Eesti Maaülikool
Estonian University of Life Sciences

NOVEL APPLICATION PRINCIPLES FOR ENERGY STORAGE TECHNOLOGIES IN NEAR ZERO ENERGY BUILDINGS

ERINEVATE ENERGIA SALVESTUSTEHNOLOOGIATE UUDSED RAKENDUSPÕHIMÕTTED LIGINULLENERGIAHOONETES

HEIKI LILL

A Thesis
for applying for the degree of Doctor of Philosophy
in Technical Sciences

Väitekiri
filosoofiadoktori kraadi taotlemiseks
tehnikateaduse erialal

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Institute of Technology,
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LIST OF ORIGINAL PUBLICATIONS

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II. Allik, Alo; **Lill, Heiki**; Annuk, Andres (2019). Ramp Rates of Building-Integrated Renewable Energy Systems. International Journal of Renewable Energy Research-IJRER , 9 (2), 572−578.

III. **Lill, Heiki**; Allik, Alo; Annuk, Andres (2019). Case study for battery bank subsidization. In: 8th International Conference on Renewable Energy Research and Applications (234−238). ICRERA 2019, Brasov: IEEE.10.1109/ ICRERA47325.2019.8996602.

IV. **Lill, Heiki**; Hovi, Mart; Loite, Kristjan; Allik, Alo; Annuk, Andres (2019). Integrated Smart Heating System in Historic Buildings. In: 7-th International Conference on Smart Grid (92−96). Newcastle, Australia: IEEE.10.1109/ icSmartGrid48354.2019.8990833.

The author's contribution to the articles:

Article	Study design	Data collection	Data processing	Manuscript preparation
I	**HL**, AA	AA, **HL**, MH	AA, **HL**	**HL**, AA, HH, EJ, AN
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III	**HL**, AA	**HL**, AA	**HL**, AA	**HL**, AA, AN
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III. Heiki Lill was the main author of the article. He created the study design, composed the literature overview and made the calculations. He had the major role in writing the article.

IV. Heiki Lill was the main author of the article. He was responsible for literature overview, calculations and partially for the study design of the article. He had the major role in writing the article.

ABBREVIATIONS AND SYMBOLS

Abbreviations

AC	alternating current
CCS	carbon capture and storage
CCU	carbon capture and utilisation
COP21	Conference of the Parties to the United Nations Framework Convention on Climate Change
DC	direct current
CDF	cumulative distribution function
TA2	interface controller
TB1	interface controller
PV	photo voltaic
G1	primary energy converter
nZEB	nearly zero energy building
TA1	primary energy interface
UC	ultracapacitor
C1	ultracapacitor stack
WG	wind generator

Symbols

B_S	battery subsidy, €
C_A	battery output capacity, A·h
C_{cell}	capacitance single UC cell, F
C_W	battery capacity, kW·h
C_Σ	total battery output capacity, A·h
DoD	depth of discharge, %
l	lag, s
M_a	feed-in tariff, €/MW·h
M_B	cost of battery, €
M_K	cost for 1 kW·h of storage, €/kW·h
M_{KS}	storage cost, €/kW·h
M_{sub}	subsidy, €/kW·h
N_{fee}	network fee, €/kW·h
P_{bat}	power input to battery, W
P_{in}	power from primary energy converter, W

P_W	battery storage capacity, kW·h
$r(l)$	autocorrelation function
S_a	annual subsidy, €/a
t	time, s
U_{cell}	rated voltage of single UC cell, V
U_{max}	maximum voltage, V
U_{min}	minimum operating voltage across UC stack, V
V_b	battery voltage, V
W_a	annual electricity production, MW·h/a
W_U	useful energy storage capacity, kW·h
$\bar{x}$	mean value of time series
n_c	number of useful cycles of battery
η_{uc}	overall efficiency of UC and converter assembly, %
η_1	share of energy sold to grid, %

INTRODUCTION

In December 2015, at the COP21 Paris Climate Conference, 195 countries adopted a global, legally binding agreement to curb global warming. The main objectives of the agreement are climate change mitigation and emission reduction. To achieve this, governments agreed on the long-term goal of keeping global average temperature rises below 2 °C compared to pre-industrial times. It was concluded that there is a need to halt global emissions growth as soon as possible, recognizing that it will take longer for developing countries (United Nations, 2015).

Prior to the Paris Climate Agreement in 2014, the European Union (EU) set itself the goals for 2030: reduce greenhouse gas emissions by 40 % compared to 1990; produce 27 % of energy from renewable sources; increase energy efficiency by 27 % (European Commission, 2013).

Targets were also set for the year 2050 in various areas. It was found, that from all the sectors, the energy sector has the greatest potential for reducing carbon emissions. Renewable energy sources (such as wind, solar, hydro and biomass) or low-carbon energy sources (nuclear or fossil fuel-based energy with carbon capture and storage (CCU and CCS)) are envisaged for electricity generation. Contributions will also be made to the development of smart grids. Emissions from residential and office buildings could be reduced by about 90 percent. The greatest success is expected in near-zero energy building (nZEB) technology, more energy-efficient renovation of legacy buildings and the replacement of fossil fuels in heating, cooling and white goods (European Commission, 2013).

In 2017, the Estonian Parliament approved the basic principles of Estonian Climate Policy until 2050. Estonia's long-term goal is to move to a low-carbon economy, which means gradually transforming the economic and energy system into a more resource-efficient, productive and environmentally friendly one. By 2050, Estonia aims to reduce greenhouse gas emissions by almost 80 percent compared to 1990 levels. The impact assessment showed that the target is achievable and is likely to have a positive impact on the economy and energy security (Ministry of the Environment, 2017).

The basic principles of Estonian Climate Policy until 2050 state several focus areas, which must be taken into actions:

- The planning of energy consumption centers and new production capacities, as well as the management of consumption and production, has to be based on the efficient interaction of the system as a whole;
- Industrial processes predominantly will use low-carbon technologies and use resources with maximum efficiency;
- Renovation of the existing building stock and planning and construction of new buildings will be based on the economic and energy efficiency of the system as a whole in order to achieve the maximum energy efficiency of the entire building stock in use;
- In the planning, construction, management and reconstruction of networks in energy systems, the economic and energy efficiency of the system as a whole will be taken into account with the aim of achieving maximum energy and resource efficiency. Electricity and heat networks operate on the principle of a free market and all market participants connected to the network have the opportunity to buy and /or sell energy on the network without discriminatory restrictions.

Based on the aforementioned information, one of the greatest potentials for increasing energy efficieny and deployment of renewables are seen in renovating the building stock and in new nZEBs. Nearly zero energy buildings are already required by law in the EU. The goal of the thesis is to offer application principles for the wider deployment of energy storage devices in nZEBs based on the identified possible new developments in the field.

From this goal, several tasks may be derived to improve renewable energy usage in nZEBs:

1. identify energy storage needs to reduce discarded energy;
2. increase electrical energy self-sufficiency of buildings;
3. find ways to enable a wider range of storage possibilities of renewable energy in buildings.

The dissertation discusses these issues and offers novel solutions.

The practical novelty of the thesis includes:

a) capacity and power ratios have been calculated for nZEB energy storage systems equipped with capacitors and batteries to flatten renewable energy production curves (I);
b) stochasticity characteristics of building-integrated renewable energy systems have been determined to aid the planning of storage capacities (II);
c) a novel subsidization scheme proposal for stationary battery banks to increase self-consumption in nZEB (III);
d) integrated smart heating solution with solid heat storage to increase renewable energy consumption and thereby offer a flexible load for the electricity grid (IV).

The structure of the study is as follows:

The thesis is based on the research and results previously presented in four articles by the author. The articles are presented at the end of the thesis.

Dissemination of results

The research for the doctoral thesis has been presented by the author at three international conferences. The author of the thesis has been the first author or co-author in seven international scientific publications. Four of these are the main publications in this thesis, all four of them are available in the Thomson Reuters WEB of Science database.

1. LITERATURE OVERVIEW

1.1. Forms and quality of energy used in buildings

In every habitable building, there is demand for different types of energy: high- and low quality energy (Sen & Bhattacharyya, 2014). Examples of high quality energy are electrical energy, mechanical energy and some forms of chemical energy. Low quality energy means in most cases low temperature heat (Jensen, 1980). In nearly-zero energy buildings, there can be several ways to accumulate and reuse energy to meet the inhabitant's needs in everyday life (Bointner, Toleikyte, & Kranzl, 2016). To cover those needs, firstly, energy should come in sustainable buildings from renewable energy sourses like wind, solar power, and biomass or ground heat (Tuohy et al., 2015). After energy collection, there must be some sort of energy accumulation systems, preferably for high quality (or potential) energy that may be converted to low quality energy, if needed (Vasko et al., 2019). For high quality energy, there is a possibility to store it in different types of batteries and capacitors (Palacky, Baresova, Sobek, & Havel, 2016). For low quality energy (heat) are possibilities to store it in water, stone or the ground (Mohamed & Ben Brahim, 2017), (Chen, Zhang, & Zhao, 2016), (Mina, 2012).

1.2. Energy storage background

In the Nordic area which has long periods with outside temperatures below 0 °C, such conditions occur also in Estonia, where the case studies of thesis are made. In these regions, there has been historically always a need to store heat in households to ensure a suitable climate for living inside the buildings. In the Nordic region, the period where heating is required, may be as long as 6 month or even more: from the end of October to the end of April. For most of the history it was common practice to obtain heat by burning solid fuel (wood) and store it in stone furnaces (also called energy storing stoves). The energy storage capacity of the stone furnaces depends on the total mass of the stones used in the particular furnace. The necessary energy storage capacity of the stone furnace depends on the house's volume and local climatic conditions. A larger house requires a heat storing stove with greater capacity. In general, the need for heat storage capacity of stone furnaces increases with locations on higher latitudes. As a rule of thumb it has been found that a distance of 1000 km further away from the equator, requires 1000 kg additional mass for a stone furnace in a house, if other parameters remain the same. Figure 1.1 presents an example of a cross section of a heat storing stove. The working principle of the furnace is to burn solid fuel (wood) in a designated place and to move hot flue gas through the intended channels inside the stove to the chimney. At the same time, the flue gas heats the surrounding stone, cooling itself. Normally, the temperature of the outer surface of the stove after heating should be below 100 °C. After the combustion of solid fuel ends, the surface temperature of the heat storing stove rises, but after 3 to 4 hours, the temperature of the stove starts to decline and releases the heat into the surrounding environment. The heat release process continues until the stove's temperature equalizes with the ambient environment. Depending on the circumstances, this may take more or less time, but the stoves are generally planned in a way for this process to usually take up to 24 hours. The process is then repeated as needed (Figure 1.1).

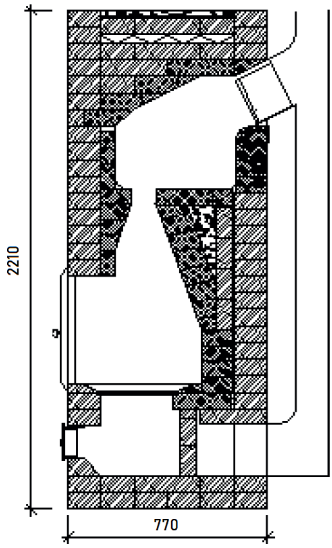

Figure 1.1. Side view cross section of heat storing stove. The front view cross section is 1030 mm wide. (*Müüritud küttekolded*, 2002)

1.3. Constraints of energy storage

In a nZEB, the annual energy demand and production have to be almost balanced on an annual basis, but depending on the season and day time, it can consume more than it produces or vice versa (European Parliament, 2010). To make the nZEBs more continuously energy self-sufficient, the system's energy flows need to be balanced. There should be an energy accumulation system where the produced energy is stored and in the time of energy deficit used to supply the household's needs (Verma, Devassy, Ram, Abhishek, & Dhakar, 2019). Usually a private household's energy accumulation system's purpose is not to supply energy towards the utility grid (Lu et al., 2018). In the case of battery banks, electrical energy is stored in potential chemical energy that is accessible through direct current (DC) but the utility grid is based on an alternating current (AC) system (Shi, Hu, Han, & Yuan, 2020). Also capacitors are also only capable of storing DC (Kabalo, Blunier, Bouquain, & Miraoui, 2011).

All chemical battery systems have a finite lifetime, that means they only tolerate a limited number of cycles of charging and discharging (Elshabrawy, Shereen, Ashour, & Robert, 2017). Also there is even a finite shelf life when the battery's chemical elements are not used.

Energy in an nZEB can be accumulated in heat, but heat usually cannot be (re)converted to electrical energy without significant complications (Sun, Wen, Zhang, & Wang, 2019). Heat storage is mostly implemented with water in hot water tanks and heat energy stored in high density building elements (accumulating stoves, stone floors) (Waser, Berger, Maranda, & Worlitschek, 2019). All those limitations have to be taken into account in the planning of nZEB based energy storage systems.

1.4. State-of-the-art energy storage technologies

People in developed countries have the highest electricity use (U.S. Energy Information Administration, 2021). This is because it is convenient to transport and convert electricity into lower forms of energy at the location of the final consumption. Each energy conversion process also means unavoidable losses to the amount of energy that is converted into the final useful form of energy. Except, in the case when the desired form of energy is heat. Therefore, it is reasonable to maintain the higher form of energy if possible from production to the final consumer. Storing electricity (kinetic energy) in battery banks (potential energy), as well as converting energy from one form to another, involves losses. However, energy storage in battery banks is associated with lower losses than energy conversion (Krstic, 2020) (Gangatharan et al., 2020).

The implementation of nZEBs usually requires some kind of local electricity generation devices, for example, solar panels or wind generators (Spertino et al., 2019). This means that from time to time the household consumes the electricity it produces and from time to time the electricity is bought from the grid. In order to increase self-consumption and be less dependent on the grid, it must be possible to store the produced electricity.

Tesla offers a state-of-the-art electricity storage technology – the Tesla Powerwall (Huang, Lopez, & Ramos, 2020). The Powerwall can be charged both from the grid and from locally installed solar panels. This can ensure the supply of electricity to the house in an off-grid situation as well as, for example, charging an electric car in the event of a power grid failure. Such devices are emerging more on the market and will make nZEBs more continuously energy self-sufficient in the future (Huang et al., 2020).

Aim of the study

The aim of the thesis was to develop new principles for the application of energy storage capacities in energy efficient buildings. The research used input data from different small scale energy production units such as wind generators and PV-panels as well as the electricity prices from the free market and the use of local solid fuels. The research focuses on the possibilities of optimal energy storage in different variants in a households and their economic viability.

The aim of the thesis is to find methods for increasing the energy consumption of renewable and low cost grid energy consumption in buildings when implementing local electricity generation. Case studies conducted by the author are supporting the findings in this thesis.

2. MATERIALS AND METHODS

2.1. Data availability and quality

Data quality and quantity has a key role in the reseach and development of the possibilities of using different forms of energy storage in increasing the more continuous energy sufficiency of nZEBs. The speed with which parameters change and the time it takes to make decisions is crucial to achieving energy efficiency (II). Data on weather-dependant energy production and energy consumption mostly caused by human day-to-day habits are the main types of data to be taken into account.

