%, respectively. As compared to the control of the NPS price based load scheduling, at annual average WD and HD, combined control enables the energy reserve capacity to be reduced by 30% and 45%, respectively.

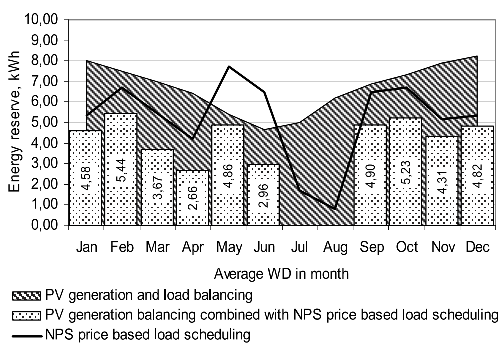

Fig. 13. Energy reserve based on monthly average WD prices

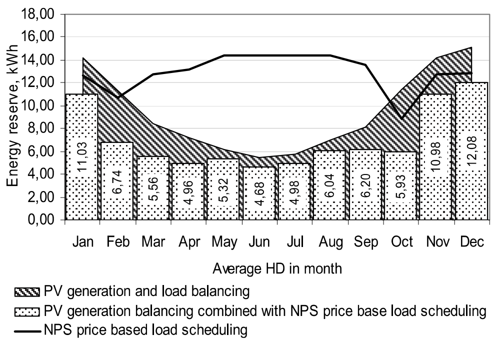

Fig. 14. Energy reserve based on monthly average HD prices

If electricity reserve calculations are based on the annual average WD or HD price as compared to hourly average prices of a month, from April to June in WD and HD, the energy reserve is not needed. Also, in the WD of January and August the energy reserve is not needed. Based on the described calculations the highest energy reserve is needed on holidays in December, which is 15.17 kWh. While in the summer season the monthly average prices are significantly lower than the annual average, it is questionable if a PV-system is suitable on that time-period.

Thus it can be concluded that the energy reserve calculated for a PV system is sufficient in the winter season for consumption scheduling from the peak-time to the off-peak time.

If the energy reserve and the prospective cycle lifetime of the storage system are known, the needed DoD (depth of discharge) and the required energy capacity of the storage system can be calculated (15).

$$E_{st} = \frac{E_{res}}{DoD} = \frac{E_{res}}{k_1 \cdot n_{cycles}^{-k_2}}, \qquad (15)$$

where k_1 – coefficient 1; k_2 – coefficient 2; n_{cycles} – amount of charge/discharge cycles.

Conclusion

An increase in the efficiency of a PV system will reduce the area of PV-panels, but it has a relatively small impact on the storage system capacity. Double efficiency of a PV-system will decrease the storage system capacity only up to 10%. The higher consumption on workdays and holiday evenings has the highest impact on the dimensioning of storage capacitance. Thus it can be concluded that the profitability of a PV-system depends mostly on the price of electricity and the consumption pattern. To assure the shortest profitability time, electricity consumption and real-time dynamic price should be increased and decreased synchronously with the PV system generation. In northern regions PV-systems are most feasible in OFF-grid systems, where the grid connection is not economically feasible. In ON-grid PV-systems, according to seasonal differences of solar radiation, it is not feasible to plan a PV area by solar radiation of the winter season. It is more feasible to cover shortage with cheaper energy stored from the grid in the OFF-peak time.

Combining both wind power and PV power would lead to minimizing the storage requirement and cost of the systems [3]. For Nordic countries it needs additional investigations, is it more profitable to combine PV power with wind power or it is more feasible to use mCHPs combined with wind or with PV power. Also price fluctuations in open energy market (like Nord Pool Spot) should be taken into account to optimize topology of microgrids.

Authors thank the Estonian Ministry of Education and Research (Project SF0140016s11) and Estonian Archimedes Foundation (Project "Doctoral School of Energy and Geotechnology II") for financial support to this study.

REFERENCES

[1] Matics J., Krost G., Intelligent Design of PV based Home Supply using a Versatile Simulation Tool, *Proceedings of the 13th International Conference on Intelligent Systems Application to Power Systems* (2005), 61-66.
[2] Marańda W., Piotrowicz M., Short-time energy buffering for photovoltaic system, *Proceedings of the 17th International Conference Mixed Design of Integrated Circuits and Systems – MIXDES* (2010), 525-528.
[3] Borowy B.S., Salameh Z.M., Methodology for optimally sizing the combination of a battery bank and PV array in a wind/PV hybrid system, *IEEE Transactions on Energy Conversion* (1966), vol.11, no.2, 367-375.
[4] Koponen P., Kärkkänen S., Experiences from spot-market based price response of residential customers, *CIRED Workshop*, Vienna, 21-24 May 2007.
[5] Belonogova N., Lassila J., Partanen J., Effects of Demand response on the end-customer distribution fee, *CIRED Workshop*, Lyon 7-8 June 2010.
[6] Keevallik S., Loitjärv K. Solar radiation at the surface in the Baltic Proper. *Oceanologia* (2010), vol. 52(4), 583 - 597.
[7] Russak V., Kallis A., Handbook of Estonian Solar Radiation Climate. *Eesti Meteoroloogia ja Hüdroloogia Instituut*. Printed by AS ILOPRINT. Tallinn 2003.
[8] Rosin A., Hõimoja H., Möller T., Lehtla M., Residential electricity consumption and loads pattern analysis, *Electric Power Quality and Supply Reliability Conference* (2010), 111-116.
[9] Tomson, T., Renewable electricity generation in Estonia, *Electric Power Quality and Supply Reliability Conference* (2010), 87-92..
[10] Quaschning, Volker. *Regenerative Energiesysteme, Technologie − Berechnung − Simulation*. Chapter 6. Neu bearbeitete und erweiterte Auflage. Hanser Verlag München, 2009. 397 s. ISBN 978-3-446-42151-6.
[11] Auväärt, A., Rosin, A., Belonogova, N., Lebedev, D., NordPoolSpot price pattern analysis for households energy management, *7th International Conference-Workshop Compatibility and Power Electronics* (2011), 103-106.

***Authors**: D. Sc. Eng Argo Rosin, Department of Electrical Drives and Power Electronics, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia, E-mail: vagur@cc.ttu.ee; Ph.D. student Kai Rosin, Marine Systems Institute, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia, E-mail: kairosin76@gmail.com; Ph.D. student Aivar Auväärt, Department of Electrical Drives and Power Electronics, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia, E-mail: aivar.auvaart@ttu.ee; Prof. Ryszard Strzelecki, Electrotechnical Institute, Pożaryskiego 28, 04-703 Warszawa / Gdynia Maritime University, Morska 81-87, 61-225 Gdynia, Poland, E-mail: rstrzele@am.gdynia.pl*

PAPER III

Rosin, A.; Auväärt, A.; Lebedev, D. (2012). Analysis of operation times and electrical storage dimensioning for energy consumption shifting and balancing in residential areas. Electronics and Electrical Engineering, 4 (120), 15 – 20.

ISSN 1392 – 1215 ELECTRONICS AND ELECTRICAL ENGINEERING 2012. No. 4(120)
ELEKTRONIKA IR ELEKTROTECHNIKA

T 190 ELECTRICAL ENGINEERING
ELEKTROS INŽINERIJA

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

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

crossref http://dx.doi.org/10.5755/j01.eee.120.4.1444

Introduction

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

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

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

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

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

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

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

Operation times of home appliances

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

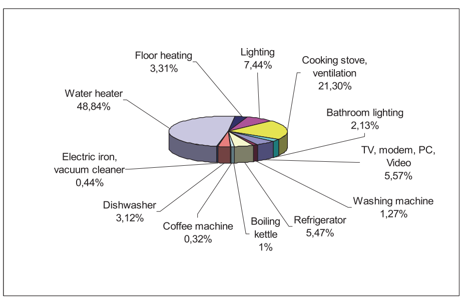

Fig. 1. Energy consumption of loads

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

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

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

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

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

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

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

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

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

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

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

Table 1. Operation times and energy consumption of home appliances

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

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

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

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

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

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

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

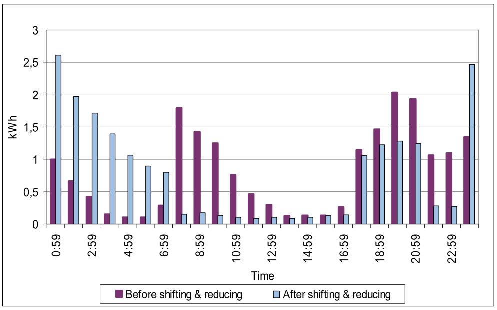

Fig. 2. Electricity consumption before and after load scheduling and power reducing on workdays

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

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

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

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

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

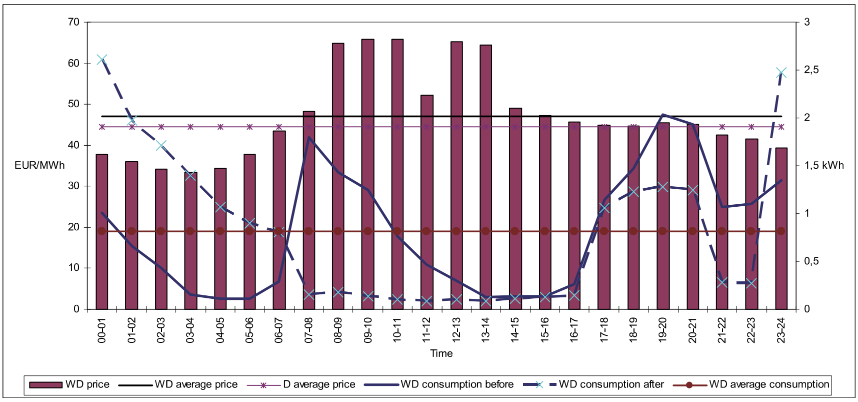

Fig. 3. Average workday price fluctuation compared to electricity consumption before and after scheduling of shiftable loads

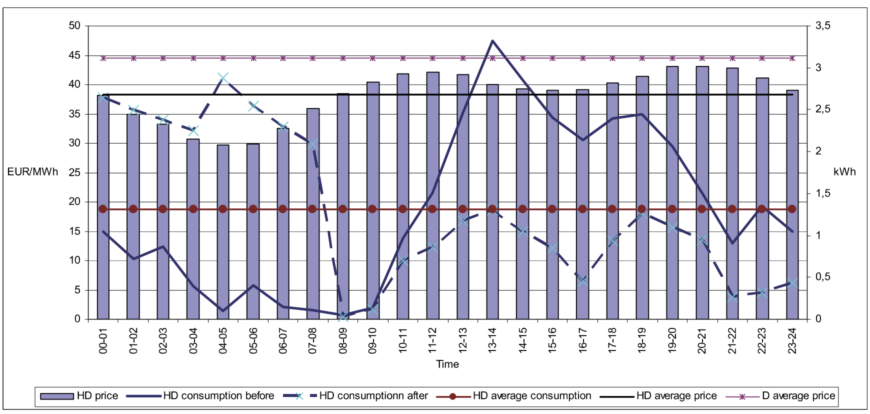

Fig. 4. Average holiday price fluctuation compared to electricity consumption before and after scheduling of shiftable loads

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

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

Storage dimensioning for consumption balancing

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

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

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

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

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

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

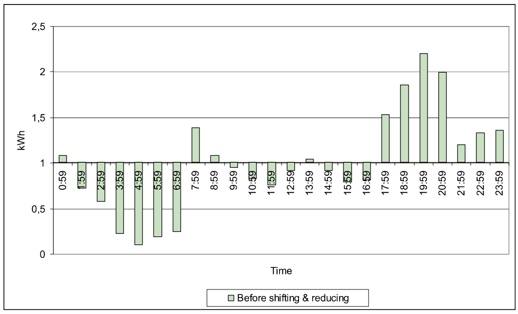

Fig. 5. Average daily electricity consumption before shiftable loads scheduling

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

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

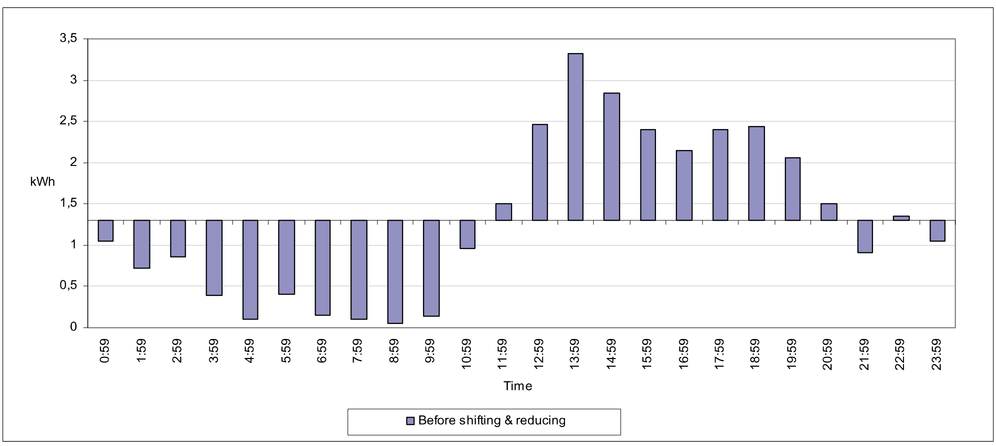

Fig. 6. Average holiday electricity consumption before shiftable loads scheduling