2.2. Subsidies

To increase interest in renewable energy production, the Estonian Government has implemented a subsidy scheme for the sale of renewable energy since 2007. The result of this scheme is that numerous solar-, wind and biomass power plants have been built. Until the end of 2020 in Estonia, power stations with a nominal capacity of up to 50 kW could apply for renewable energy subsidies.

The approximate capacity factor (CF) of photovoltaic power plants in Estonian climate is around 11 % (Perpiña Castillo, Batista e Silva, & Lavalle, 2016). It can be derived from that CF that a 15 kW PV plant produces 14.45 MW·h/a (a mean of 39.6 kW·h per day). It is also known that the self-consumption share in private households is on average 25 % when using PV electricity (Luthander, Widén, Nilsson, & Palm, 2015). That means 75 % of the produced energy is sold to the utility grid, and could potentially have been stored locally. Based on the data above, the currently paid subsidy can be calculated by using equation (1).

$$S_a = W_a \eta_1 M_a, \tag{1}$$

where S_a is the calculated annual subsidy for the powerplant (€/a), W_a is the calculated annual electricity production (MW·h/a), η_1 represents the energy sold to the grid (%) and M_a is the feed-in tariff (€/MW·h).

The levelized cost for 1 kW·h of electricty storage capacity per year is for residential applications between 569 $ to 594 $ (503 € to 525 €) (Lazard, 2017) (III).

2.3. Main energy carriers in household use

The type of energy used in the households depends mainly on their availability at the location. In Estonia, the majority of households are connected to the electricity grid. However, the use of electricity for residential heating is slight. District heating is common in urban areas. The use of wood for heating is very traditional in private households in both rural and urban areas. Gas is used in households mainly in urban areas where gas pipelines have been developed. Table 2.1 shows the main energy carriers in Estonian homes in 1999, 2009 and 2018.

Table 2.1 Annual energy consumption of Estonian households, GW·h (Statistics Estonia, 2021)

Year	**1999**	**2009**	**2018**
Wood based fuels	3812	4524	4314
District heating	4788	3845	3750
Electricity	1363	1884	1860
Gas	583	662	743

2.4. Heat consumption

The weather data used in this thesis is specific to Northern Europe. This means that there are large seasonal fluctations in the temperatures. In Northern Europe in summer times and parts of spring and autumn, residential buildings usually do not need additional heating. The nZEB buildings must according to regulations be designed so, that 1 m^2 of floor area does not consume more than 145 kW·h total energy in one year. The newly built living space in a statistically common residential building in 2020 can be considered to be 93.2 m^2 (Statistical database of Statistics Estonia, 2021). This means that a one-family detached nZEB building with an area of 93 m^2 would need on average 13514 kW·h of external energy in a year.

Traditionally, solid fuel furnaces have been used to heat residential houses in Estonia. The average mass of solid fuel furnaces in Estonia is about 2000 kg. In residential households, there is usually one furnace to heat the detached house and the furnace is made out of brickstone. The specific heat capacity of stone used in these furnaces (or stoves) is 1 $kJ \cdot kg^{-1} \cdot K^{-1}$. During the active heating period, the furnace's minimal temperature is kept around 40 ^{0}C and maximal outer surface temperature should not exceed 80 ^{0}C. Using the following equation (2), the energy stored to a furnace can be calculated (IV)

$$Q = \Delta tmc, \tag{2}$$

where Q is the amount of energy (J), Δt is the temperature difference (K), m is the mass of the object (kg) and c is the specific heat of the material ($J \cdot kg^{-1} \cdot K^{-1}$).

Fluctuations in the outdoor temperature affects directly the temperature inside the building and the need for heating. The fluctuation of the outdoor temperature in Tartu can be seen in Figure 2.1, showing the average temperatures for the months of 2019 (University of Tartu, 2021).

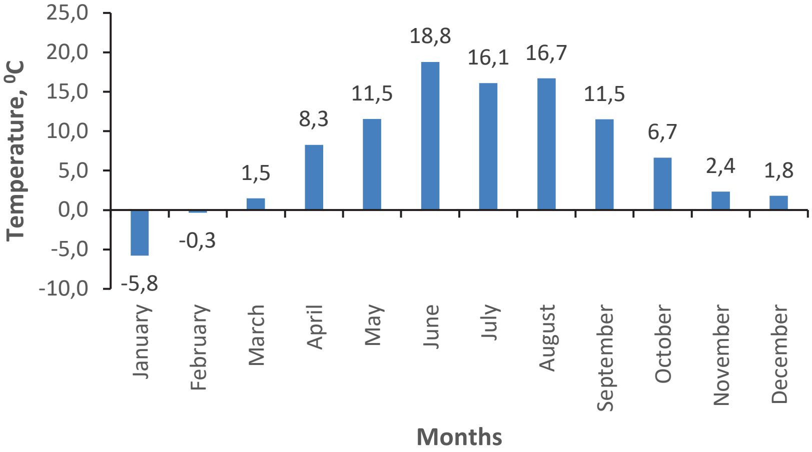

Figure 2.1. Monthly average outside air temperatures in Tartu in 2019

By knowing the hourly outdoor temperatures, the heating demand for a nZEB can be calculated for the heating period (Ministry of Economic Affairs, 1997). The resulting heating load schedule is presented in Figure 2.2.

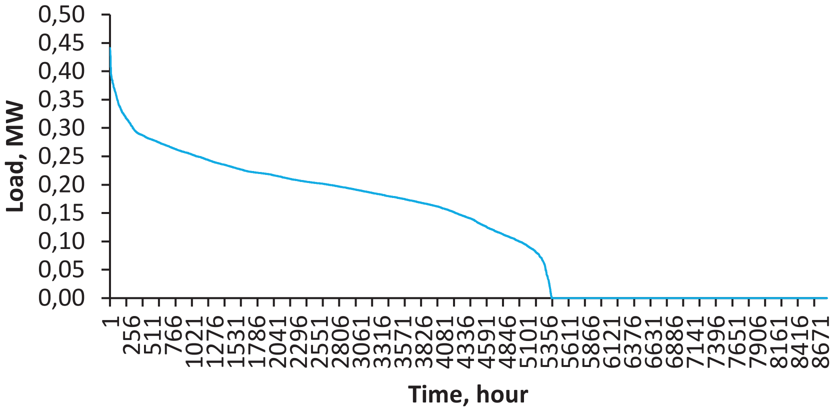

Figure 2.2. 2019 heating load curve.

2.5. Weather data

Wind speed and properties of flow determine a wind turbine's electricity production. A relationship is observed that intermittent high wind speeds (gusts) increase with the rise of the average wind speed (Brasseur, 2001). Wind energy production data from a small wind turbine (3.5 kW) was used for the research (Figure 2.3). It is also known that wind speed is usually less stable and less predictable than solar radiation. Wind energy is by far less often used for on-site enegy generation for residential consumers. In the rare cases when it is used locally it has a good coincidence with the consumption, which is also called self-consuption (Brasseur, 2001), (Annuk, Andres; Allik, Alo; Pikk, Priit; Toom, Kaupo; Jasinskas, 2012) (II).

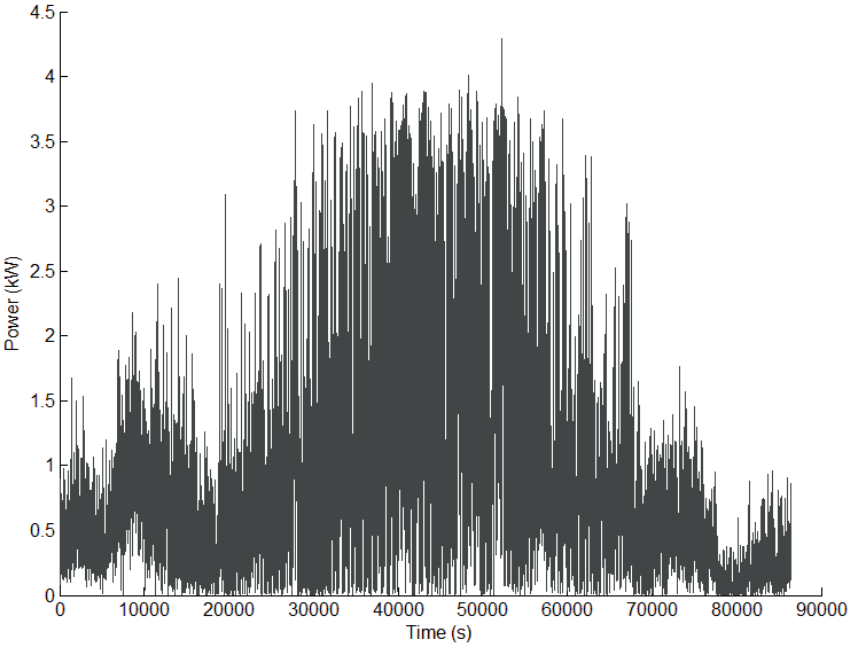

Figure 2.3 Output data of the analyzed wind turbine during 24 h (I).

In cases with rapid energy output changes, the use of short-term storage, like capacitors, can be highly beneficial. Autocorrelation functions can be used to determine the speed of changes and therefore mitigation necessity (Figure 2.4) (I).

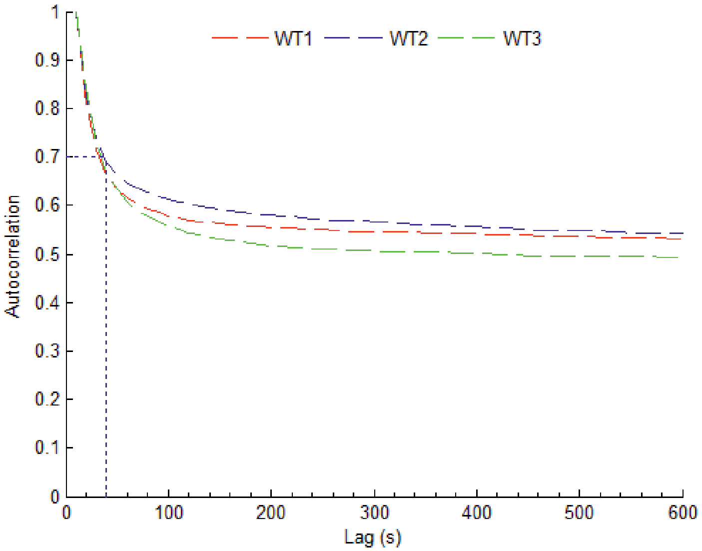

Figure 2.4 Autocorrelation functions of three different wind turbine output time series as functions of time lags (Alo Allik & Annuk, 2016).

2.6. Energy storage needs

In the nZEB, the energy loss must be at the minimum level, ideally at zero (European Parliament, 2010). The law provides exeptions to achieve the nearly-zero energy building certificate even if the energy consumption is higher than 145 kW·h/m^2 in a year (Minimum Energy Performance Requirements for a Building, 2020). Those exceptions include for example municipal buildings but those are not in the focus of these thesis. The option is to install some sort of renewable energy converter, such as PV panels or a wind generator to the building's energy system. In this case, the renewable energy generation is subtracted from the consumption. The renewable energy generator should provide as much energy as it is needed to reach the 145 kW·h/m^2 level.

The output power of renewable energy production units, specifically wind- and solar energy production, fluctuates. Their output power forecasts have improved over time, but have still occasionally significant errors (Xiaoming, Yuguang, Bo, Yuanjie, & Fan, 2018), (Lappalainen & Valkealahti, 2017). This is mainly due to the stochastic nature of the weather conditions (Wright & Wood, 2004). There is a large scale of periodicity in the weather: summer-winter, day-night. Weather forecasts for the next few days are also made, but those forecast do not predict the magnitude of wind gusts.

Hourly average production is usually used in renewable energy calculations. However, in real life there are very large fluctuations in wind turbine production schedules (Alo Allik & Annuk, 2017).

A household with installed renewable energy sources has always a problem with the timing of production and consumption. This means that an energy storage device must be installed in the system to ensure security of electrical energy supply. Due to the wind gusts mentioned above, there are situations when the amount of electricity produced by the wind turbine exceeds the storage speed of the battery bank. This can be explained by the Ragone plot principle (Zhang, Tang, Qi, & Liu, 2015), (Ratniyomchai, Tricoli, & Hillmansen, 2014) (I).

2.7. Methods for the analysis of storage performance

This chapter consists of mathematical principles and equations used in the published articles to analyze residential renewable energy systems. Various analysis have been performed in Matlab software (I, II).

Electricity generation data was normalized and scaled up or down for better comparability with consumption. For production equipment, only values above zero were used in the analysis, as longer periods without output would give in statistical figures the impression of greater output stability.

The night-time data of the photovoltaic power station and the wind generator data from lull periods were eliminated. On the other hand, the household consumption power is almost never zero because of standby devices and ohter base loads. Standard deviation figures were used to analyse the amplitude of changes in the data series (Ajeigbe, Chowdhury, Olwal, & Abu-Mahfouz, 2018), ramp rates enable the analysis of rapid short-term changes in the time series and autocorrelation functions enabled the analysis of the temporal continuity of the time series (II).

A ramp rate is defined in the context of the current thesis as the speed of change in consumption or production power during a given time period (Hossain & Ali, 2014). If the power decreases, then the process is defined as ramping down and in the opposite situation it is ramping up (II).

Autocorrelation functions can be applied among ohter methods for the analysis of the speed of transition processes (Haessig et al., 2014). The correlation of a time series with itself under varying time lags has been previously presented for the pace of changes in weather parameters like temperature and wind speed (Alo Allik et al., 2016), (Widén & Wäckelgård, 2010). The following equation was used to determine the Pearson's based autocorrelation function r(l), that is dependent on time lags (l) (Darbellay & Slama, 2000), (Lee Rodgers & Alan Nice Wander, 1988) (II):

$$r(l) = \frac{\sum_{(i=1)}^{(N-l)} (x_i - \bar{x})/(x_{i+1} - \bar{x})}{\sum_{(i=1)}^{N} (x_i - \bar{x})^2}, \qquad (3)$$

where, *r(l)* is the autocorrelaction function dependent on the time offset. The time offset is also called lag, it is the time between the analysed values in the series. The symbol x_i represents the values and $\bar{x}$ the mean of all values. The interpretation of correlation coefficients in a renewable energy related context is described in (A. Allik, Uiga, & Annuk, 2014).

With fast energy production changes, the system needs a high power energy storage. If an ultracapacitor stack (UC) is used for the mitigation of intermittent power pulses, two main parameters have to be considered, the maximum power constraint and also the energy storing capacity (I).

The output power of a UC for any given point in time can be calculated with the following equation (I):

$$P_{UC}(t) = P_{in}(t) - [P_{bat}(t) - P_{load}(t)], \tag{4}$$

where charnging is expressed with positiive values and discharging is presente with negatiive values. The power input from the renewable energy supply is marked as P_{in} and P_{bat} is the power input to the battery. The energy stored (W_{UC}) to the UC in any point of time is (I):

$$W_{UC}(t) = \int_{t=0}^{t=t_{max}} P_{UC}(t)dt. \tag{5}$$

The minimum storage capacity of the UC can be calculated with (I):

$$W_{UC} = \max_{0\ldots t_{max}} W_{UC}(t) - \min_{0\ldots t_{min}} W_{UC}(t), \tag{6}$$

whereby the maximum power of the UC and the accompanying converter can be found with (I):

$$P_{UC} = \max_{0\ldots t_{max}} P_{UC}(t). \tag{7}$$

The nominal capacitance of the UC stack can be found with the following equation (I):

$$C_{UC} = \frac{2W_{UC}}{\eta_{UC}(U_{max}^2 - U_{min}^2)}, \tag{8}$$

where the minimum operating voltage on the UC terminals is U_{min} and the maximum allowed voltage is U_{max}. The total efficiency of the whole UC and converter assembly is η_{UC}. In real world conditions it is $\eta_{UC} \approx 0.9$.

The result of the calculation of neccessary UC cells in series should always be rounded to the next highest integer (I):

$$n_s = \left[\frac{U_{max}}{U_{cell}}\right], \tag{9}$$

where the U_{cell} presents the nominal voltage of the UV cell under observation. The result of the calculation of neccessary UC cells strings should also be rounded to the next highest integer, similarly to the calculation of neccessary UC cells in series (I):

$$n_p = \left[C_{UC}\frac{n_s}{C_{cell}}\right], \tag{10}$$

where the capacitance of the UC cell is represented by C_{cell}.

2.8. Comparison of capacitor and battery

Capacitors and batteries have different self-discharge rates. An experiment was performed to understand their properties and the results are presented in Figure 2.3. The used devices specifications are shown in the Table 2.2. Both device sets were discharged before the experiment. As the first stage of the test, the battery and UC stack received a full charge and the voltage readings were taken from their terminals.

Table 2.2. Storage devices (I)

Device	Specification
SkelCap SPA0350 x 2	350 F; 2.85 V; 0.4 W·h
Samsung ICR18650-26H	2600 mA·h; 3.6 V

The voltage at full charge was in both cases 3.517 V. It was observed after $2.16 \cdot 10^4$ s (6 h) that the capacitor's voltage was lover than the voltage of the battery, as expected (I).

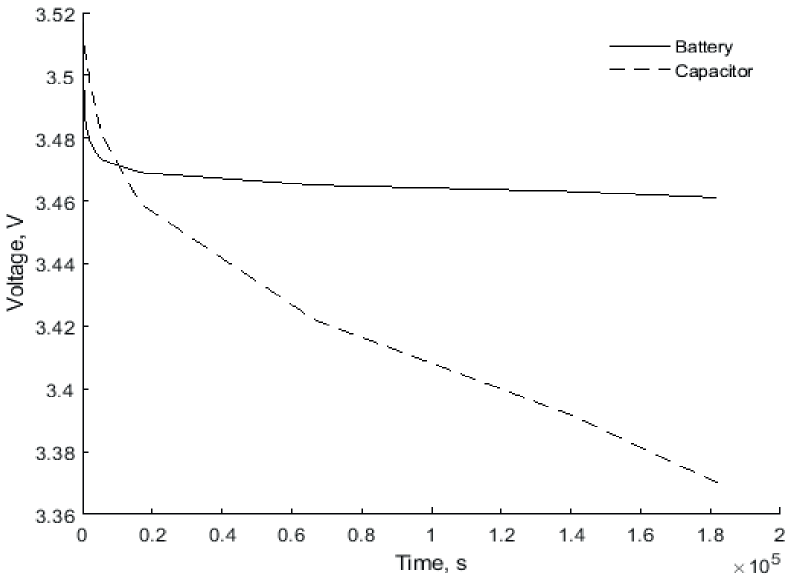

Figure 2.3. Comparison of capacitor and battery self-discharge (I).

The measurements show how the voltage and therefore the charge in the UC decreases with time. It is reconfirmation of the known property of capacitors, that they are not suitable for storing energy over extended periods of time, batteries are much better for this purpose (I).

2.9. Wind generator and photovoltaic array output

The power measurements of WG and PV were carried out in an urban environment at (58°23’19” N, 26°41’37” E), PV panels were at a 40degree tilt and faced directly to South, the hub height of the WG was 25 m. The measurement system technical specifications are shown in Table 2.3.

Table 2.3. System specifications (II)

Device	Specification
Wind generator (WG)	WindSpot 3.5, Horizontal axis, 3.5 kW, permanent magnet generator, passive yaw control
WG inverter	SMA Windy Boy 3600TL
Photovoltaic (PV) panels (10 panels)	Yingli solar 245 W
PV inverter	Solivia 2.5 EU G3
Measurement system	Janitza UMG 605, Circutor P2 TC5 M70312

The power production of the PV array during an example day is shown in the Figure 2.5. The data was logged with 250 ms integration period. The output data changes are caused by cloudy weather.

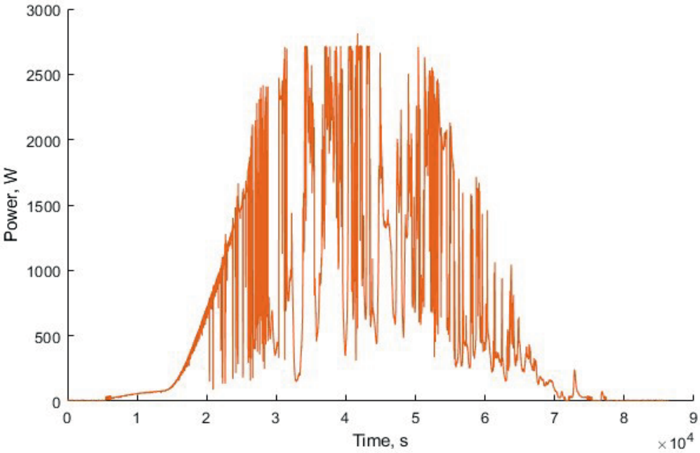

Figure 2.5. PV-array output on a sample day (June 18-th 2014, 250 ms integration period) (II).

The rapid fluctuations in Figure 2.6 output power are caused by wind gusts from diferent directions (Luo, Banakar, Shen, & Ooi, 2007).

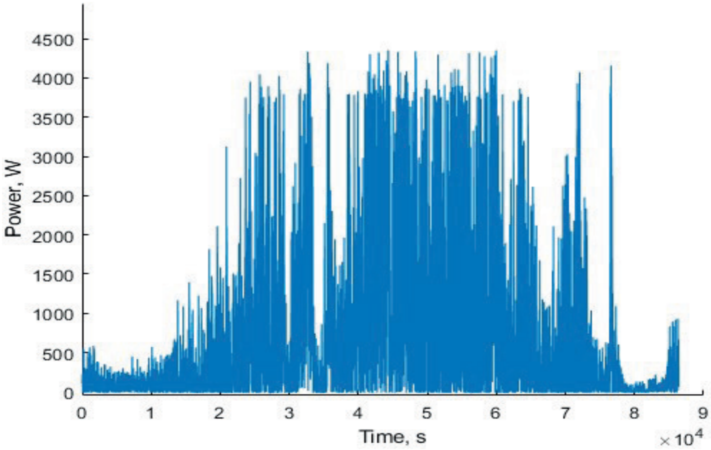

Figure 2.6. WG output on a sample day (June 18-th 2014, 250 ms data) (II).

To compare the stability of WG and PV energy sources they are presented graphically in the following figure (Figure 2.7).

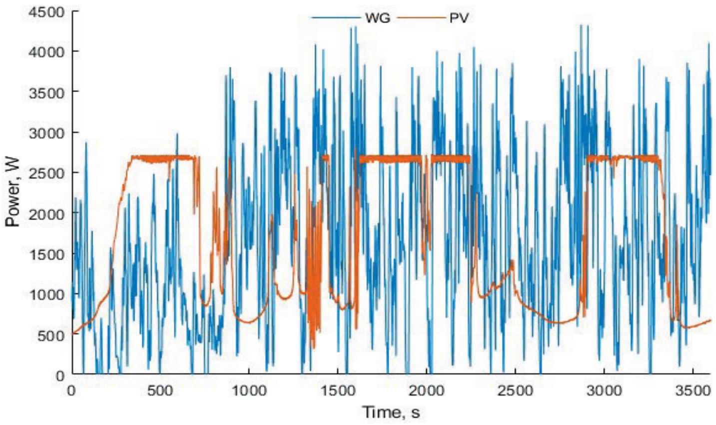

Figure 2.7. Sample WG and PV data with 250 ms integration period (II).

At noon, both energy sources reach their nominal power. Figure 2.7 shows the part of the output power for this period (12:00-13:00).

2.10. Battery bank specifications

The average household in Estonia used electricity in 2016 about 1913 kW·h/a, (Statistical database of Statistics Estonia, 2017) and European average is about 3650 kW·h/a. (Tutkun, Can, & San, 2015). This means that in Europe the average household uses roughly two times more electrical energy than in Estonia.

To ensure the security of supply of the house from renewable energy sources for 24 hours, it is possible to calculate the capacity of the battery bank.

Caused by resident's daily routine, the demand for electricity in household is higher in the morning and evening hours. The rest of the time the demand for electricity is caused mainly by white goods. A battery bank lifetime depends on several factors such as temperature, both the environmental on and the batteries itself, charging and discharging time, voltage and current, the depth of discharge.

The chosen depth of discharge appoints the capacity of a battery bank. The Figure 2.8 illustrates how a lower percentage of use of a battery guarantees battery longer lifetime. To ensure required RE supply for 24 hours, and to guarantee a battery long lifetime it is necessary to ensure the system plethora of battery capacity. To calculate the average household needed battery bank capacity output (5.24 kW·h) with depth of discharge 30% the equations 11 and 12 must be used. (III)

$$C_A = \frac{1000 \cdot C_W}{V_b} \tag{11}$$

where C_A is battery output capacity (A·h), C_W is battery capacity in kW·h, V_b is battery voltage (V).

$$C_\Sigma = \frac{100 \cdot C_A}{DoD}, \tag{12}$$

where C_Σ is total battery output capacity (A·h) and *DoD* is depth of discharge (%).

With the depth of discharge of 30%, the battery bank should be at least 1456 A·h to ensure 24h electricity supply for the average household.

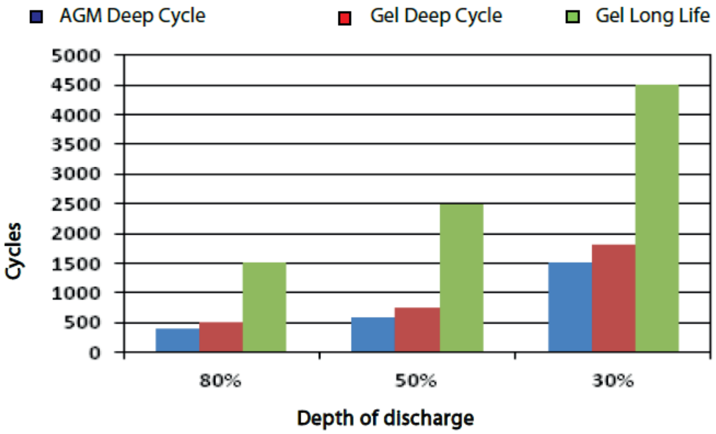

Figure 2.8. Depth of discharge of AGM battery (III) (Victron Energy, 2018).

The number of charging cycles are defined by the depth of discharge of the battery as shown in Figure 2.8. If the AGM batteries are discharged only to 30% of their capacity, the possible number of charging cycles of the AGM batteries goes up to three times compared to situation where the 80% DoD is used (III).

2.11. Electricity price

Nord Pool Spot is a Nordic power exchange where the electricity is traded between Norway, Denmark, Sweden, Finland, Estonia, Latvia and Lithuania. In 2010 Estonia joined the Nord Pool Spot. In Estonia produced electricity is mainly from non-renewable resources, while in Denmark electricity is mainly generated from renewable sources. Figure 2.9 and Figure 2.10 show the frequency of electricity prices in 2018 in Estonia and in the DK1 region of Denmark. In this thesis, the Nord Pool Spot market prices are used *(Nordpool Spot Electricity Pric*e, n.d.) (IV).

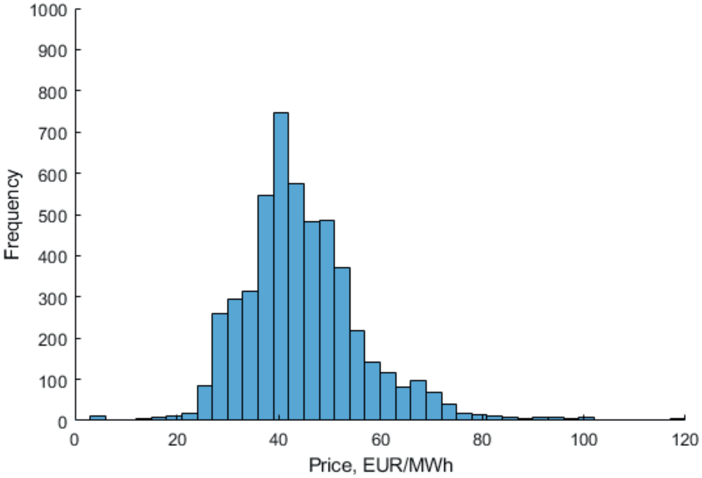

Figure 2.9. Electricity market prices during the heating period in Estonia (IV).

As the graphs show, the price of electricity sold in the Estonian price area in 2018 has not been less than 0 €, this has occurred in the Danish DK1 region (Figure 2.10) (IV).

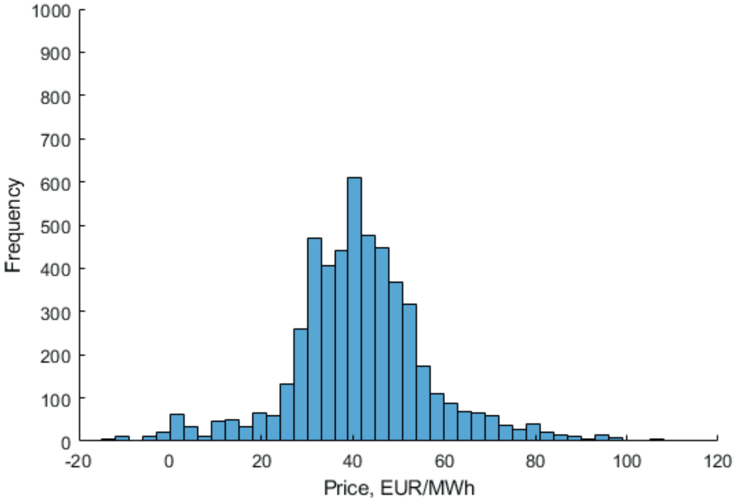

Figure 2.10. Electricity market prices during the heating period in the Danish price region DK1 (IV).