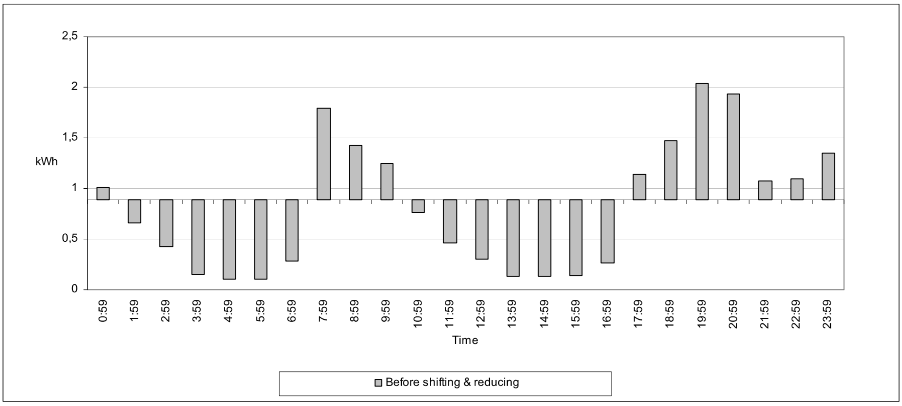

Fig. 7. Average workday electricity consumption before shiftable loads scheduling

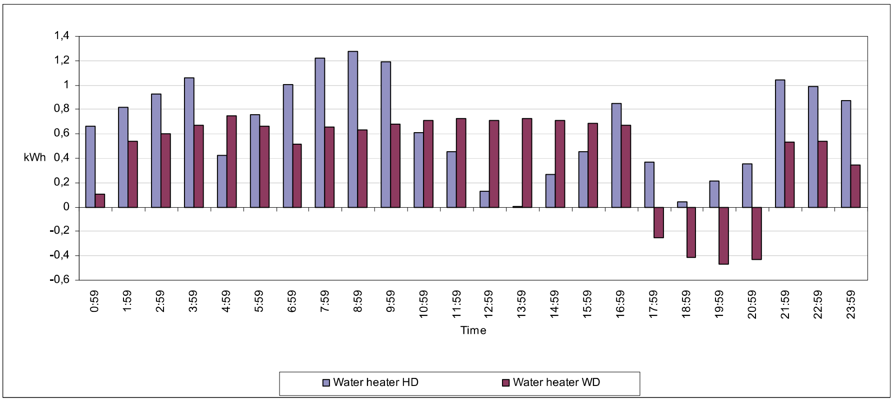

Fig. 8. New consumption pattern for water heater HD and WD consumption

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

Consumption balancing with water heater consumption shifting

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

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

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

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

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

Conclusions

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

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

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

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

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

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

Acknowledgements

Authors thank Estonian Ministry of Education and Research (Project SF0140016s11) and Estonian Archimedes Foundation (Project “Doctoral School of Energy and Geotechnology II“) for financial support to this study.

References

1. **2008 Buildings Energy Data Book.** – U.S. Department of Energy. – Energy Efficiency and Renewable Energy, 2009.
2. **Energy Conservation Committee Report and Recommendations**. – Reducing Electricity Consumption in Houses. – Ontario Home Builders’ Association, 2006.
3. **Hamed A., Rad M., Wong V. W. S., Jatskevich J., Schober R.** Optimal and Autonomous Incentive–based–Energy Consumption Scheduling Algorothm for Smart Grid // Innovative Smart Grid Technologies (ISGT), 2010. – P. 1–6.
4. **Kadar P.** ZigBee controls the household appliances // Intelligent Engineering Systems (INES‘2009), 2009. – P. 189–192.
5. **Rosin A., Möller T., Lehtla M., Hõimoja H.** Analysis of household electricity consumption patterns and economy of water heating shifting and saving bulbs // Power and Electrical Engineering. – Riga Technical University. – No. 27. – P. 15–20.
6. **Firth S., Lomas K., Wright A., Wall R.** Identifying trends in the use of domestic appliances from household electricity consumption measurements // Energy and Buildings, 2008. – No. 40. – P. 926–936.
7. **Rosin A., Hõimoja H., Möller T., Lehtla M.** Residential electricity consumption and loads pattern analysis // Electric Power Quality and Supply Reliability Conference (PQ), 2010. – P. 111–116.
8. **Handa T., Oda A. Tachikawa T., Watanabe Y., Ichimura J., Nishi H.** Table–based scheduling method for distributed demand side management // Industrial Electronics (IECON‘2008), 2008. – P. 2748–2753.
9. **Mauri G., Moneta D., Gramatica P.** Automation systems to support smart energy behaviour of small customers // SmartGrids for Distribution, 2008. – P. 1–4.

Received 2011 03 14
Accepted after revision 2011 09 28

A. Rosin, A. Auvaart, D. Lebedev. Analysis of Operation Times and Electrical Storage Dimensioning for Energy Consumption Shifting and Balancing in Residential Areas // Electronics and Electrical Engineering. – Kaunas: Technologija, 2012. – No. 4(120). – P. 15–20.

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

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

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

PAPER IV

Auväärt, A.; Rosin, A.; Belonogova, N.; Lebedev, D. (2011). Nord Pool Spot price pattern analysis for households energy management. *In: 7th International Conference-Workshop Compatibility and Power Electronics (CPE2011), Tallinn, Estonia, June 01-03, 2011:* IEEE, 2011, 103 - 106.

NordPoolSpot price pattern analysis for households energy management

Aivar Auväärt[1], Argo Rosin[1], Nadezhda Belonogova[2], Denis Lebedev[1]
[1] Tallinn University of Technology, [2] Lappeenranta University of Technology
aivar.auvaart@ttu.ee, vagur@cc.ttu.ee, Nadezhda.Belonogova@lut.fi, denis.lebedev@saksa-automaatika.ee

Abstract - This paper describes the analysis of price fluctuations in the Nord Pool Spot (NPS) and the possibilities to introduce consumption scheduling and energy storage equipment to reduce price fluctuations in households using the real-time open market electrical energy tariffs.

I. Introduction

The deregulation of electricity industry is giving way to global trends toward the commodization of electric energy. [1,2]. This trend has intensified in Europe and North America, where market forces have pushed legislators to begin removing artificial barriers that have shielded electric utilities from competition. The price of electricity is far more volatile than that of other commodities normally noted for extreme volatility. Relatively small changes in load or generation can cause large changes in price and all in a matter of hours. Unlike in the financial markets, electricity is traded every hour of the year - including nights, weekends and holidays. Unlike other commodities, electricity cannot be stored efficiently. Therefore, delicate balance must be maintained between generation and consumption 8760 hours a year.

There is, however, a great difference between electricity and the other energy (and commodity) markets in that the variable costs of production vary so greatly between different types of installation – Wind and Hydropower with a virtual nil cost at one extreme and Gas Turbines at the other end of the scale. In order to satisfy fluctuating consumer demand at the lowest cost, a broad variety of generating techniques are required. Some installations are capital intensive but can be run year round and are relatively fuel efficient (hydro, nuclear, coal-fired). Other units such as co-production of heat and power are used less frequently to cover winter heating demand at times of higher prices. Whilst energy intensive units such as Gas Fired Turbines are used for brief periods of very high price and demand.

Although the principle of generation electricity is simple, generating electricity for an area as large as Europe, means a complex balancing process. One of the biggest problems faced by the system operator is congestion. When congestion occurs, zonal prices supersede power exchange's market clearing price, which is based on the aggregated energy supply and demand curve intersection point for each hour [5]. In such a case, electricity prices can increase or decrease dramatically. The primary role of a market price is to establish equilibrium between supply and demand. This task is especially important in the power markets because of the inability to store electricity efficiently and the high costs associated with any supply failure. NPS runs the largest market for electrical energy in the world, offering both day-ahead and intraday markets to its participants. 330 companies from 20 countries trade on the Exchange. In 2009 the NPS group had a turnover of 288TWh [7]. The spot market at NPS is an auction based exchange for the trading of prompt physically delivered electricity. The spot market carries out the key task of balancing supply and demand in the power market with a certain scope for forward planning. In addition to this, there is a final balancing process for fine adjustments in the real time balancing market. The spot market receives bids and offers from producers and consumers alike and calculates an hourly price which balances these opposing sides. NPS publishes a spot price for each hour of the coming day in order to synthetically balance supply and demand. Every morning Nord Pool participants post their orders to the auction for the coming day. Each order specifies the volume in MWh/h that a participant is willing to buy or sell at specific price levels (€/MWh) for each individual hour in the following day. The SESAM (Elspot trading system) calculation equation (1) is based on an application of the social welfare criteria in combination with market rules. SESAM is maximizing the value of the objective function subject to physical constraints; like volume constraints, area balances, transmission and ramping constraints.

$$Max\sum_{n}\left\{\int_{0}^{d^a} D^a(x)dx - \int_{0}^{s^a} S^a(y)dy\right. , \qquad (1)$$

where a represents an area, d^a is the demand in the area a and D^a is the demand function in the area a, s^a is supply in the area a, S^a is the supply function in the area a, and n is the number of areas. The system price (SP1) for each hour is determined by the intersection of the aggregate supply and demand curves which are representing all bids and offers for the entire Nordic region [7]. In addition to area price there is also an annual fixed fee and a variable trading fee for all market participants.

978-1-4244-8807-0/11/$26.00 ©2011 IEEE

In the political debate surrounding energy, this type of price formation is labeled a marginal price setting. This gives a false impression that the establishment of prices in the electricity market is different from the price formation process in other commodity markets. The only difference lies in the significantly higher requirements for the secure delivery of electricity because it must be delivered at the precise moment it is needed by the consumer. The inelasticity caused by the inability to store electricity is the reason of this difference.

II. AVERAGE DAILY PRICE

To find the possibilities to use the possible fluctuations we constructed an average day from actual data from the NPS trading system. We studied a period of seven months starting in April 2010. An average was calculated with the well-known formula of a generalized mean

$$\bar{x} = \sqrt[m]{\frac{\sum_{i=1}^{n} x_i^m}{n}}, \qquad (2)$$

where X_i is the price of electrical energy in the instance i

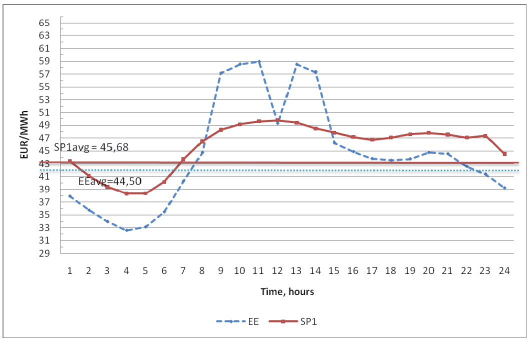

Fig. 1 Average daily price at the EE area and SP1 area

Equation (2) is used to calculate the average price during the period in the EE area. It is calculated as 44.500€/MWh. One hour is the smallest time interval when prices can change, because on spot electricity trading prices are set constant for delivery of power during a certain hour. The chart in Fig. 1 compares an arithmetic average price during the day in the NPS SP1 area and EE area. It shows very clearly that fluctuations in the system area are small - around 11.00€/MWh, but in the EE area the amplitude of the price during the day is much higher at 26.35€/MWh. The high price amplitude in the local market provides opportunities to use consumption scheduling models in residential areas to gain economy.

We can also observe differences on workdays and at weekends in figures 2 and 3

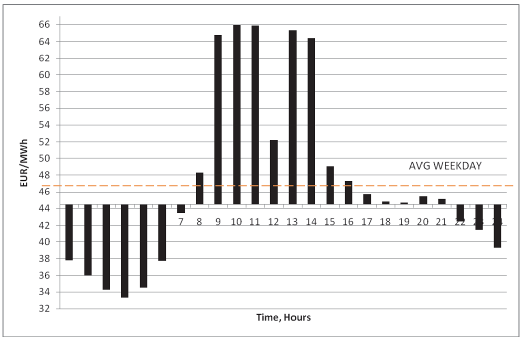

Fig. 2 Average daily price on workdays in the EE area

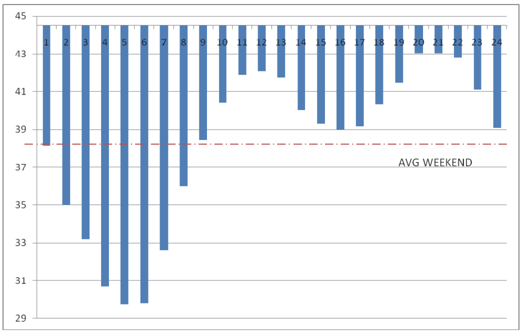

Fig. 3 Average daily price at weekends in the EE area

The price curve is not similar on workdays and at weekends. The maximum price on workdays is 65.93€/MWh and the minimum is 33.35€/MWh. At weekends the maximum and minimum prices are 43.05€/MWh and 29.76€/MWh,

Average price below the EE area average (44.500€/MWh) is 38.02€/MWh (-14.55%) on workdays and 38.256€/MWh (-14.03%) at weekends. Average price above the EE area average is 53.496 €/MWh (20.22%) on workdays and does not exceed the average at weekends.