In Figure 2.9 and Figure 2.10 it is shown only the price for the electrical energy. The customer also has to pay the transmission fees and taxes. These fees and taxes sums up to 50 €/MW·h, which is equal to the cost of heat energy produced from local solid biofuel. This leads to a situation, where it is economically reasonable to the customer to heat with electricity when the price of electrical energy is below 0 €/MW·h (IV).

2.12. Modernized furnace heating system

Solid fuels are often used for local heating with heat storing furnaces. Electric heating elements can be easily installed in a heat storage furnace for use during periods of renewable electricity oversupply. In this case, the furnace itself constitutes a heat storing mass. The correct heating elements must be selected, according to the furnaces's maximum power to avoid damage to the furnace (IV).

Electric heating elements could be installed in the furnace during a refurbishing so that the connection cables and heating elements would not be damaged by the fire. The simplest way to add electric heating elements is when building a new furnace or completely disassembling and renovating an old one (IV).

3. SYSTEM SETUPS

3.1. Connection possibilities for the ultracapacitor stack

To make the RE system more efficient by using the UC as a buffer, in this example, the UC can be connected to the system in two major ways. Electrical power from the PV panel or a rectified WG output (primary energy converter G1). A possible topology is to connect the UC through an interface controller (TA2) to the battery terminals (G2) (Figure 3.1). The interface converter limits the voltge directed towards the battery and directs power to the UC if the upper limit is reached. A drawback of the topology is that all energy must flow through the central controller (TA1) (I).

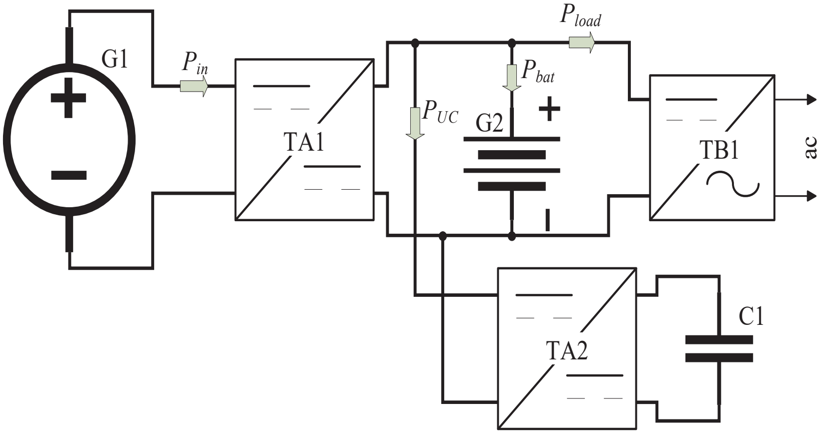

Figure 3.1 UC stack and its interface controller connected in parallel onto the battery terminals (I).

Another setup possibility is to use an "active parallel" connection. It means connecting the UC through it's connection interface (TA2) to the main energy generation unit in paralleel with the battery's interface controller (TA1). Such similar solution is used for storing heat energy (Figure 3.2) (I).

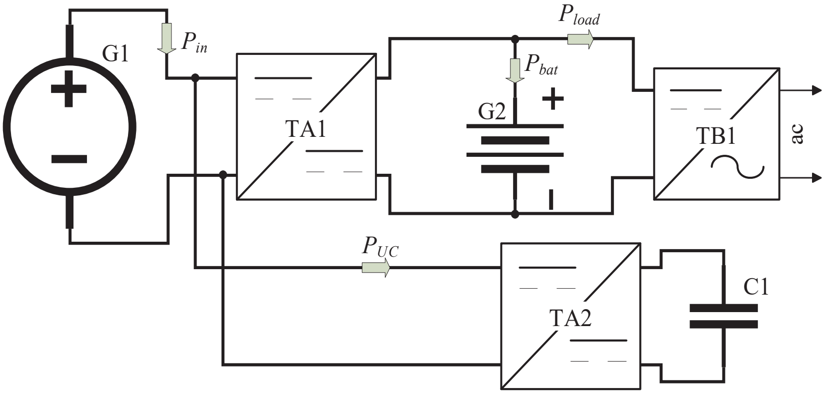

Figure 3.2 UC stack connected actively in parallel onto the primary controller terminals (I).

If the main energy generation unit conists of a PV panel array, the UC stack can be connected directly with the array's terminals, if devices are chosen with matching parameters. This would create a paralleel connection that operates passively (Figure 3.3). The difficulty in applying such a setup, is the voltage synchronization with maximum output of the converter of the primary energy supply. This solution may be used when the response time must be shorter (Kuperman, Aharon, Malki, & Kara, 2013) (I).

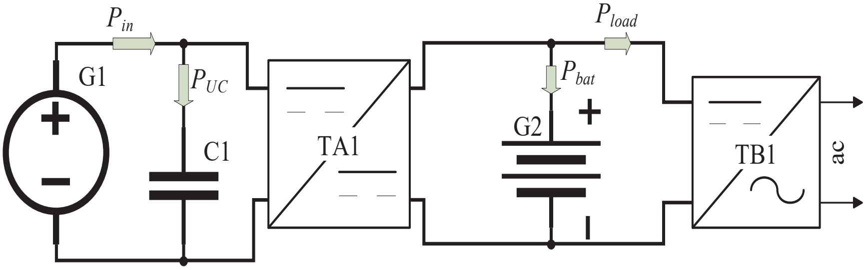

Figure 3.3 UC stack connected passively in parallel onto the battery terminals (I).

3.2. Ultracapacitor management

The logic diagram of the electrical storage system when using a chemical battery for storing energy over longer periods of time and the UC to mitigate high-power pulses is described in Figure 3.4. The battery has a priority in this case. In Figure 3.5 is presente the same logic in the Simulik model.

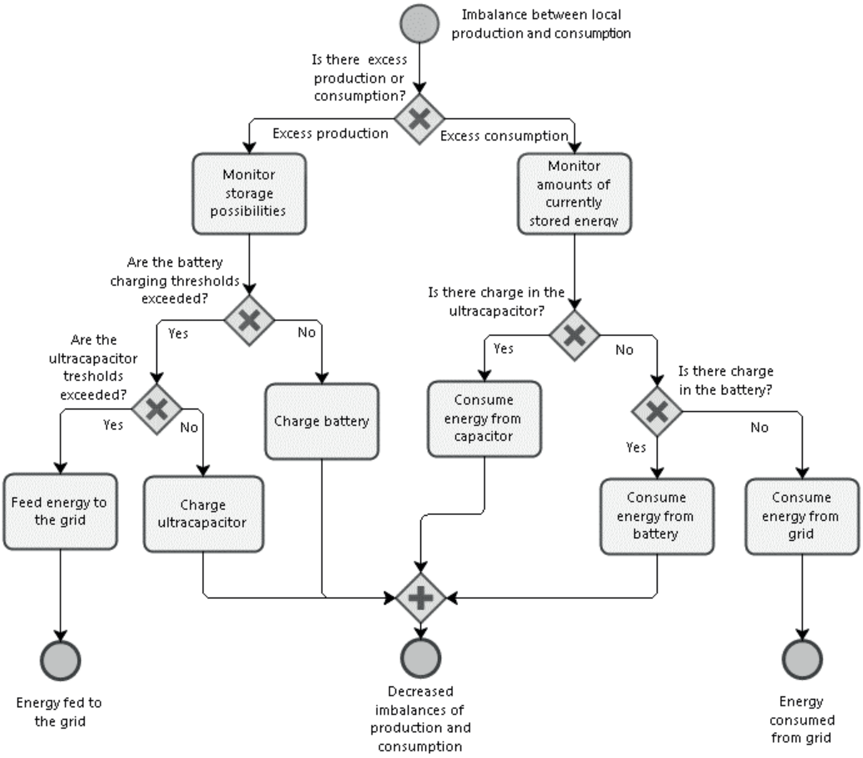

Figure 3.4 Energy management of the system (I).

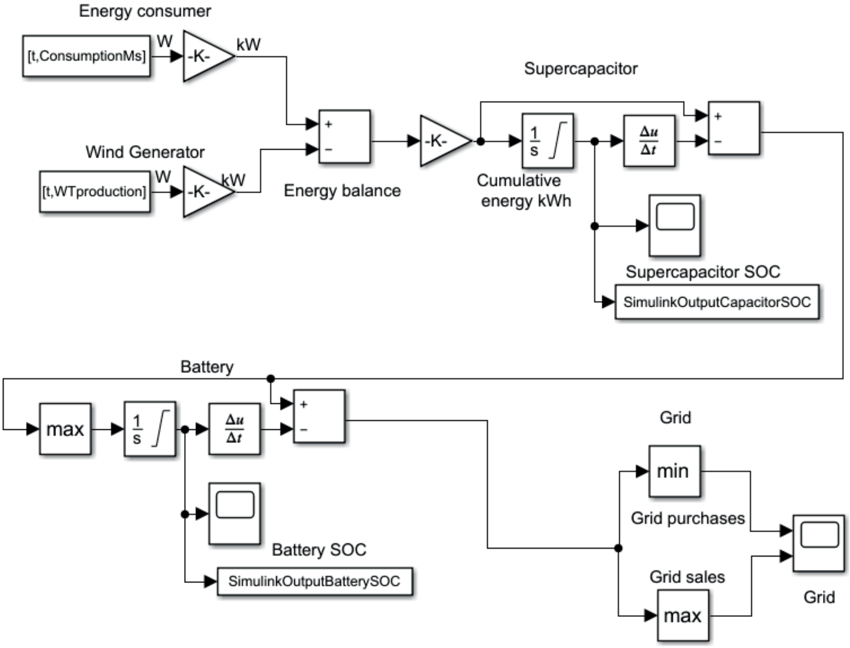

Figure 3.5 Simulink model of the analysed system (I).

Electricity production and consumption are out of balanced, so there Simulink model (Figure 3.5) can have both positive and negative outputs for the output signal.

3.3. Demand response systems

Every alternating current electrical system consists generally of three main parts: the production, transmission with transformers and the consumers. The production units, like WG and PV, supply consumers with electricity. For PV production unit, the PV panels cannot change the power generation on demand. Usually the problem is in the inertia of the production units or, in this case, caused by the weather conditions.

It is necessary that the electricity production and consumption in the system are balanced. The unbalanced system can lead to the shutdown of generating units, the instability of electricity consumers and power blackouts. In an open market the price of electricity is corrected of over- and under-production.

Low electricity prices attract to consume the electricity, but the high electricity prices do not favor the use of electricity. It is called demand response (DR) (Annuk et al., 2017).

At the moments of low consumption the additional load can be turned on and the stability of the utility grid is guaranteed (Kumar & Naik, 2017)(Annuk et al., 2018) (IV).

3.4. Furnace management system

The proposed furnace heating system needs intelligent integrated control that takes into account a number of real-time changing data. The proposed control system has five stages and requires network access. As can be seen in Figure 3.6, the decision of the control system to use electric heating elements to heat the furnace begins with the measurement of the room temperature. The second step in the control system is to measure the temperature of the furnace itself.

Weather conditions change over time and the indoor temperature depends directly on the outdoor temperature. Therfore the the third step for the controller is to obtain weather forecast data.

The fourth step in the logic system is to obtain electricity price information from the Nord Pool Spot. If it is expedient to heat with electricity, the maximum level of electricity price must be set by the user. The final step is to switch the heater on or off. The system needs to control all the input parameters all the time and continue heating if it is nessesary.

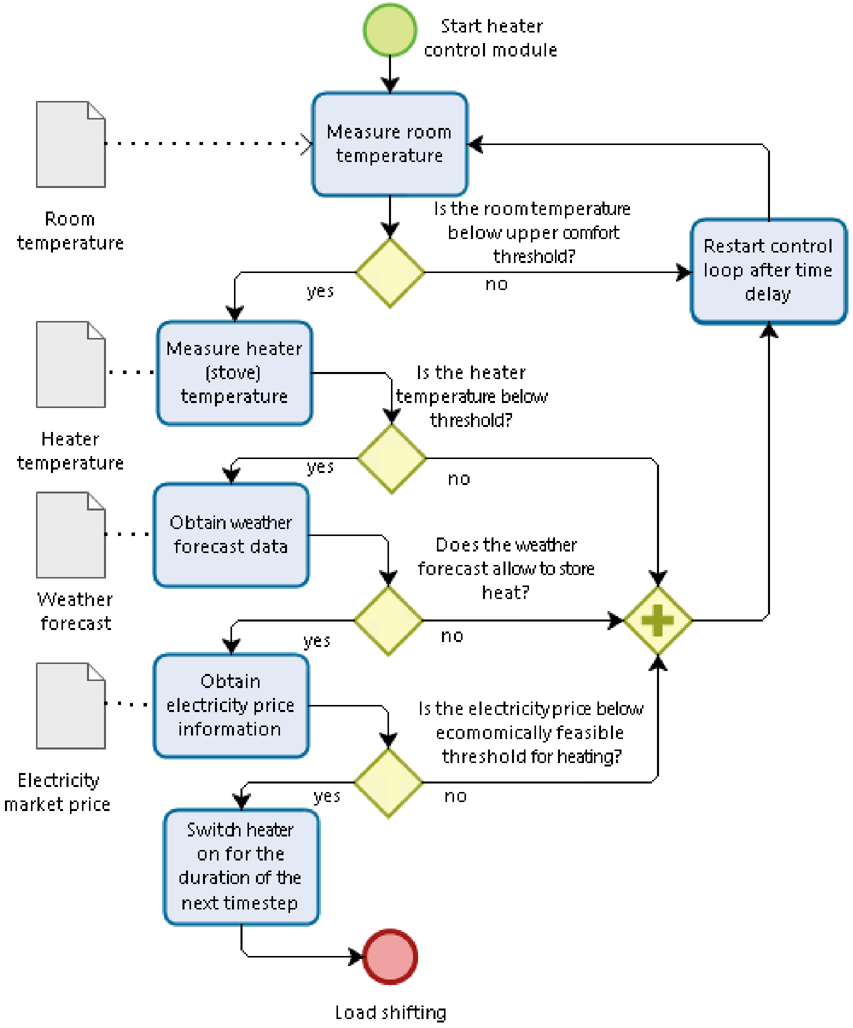

Figure 3.6 Control logic of the demand response method (IV).

4. ENERGY STORAGE TECHNOLOGY COMPARISON

4.1. Storage needs for the use of different RE sources

RE generators have always some sort of power fluctuations. The analyzed RE generation devices are presented in Table 4.1.

Table 4.1. Statistical figures of the power output of the analysd PV array and WT (II)

Statistical parameters	**Technology**	
	Photovoltaic	**Wind generator**
Mean power when in operation (% of P_n)	32.58 %	13.20 %
Standard deviation (% of P_n)	31.07 %	13.56 %
Maximum daily standard deviation (% of P_n)	63.05 %	23.18 %

In the Figure 4.1 is presented the solar energy production with normalised ramp rates. To analyse the ramp rates, a cummulative distribution function (CDF) was created. It is presente in Figure 4.2.