III. AVERAGE PRICE DEVIATION

Fig. 4 shows the deviation calculated by the simple formula (3) from the average price to analyze possibilities to use off-peak hours to store energy or shift the load to off-peak hours. We needed an assurance of off-peak hours available to recharge the batteries or other storage equipment. We found that the average duration of peaks that are higher than the average area price is 9.59 hours and the average duration of off-peaks is 13.48 hours. That means there is plenty of time to recharge storage equipment during the off-peak time.

Deviation from an average price is higher at peak hours, but peak hours last less than off-peak hours. It is most profitable to save energy between the 23...06 o'clock, then the price is lower than 10% compared to average. There is also a possibility to save energy between 16...19 o'clock when the price is about 2-3% lower than average.

$$S = \frac{\sum_{n=1}^{k} \frac{x_i}{n} - X_F}{X_F}, \quad (3)$$

where X_i is the price of electrical energy in the instance i (from 0-24 hours) and X_F is the average area price.

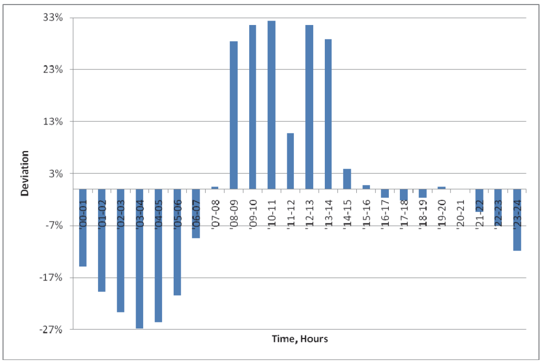

Fig. 4 Average EE area price deviation

Another feature of volatility of electricity price is its seasonal character. The daily and weekly seasonality can be illustrated by intra weekly plot of mean absolute hourly price changes (Fig. 5). The patterns of volatility are clearly correlated to the on-peak/off-peak specification of the market. The lowest volatility is observed at the weekends and during night. The huge increase of price within hours 33-39 is a result of emergency shutdown of the thermal power plant section in the EE area. For electricity spot price returns there is strong 7-day dependence. It is surprising that this dependence lasts almost forever [4].

Another seasonal phenomenon is observed on yearly basis as we compare NPS SP1 prices in 2009 the price is much higher on the winter season but remains nearly the same in other seasons as plotted in Fig. 6. The price curve in summertime for the EE area in 2010 is quite similar to trends observed in the SP1 area on summertime.

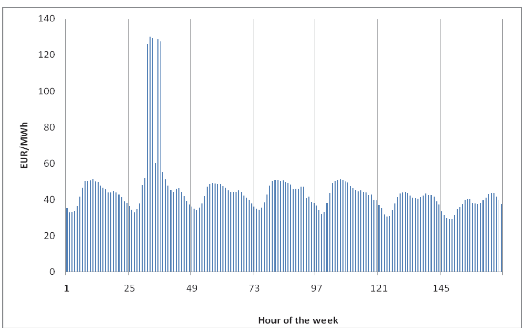

Fig. 5 Intra-weekly plot of mean absolute hourly EE area price changes for the NPS market. The statistical week is divided into 168 hours from Monday 0:00 to Sunday 24

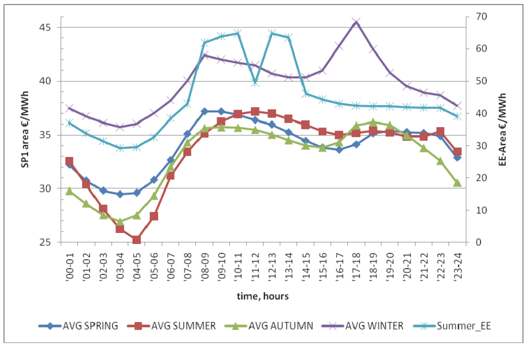

Fig. 6 Average daily price at the SP1 area on the seasonal scale compared to the EE price at summertime

IV. DISTRIBUTION OF PRICE RANGE

As seen in Fig. 7 the distribution of prices is symmetric and leptokurtic. With the leptokurtic distribution, the price will have a relatively low amount of variance, because return values are close to the mean. This could mean that energy producers will not try to invest to storage facilities as there could be quite small return on investment. This gives us an opportunity to continue our research on the profitability of using energy storing and shifting on the demand side.

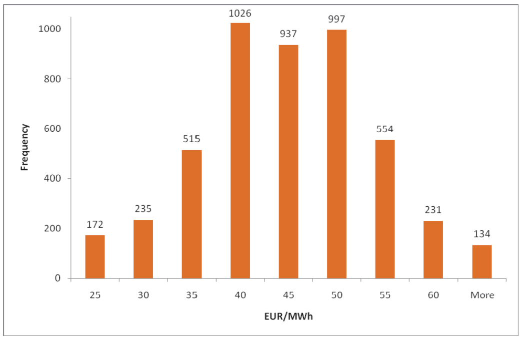

Fig. 7 Distribution of price range in the EE area

V. HOUSEHOLD ENERGY CONSUMPTION COMPARED TO AVERAGE PRICE DEVIATION

Energy consumption in households in the UK is reported in [8] and in Estonia in [3]. Peak hours for UK households form 06-08 and 13-18. Main peak hours for Estonian average households are at 7-8 and 19-21 on workdays and 12-14 and 19-21 at weekends. It is quite easy to see the possible use of energy storage to smoothen the loads at morning or midday use and even the evening use at weekends. However, some exact calculations are needed in terms of the possibilities to conserve energy at low price before evening peak hours on working days.

VI. POTENTIAL OF ENERGY STORAGES IN HOUSEHOLDS

NPS prices have been already implemented for large industrial customers in Finland. Spot market prices open opportunities also for demand response, i.e. load control for small customers. Moreover, price demand response has been already tested in Finland on residential customers and has revealed the benefits for energy costs optimization [9].

In future, energy storages will help reduce price fluctuations in spot market if used smartly. Storages can be classified into heating and electrical ones. In heating storage energy is charged and discharged in form of heating, while in electrical energy storage – in form of electricity. Electrical energy storage can be stationary (batteries) or mobile (electric vehicles). Heating energy storage represents water and/or space heater in residential houses with electrical heating loads. Although this kind of energy storage is already available in many households, as well as it has rather high energy density compared to other household appliances and therefore could have a significant impact on market prices if adjusted to them, it is less flexible in time because its usage is limited by customer's comfort requirements.

The usage of electrical energy storage is, on the contrary, less dependent on customer's requirements, but on market prices. It is in customer's interests to use (discharge) energy storage in high price hours and charge it in low price hours. The recent research shows that technical profitability of peak power reduction using energy storages is limited to 30% of network penetration [10]. Optimization of electrical energy storage charging/discharging cycles according to market prices is an important further research question. The main objective of customers is to minimize their energy costs. At the same time, they contribute to leveling peak powers in the network and to reducing the volatility of spot prices in the market. That way, residential customers can contribute to their own welfare and welfare of other market players, since the price risk of energy supplier will be minimized due to stable market prices as well as both distribution company and customer will benefit from good quality of electricity supply.

VII. CONCLUSION

This paper analyzes the fluctuations of electrical energy price in the NPS EE price area and to some extent in the SP1 area. The NPS area is currently the largest free electricity market today with a turnover of 277TWh/year. Our analysis shows that energy price in the open market is far more volatile than other commodities, but it does not behave like most financial instruments as it has a strong seasonal character.

There is a possibility to use renewable energy for local production of electricity during peak times. Solar and wind power generation would be most suitable for households.

The most perspective type could be solar power as it is usable at high peak times during the day, but the main problem in the NPS area is winter period when the effectiveness of photovoltaic panels decreases. Another possibility is to use wind power but this source is far less reliable than the sun and could not be generated without opposition from inhabitants in densely populated areas.

We observed the EE area price during 4802 hours starting from 1 April 2010 when Estonia entered the NPS market. During that time an average hourly price for the EE price area was 44.5€/MWh and it is slightly lower than the price in the system area. The price curve is similar on weekdays and at weekends. At weekends the average hourly price remains under an average area price during the observation time.

The price will always be lower than average at off-peak times. An average off-peak time lasts for 13.48 hours, which is long enough to store energy with cheaper storage equipment or shift the power usage to a less expensive time period without losing customer's comfort requirement.

Some economic impact on consumers who will buy their electricity from the open market could occur. As the prices for next day are known at least 12 hours in advance, the complex prediction models for scheduling or storing energy are not necessary. It is quite clear that until the electrical energy producers will not use energy saving technologies, the price will fluctuate almost in the same way as described in this paper. Additionally, some questions remain about changes in the behavior of prices when the households or other micro grids join the NPS market.

ACKNOWLEDGEMENTS

Authors thank Estonian Ministry of Education and Research (Tallinn University of Technology Grant No SF0140016s11 and B613A) and Archimedes Foundation (project Doctoral school of energy- and geotechnology II) for financial support of this study.

REFERENCES

[1] Strecker S, Weinhardt C.; Electronic OTC Trading in the German Wholesale Electricity Market, Lecture Notes in Computer Science, 2000, Volume 1875/2000, 280-290.

[2] S. Green, Power Eng. Int. 7 (4) (1999) 45.

[3] Rosin, A.; Hõimoja, H.; Mo□ller, T.; Lehtla, M.; , "Residential electricity consumption and loads pattern analysis," *Electric Power Quality and Supply Reliability Conference (PQ), 2010* , vol., no., pp.111-116, 16-18 June 2010.

[4] Weron, *R.*, Przybylowicz, B., Hurst analysis of electricity price Dynamics, Physica A: Statistical Mechanics and its Applications Volume 283, Issues 3-4, 15 August 2000, Pages 462-468.

[5] Weron, R., Energy price risk management, Physica A285 (2000) 127-134.

[6] Kian, A.; Keyhani, A.; , "Stochastic price modeling of electricity in deregulated energy markets," *System Sciences, 2001. Proceedings of the 34th Annual Hawaii International Conference on* , vol., no., pp. 7 pp., 3-6 Jan. 2001.

[7] NPS homepage www.nordpoolspot.com (2010).

[8] Firth S., Lomas K., Wright A., Wall R., Identifying trends in the use of domestic appliances from household electricity consumption measurements, Energy and Buildings 40 (2008) 926–936.

[9] Koponen P., Kärkkänen S., Experiences from spot-market based price response of residential customers, CIRED Vienna, 21-24 May 2007.

[10] Belonogova N, Lassila J, Partanen J, „Effects of Demand response on the end-customer distribution fee“, CIRED Workshop Lyon 7-8 June 2010, Paper 0081.

PAPER V

Rosin, A.; Palu, I.; Rosin, K.; Auväärt, A. (2012) Dimensioning of Electricity Storage according to Small Wind Turbine Power Generation and Household Load Patterns. *In: 38th Annual Conference on IEEE Industrial Electronics Society (IECON), Montreal, Canada, 25 - 28 October, 2012: IEEE, 2012, 5155 – 5160.*

Dimensioning of Electricity Storage according to Small Wind Turbine Power Generation and Household Load Patterns

Argo Rosin, Ivo Palu, Kai Rosin, Aivar Auväärt
Tallinn University of Technology
argo.rosin@ttu.ee, ivo.palu@ttu.ee, kairosin76@gmail.com, aivar.auvaart@ttu.ee

***Abstract*- This paper analyzes wind speed data measured in the Tallinn-Harku Aerological Station (Estonia). Dimensioning of a wind turbine and electricity storage for a typical household is discussed. The final part describes electricity storage dimensioning based on a combination of Nord Pool Spot (NPS) prices and grid connected household wind turbine generation.**

I. Introduction

The use of large wind turbines is common almost in every European country, at the same time expansion of small wind turbines expends great efforts. There are many small wind turbine manufacturers and importers, but due to the relatively high cost of the small-scale devices and lack of financial support from the governments the market is still inconsiderable.

Both the payback time of the investment and the technical practicability to use the solution are to be taken into account. Small wind turbines discussed in this article are considered to be in the range of 1 – 20 kW, with typical tower height not exceeding 10-20 meters. Wind speeds closer to ground are always smaller than those at the heights of MW-scale wind turbines since they are more affected by surrounding obstacles [1].