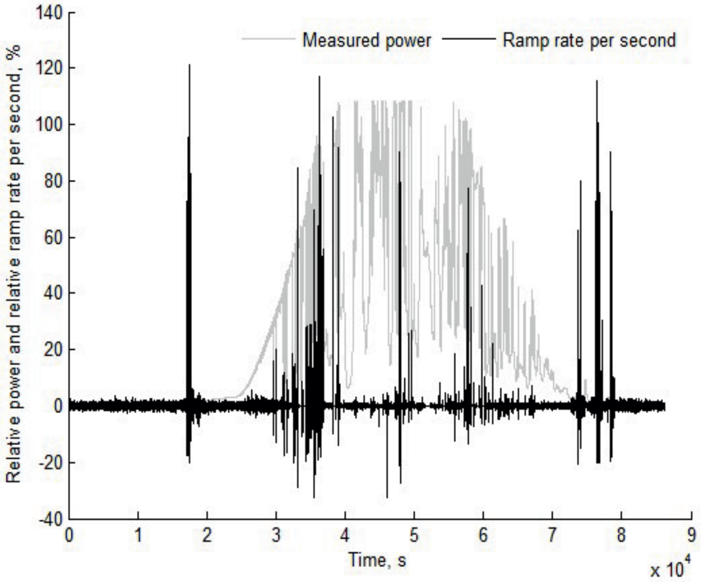

Figure 4.1. PV output power in relation to nominal power and ramp rate in relation to previous time step during a sample day (II).

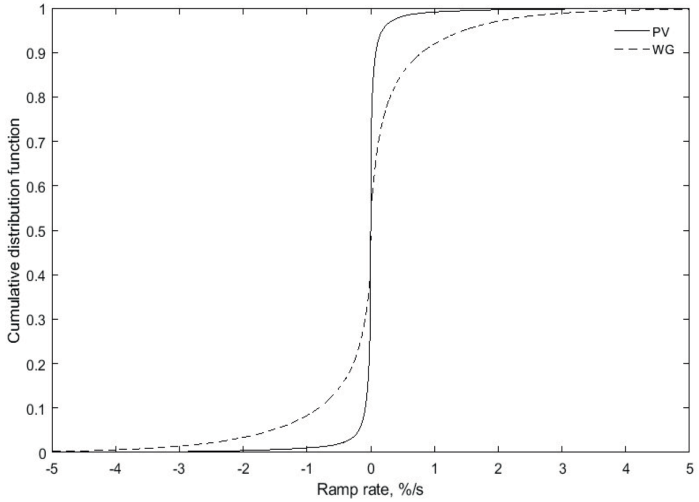

Figure 4.2. Cumulative distribution function of PV and WG output rates of changes (II).

In Figure 4.2 it is visible, that the positive and negatiive ramp rates have upside down, but similar shapes. Which means that the analysed energy source power outputs increase at a similar rate as they decrease. The Figure 4.2 also confirms that the PV has more stable and lower ramp rates than the WG.

Compared the RE production and energy consumption, the consumption is significantly more stable, as can be seen in Figure 4.3.

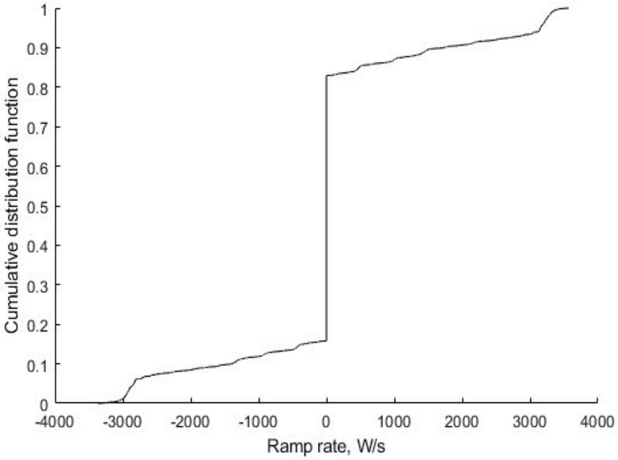

Figure 4.3. Cumulative distribution function of changes in consumption power (II).

Figure 4.3 shows that power is increasing 17.06 % of the time and in 15.8 % of the time the consumption power is decreasing, which means 67.14 % of the time the consumption is stable, or the changes are imperceptible. The periods with stable output power are characterized in Figure 4.3 by the vertical line in the centre. By comparing Figure 4.2 and Figure 4.3 it can be concluded that the energy consumption has by far more time steps with stable power in comparison to energy production (I).

The comparison of WG and PV output shows Figure 4.4 that the WG output have faster fluctuations. Longer periood WG power autocorrelation plots indicates 24-hour cycles (Soberanis, Bassam, & Mérida, 2016).

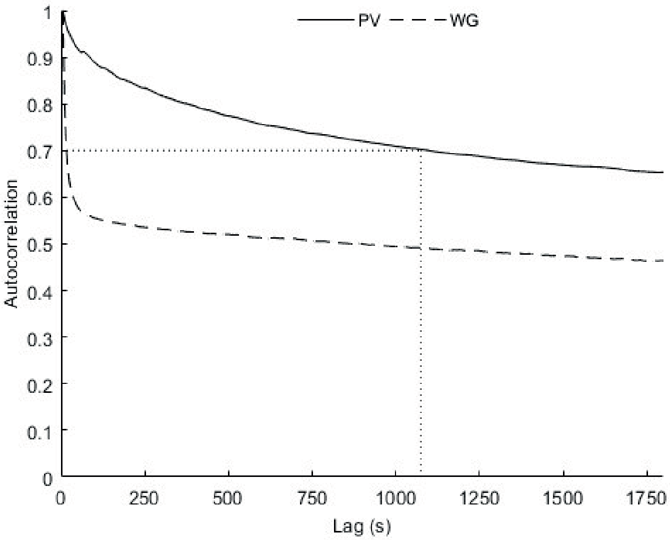

Figure 4.4. Autocorrelation functions of PV and WG output data with 5-second integration periods (Alo Allik & Annuk, 2016).

The output power of the analysed PV array had on average a strong correlation (≥ 0.7) with itself (autocorrelation) until the time distance reached 1040 s (Figure 4.4). The same time distance for strongly autocorrelated WT output is only 40 s. On the basis of Figure 4.4 and Figure 4.5 it can be concluded that PV have in this case higher stability of output than WG. 250 ms data from a sample day (Figure 4.5) shows a similar situation like 5 s data on the figure above (Figure 4.4) (II).

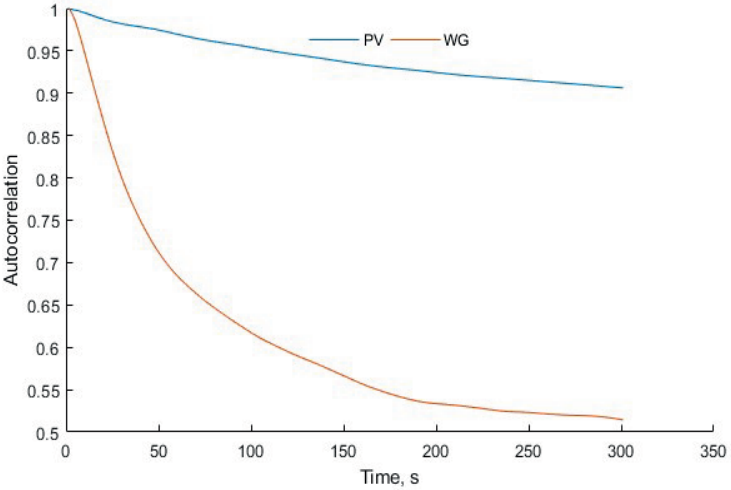

Figure 4.5. Autocorrelation functions of a PV array and WG output data with 250 ms integration period (Alo Allik & Annuk, 2016).

Days with actively changing cloudiness can create the highest standard deviations of PV array outputs. Still, on average the power output of PV arrays has higher stability that the power from wind generators. The small WT that was analysed has too low mechanical rotating mass to act as a power stabilizer. The local wind condtions have a key role in creating the fluctuations (Alo Allik & Annuk, 2016) (II).

4.2. Energy storage with ultracapacitors

In order to understand the need for a capacitor, a sample day was chosen and the data were used to run tests. During charging/discharging cycle when the excess energy is present, the UC reaches full load level in relatively short time (Figure 4.6) but loses its load rapidly when balance turns negative. The ultracapacitor achieves and maintains the fully charged state when 3500 s of day the solar energy is available. The performance of short-term storage is presented in Figure 4.6.

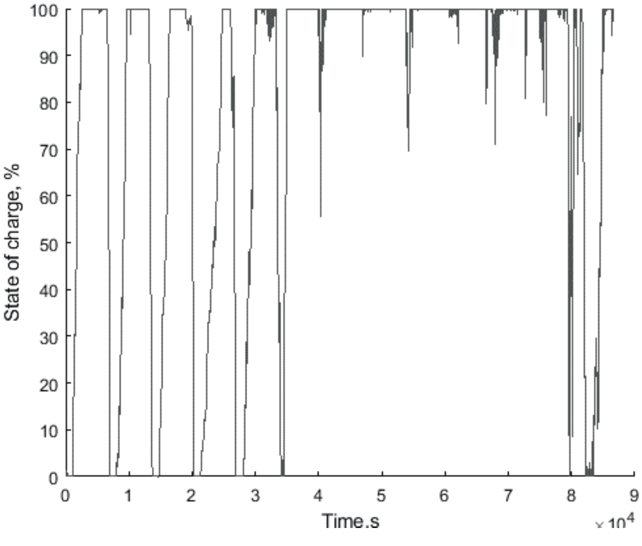

Figure 4.6. State of charge of the ultracapacitor during the sample day (I).

The UC is charged and discharged several times during the sample day (Figure 4.7).

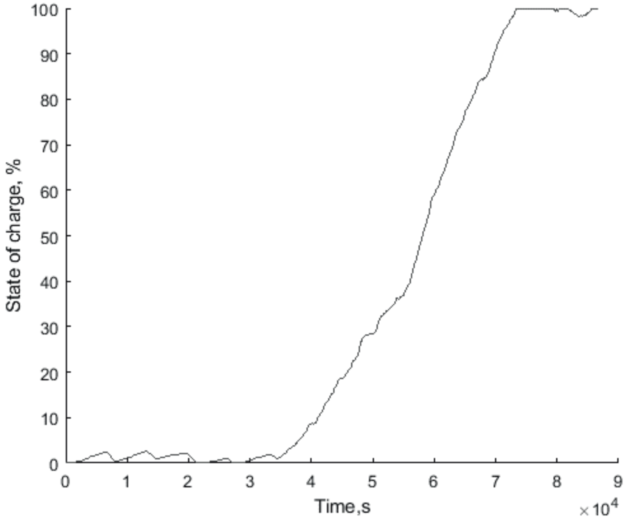

Figure 4.7. State of charge of the battery bank during the example day (I).

Energy storage can decrease the load on the electricity grid. Below is an example (Figure 4.8). The energy that is stored to a thermal storage is marked red on the negative side and the positve values marked with red represent the energy consumed from the storage.

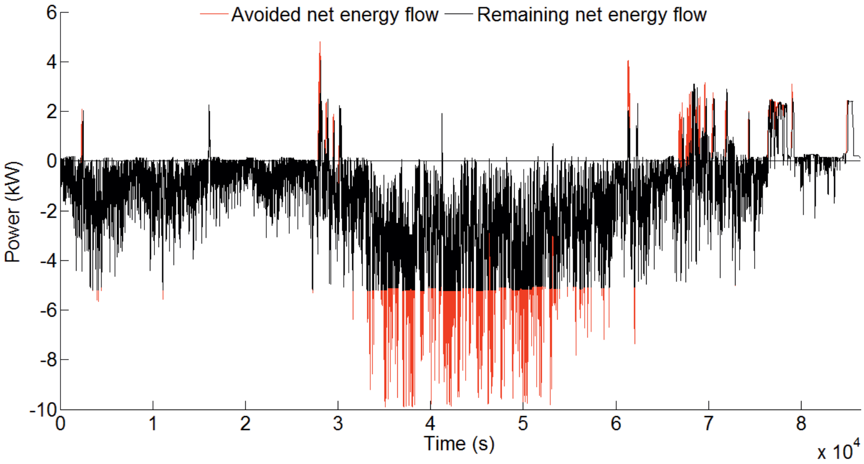

Figure 4.8. Output data of an analyzed wind turbine system before and after adding energy storage (Alo Allik, Märss, Uiga, & Annuk, 2016).

To illustrate the scale of a neccessary short-term storage device the following situation is described. A local energy generator has a mean generation power of 1 kW during times when it operates. It would need an energy storage device with 0.0167 kW·h capacity, to overbridge short pulses of up to 60 s. If an UC is used for this purpose, it would need a capacitance of 52 F at 48 V. The experimental system (Figure 3.1) had a capacitance of 165 F and nominal voltage of 48 V. This translates to 0.0528 kW·h energy storage capacity (I).

For the medium term energy storage a battery would be needed that can ideally overbridge 24 hours (Alo Allik et al., 2016), in the same example case as decribed above, it's energy stroage capacity should be 24 kW·h. Considering these parameters a ratio of 1:1440 would be between the UC and battery capacity (or more generally, short and medium period storage) (24/0.0167=1440) (I).

4.3. Energy storage with subsidised battery banks

Three absorbent glass mat (AGM) batteries with different characteristics were used to analyze the possibility of subsidies. The battery specifications are shown in Table 4.2

Table 4.2 Battery information

Battery name	Capacity, A·h	Size, kW·h
BTL 12-200 AMG	200	2.4
BTL 12-150 AMG	150	1.8
BTL 12-100 AMG	100	1.2

Taking into account the depth of discharge of the battery, it is possible to calculate (equation 13) the useful power (W_u, kW·h) stored during one charging cycle. Battery capacitance is marked as P_W.

$$W_U = P_W \cdot DoD \tag{13}$$

To calculate the cost of storing 1 kW·h of energy into the battery (M_K, €/kW·h) during its liftime the useful charging cycles (η_c) and the cost of the battery (M_B, €) is needed to know. It is calculated using equation (14).

$$M_K = \frac{M_B}{W_U \cdot \eta_c} \tag{14}$$

The hypothesis of this reasoning is that the battery bank's installation subsidy of 100 €/kW·h for energy storage capacity makes the investment attractive to renewable energy producers. The first battery in Table 4.2 has a capacity of 2.4 kW·h. The subsidies for that battery, in this case, should be 240 €. Therefore the storage cost of 1 kWh energy (M_{KS}, €/kW·h) is also lower (equation 15). B_S is the value of the battery subsidy (€).

$$M_{KS} = \frac{M_B - B_S}{W_U \eta_c} \tag{15}$$

Calculations with 2019 prices for the three different battery are presente in the Table 4.2 and their different conditions of depths of discharges were made and it tourned out that the most economical way to use of them is at the 30% depht of discharged as presente in the Table 4.3.