In order to comply with power peaks, to reduce the installed generation capacity and to balance missing long- and short-term coincidence between power generation and demand, energy storage (ES) is a crucial component of distributed generation systems [2]. Optimal dimensioning of electricity storage according to the energy production of micro-scale renewables (in residential areas and households) and electricity consumption are important topics in the development of micro- and smartGRID technologies to increase system reliability and to reduce the profitability time.

Opening of electricity market gives new opportunities to renewable energy sources. Optimization of renewable systems (including hybrid renewable systems and wind turbines with energy storages) have been studied in detail in Estonia [3-6] and in world [7], however, only few analyses are available about small-scale wind energy systems (including feasibility analysis, dimensioning of energy storages and small-scale wind turbines) for households, and optimization of energy storages of wind turbine systems according to open electricity market prices (e.g. Nord Pool Spot).

This article reports on the feasibility of small wind turbines to cover household electricity consumption. No direct attention is paid to the payback time or cost of the investment. Main value of this article is to present the possible size of the wind turbine and possible storage capacity for load coverage of an average household (also in open-market conditions).

II. Wind Speed Analysis

In Estonia (also in Scandinavia) the strongest average wind is in autumn and winter months, especially during November, December and January, when the average wind speed is about 8 m/s on coastal areas and 5 m/s on inland. The following analysis shows us similar seasonal differences. The analysis below is based on the wind speed data measured in the Tallinn-Harku Aerological Station (latitude N 59°23′53′′; longitude E 24°36′10′′, height above sea level 33 m), and on average household energy consumption data described in [8]. As a result of the wind speed analysis, the average wind speed of an average day in July compared to January is up to 1.46 times lower. In July at the peak hour (12 o'clock), the average wind speed is up to 1.12 times lower than in December at the peak hour (11 o'clock). In July at the lowest hour (21 o'clock), the average wind speed is up to 2.16 times lower than in December at the peak hour (23 o'clock). About 61% of the resource is concentrated on the winter season from October until March, when the average hourly wind speed is mostly over annual average (Fig. 1).

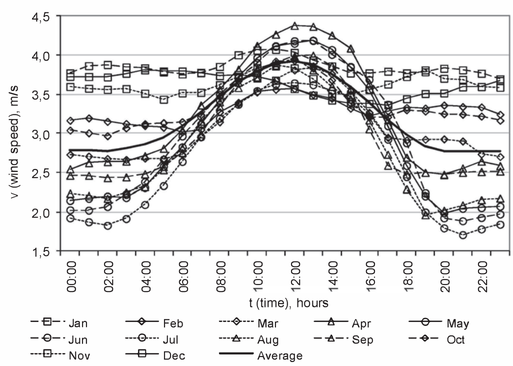

Fig. 1. Average daily wind speed by months (Harku 2005-2009)

978-1-4673-2421-2/12/$31.00 ©2012 IEEE

As shown in Figure 2, during the last five years, about 27% of hours the average wind speed was above 3 m/s.

For further analysis the wind turbine with the rated power of 5 kW was chosen. The power characteristic of the wind turbine can be presented as the fourth order polynomial function (Fig. 3) of wind speed (R-squared value of the trend is 0.997). As a result of the energy generation analysis, the average energy generation of an average day in July compared to January is up to 2.8 times lower.

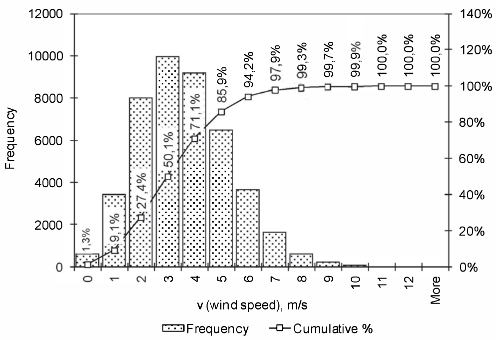

Fig. 2. Histogram of wind speed (Harku 2005-2009)

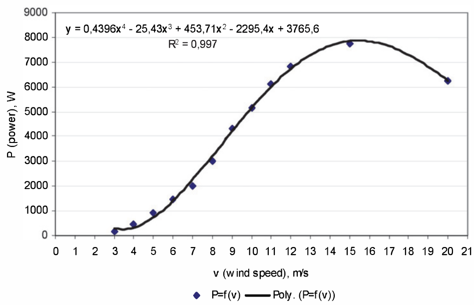

Fig. 3. $P=f(v)$ characteristic of the chosen wind turbine

III. Wind Turbine Dimensioning for Typical Households

The following calculations (1-2) are simplified and do not take into account the wind-turbine performance ratio, including system losses and efficiency of power electronics.

$$P = \frac{\pi \cdot \eta \cdot \rho \cdot d^2 \cdot v^3}{8} = c_p \cdot \frac{1}{2} \cdot \rho \cdot A \cdot v^3, \qquad (1)$$

$$P_{r,c} = P_{r,g} \cdot \frac{E_c}{E_g}, \qquad (2)$$

where A – rotor area; ρ - density of air; η - efficiency; d – diameter of rotor; v - wind speed; c_p – power coefficient; E_c – electricity consumption per day; E_g – electricity generation of a wind-turbine per day; $P_{r,g}$ – rated power of a wind turbine; $P_{r,c}$ – needed rated power of a wind turbine for covering daily electricity consumption.

Average electricity consumption (in common household of Estonia) is on average day (about 0.5 kWh per hour) [9], without consumption of an electrical water heater, in July can be covered by a wind turbine (with the described $P=f(v)$ characteristic) with the rated power of 12.56 kW (Fig. 4). To cover average electricity consumption in January, a wind turbine with the rated power of 4.46 kW should be installed.

In accordance with the average holiday/weekend (HD) and workday (WD), electricity consumption (0.66 kWh/h and 0.38 kWh/h) of the rated power of wind turbines was calculated for an average day of each month. It was found that the smallest electricity generation is in July, and the highest one is in January. Based on the calculations, the highest rated power of the chosen wind turbine (in accordance with the wind turbine characteristic) should be approximately 17 kW (holiday in July) and the lowest one 3.4 kW (workday in January) (Fig. 4).

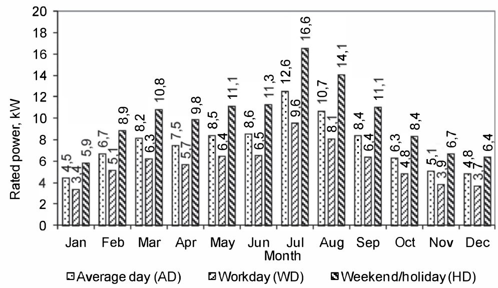

Fig. 4. Rated power of a wind turbine according to the monthly wind speed

Based on annual average electricity generation and household consumption, the rated power of a wind turbine should be approximately from 6.5...7.6 kW. The annual average rated power of a wind turbine should be 5.84 kW for a workday (WD) and 10.08 kW for a weekend (HD). On workdays the energy consumption is much lower than on weekends. The rated power of a wind turbine was chosen in accordance with the annual average rated power of a weekend, which is approximately 10 kW. To have rated power of 10 kW, two wind turbines with the characteristic described in Fig. 3 should be used. As shown, the rated power on workdays in each month is lower than 10kW. This means that theoretically it is possible to store surplus of energy on workdays and to use it on weekends. Practically it does not work in this way, while there are long zero-generation periods, which should be covered from an additional energy source. Our further calculations are based on 2 x 5 kW wind turbines. Two wind turbines with the rated power of 5 kW will have theoretically the maximum total day generation of 27 kWh (January) and the minimum 9.6 kWh (July).

In different seasons the deviation of energy generation of wind turbines compared with a PV-system is relatively low

[9]. The coefficient of variation V_R of monthly generation is 25% (for a PV system 72%) (3).

$$V_R = \frac{\sum_{i=1}^{n} \left| E_{wt,i} - \overline{E_{wt}} \right|}{n \cdot \overline{E_{wt}}} , \tag{3}$$

where $E_{wt,i}$ – generated electricity at the hour i; n – 24 hours in a day; $\overline{E}_{wt}$ – average daily electricity generation.

As compared to a PV system, lower variations in annual electricity generation are the main advantage to use wind turbines.

In an OFF-grid system for load coverage in the winter season, when there exist long zero-generation periods (up to 150 hours), it is reasonable to use additionally a micro-CHP or a diesel generator. A micro-CHP produces additional thermal energy, which can be fully used in the winter season. In an ON-grid system, in the winter season covering the shortage of electricity with low-tariff energy stored in the Wind-system energy storage is a suitable solution. Next, energy balance of a household wind energy system and energy reserve dimensioning for a storage system are analyzed.

IV. Electricity Reserve Dimensioning of a Household Wind Energy System for Load Coverage

Energy balance of a wind energy system can be described according to the following simplified formula (4):

$$\begin{aligned} E_{wt} &= E_c + E_{sp} + E_{los} \\ E_{wt} &= \underbrace{E_{dir} + E_{res}}_{E_c} + E_{sp} + E_{los} , \end{aligned} \tag{4}$$

where E_{wt} – electricity generated by a wind energy system; E_c – electricity consumption; E_{sp} – surplus of generated electricity; E_{los} – total losses; E_{dir} – direct consumption of electricity generated by a wind system; E_{res} – indirect consumption of electricity generated by a wind energy system (stored energy reserve of wind turbine generated energy).

In the calculations system losses are not taken into account (E_{los} = 0).

A. Balance between generation and load

The first step to define the capacitance needed for electricity reserve for load coverage of a household wind-system is the analysis of balance between wind turbine generation and load consumption on an average day of each month (5). While the WD and HD have different consumption curves, the analysis should be made separately for both days.

$$E_{bal,i} = E_{c,i} - E_{wt,i} , \tag{5}$$

where $E_{bal,i}$ – energy balance at the hour i.

According to the calculations (5) at WD, the surplus of generated energy is the highest on midday, when the load is trivial. Load maximum prevails in the evening from 16 to 21 o'clock. This means that generated energy should be stored for the evening period (Fig. 5).

Measures should be taken to solve this surplus problem. On HD the direct load coverage is better than on WD. In the summer season main problems are shortage and higher needs for energy reserves as compared to the winter season. In the summer season energy reserves needed on HD are similar to those needed on WD. (Fig. 6).

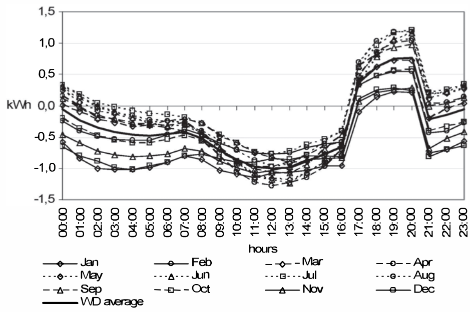

Fig. 5. Balance of WD consumption and generation

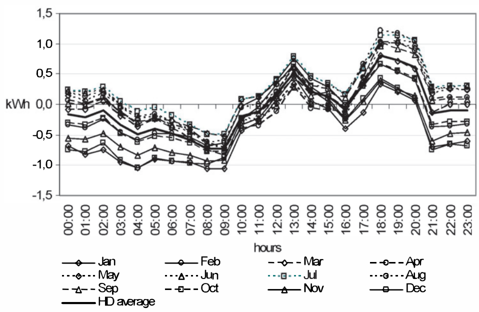

Fig. 6. Balance of HD consumption and generation

B. Electricity surplus and shortage

The analysis (6) below shows that a wind turbine with the rated power of 10 kW can cover WD electricity consumption from January to December (Fig. 7). On HD electricity consumption can be covered from October to February. While in the calculations used electricity data is measured in February and March, and electricity consumption in the summer season is reduced about 20...30%, it can be theoretically expected that a wind turbine with the rated power of 10kW can cover also consumption of the summer season.

$$k_{sp} = \frac{E_{sp}}{E_c} = \frac{\sum_{i=1}^{n} (E_{wt,i} - E_{c,i})}{\sum_{i=1}^{n} E_{c,i}} ; n = 24 , \tag{6}$$

where $E_{wt,i}$ – generated electricity at the hour i; n – 24 hours in a day; $E_{c,i}$ – electricity consumption at the hour i.

Without losses the average annual surplus of electricity generation of a wind turbine-system on holidays and workdays is 8.5% and 87.5%, accordingly. In the summer season an average surplus is 10.3%, on WD and HD, accordingly 44.5% (surplus) and -16.4% (shortage). In the winter season the average surplus is 76%, on WD and HD, accordingly 130.5% and 33.4%.