Table 4.3. Battery data at 30% depht of discharge (III)

Battery	Useful electricity, kW·h	Battery price, €	Battery useful cycles	1 kW·h storage cost, €	1 kW·h storage cost (with subsides), €
BTL 12-200 AGM	0.72	364	1100	0.450	0.1568
BTL 12-150 AGM	0.54	300	1100	0.506	0.2026
BTL 12-100 AGM	0.36	198	1100	0.501	0.1972

The storage cost for 1 kW·h of electrical energy without and with subsides differs 2.5 to 3 times.

In Estonia the fee for consumed electricity apportioned approximately as follows: 38% for consumed electricity, 49% for network service charge and 13% for renewable energy and electricity excise. In the 2019 it was 0.0793 €/kW·h. In Table 4.3 it can be seen that battery BTL 12-200 AMG at depth of discharge 30% is the most cost effective for storing the energy in this case. It points out that storing 1 kW·h energy cost 0.4599 € and with subsidy 100 €/kW·h it is 0.1568 €. But it is still about two times higher than the fee for network service and renewable energy together (III).

To untie the renewable energy producers from the utility grid it is necessary to bring the cost of the battery bank to the level where it is comparable to the network fee. In this case – 0.0793 €/kW·h. Using equation 16 the subsidy for 1 kW·h in battery can be calculated. M_{sub} is subsidy (€/kW·h), N_{fee} is the fee for network service and renewable energy (€/kW·h)

$$M_{Sub} = \frac{M_B - (N_{Fee}\eta_c W_u)}{P_W}. \tag{16}$$

Calculations with 2018 battery prices shows, that subsidy for battery BTL 12-200 AMG at depth of discharge 30% is 129.95 €/kW·h and for batteries BTL 12-150 AMG and BTL 12-100 AMG it is 145.04 and 143.26 €/kW·h. In Table 4.4 is shown the amount of needed batteries when depth of discharge is 30% and daily energy need is 10 kW·h (average European household) (World Energy Council, 2015) (III).

Table 4.4. Cost of battery bank and subsidy comparaison (III)

Battery	Useful electricity, kW·h	Battery price, €	Needed amount of Batteries	Cost of batteries, €	Subsides, €	Percentage of the subsidy, %
BTL 12-200 AGM	0.72	364	14	5099	4220	83
BTL 12-150 AGM	0.54	300	19	5706	4811	84
BTL 12-100 AGM	0.36	198	28	5546	4667	84

As shown in Table 4.4 the subsidies for batteries in 2019 covers more than 80% of the cost of the batteries. The maximum capacity, eligible for subsidization, for the RE parks is 15 kW but private households have lower capacity PV parks (Tutkun et al., 2015). For comparaison, a 3.3

kW PV panel park will be used. Calculations have been made and the results are presented in Table 4.5 (III).

Table 4.5. PV panel park capacity and output (III)

PV panel park capacity, kW	Period, h	Capacity factor, %	Annual output, kW·h	Average self-consumption, (25%), kWh/a	Sold to the grid (75%), kW·h/a	75 % Subsidization, €
3.3	8760	11	3179.9	795	2385	126.41

In Table 4.5 it is pointed out, that yearly subsidition for renewable energy is 126.41 € if the PV park is at capacity 3.3 kW and 75% of produced energy is sold to the utility grid. Battery lifetime is about 10 years, that means that yearly subsidition to the battery bank is about 422-481 €. This is roughly 3.3-3.8 times more than subsiditon to the PV panels produced energy sold to the grid (III).

Table 4.6 Cost of battery bank and subsidy comparaison 2021

Battery	Useful electricity, kW·h	Battery price, €	Needed amount of Batteries	Cost of batteries, €	Subsides, €	Percentage of the subsidy, %
BTL 12-200 AGM	0.72	303	14	4242	3362	79
BTL 12-150 AGM	0.54	196	19	3724	2829	76
BTL 12-100 AGM	0.36	145	28	4060	3180	78

The first survey was conducted two years ago, and battery prices have fallen by 16 to 35% since then as seen in Table 4.7.

Table 4.7 The cange of battery prices

Battery	Price 2019, €	Price 2021, €	Change, %
BTL 12-200 AGM	364	303	-16.8
BTL 12-150 AGM	300	196	-34.7
BTL 12-100 AGM	198	145	-26.8

Thus, the use of battery banks to store energy has also become more advantageous during this time. The more batteries are used, the faster the price of batteries will fall, and it is therefore sensible to apply state subsidies for the installation of battery banks.

4.4. Heat energy storage in furnaces

The additional load in the electrical system must be applied to maintain stability and balanced it. Additional load may consume a relatively large amounts of electricity in a short period of time. The system wich can be controlled by the control device is required, such as electrical heating elements in the heating furnace.

The proposed system enables additional balancing reserves for the electricity grid operator. Based on statistics roughly 172 thousand households are heated by solid fuel furnaces in Estonia (Statistical database of Statistics Estonia, 2021). Calculations show, that the heat storage capability of an average heating furnace in 24 h is 80 MJ. By multiplying these values, the heat capacity for all Estonian heating furnaces could be estimated to 13.79 TJ (IV).

An average heater element for an application to heat the heating furnaces could be in the range of 2 kW, the calculated total controllable load could be 345 MW. Compared to the maximum load (1560 MW) of the Estonian electricity grid which occurs during the coldest winter days, it is 22 %.

The control system for the modernization of the stove heating system is described in Figure 3.6. Using this technology in rural areas reduces air pollutions and gives back the purpose to the furnaces in historic houses (IV).

5. DISCUSSION AND FURTHER WORK

Nearly zero energy houses one component may be PV, WG or both, in order to achieve the statutory limit on the maximum external purchase of energy. In order to avoid electrical energy losses and increase self-consumption, the energy consumption system needs to be improved. However, any new technology, in general, is expensive. Same principle is for the renewable energy technologies. When setting energy efficiency targets under the Paris Climate Agreement, different RE technologies need to be introduced and, where possible and appropriate, combined with already existing ones.

The energy production of solar panels in Estonian climatic conditions is strongly related to the seasons. The energy production of solar panels in Estonian climatic conditions is strongly related to long-term changes: the change of seasons. Also well known middle-term changes such as day and night (Xie, Liao, Tai, & Hu, 2017). In Estonia, due to its location, the capacity factor for PV panels is only 11 %.

PV panels in the same location have a more stable output than WG (II). Same time the household consumption power has much higher stability in the building than the RE generators production outlet. This subject brings up the need of storage capacity and direct consumption in the household. Therefore, as a local energy generator, the wind turbine needs short-term storage capacitance to increase on site consumption. There are several ways to smooth out the RE output fluctuations (II).

One way to smooth out power fluctuations is to add a capacitor to the system. (Choi, Kim, & Seo, 2012) (I). Managing the demand with power electronics (Kordonis, Takahashi, Nishihara, & Hikihara, 2015), increase network transmission capacity (Esslinger & Witzmann, 2011), (Popavath & Palanisamy, 2015) or batteries (Sandhu & Mahesh, 2016), (Zurfi & Zhang, 2018) (II).

All of these methods can be used to smooth the rapid short-term fluctuations, but they all have their advantages and disadvantages. The use of household demand management system in residential building is not feasible for local peak energy production (Figure 2.5 to Figure 2.7), because the peaks in RE production are too short for this (Figure 4.4) (II).

Electricity storage devices are needed with the application of demand-side management, because energy consumers operate with a longer working cycle than the production fluctuations of RE production (II).

In Estonia it is common for RE producers to use the utility grid as a battery bank. But due to historical reasons, about 86% of the electricity produced is from non-renewable sources. Therefore, those electricity producers that use the utility grid, indirectly support the use of non-renewable resources.

To increase the use of onsite produced electrical energy, it is reasonable to add a battery bank to the system. This gives opportunity to use the RE when there is no production at the moment. Depend on weather conditions, on site produced energy usage may reach to 100 %.

Due to their relatively high price, battery banks have not found widespread use. In order to motivate RE producers to include a battery bank to the system, consideration should be given to introducing state subsidies for the installation of battery banks.

Proposed subsidy system covers about 75-80 % of the battery bank value. The proposed subsidy includes only batteries and not any other control devices or inverter (III).

The hypothesis is that an installation subsidy of 100 € per 1 kW·h of energy storage capacity of a battery bank makes the investment feasible for renewable energy producers and increases energy security. The calculations show, that 100 € per 1 kW·h was too low to reach that objective in 2019, but in 2021 it is reasonable ammount of subsidy (III).

The calculations show that in 2021 the batteries price has fallen and with proposed subsidize, the cost of 1 kW·h storage energy is about the same level than the grids fees and taxes combined.

The study show, that the depth of discharge is effective way to guarantee the useful lifetime of the battery. It turns out that the 30% DoD is the most effective for battery lifetime capacity (III).

Adding a ultracapacitor to the battery bank as a buffer, the energy storage capacity rises. Thus, the efficiency of the system also increases. Because the battery storage system no longer has to meet the maximum capacity of the production unit, the battery bank can be downsized (I).

As a buffer, the ultracapacitors smooth the power fluctuation during its transmission, making the input and output capacities of the batteries less volatile, which results in their life expectancy. Also, benefits from that kind of storage system result from savings in grid connection expenses (I).

The self-discharge rates of ultracapacitors and batteries are different, therefore their usage in energy storing systems are different. Batteries act as a long-term storage capacity and for short-term, there are the ultracapacitors (I).

In addition to the battery bank, it is also possible to store energy in the form of heat. It is possible and sensible to do this when the battery bank is fully charged and it is not expedient to sell the remaining energy to the grid or very cheap electricity is available in the grid. The storage of energy in the heat facilities could partially supplement the battery storage system which is needed in smaller energy systems (Zurfi, Albayati, & Zhang, 2017),(Dharavath & Raglend, 2019) (IV).

In heating period of 2018 a 49 occasion happened when the electricity price was below and including 0 €/kW·h in the DK1 price area. All those cases in the DK1 price area, when the price of electricity was less than 0 €/kW·h, happened to take place in the heating season. In those occasions, it is effective to heat dwellings with electricity (IV).

Considering that the solid fuels, the traditional energy sources for heat storing furnaces, also have their price list, it may be wise to calculate the breaking point of storing electricity as a heat energy. The breaking point, when the control logic should turn on the heating system, is higher than 0 **€**/kW·h and it depends of the local solid fuel price used in heating stove and the utility grid fees and taxes (IV).

Future work can emphasis of forecasting possible disruptive developments that could make local storage in buildings obsolete. Some energy storage options like hydrogen fuel cells were not in the scope of this thesis, but will be of interest in the future. Related to the possible use of hydrogen energy storage in buildings is the question of their safety. The safety of energy storage technologies in general is an important factor that deserves further research.

The effects of further price decreases of batteries will probably accelerate the implementation of electricity storage in buildings in the near future and will rise many new research questions.

CONCLUSIONS

It is commonly accepted, that renovating the building stock and constructing new energy efficient buildings are the most promising methods to achieve the climate change mitigation goals. The insulation of the buildings is a logical step to increase the energy efficiency. The second step is to apply renewable energy production units. The future step is to apply wide spread energy storage devices in buildings.

The study demonstrates diffrent storage possibilities for future applications in nearly zero energy buildings. Energy storage is needed to bridge the diferent timings of consumption and production. Ramp rates were used to demonstrate that the electricity consumption power in building-based energy systems is generally more stable than the production power of renewable energy generation devices that may be installed on the same buildings. It was also concluded that power production from PV power stations is more stable in comparison to a wind generation with similar nominal power that is installed in the same location. The consistency of energy flows is an important factor for local energy management and energy storage optimization.

Fluctuations in electricity generation from renewable sources are caused by changes in environmental conditions (weather). The statistical indicators for power output stability can vary day to day by a large extent. The standard deviation of power output is especially high in the analysed locations on the season of spring, when the weather conditions can change rapidly.

On the basis of measured data the following conclusions were made:

the study showed that it is beneficial in buildings to combine short and medium term storage devices similarly to the practice used in electric vehicles. Ultracapacitors mitigate short power pulses and support the operation of the medium term storage (the chemical battery). This improves the system’s total efficiency and life expectancy.

The high energy loss due to self-discharge over time is the main drawback of ultracapacitors. Therefore, the ultracapacitors are not suitable for medium term energy storage and can only support the operation of the battery. The study conclued that a ratio of 1 to 1440 is operationally best between the energy capacities of short and medium term storage in a building. The favouralbe ratio of installed powers between the devices is oppositely in favour of the short-term storage, 549 to 1.

The energy to be stored would be mostly originating from local solar energy generation or wind energy from wind parks that can be acuired occasionally under favourable conditions from the electricity grid.

By subsidizing electricity storage capacity installations with a rate of 100 €/kW·h, the energy stored by the battery banks would cost 2.5 to 3 times less in comparison to a situation where the batteries are installed without subsidy. Thus, it can be assumed that by subsidizing battery banks rather than subsidizing the sold electricity increases the establishment of battery banks. This will also increase the household's local self consumption and energy security. Although, calculations show that 100 € per 1 kW·h capacity may not be enough to untie electricity self consumption from the utility grid, it may have a positive effect.

To give to the renewable energy producers the same electricity storage cost as they are using the utility grid. This lead to the conclusion that subsidies should be approximately 125 to 130 €/kW·h of installed battery capacity at the current price levels. Thouse figures have decrease during the compilation of the researh this thesis, wich indicates a potential for implementation in buildings.

To avoid the potential misuse of subsidies and put it in long-term purpose, the batteries depth of discharge and useful charging cycles must be compared. The greater amount of energy that can be stored to the battery over it´s lifetime, the better the battery is.

The current research studied the option for retaining the heating purpose of historic stoves by using smart grid technology. For that purpose, a smart control system was modelled. In this model, real-life data must be used: indoor temperature, stove temperature, weather forecast and electricity price prognosis.

When applying the here proposed methods the specific conditions have to be considered, like the building's location, purpose, needs of the inhabitants and economic possibilities.

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SUMMARY

Standards for the construction of near-zero energy buildings have been introduced in the European Union, including Estonia. In order to achieve high energy efficiency, new buildings are increasingly equipped with on-site renewable energy production. This doctoral dissertation looks at the next potential big leap in the energy systems of buildings - the widespread use of energy storage devices. When using energy storage devices, the issues to be solved are the joint use and synchronized management of different production, consumption and storage systems. An important issue in managing energy storage is the further use of the stored energy for the user. Is the stored energy later used to heat a building or domestic water, or is electricity needed? When storing electricity in buildings, the question is, how long should this energy be stored? The average period of energy storage is an important input in the planning of a building-based system, because different technologies have different self-discharge rates. In addition to the technology used, production and consumption characteristics are important for the energy system with the recorder. Taking these criteria into account, the dissertation offers a ratio for dimensioning building-based energy systems using short-term energy storage devices (capacitors) and chemical energy accumulators. The work also offers a methodology for calculating the subsidy that facilitates the acceleration of the introduction of energy storage devices in buildings.