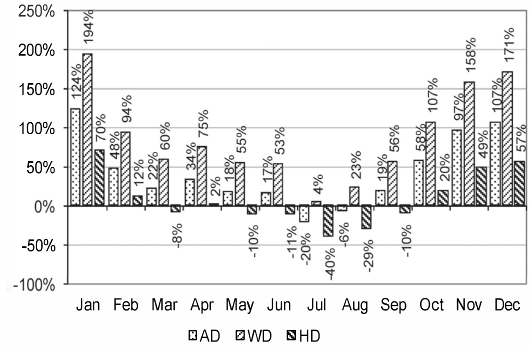

Fig. 7. Surplus/shortage of an average day of a month

C. *Dimensioning of electricity reserve in accordance with average energy generation*

Approximately 39% of wind turbine generated energy can be directly used on workdays and 72% on holidays. This is about 73% of a workday and 78% of holiday total electricity consumption (7-9).

$$E_{dir} = \sum E_{c,i} - \underbrace{\sum_{E_{wt,i} \le E_{c,i}} (E_{c,i} - E_{wt,i})}_{E_{res,i}}, \tag{7}$$

$$E_{dir} = \sum_{E_{wt,i} \le E_{c,i}} E_{wt,i} + \sum_{E_{wt,i} > E_{c,i}} E_{c,i}, \tag{8}$$

where E_{dir} – directly from wind turbine consumed electricity.

$$k_{dir} = \frac{E_{dir}}{E_c}, \tag{9}$$

About 56% of annual average wind turbine generated energy is used directly, which makes approximately 80 % of the annual average consumption.

The easiest way to calculate the energy reserve needed (storage capacitance) for indirect load coverage is based on the difference of average hourly electricity generation and consumption (10 - 11).

Depending on the consumption pattern, about 15 to 20 % of the generated energy should be stored in energy storage, making up 22 to 27 % of the consumption.

$$E_{wt,i} \le E_{c,i}, \tag{10}$$
$$\Downarrow$$

$$E_{res} = \sum_{i=1}^{n} E_{res,i} = \sum_{i=1}^{n} (E_{c,i} - E_{wt,i}) = \sum_{i=1}^{n} \left| E_{wt,i} - E_{c,i} \right|, \tag{11}$$

where $E_{res,i}$ – energy reserve needed at the hour i; E_{res} – average daily energy reserve needed.

On WD, the highest energy reserve is needed in July (5.29 kWh) and the lowest in January (0.57 kWh) (Fig. 8). On HD, in turn, the highest energy reserve needed is 7.96 kWh and the lowest is 1.19 kWh (Fig. 9).

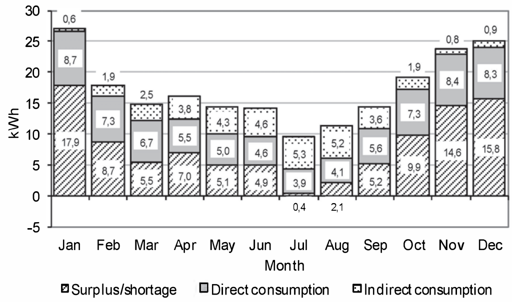

Fig. 8. Direct and indirect load coverage of an average WD of a month

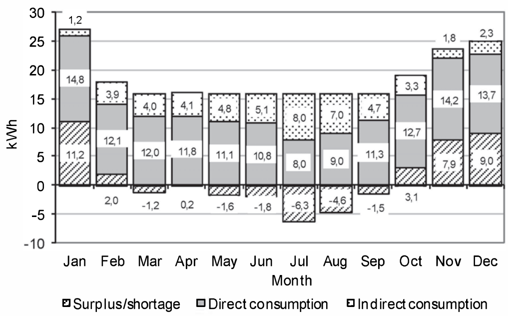

Fig. 9. Direct and indirect load coverage of an average HD of a month

D. *Dimensioning of electricity reserve in accordance with duration of periods without power generation*

Another calculation method of the energy reserve, however rarely used, is based on the analysis of the frequency of the duration of hours without power generation (PG) and average electricity consumption. The following histogram (Fig. 10) shows that 92% of periods without power generation are shorter than 24 hours. In accordance with Figure 10, over 90% of periods without power generation are shorter than 22 hours. In accordance with the presented histogram, the energy reserves for an average day, workday and holiday should be 11.1, 8.5 and 15 kWh. It is almost two times more than described above.

Another possibility to define an energy storage needed for load scheduling is to take into account the longest daily average periods without power generation. The longest average periods without power generation (Fig. 11) per day are in July (11.15 hours) and in January (10.62 hours). Based on an average daily (0.504kWh/h), workday (0.385 kWh/h) and holiday (0.665kWh/h) consumption (without electrical water heater) [9] and the longest monthly average period without power generation, the calculated energy reserves for a period without power generation in July on an average day should be accordingly 5.6, 4.3 and 7.5 kWh. Calculated energy reserves are quite similar to the energy reserves described in Figures 8 and 9.

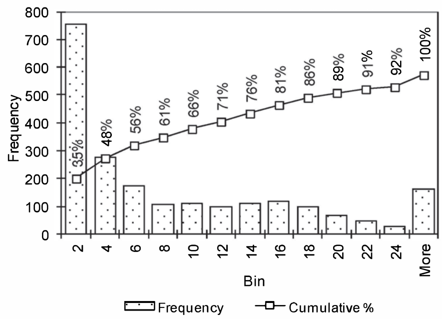

Fig. 10. Histogram of hours without power generation (2005-2009)

It can be seen from Figure 10 that over 7 % of hours without energy generation are longer than 24 hours. It is useful to have an overview about these periods to plan an additional energy source. The longest periods without power generation calculated from the measured wind speed (from 2005 to 2009) in accordance with the characteristics of the wind turbine were in January 2006 (146 hours) and in October 2007 (155 hours). The longest shortage in power generation could be over 6 days (Fig. 11). According to the longest shortage and possible weighted average consumption (including consumption of workdays and holidays), the additional energy source should cover during these days energy consumption up to 80 kWh and peak power up to 8 kW. With priority based load control the needed peak power could be reduced up to 4 times (real reduction depends on the used appliances and customer demands).

For a customer another interesting value is annual working hours of the additional energy source to cover the shortage of wind energy. In accordance with average maximum shortages of each month (Fig. 12), the total annual need for an additional energy source could be at least 670 h (approximately equal to 350 kWh of average electricity consumption).

According to the calculations, the highest energy generation was found in January and the lowest in July. As seen in Figure 13, the average maximum hours without PG are the longest in January and the shortest in July. The relation between average maximum hours without PG to the total hours in a month shows that probability of longer periods without PG is higher than in other months. This phenomenon shows us that better PG in January does not mean lower demands for an additional power generation system.

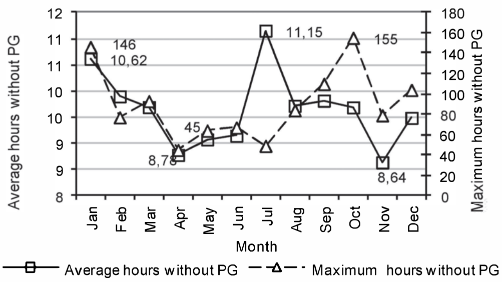

Fig. 11. Average and maximum hours without power generation (2005-2009)

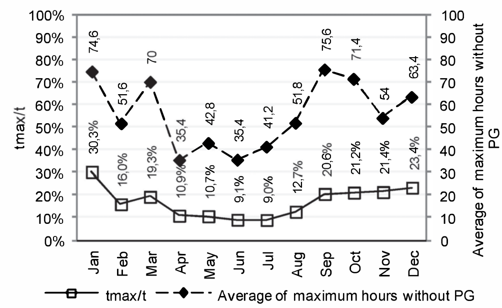

Fig. 12. Average maximum hours without PG and relation of average maximum hours to average total hours without PG (2005-2009).

V. Electricity Reserve Dimensioning for ON-grid Connected Wind Turbine System by Covering Lulls with Low Spot Price

Average NPS (Nord Pool Spot) price during the measured period (April 2010 to March 2011) in the EE (Estonia) area was calculated as 46.30€/MWh. The NPS price curve is similar on workdays and at weekends. The average price of workdays is 47.81 €/MWh and that of weekends is 42.62€/MWh. The main difference of WD and HD curves is higher midday peak on WD and higher evening peak on HD). More detailed analysis of the first half year is described in [10], and profitability of energy storages is described in [11].

The analysis below should show if it is possible to use a calculated energy reserve to cover lulls with cheaper electricity from spot market. The following electricity reserve calculations are based on hourly prices of an average day in months. If the hourly price is lower than the average WD or HD price of the month, the electricity consumption and storage charging are covered from the grid. If the hourly WD or HD price is higher than the average price of the month, the electricity consumption is covered by electricity storage (12).

$$p_{m,i} > \overline{p_m} \Rightarrow E_{res} = \sum_{i=1}^{n} E_{c,i} \ , \qquad (12)$$

where $p_{m,i}$ – average price of the hour i in a month m, $\overline{p_m}$ – average price of a month m

Based on the described calculations (14), the highest needed energy reserve is required on holidays from May to August, which is 14.4 kWh (Fig. 13). On workdays the highest energy reserve, 7.7 kWh, is needed in May.

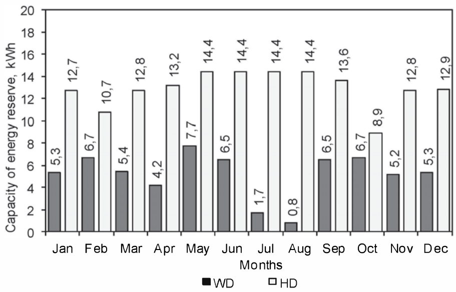

Fig. 13. Energy reserve based on monthly average WD and HD prices

If we compare an electricity reserve in accordance with the duration of periods without power generation (Fig. 10), it can be concluded that for wind turbine calculated electricity reserve (15 kWh) it is sufficient to schedule the load according to the average spot price.

VI. Conclusion

According to average electricity consumption and depending on the monthly average wind speed, the rated power of a wind turbine should be chosen from 5 to 20 kW.

Over 90% of periods without power generation are shorter than 22 hours. Energy reserves for an average day, workday and holiday should be 11.1, 8.5 and 15 kWh. It is also sufficient to schedule the load according to average spot prices.

Different methods used for electricity storage dimensioning give completely different and inappropriate results. For example, calculations based on periods without power generation give us more realistic results than the results calculated according to the average hourly wind speed and consumption at an average day of a month. The longest periods without power generation calculated from the measured wind speed (from 2005 to 2009) in accordance with the characteristics of the wind turbine were in January 2006 (146 hours) and in October 2007 (155 hours). In accordance with average maximum shortages of each month, the total annual need for an additional energy source could be at least 670 h (approximately equal to 350 kWh of average electricity consumption).

The unbalance between consumption and power generation has the highest impact on the dimensioning of storage capacitance. Profitability of a wind turbine depends mostly on the price of electricity and the consumption pattern. To assure the shortest profitability time, electricity consumption and real-time dynamic price should be increased and decreased synchronously with the wind turbine generation.

Today in northern regions, such as Baltic countries, small wind turbines are only feasible in OFF-grid systems, where the grid connection is not economically feasible and an additional energy source (e.g. diesel generator) for balancing is available. In ON-grid wind turbine systems, it is more feasible to cover shortage with cheaper energy stored from the grid in the OFF-peak time. For Nordic countries, additional investigations are needed to find out if it is more profitable to combine PV power with wind power or if it is more feasible to use microCHPs combined with wind or with PV power. Also, the intelligent real-time price based load scheduling possibilities of households should be taken into account.

Acknowledgment

Authors thank the Estonian Ministry of Education and Research (Project SF0140016s11) and Estonian Archimedes Foundation (Project "Doctoral School of Energy and Geotechnology II") for financial support to this study.

References

[1] Manwell, J. F., McGowan, J. G., Rogers, A. L., Wind Energy Explained: Theory, Design and Application, Second Edition, Wiley, 2009, pp 689.

[2] Matics, J.; Krost, G.; , "Intelligent Design of PV based Home Supply using a Versatile Simulation Tool," Intelligent Systems Application to Power Systems, 2005. Proceedings of the 13th International Conference on , vol., no., pp.61-66, 6-10 Nov. 2005

[3] Põder, Vahur; Lepa, Jaan; Palge, Veli; Peets, Tõnis; Annuk, Andres (2009). The Estimation of Needed Capacity of a Storage System According to Load and Wind Parameters. Oil Shale, 26(3), 283 - 293.

[4] Palu, I.; Oidram, R.; Keel, M.; Tammoja, H. (2009). Balancing of wind energy using oil-shale based power plants at erroneous wind forecast conditions. Oil Shale, 26(3 S), 189 - 199.

[5] Agabus, H.; Tammoja, H. (2009). Estimation of wind power production through short-term forecast. Oil Shale, 26(3 S), 208 - 219.

[6] Pertmann, I. (2011). Estonian Wind Farms Need for Full Balance Power. Oil Shale, 28(1S), 193 - 202.

[7] Borowy, B.S.; Salameh, Z.M.; , "Methodology for optimally sizing the combination of a battery bank and PV array in a wind/PV hybrid system," Energy Conversion, IEEE Transactions on , vol.11, no.2, pp.367-375, Jun 1996

[8] Rosin, A.; Hõimoja, H.; Möller, T.; Lehtla, M.; , "Residential electricity consumption and loads pattern analysis," Electric Power Quality and Supply Reliability Conference (PQ), 2010 , vol., no., pp.111-116, 16-18 June 2010.

[9] Rosin, A.; Rosin, K.; Auvaart, A.; Strzelecki, R. "Dimensioning of household electricity storage for PV-systems and load scheduling based on Nord Pool Spot prices." Przegląd Elektrotechniczny 88.4B (2012):37-40.

[10] Auväärt, A.; Rosin, A.; Belonogova, N.; Lebedev, D.; , "NordPoolSpot price pattern analysis for households energy management," 7th International Conference-Workshop Compatibility and Power Electronics, 2011 , pp.103-106, June 01 - 03, 2011.

[11] Rosin, A.; Auväärt, A.; Lebedev, D. (2012). Energy storage dimensioning and feasibility analysis for household consumption scheduling based on fluctuations of Nord Pool Spot price. Przeglad Elektrotechniczny, 88(1a), 37 - 40.

PAPER VI

Aivar Auväärt, Argo Rosin, Kai Rosin, Imre Drovtar, Madis Lehtla. (2013) Comparison of Renewable Electricity Generation Options with Household Electrical Load Patterns. In: IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society, Vienna, Austria, 10 - 13 November, 2013: IEEE, 2013, 1553 – 1558.

Comparison of Renewable Electricity Generation Options with Household Electrical Load Patterns

Aivar Auväärt, Argo Rosin, Kai Rosin, Imre Drovtar, Madis Lehtla
Tallinn University of Technology
Tallinn, Estonia
aivar.auvaart@ttu.ee, argo.rosin@ttu.ee, kairosin76@gmail.com, imre.drovtar@ttu.ee, madis.lehtla@ttu.ee

Abstract—**This paper analyzes output time-series of different small scale power generation systems such as wind and photovoltaic (PV) systems and their combinations, according to the wind and global irradiance data measured in the Tallinn-Harku Aerological Station (Estonia) and household load patterns. Renewable energy resources and energy production are reviewed and household loads and their need for stored energy reserves to cover periods without power generation are analyzed.**

Keywords — household electricity, load patterns, electricity generation; wind; solar; microgrids

I. INTRODUCTION

Liberalization of the electricity markets presents new opportunities for producers of renewable energy. Optimization of wind and solar energy systems (including wind turbines with energy storages) has been widely analyzed in Estonia [1-5]. Nevertheless, optimization and feasibility analyses or dimensioning of energy storages for household small scale hybrid energy systems are scarce. Moreover, only some analyses cover comparison and application of small scale wind, photovoltaic and hybrid systems for weather conditions of Baltic Countries and Scandinavia.

Energy storage (ES) is a crucial component of distributed generation systems in order to comply with power peaks, reduce installed generation capacity and to balance missing long and short term coincidence between power generation and demand [6]. As described by B. S. Borowy and Z. M. Salameh, the optimum combination of PV modules and batteries depends on the particular site, load profile, and the desired reliability of the hybrid system [7]. Optimal dimensioning of the energy storage (ES) according to the micro-scale renewable energy production and electricity consumption in residential areas or households is a key issue in the development of micro- and smart-grid technologies. In addition, to optimize systems it is necessary to increase the system reliability and to reduce the investment payback period using the optimal configuration of a renewable electricity generation system in accordance with geographical climate conditions. Economically sustainable use of electricity grids needs permanent online balancing of supply and demand, including grid losses. A local generation system that is properly chosen can reduce the demand for on-site power balancing. Electrical energy storage technologies will allow smoothing the power surges, thus improve voltage quality and will allow electricity to be used later more efficiently.

II. WIND AND SOLAR RESOURCES

Solar surface irradiance depends mainly on astronomical factors, but is greatly influenced by cloudiness, atmospheric transparency and snow cover. These factors show significant spatial and temporal variability, which is reflected in the variability of solar flux [8]. Detailed long-term global irradiance data about Estonia are described in [9]. The analysis described below is based on the global irradiance data measured in the Tallinn-Harku Aerological Station (latitude N 59°23′53′′; longitude E 24°36′10′′), at a height of 33 m above sea level and on local average household energy consumption data described and analyzed in [10,11]. The results of the global radiation analysis show that global radiation of an average day in June is from 20 to 50 times higher than in December. The total radiation in June at the peak hour (11 o'clock) is up to 18 times higher than in December. About 85% of the solar resource is concentrated on the summer season from April to September, when energy generation is above average [12].

The wind speed analysis indicates that the average wind speed on an average day in July is up to 1.46 times lower than in January. The average wind speed in July at the peak hour (12 o'clock) is up to 1.12 times lower than in December at the peak hour (11 o'clock). The average wind speed at 21 o'clock in July is also up to 2.16 times lower than in December at the peak hour (23 o'clock). Thus, about 61% of the wind energy resource is concentrated on the winter season from October until March, when the average hourly wind speed is mostly over the annual average (Fig. 1). The power characteristic of a wind turbine can be presented as a fourth order polynomial function (1) of the wind speed (R-squared value of the trend is 0.997) [13].

$$P(v) = 0.4396v^4 - 25.43v^3 + 453.71v^2 - 2295.4v + 3765.6\,, \quad (1)$$

where P - output power of a wind turbine, v - wind speed.

Our wind turbine analysis reveals that the average power generation in July is up to 2.8 times lower than in January.

The analysis below compares the following three micro-generation systems:

- PV system (PV) with an area of 34 m^2 and efficiency of 20% [12];

- wind turbine (WT) system – with a rated power of 10 kW [13];
- hybrid system (HY) that consists of a PV system with an area of 18 m^2 and efficiency of 20%, and WT system – with a rated power of 5 kW.

The efficiency of 20% corresponds to that of recent best PV panels on the market. Efficiencies of generation units are important for generation system dimensioning but affect less the correlation between load and generation, as dimensions of energy storage system. For example, by increasing of PV system efficiency up to 40% could be decreased the capacitance of energy storage only up to 10%.

III. ELECTRICITY GENERATION AND LOAD BALANCE

First, the diversity of power generation was analyzed with the load on an average day of each month (2). Since the workday (WD) and weekend (HD) have different consumption patterns, the analysis is made separately for both periods. Energy balance $E_{bal,i}$ at the hour i can be calculated using equation (2):

$$E_{bal,i} = E_{c,i} - E_{g,i} \, , \tag{2}$$

where $E_{g,i}$ – electricity generated at the hour i, $E_{c,i}$ – electricity consumption at the hour i.

According to the calculations at the WD, the average surplus of the generated energy is the highest in midday, when the load is trivial compared to evening. Load maximum prevails in the evening from 16 to 21 o'clock. This means that the generated energy should be stored for the evening period (Fig. 1).

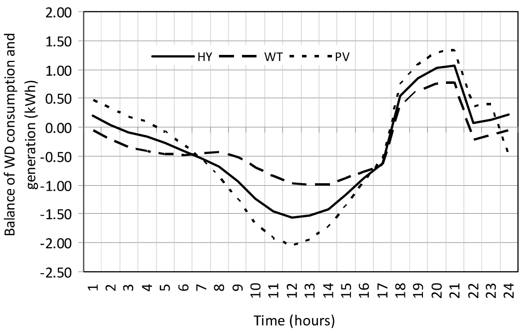

Fig. 1. Balance of WD consumption and generation

Solutions should be found for more efficient utilization of this generated electricity surplus. On the HD the direct load coverage from all renewable energy sources is better than on the WD (Fig. 2). Surplus energy of the WD or HD could be stored in energy storage or used by controllable (shiftable) loads, such as a refrigerator, a water heater or a washing machine proposed in the ECOGRID project [14].

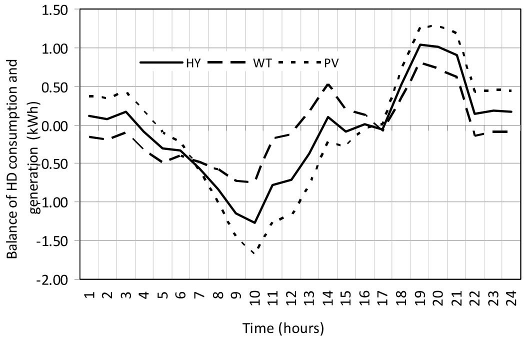

Fig. 2. Balance of HD consumption and generation

IV. ELECTRICITY SURPLUS AND SHORTAGE

According to the seasonal analysis, the PV system has the highest electricity surplus during the summer season (from April to September) and highest shortage during the winter season (from October to March). The analysis indicated that in particular household conditions the WT system is most optimal. The result revealed a minor shortage during the HD in the summer season, which could be easily solved by proper load management. The analysis also showed that electricity consumption over the summer season is at least 15% smaller than in winter (Fig. 3). If the electricity supply system has a grid connection, then zero-generation hours can be covered with cheaper off-peak electricity from the electricity market.

The main disadvantage of a hybrid system is its higher initial system cost and shortage in power generation during winter holidays.

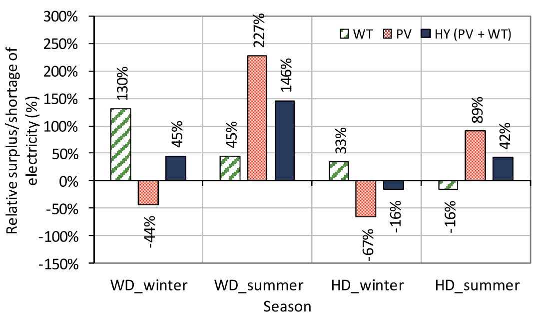

Fig. 3. Seasonal electricity surplus/shortage of the three systems

According to the monthly analysis, the wind energy system and hybrid energy systems could theoretically cover the average WD electricity consumption during the entire year. The wind energy system has a higher surplus from October to February when electricity consumption is the highest. This is an advantage compared to the other systems (Fig. 4). The relative electricity surplus coefficient k_{sp} can be calculated using equation (3):

$$k_{sp} = \frac{E_{sp}}{E_c} = \frac{\sum_{i=1}^{n}(E_{g,i} - E_{c,i})}{\sum_{i=1}^{n} E_{c,i}} , \qquad (3)$$

where E_{sp} – daily surplus of electricity; E_c – total daily electricity consumption; $E_{g,i}$ – electricity generated at the hour i; n – 24 hours a day; $E_{c,i}$ – electricity consumption at the hour i.

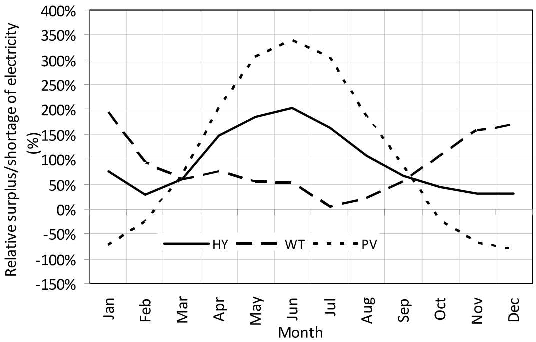

Fig. 4. Relative electricity surplus and shortage of an average WD of a month

The monthly energy balance analysis shows that all three described systems have trouble covering the average HD electricity consumption during the entire year (Fig. 5).

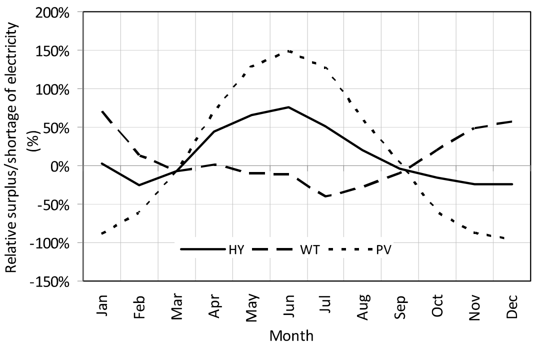

Fig. 5. Relative electricity surplus and shortage of an average HD of a month

The coefficient of variation V_R of monthly power generation of WT is 25% (for a PV system - 72%, and a hybrid system - 28%) (4).

$$V_R = \frac{\sum_{i=1}^{n}\left|E_{g,i} - \overline{E_g}\right|}{n \cdot \overline{E_g}} , \qquad (4)$$

where $E_{g,i}$ – electricity generated at the month i; n – 12 months a year; $\overline{E}_g$ – average annual electricity generation.

Wind turbines or a hybrid system have an advantage of lower variations in annual electricity generation over a PV system (Fig. 6).