KOKKUVÕTE

Euroopa Liidus ja sealhulgas Eestis on juurutatud liginullenergiahoonete ehitamise standardid. Uued hooned on kõrge energiatõhususe saavutamiseks üha sagedamini varustatud kohapealse taastuvenergia tootmisega. Antud doktoritöö vaatleb hoonete energiasüsteemides järgmist potentsiaalset suurt arenguhüpet – energiasalvestite laialdast kasutust. Energiasalvestite kasutamisel on lahendamist vajavad küsimused erinevate tootmis-, tarbimis- ja salvestussüsteemide kooskasutamine ja sünkroniseeritud juhtimine. Energiasalvetite juhtimisel on oluliseks küsimuseks salvestatava energia edasine otstarve kasutaja jaoks. Kas salvestatavat energiat kasutatakse hiljem hoone või tarbevee kütmiseks või on vaja elektrienergiat? Elektrienergia salvestamisel hoonetes on omakorda küsimus kui pikaks ajaks seda energiat salvestada tuleb? Energia salvestis hoidmise keskmine periood on oluline sisend hoonepõhise süsteemi planeerimisel, sest erinevatel tehnoloogiatel on erinevad isetühjenemise määrad. Lisaks kasutatavale tehnoloogiale on salvestiga energiasüsteemi jaoks olulised tootmise ja tarbimise karakteristikud. Doktoritöös pakutakse neid kriteeriume arvestades suhtarve hoonepõhiste energiasüsteemide dimensioneerimiseks, milles kasutatakse lühiajalisi energiasalvestiteid (ülikondensaatoreid) ja keemilisi energiaakumulaatoreid. Töös pakutakse ka energiasalvestite hoonetes kasutuselevõtu kiirendamist soodustavat toetuse arvutamise metoodikat.

I

ORIGINAL PUBLICATIONS

Lill, Heiki; Allik, Alo; Jõgi, Erkki; Hovi, Mart; Hõimoja, Hardi; Annuk, Andres (2018). Capacitor and Battery Energy Storage System Sizing Ratio for Wind Microgenerators. IEEE Xplore, 940−945

Capacitor and Battery Energy Storage System Sizing Ratio for Wind Microgenerators

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Abstract – The power output of wind farms is directly dependent on the instantaneous wind speed. At variable weather conditions there will be an instantaneous excess of electrical power that cannot be stored by a conventional battery bank. In recent years, great progress has been made in the development of short term storage units like ultracapacitors, which are capable of absorbing high power pulses within seconds. Another advantage of ultracapacitors is a high number of charge cycles. This article focuses on a hybrid energy storage system consisting of ultracapacitors and a battery bank. Ultracapacitors are used to store temporarily the energy that the batteries are unable to absorb due to the power limit in the charging process caused by their electrochemical properties. Afterwards the energy stored in the capacitors is transferred to the batteries. The article is focused on the optimal battery-to-capacitor ratio. The hypothesis is a storage capacity ratio of 1:1500 in favour of batteries. Simulations on the basis of measured solar and wind production data are made for this purpose.

Keywords – ultracapacitors; energy storage; wind energy; AGM batteries

I. INTRODUCTION

The output power of wind farms is rapidly changing and is unpredictable even in a small amount of time. There is also problem with consumption - it is not schedule with the wind produced electrical power outcomes. In case of solar energy production there is day - night and winter - summer periodicity, but for wind power, there is no known typical short time periodic system. By the economical and energy security reasons it is important to consume energy from renewable energy sources near the producing unit. It is because the energy from utility grid is more expensive, even with subsidies, than the energy that is sold to the utility grid. So, it is expedient to consume locally produced energy on site without trading it from the utility grid. It is not possible to wholly synchronize the produced and consumed energy schedules therefore, to increase consumption on site it is necessary to improve energy accumulation system [1][2]. The electrical energy accumulation system may be AGM battery, ultracapacitor or heat recovery device, such as a hot water tank. The first two systems are the systems, where users can get electrical energy back and use it. In the third system there is no good input-output ratio transmission back to electricity possible so the heated water must be consumed or used in heating system locally [3] . These systems can be applied separately or in complementation of each other. The paper in hand gives results of research outcome, what might be the optimal ratio of battery and capacitor capacitance as a storage device of small-scale wind turbine. Such power generator can produce relatively large short-term electrical capacities that the battery bank is not capable to absorb. The ultracapacitor can absorb high capacities, but the capacitance is relatively small and self-discharge is high. The synergy of combined battery bank and ultracapacitor could lead to the increased local energy consumption in small households.

In battery-ultracapacitor hybrid electricity storage systems, the ultracapacitors act as low-pass filters, absorbing the rapid changes in power flows and releasing them later on demand [4]. The principle itself is founded on the different power densities of used storage media, i.e. how much power can be absorbed and released per mass or volume unit, expressed by the well-known Ragone plot [5] [6].

As for lead-acid battery stacks, the inability to absorb incoming power is characterised by excess voltage across its terminals. In such type of batteries, overvoltage brings along gassing and premature ageing. The optional interface converter between the battery and the ultracapacitor (UC) stack operates in the voltage control mode, trying to stabilise the battery terminal voltage.

This approach differs from the classical ones in the aspect that we use real world data with a high temporal resolution. We express the result as a ratio of long and short term storage capacities.

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II. MATERIALS AND METHODS

A. Comparison of Capacitor and Battery

A test was conducted to understand the difference of self-discharge of the capacitor and the battery. The test results are presented in Fig. 1. SkelCap SPA0350 350F; 2x2.85 V; 0.4 Wh capacitors in series and 2600 mAh, 3.6V Samsung ICR18650-26H single cell were used. In the beginning of the test, the battery and the capacitors were fully charged and then their voltages measured. Both were charged until they reached their final voltage of 3.517 V. In the beginning of the test, the capacitor voltage was higher than the cell's, but in time it changed. It turns out that after six hours of self-discharge, the battery cell voltage is higher than the capacitors'.

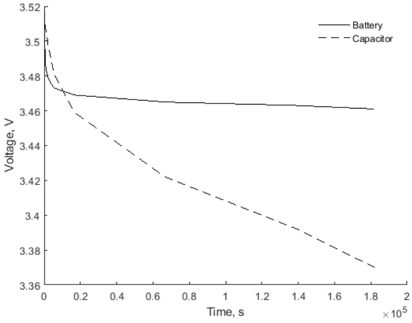

Fig. 1 Comparison of capacitor and battery self-discharge.

The test results show charging level change in the measured time. It is visible that the capacitor is not good for long-term electrical energy storage and the battery is much stable in holding the charge.

B. Connection possibilities of the ultracapacitor stack

DC power from the primary energy converter G1, e.g. a PV panel or a rectified wind generator output can be buffered in a hybrid electricity buffer in two major ways. The first option is to connect the UC stack C1 together with the interface converter TA2 onto the battery G2 terminals (Fig. 2). The control system detects passing the upper voltage limit and diverts the excess power into the UC stack. The major disadvantage of this solution is that the primary energy interface TA1 must pass through all incoming power.

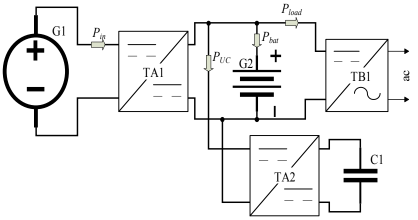

Fig. 2 UC stack and its interface converter connected in parallel onto the battery terminals.

The second option encompasses the ultracapacitor system C1+TA2 connected in parallel with the primary energy interface UC stack C1 and its interface converter TA2. Because of the presence of the interface converter, such configuration is sometimes referred to as "active parallel". Such similar solution is used for storing heat energy Fig. 3.

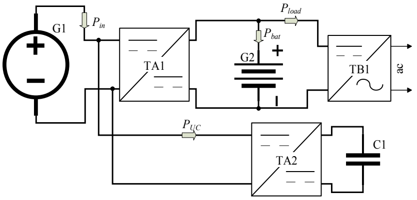

Fig. 3 UC stack connected actively in parallel onto the primary converter terminals.

With short-circuit proof primary energy converters, as in the case of PV panels, the UC stack can be tied directly into its output terminals, creating a passive parallel connection (Fig. 4). A disadvantage of such solution is that the UC stack maximal voltage must coincide with the primary energy converter's maximum output. In the other hand, without an interface converter the response time is shorter [7].

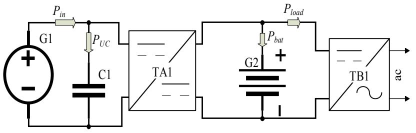

Fig. 4 UC stack connected passively in parallel onto the battery terminals.

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C. UC stack design general guidelines

While designing an UC stack for fast energy storage, both power and energy requirements must be taken into consideration.

Instantaneous power of the UC stack is calculated with the equation:

$$P_{UC}(t)=P_{in}(t)-[P_{bat}(t)-P_{load}(t)], \tag{1}$$

where positive values represent charging and the negative ones discharging. P_{in} stands for incoming power from the primary energy converter and P_{bat} power absorbed by the battery.

Energy accumulated inside the UC at time t

$$W_{UC}(t)=\int_{t=0}^{t=t_{max}} P_{UC}(t)\,dt \tag{2}$$

Necessary energy capacity of the UC stack

$$W_{UC}=\max_{0\ldots t_{max}} W_{UC}(t)-\min_{0\ldots t_{max}} W_{UC}(t) \tag{3}$$

Design power of the UC stack and interface converter assembly

$$P_{UC}=\max_{0\ldots t_{max}} P_{UC}(t), \tag{4}$$

Design capacitance of the UC stack

$$C_{UC}=\frac{2W_{UC}}{\eta_{UC}(U_{max}^2-U_{min}^2)}, \tag{5}$$

where U_{max} and U_{min} are the maximum and minimum allowable voltages across the UC stack terminals, respectively and η_{uc} the sum efficiency of the UC stack and converter assembly. In practice, $\eta_{uc} \approx 0.9$.

Number of cells in series is rounded up to next integer

$$n_s=\left[\frac{U_{max}}{U_{cell}}\right], \tag{6}$$

where U_{cell} is the rated voltage of the selected single UC cell.

Number of parallel ultracapacitor strings is rounded up to next integer

$$n_p=\left[C_{UC}\frac{n_s}{C_{cell}}\right], \tag{7}$$

where C_{cell} is the capacitance of the selected single UC cell.

TABLE I. COMPONENTS USED IN THE EXPERIMENT.

Device	Specification
Wind generator	3.5 kW Wind Spot
Ultracapacitor module	Maxwell BMOD0165, 165F, 48V, 97kW [8]
Battery energy storage	Victron Energy BAT412201080 , 176.4W/bat, 220 Ah, grouped into two 48 V arrays [9]

The energy management logic of the system is described in Fig. 5.

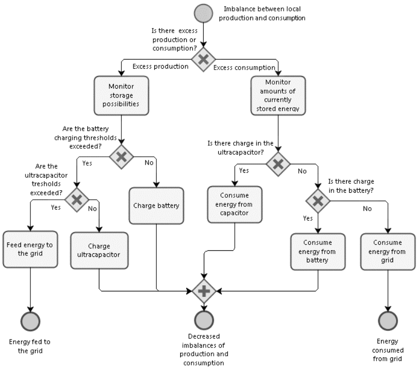

Fig. 5 Energy management of the system.

Fig. 5 illustrates that the battery has priority as a long term storage and the ultracapacitor as a high-power storage. The same logic was used in the Simulink model (Fig. 6).

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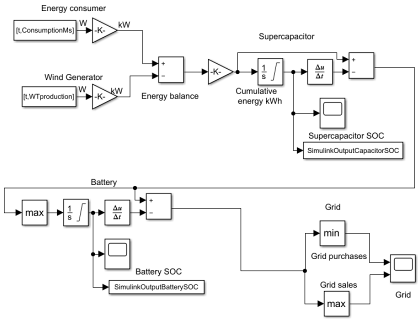

Fig. 6 Simulink model of the analysed system.

The signal in the Simulink model (Fig. 6) describes the imbalance of production and consumption in the system, therefore it can have both, negative and positive values.

D. Data

WG output is in direct relation to wind speed. Wind speed stability or gusts are directly caused by physical mechanisms [10]. Therefore the boundaries for the speed of alternations in WG output are final. There is also a tendency that gusts increase with higher average wind speeds [10]. Sample data from a 3.5 kW wind turbine was used for the present analysis (Fig. 7). Wind is less stable and predictable than solar energy. Mostly wind speeds have no daily periodic component and changes in wind speed are hardly predictable. While comparing two sources of energy: wind and solar, then for residential consumers wind has more influence on self-consumption [10] [11].

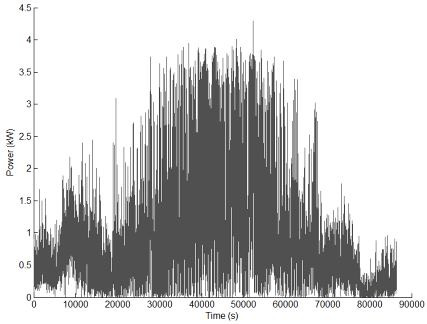

Fig. 7. Output data of the analyzed wind turbine during 24 h.

The speed of changes (or ramp rate) is crucial for the mitigation of short term fluctuations. Autocorrelation functions were used to analyze the speed of wind speed changes (Fig. 8).

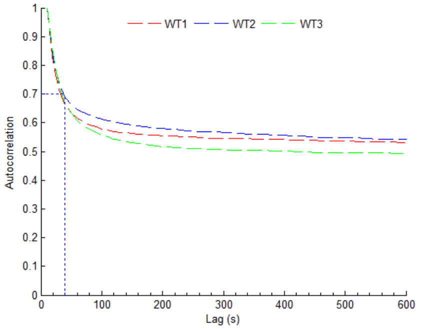

Fig. 8 Autocorrelation functions of three different wind turbine output time series as functions of time lags [12].

If the wind generator has an average power output of 1 kW during the period when it is operational and the short term storage should store energy pulses during 60 s, then a 0.0167 kWh storage capacity is needed. At voltage of 48 V this capacity translates to 52 F. A 165 F and 48 V capacitor presented in the example case in Table I has an energy storage capacity of 0.0528 kWh.

The battery storage should ideally last for 24 hours [13], which translates to a capacity of 24 kWh. In this theoretical case the ratio between short and medium term storage would be 1:1440 (24/0.0167=1440).

III. RESULTS

A sample day was chosen with excess energy production in comparison to production and therefore a situation was simulated where the battery storage reached its capacity threshold at the end of the day. During storing/utilizing cycle as excess energy is present, the ultracapacitor reaches its saturation point with relatively short time (Fig. 9) but loses its charge rapidly as energy flow from source ceases and balance turns negative. Starting at 3500 s of day due solar energy presence, the ultracapacitor achieves and maintains the fully charged state.

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As the batteries take time to charge due chemical processes, the low yield input does not give signific effect to the charge level of battery bank.

The short term storage performance is presented in Fig. 9.