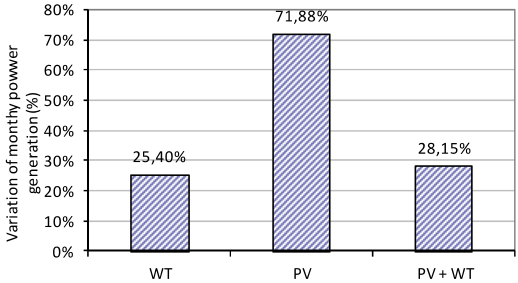

Fig. 6. Variation of monthly power generation

V. Demand for Stored Energy to Cover Household Electrical Power Consumption on Average Day

The demand for stored energy (5) to cover household power consumption from energy storage (ES) (during low power generation hour) in the WD and the HD during summer months (from May to August) is almost equal for all three analyzed systems. The highest differences in the requirements were detected from November to January. Figure 7 and 8 shows that the hybrid system has the smallest variation between seasons.

$$E_{g,i} \le E_{c,i} \Rightarrow E_{res} = \sum_{i=1}^{n}(E_{c,i} - E_{g,i}) = \sum_{i=1}^{n}\left|E_{g,i} - E_{c,i}\right|, \quad (5)$$

where E_{res} – daily demand for stored energy; $E_{res,i}$ – demand for stored energy at the hour i; $E_{g,i}$ – electricity generated at the hour i; n – 24 hours a day.

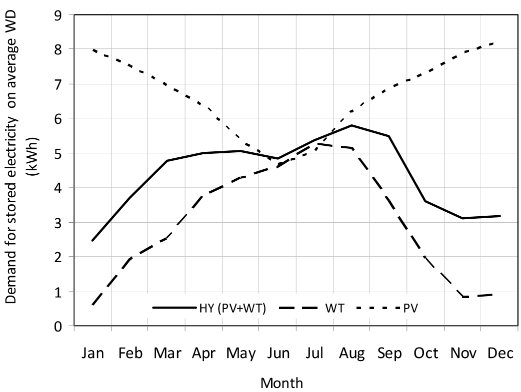

Fig. 7. Demand for stored electricity to cover household load on average WD of a month

To describe the relative daily demand for stored electricity compared to total demand (i.e. consumption), the coefficient k_{res} (6) can be used.

$$k_{res} = \frac{E_{res}}{E_c} = \frac{\sum_{E_{g,i}<E_{c,i}} (E_{c,i} - E_{g,i})}{\sum E_{c,i}}, \quad (6)$$

where k_{res} – relative daily demand for stored electricity compared to total demand (i.e. consumption); $E_{c,i}$ – electricity consumption at the hour i; $E_{g,i}$ – electricity generated at the hour i.

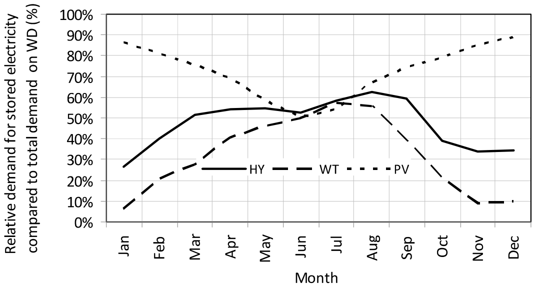

Fig. 8. Relative demand for stored electricity compared to total demand on an average WD of a month

At an average WD the household with wind energy system had the lowest maximum stored electricity demand (about 5.2 kWh). The household with hybrid system had the second lowest maximum stored electricity demand, i.e. about 12% higher demand than that of the wind energy system (Fig. 9).

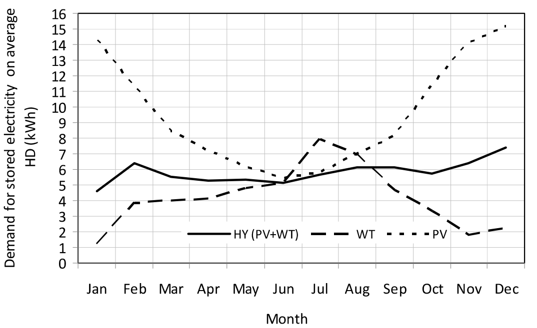

Fig. 9. Average demand for stored electricity for indirect load coverage on an average HD of a month

At an average HD the household with hybrid energy system had the lowest maximum stored electricity demand in December (about 7.4 kWh). The wind energy system had the second lowest maximum stored electricity demand, about 8% higher than that of the hybrid energy system (Fig. 10). Generation systems should be oversized according to Figs. 7-10 to cover loads at the winter season.

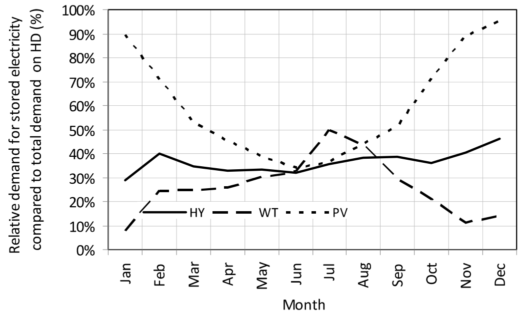

Fig. 10. Relative demand for stored electricity compared to total demand on an average HD of a month

VI. Direct coverage of household electrical loads from renewable energy sources

Figures 8-10 illustrate how the energy consumption can be directly covered by different systems. No differences exist between the three systems during workdays, meaning that about 50% of energy consumption can be covered directly from the renewable energy source (Fig. 11).

The main difference in the Nordic region turned out to be during the winter season, when WT and HY systems have significant advantages over PV systems. The WT and HY system can cover respectively about 90% and 70% of energy consumption directly during the coldest three months in winter (from November to January). Electricity directly consumed (E_{dir}) from a WT, PV or HY can be calculated, as in (7, 8):

$$E_{dir} = \sum E_{c,i} - \underbrace{\sum_{E_{g,i} \le E_{c,i}} (E_{c,i} - E_{g,i})}_{E_{res,i}} = \sum_{E_{g,i} \le E_{c,i}} E_{g,i} + \sum_{E_{g,i} > E_{c,i}} E_{c,i}, \quad (7)$$

$$k_{dir} = \frac{E_{dir}}{E_c}. \quad (8)$$

where E_{dir} –average daily directly consumed electricity; E_c – daily total energy consumption; k_{dir} – relative direct coverage of load

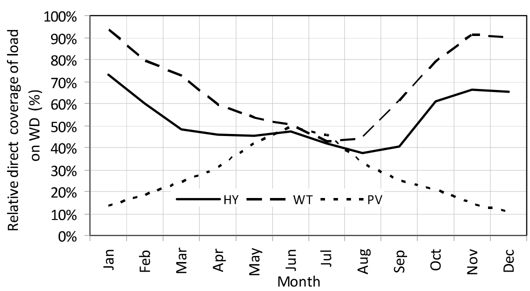

Fig. 11. Relative direct coverage of the household load on an average WD of a month

The HD consumption pattern had the highest impact on the direct consumption coverage in a PV and a HY system and lowest in a WT system (Fig. 12). Annual average direct load coverage in a HD is 10-13% percent higher than on a WD. The same indicator for a WT system is about 5%. These numbers show clearly that generation curves of PV and HY systems are more similar to power consumption curves on weekends.

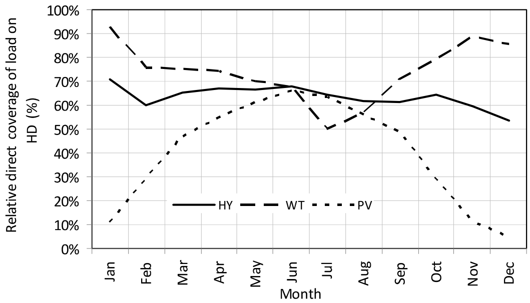

Fig. 12. Relative direct coverage of the household load on an average HD of a month

VII. DEMAND FOR STORED ENERGY ACCORDING TO ZERO GENERATION PERIODS

Comparison of the three systems reveals that in hybrid systems 90% of periods without power generation are shorter than 12 hours. In a PV and a WT system these numbers respectively are 18 and 22 hours (Fig. 13).

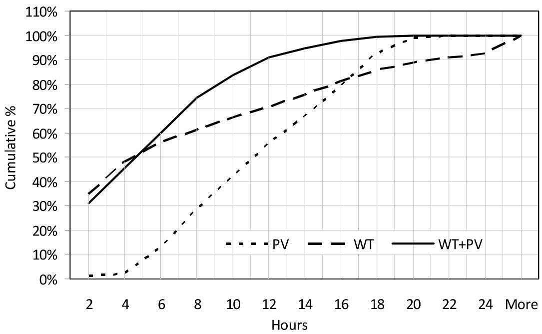

Fig. 13. Histogram of periods without power generation (2005-2009)

Compared to a PV and a WT system, the periods without power generation (PG) can be reduced with a hybrid system by 33% and 45%, accordingly. In addition, the demand for stored electricity to cover the 90% of periods without PG could be also proportionally smaller. In hybrid systems the average monthly periods without power generation are shorter than in the PV or WT systems. For a hybrid, a PV and a WT system, the annual average periods without PG are 6, 12 and 10, respectively (Fig. 14).

Figure 15 illustrates the average maximum periods without power generation over the year (according to weather analysis from 2005 to 2009).

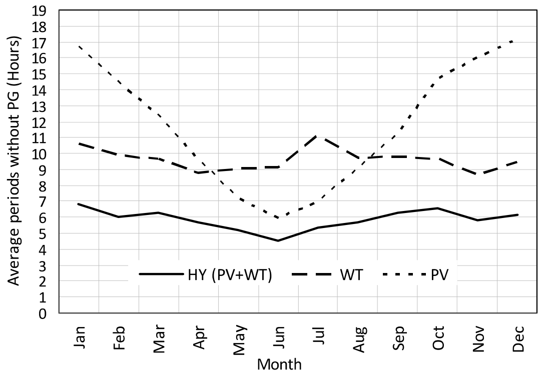

Fig. 14. Average periods without power generation (2005-2009)

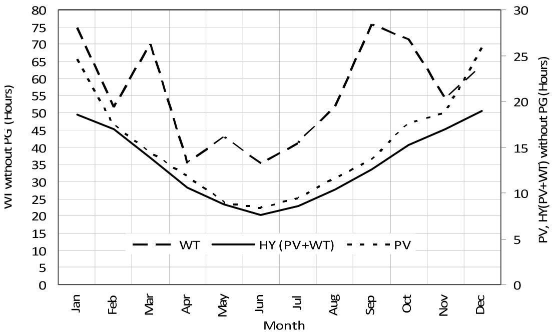

Fig. 15. Average maximum periods without power generation

In the Nordic regions, the average maximum periods without power generation in December are two times longer than in June. According to the presented curve of hybrid systems, the demand for an additional energy source in winter is higher than in the summer season, but duration of periods is approximately three times shorter than in the WT system. In hybrid systems, during winter seasons the wind turbines have the highest impact on the power generation, while the power generation of a PV system in December is 20 times lower than in June. An additional energy source is anyway needed to cover long wind-lulls, because power generation from PV-panels is very low in the winter season - approximately 15% from annual production. In WT- and PV-based household systems about 50% of hours should be covered from storage or an additional power generation unit. In a hybrid system it is 25%.

VIII. CORRELATION BETWEEN LOCAL POWER GENERATION, LOAD AND SPOT PRICE

The correlation (COR) analysis of power generation and consumption shows that the WT system is most suitable for Nordic countries in coastal areas. However, a disadvantage of all the systems is the bad correlation between the workday load and power generation (Table I).

$$Cor(x,y)=\frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2\sum(y-\bar{y})^2}}, \tag{9}$$

where x is the first range of values (e.g. power generation) and y is the second range of values (e.g. power consumption).

AL in Table 1 corresponds to an average load. Negative correlation values refer to possible difficulties when covering household loads from these renewable sources on WDs. Comparison of average annual values gives greater (more positive) results than hour-based analysis, thus the following hour-based analysis can be made in future to find out necessary details.

TABLE I
CORRELATION BETWEEN AVERAGE POWER GENERATION AND CONSUMPTION

	PV	WT	WT+PV
AL	-14%	5%	-11%
WD	-49%	-40%	-48%
HD	24%	49%	28%

According to the data of electricity spot price from 2011 to 2012 (a year after opening of the electricity market in Estonia) all the described renewable power generation systems have a good correlation with the spot price at the electricity market. The most suitable PG solution seems to be a hybrid or a PV system (Table II). This means that excess of energy could be sold with the best spot price.

TABLE II
CORRELATION BETWEEN AVERAGE SPOT PRICE AND POWER GENERATION

	COR
WT+PV	83,9%
WT	81,9%
PV	83,6%

The correlation between average power consumption and spot prices is worse on the weekend while the correlation coefficient is the highest (Table III).

TABLE III
CORRELATION BETWEEN AVERAGE SPOT PRICE AND POWER CONSUMPTION

	COR
AL	26,6%
WDL	-11%
HDL	72,5%

IX. CONCLUSION

According to seasonal electricity surplus/shortage of generation units, and correlation with energy consumption, a WT system suits properly, as it covers the seasonal and daily power demand best. According to the annual total zero generation hours, the demand for stored electricity in households should be approximately 1.1 MWh for a hybrid system, and 2.2 MWh for PV or WT systems.

According to WT-system average maximum shortages of each month, the total annual demand for an additional energy source is between 570...670 h. The corresponding demand is 300...350 kWh. In the hybrid system the total annual need for an additional energy source is 160...350 h, which corresponds to 80...180 kWh.

Disregarding environmental restrictions and restrictions of local authorities, the best solution is the wind turbines. The main reason to use WTs is that they provide the best correlation between consumption and generation, and a good prospect to sell the excess of energy on the spot market with the highest price (e.g. at workday). Our analysis shows that the hybrid or wind power systems are more feasible in autonomous power generation systems where the correlation between power consumption and generation is better.

ACKNOWLEDGMENT

Authors thank the Estonian Ministry of Education and Research (Project SF0140016s11) and Estonian Archimedes Foundation (Project "Doctoral School of Energy and Geotechnology II") for financial support to this study.

REFERENCES

[1] Tomson, T.;, "Renewable electricity generation in Estonia," Electric Power Quality and Supply Reliability Conference (PQ), 2010 , vol., no., pp.87-92, 16-18 June 2010.

[2] Põder, Vahur; Lepa, Jaan; Palge, Veli; Peets, Tõnis; Annuk, Andres (2009). The Estimation of Needed Capacity of a Storage System According to Load and Wind Parameters. Oil Shale, 26(3), 283 - 293.

[3] Palu, I.; Oidram, R.; Keel, M.; Tammoja, H. (2009). Balancing of wind energy using oil-shale based power plants at erroneous wind forecast conditions. Oil Shale, 26(3 S), 189 - 199.

[4] Agabus, H.; Tammoja, H. (2009). Estimation of wind power production through short-term forecast. Oil Shale, 26(3 S), 208 - 219.

[5] Pertmann, I. (2011). Estonian Wind Farms Need for Full Balance Power. Oil Shale, 28(1S), 193 - 202.

[6] Matics, J.; Krost, G.; , "Intelligent Design of PV based Home Supply using a Versatile Simulation Tool," Intelligent Systems Application to Power Systems, 2005. Proceedings of the 13th International Conference on , vol., no., pp.61-66, 6-10 Nov. 2005

[7] Borowy, B.S.; Salameh, Z.M.; , "Methodology for optimally sizing the combination of a battery bank and PV array in a wind/PV hybrid system," Energy Conversion, IEEE Transactions on , vol.11, no.2, pp.367-375, Jun 1996

[8] Keevallik S., Loitjärv K. Solar radiation at the surface in the Baltic Proper. *Oceanologia* (2010), vol. 52(4), 583 - 597.

[9] Russak V., Kallis A., Handbook of Estonian Solar Radiation Climate. *Eesti Meteoroloogia ja Hüdroloogia Instituut*. Printed by AS ILOPRINT. Tallinn 2003.

[10] Rosin, A.; Hõimoja, H.; Möller, T.; Lehtla, M.;, "Residential electricity consumption and loads pattern analysis," Electric Power Quality and Supply Reliability Conference (PQ), 2010 , vol., no., pp.111-116, 16-18 June 2010.

[11] Rosin, A.; Auväärt, A.; Lebedev, D. (2012). Analysis of operation times and electrical storage dimensioning for energy consumption shifting and balancing in residential areas. Electronics and Electrical Engineering, 4 (120), 15 - 20.

[12] Rosin, A.; Rosin, K.; Auväärt, A.; Strzelecki, R. (2012). Dimensioning of household electricity storage for PV-systems and load scheduling based on Nord Pool Spot prices. Przeglad Elektrotechniczny, 88(4b), 294 - 299.

[13] Rosin, A.; Palu, I.; Rosin, K.; Auväärt, A. (2012). Dimensioning of Electricity Storage according to Small Wind Turbine Power Generation and Household Load Patterns . In: IECON 2012 - 38th Annual Conference on IEEE Industrial Electronics Society: 38th Annual Conference on IEEE Industrial Electronics Society, Montreal, Canada, 25 - 28 October. IEEE, 2012, 5155 - 5160.

[14] Aleixo, L.; Rosin, A.; Saele, H.; Morch Z. A.; Grande, S. O.; Palu, I. (2013). Ecogrid EU Project – Real Time Price Based Load Control and Economic Benefits in a Wind Production Based System. CIRED 22 International Conference on Electricity Distribution, 10-13 June 2013, Stockholm, Sweden. Paper 1474.

DISSERTATIONS DEFENDED AT TALLINN UNIVERSITY OF TECHNOLOGY ON *POWER ENGINEERING, ELECTRICAL ENGINEERING, MINING ENGINEERING*

1. **Jaan Tehver**. Boiling on Porous Surface. 1992.

2. Salastatud.

3. **Endel Risthein.** Electricity Supply of Industrial Plants. 1993.

4. **Tõnu Trump**. Some New Aspects of Digital Filtering. 1993.

5. **Vello Sarv.** Synthesis and Design of Power Converters with Reduced Distortions Using Optimal Energy Exchange Control. 1994.

6. **Ivan Klevtsov**. Strained Condition Diagnosis and Fatigue Life Prediction for Metals under Cyclic Temperature Oscillations. 1994.

7. **Ants Meister**. Some Phase-Sensitive and Spectral Methods in Biomedical Engineering. 1994.

8. **Mati Meldorf**. Steady-State Monitoring of Power System. 1995.

9. **Jüri-Rivaldo Pastarus**. Large Cavern Stability in the Maardu Granite Deposit. 1996.

10. **Enn Velmre**. Modeling and Simulation of Bipolar Semiconductor Devices. 1996.

11. **Kalju Meigas**. Coherent Photodetection with a Laser. 1997.

12. **Andres Udal**. Development of Numerical Semiconductor Device Models and Their Application in Device Theory and Design. 1998.

13. **Kuno Janson**. Paralleel- ja järjestikresonantsi parameetrilise vaheldumisega võrgusageduslik resonantsmuundur ja tema rakendamine. 2001.

14. **Jüri Joller**. Research and Development of Energy Saving Traction Drives for Trams. 2001.

15. **Ingo Valgma**. Geographical Information System for Oil Shale Mining – MGIS. 2002.

16. **Raik Jansikene**. Research, Design and Application of Magnetohydrodynamical (MHD) Devices for Automation of Casting Industry. 2003.

17. **Oleg Nikitin**. Optimization of the Room-and-Pillar Mining Technology for Oil-Shale Mines. 2003.

18. **Viktor Bolgov**. Load Current Stabilization and Suppression of Flicker in AC Arc Furnace Power Supply by Series-Connected Saturable Reactor. 2004.

19. **Raine Pajo**. Power System Stability Monitoring – an Approach of Electrical Load Modelling. 2004.

20. **Jelena Shuvalova**. Optimal Approximation of Input-Output Characteristics of Power Units and Plants. 2004.

21. **Nikolai Dorovatovski**. Thermographic Diagnostics of Electrical Equipment of Eesti Energia Ltd. 2004.

22. **Katrin Erg**. Groundwater Sulphate Content Changes in Estonian Underground Oil Shale Mines. 2005.

23. **Argo Rosin**. Control, Supervision and Operation Diagnostics of Light Rail Electric Transport. 2005.

24. **Dmitri Vinnikov**. Research, Design and Implementation of Auxiliary Power Supplies for the Light Rail Vehicles. 2005.

25. **Madis Lehtla**. Microprocessor Control Systems of Light Rail Vehicle Traction Drives. 2006.

26. **Jevgeni Šklovski**. LC Circuit with Parallel and Series Resonance Alternation in Switch-Mode Converters. 2007.

27. **Sten Suuroja**. Comparative Morphological Analysis of the Early Paleozoic Marine Impact Structures Kärdla and Neugrund, Estonia. 2007.

28. **Sergei Sabanov**. Risk Assessment Methods in Estonian Oil Shale Mining Industry. 2008.

29. **Vitali Boiko**. Development and Research of the Traction Asynchronous Multimotor Drive. 2008.

30. **Tauno Tammeoja**. Economic Model of Oil Shale Flows and Cost. 2008.

31. **Jelena Armas**. Quality Criterion of road Lighting Measurement and Exploring. 2008.

32. **Olavi Tammemäe**. Basics for Geotechnical Engineering Explorations Considering Needed Legal Changes. 2008.

33. **Mart Landsberg**. Long-Term Capacity Planning and Feasibility of Nuclear Power in Estonia under Certain Conditions. 2008.

34. **Hardi Torn**. Engineering-Geological Modelling of the Sillamäe Radioactive Tailings Pond Area. 2008.

35. **Aleksander Kilk**. Paljupooluseline püsimagnetitega sünkroongeneraator tuuleagregaatidele. 2008.

36. **Olga Ruban**. Analysis and Development of the PLC Control System with the Distributed I/Os. 2008.

37. **Jako Kilter**. Monitoring of Electrical Distribution Network Operation. 2009.

38. **Ivo Palu**. Impact of Wind Parks on Power System Containing Thermal Power Plants. 2009.

39. **Hannes Agabus**. Large-Scale Integration of Wind Energy into the Power System Considering the Uncertainty Information. 2009.

40. **Kalle Kilk**. Variations of Power Demand and Wind Power Generation and Their Influence to the Operation of Power Systems. 2009.

41. **Indrek Roasto**. Research and Development of Digital Control Systems and Algorithms for High Power, High Voltage Isolated DC/DC Converters. 2009.

42. **Hardi Hõimoja**. Energiatõhususe hindamise ja energiasalvestite arvutuse metoodika linna elektertranspordile. 2009.

43. **Tanel Jalakas**. Research and Development of High-Power High-Voltage DC/DC Converters. 2010.

44. **Helena Lind**. Groundwater Flow Model of the Western Part of the Estonian Oil Shale Deposit. 2010.

45. **Arvi Hamburg**. Analysis of Energy Development Perspectives. 2010.

46. **Mall Orru**. Dependence of Estonian Peat Deposit Properties on Landscape Types and Feeding Conditions. 2010.

47. **Erik Väli**. Best Available Technology for the Environmentally Friendly Mining with Surface Miner. 2011.

48. **Tarmo Tohver**. Utilization of Waste Rock from Oil Shale Mining. 2011.

49. **Mikhail Egorov**. Research and Development of Control Methods for Low-Loss IGBT Inverter-Fed Induction Motor Drives. 2011.

50. **Toomas Vinnal**. Eesti ettevõtete elektritarbimise uurimine ja soovituste väljatöötamine tarbimise optimeerimiseks. 2011.

51. **Veiko Karu**. Potential Usage of Underground Mined Areas in Estonian Oil Shale Deposit. 2012.

52. **Zoja Raud**. Research and Development of an Active Learning Technology for University-Level Education in the Field of Electronics and Power Electronics. 2012.

53. **Andrei Blinov**. Research of Switching Properties and Performance Improvement Methods of High-Voltage IGBT based DC/DC Converters. 2012.

54. **Paul Taklaja**. 110 kV õhuliinide isolatsiooni töökindluse analüüs ja töökindluse tõstmise meetodid. 2012.

55. **Lauri Kütt**. Analysis and Development of Inductive Current Sensor for Power Line On-Line Measurements of Fast Transients. 2012.

56. **Heigo Mõlder**. Vedelmetalli juhitava segamisvõimaluse uurimine alalisvoolu kaarleekahjus. 2012.

57. **Reeli Kuhi-Thalfeldt**. Distributed Electricity Generation and its Possibilities for Meeting the Targets of Energy and Climate Policies. 2012.

58. **Irena Milaševski**. Research and Development of Electronic Ballasts for Smart Lighting Systems with Light Emitting Diodes. 2012.

59. **Anna Andrijanovitš**. New Converter Topologies for Integration of Hydrogen Based Long-Term Energy Storages to Renewable Energy Systems. 2013.

60 **Viktor Beldjajev**. Research and Development of the New Topologies for the Isolation Stage of the Power Electronic Transformer. 2013.

61. **Eduard Brindfeldt**. Visually Structured Methods and Tools for Industry Automation. 2013.

62. **Marek Mägi**. Development and Control of Energy Exchange Processes Between Electric Vehicle and Utility Network. 2013.

63. **Ants Kallaste**. Low Speed Permanent Magnet Slotless Generator Development and Implementation for Windmills. 2013.

64. **Igor Mets**. Measurement and Data Communication Technology for the Implementation in Estonian Transmission Network. 2013.

65. **Julija Šommet**. Analysis of Sustainability Assessment in Carbonate Rock Quarries. 2014.

66. **Tanel Kivipõld**. Real-Time Electricity Tariff System for Retail Market. 2014.

67. Priit Uuemaa. Industrial CHP Optimal Management Model in the Energy Market under Incomplete Information. 2014.

68. **Anton Rassõlkin**. Research and Development of Trial Instrumentation for Electric Propulsion Motor Drives. 2014.

69. **Toomas Vaimann**. Diagnostics of Induction Machine Rotor Faults Using Analysis of Stator Signals. 2014.