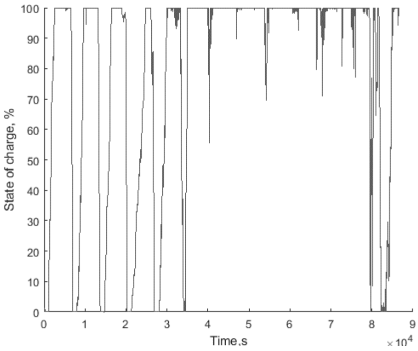

Fig. *9* State of charge of the ultracapacitor during the sample day.

The ultracapacitor reaches its saturation point and also complete emptiness on multiple occasions during the day (Fig. 10).

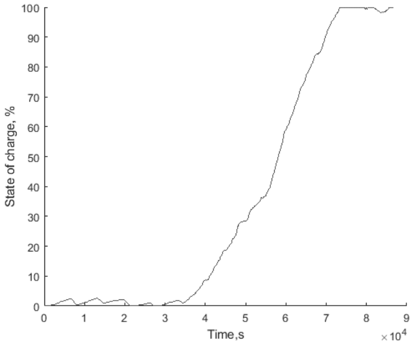

Fig. 10 State of charge of the battery bank during the example day.

The mitigated output fluctuations with added short and medium term storage are shown in Fig. 11. The ultracapacitor and battery storages were dimensioned according to the ratio found above. Fig. 11 shows the energy flows that pass through the storage, are consumed and supplied to the grid, during a day.

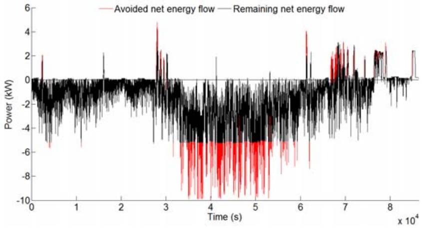

Fig. 11 Output data of an analyzed wind turbine system before and after adding energy storage [13].

IV. DISCUSSION

The storage devices are needed because of energy demand and production discrepancies. These discrepancies occur periodically and are well predictable because of naturally occurring cycles. There are short term (within minutes), middle (within a day) and long term (seasonal) cycles [14]. It is assumed that a stable power output is most desirable [14].

The efficiency of the proposed system is higher and the necessary battery capacity is lower, because of the lower charge and discharge currents. Therefore the battery can be downsized.

The economic benefits that may result from such a storage system include savings in grid connection power and grid energy exchange. Moreover, the ultracapacitors act as smoothing elements during power delivery, making the batteries' output less fluctuating, which helps to increase their life expectancy.

The self-discharging rates of ultracapacitors and batteries are different due to their storage principles and internal structures (electrostatic vs electrochemical). As follows, the batteries are best suited for long term storage and ultracapacitors for short-term power exchange.

This is related to the need of automatic charging systems to check battery charge to prevent it from over-charging. This could be clarified with further studies of computer models and field experiments.

V. CONCLUSIONS

On the basis of real world data the following conclusions were made:

In the designed hybrid storage systems, ultracapacitors can effectively smooth the power absorbed and delivered by the main storage battery, thus making its state of charge (SoC) changes slower, which results in increased life expectancy and full trip cycle efficiency.

The high self-discharge rate of the ultracapacitor is the main reason not to use it as a long term storage, it acts as an additional buffer to the AGM battery.

It was found that the ratio of storage capacities is 1:1440 in favour of the battery storage. The power ratios of the storage devices is 549:1 in favour of the ultracapacitors.

ACKNOWLEDGMENT

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II

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A.Allik et al., Vol.9, No.2, June, 2019

Ramp Rates of Building-Integrated Renewable Energy Systems

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Abstract- This article analyses the ramp rates of household electricity consumption and the power production of building-integrated PV panels and wind generators. These aspects are important for the optimization of energy storage and demand-side management in buildings with prosumer status. The output power data from PV panels and a wind generator from the same building were used. It was found that the yearly standard deviation of solar energy output is greater than the standard deviation of output from the analyzed wind generator but the ramp rates are higher for the wind turbine. Ramp rates of the solar energy power plant have a slower rising slope comparatively to the same parameter from the wind generator. This shows higher temporal stability in PV output, which was also validated with autocorrelation functions.

Keywords- Electricity consumption, wind generator, photovoltaic array, output fluctuations, ramp rates.

NOMENCLATURE

l	Time lag between values
P_n	nominal power
r(l)	autocorrelation function
x_i	values in a time series
$\bar{x}$	mean of the time series
CDF	cumulative distribution function
PV	photovoltaic
WG	wind generator

1. Introduction

The stochastic nature of large wind generators (WG) and photovoltaic (PV) power plants is evident from earlier research [1], [2] and changes in output power of building-integrated PV and wind generators are described in [3]–[5]. The stochasticity of WG output is caused by sudden wind gusts and turbulence [6], [7] on the other hand fast changes of out from PV panels are caused mainly by the movement of clouds [8], [9]. This can affect the voltage stability in the distribution grid [10]. One proposed solution to mitigate this problem is the geographic dispersion of generation units [11], another one is storage [12][13].

The stochasticity of those energy sources has been compared on the scale of European countries [11], but even if we assume that the large scale fluctuations could be mitigated by robust interconnections between countries, then the local issues like voltage quality and economic factors related to renewable energy self-consumption remain [14]–[17]. These topics are especially topical because of regulations that incentivize the installation of renewable energy generation devices on all new buildings [18].

Hourly average values are often used for the modelling of small renewable energy systems, which gives the impression that the energy generation and production during an hour are constant, but renewable energy sources have significant intra-hourly fluctuations [19]. The use of hourly average data series may result in models that appear more stable than the reality that they describe [20]. The hourly time resolution is somewhat acceptable in describing processes that occur in the transmission grid, because of the large number of interactors that use the transmission and distribution grids, but a higher time resolution could be beneficial even there [21]. Energy is currently commercially measured as hourly averages (“Nordpool spot Electricity price,”). In the same time, it is foreseeable that data acquisition with higher resolution will be necessary to facilitate the needs of distributed energy generation and use the full potential of remote metering possibilities. The application of real-time tariffs in the future is also a possibility [22]. The novelty of this paper lies in the application of analysis methods on building based energy systems which are until now only used on grid-scale facilities, like wind parks.

The aim of this study is to demonstrate the rate of changes in both, the consumption and production output in building integrated energy systems. The results can be used to optimize energy management and storage possibilities for different building-integrated WG and PV applications.

2. Materials and Methods

2.1. Data

WG and PV output variability is in strong relation to local weather conditions. The study compares the technologies in a case study where both are in the same location in a city. Differences in wind resources are more influenced by surrounding obstacles, and solar irradiation conditions are more dependent on the atmospheric conditions (cloudiness). The measurements were conducted in an urban environment at (58°23'19'' N, 26°41'37'' E), PV panels were faced directly to South at a 40-degree tilt and the hub height of the WG was 25 m. The technical specifications of the used devices and measurement system are shown in Table 1.

Table 1. System specifications

Device	**Specification**
Wind generator (WG)	WindSpot 3.5, Horizontal axis, 3.5 kW, permanent magnet generator, passive yaw control [23]
WG inverter	SMA Windy Boy 3600TL [24]
Photovoltaic (PV) panels(10 panels)	Yingli solar 245 W [25]
PV inverter	Solivia 2.5 EU G3 [24]
Measurement system	Janitza UMG 605 [26], Circutor P2 TC5 M70312 [27]

The power output data was logged with 250 ms integration periods and a sample of the PV inverter output during an example day is shown in the next figure (Fig. 1).

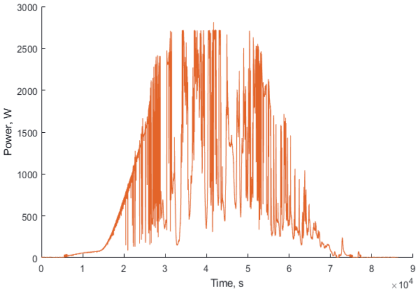

Fig. 1. PV-array output on a sample day (June 18-th 2014, 250 ms integration period).

The PV output changes shown in Fig. 1 are caused by cloud movements whereby WG output changes (Fig. 2) are caused by changes in wind direction and speed [28].

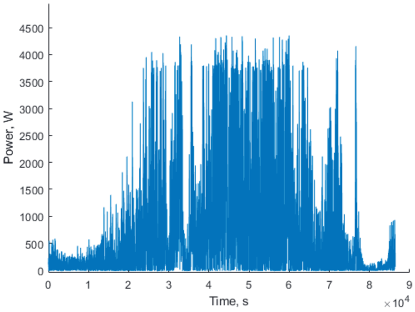

Fig. 2. WG output on a sample day (June 18-th 2014, 250 ms data).

The WG output changes are very frequent and fast during the day, and for the comparison of the energy sources, a characteristic 60-minute fragment of WG and PV data is presented in Fig. 3.

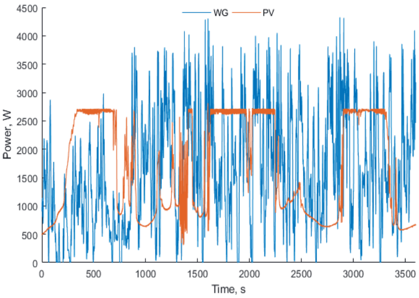

Fig. 3. Sample WG and PV data with 250 ms integration period.

Fig. 3 shows an output power section during the midday when both energy sources reach their nominal power. It supports the hypothesis that PV output is more stable than WG output. The opposite side of the analysed small energy system, the consumption pattern, is presented in the next figure (Fig. 4).

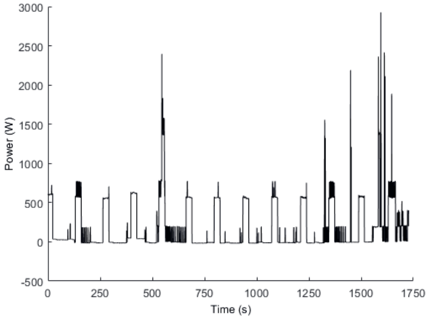

Fig. 4. Sample consumption pattern.

Additionally, for the long-term analysis of the energy producers, 5-second integration periods were used. This integration period was chosen because the yearly data amount remained in manageable confines and still offered the necessary information about variability.

2.2. Methods

The data was normalized for better comparability, by dividing the data series by the nominal power of the devices. For the generation devices, only the values greater than zero were used in the analysis, because extended periods of no output would give the impression of higher output stability. For example, the night-times of the PV and the wind-lulls of the WG were eliminated. On the other hand, consumption power is almost never zero because of base loads like internet routers or surveillance systems. Standard deviation figures were used to analyse the amplitude of changes in the data series [29], ramp rates enable the analysis of rapid short term changes in the time series and autocorrelation functions enabled the analysis of the temporal continuity of the time series.

A ramp rate is defined in the context of the current article as the speed of change in consumption or production capacity up or down during a given time period [30]. If the power decreases then the process is defined as ramping down and in the opposite situation it is ramping up.

Further, we used autocorrelation functions to analyse the pace of changes by comparing the correlation of the time series with themselves under different time lags [31]. Autocorrelation functions have been used in renewable energy-related research to show the changes in daily and yearly wind speeds and temperatures [32], [33]. The Pearson's product-moment based autocorrelation function r(l) dependent on time lag (l) was calculated with the following equation [34], [35]:

$$r(l) = \frac{\sum_{(i=1)}^{(N-l)} (x_i - \bar{x})/(x_{i+1} - \bar{x})}{\sum_{(i=1)}^{N} (x_i - \bar{x})^2} \qquad (1)$$

where, l is the lag, which is the time distance between pairs of values in the analysed time series, xi are the values and x̄ is the mean of the time series. The interpretation of correlation coefficients is described in [36].

3. Results

Standard deviations of the output power of the analyzed energy generation devices are presented in (Table 2).

Table 2. Output characteristics of the analysed energy generation devices

	Technology	
Statistical parameters	**Photovoltaic**	**Wind generator**
Mean power when in operation (% of P_n)	32.58 %	13.20 %
Standard deviation (% of P_n)	31.07 %	13.56 %
Maximum daily standard deviation (% of P_n)	63.05 %	23.18 %

Ramp rates of the output power were found for further analysis. Fig. 5 presents the solar energy production with normalised ramp rates.

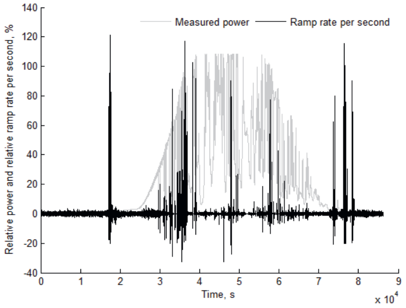

Fig. 5. PV output power in relation to nominal power and ramp rate in relation to previous time step during a sample day.

A cumulative distribution function (CDF) was created for further analysis of the ramp rates presented above (Fig. 5), which is given in the next figure (Fig. 6).

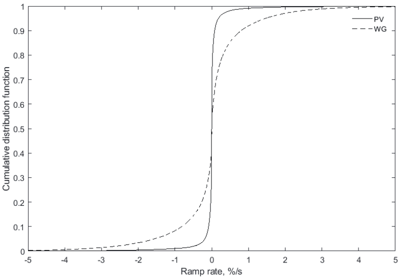

Fig. 6. Cumulative distribution function of PV and WG output rates of changes.

The CDF shows visually, that negative and positive ramp rates have a similar distribution shape, although turned upside down (Fig. 6), which means that the power outputs of the analysed energy sources increase at a similar pace as they decrease. The CDF-s presented in Fig. 6 also confirm that the WG has more frequent and higher ramp rates than the PV. For example, 10 % of the WG's ramp-up and ramp-down occurrences are greater than 1 %·s-1, while 10 % of the most extreme PV ramp up and down rates are greater than 0.1 %·s-1. Consumption power is much more stable, as can be seen from the CDF of the consumption ramp rates presented in the next figure (Fig. 7).

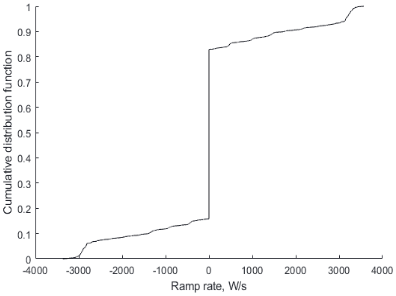

Fig. 7. Cumulative distribution function of changes in consumption power.

Fig. 7 shows that in 15.8 % of the time steps the consumption power is decreasing and 17.06% of the time power is increasing, which means 67.14% of the time (on a timescale of seconds) the consumption is stable, or the changes are imperceptible. The periods with stable output power are characterized in Fig. 7 by the horizontal line in the centre. By comparing Fig. 6 and Fig. 7 it can be concluded that the energy consumption has by far more time steps with stable power in comparison to energy production.

The autocorrelation analysis of the production output further shows that there are faster fluctuations of WG output in comparison to the PV output (Fig. 8). Autocorrelation plots of WG power during longer periods show that their autocorrelations have a 24-hour cycle [37].

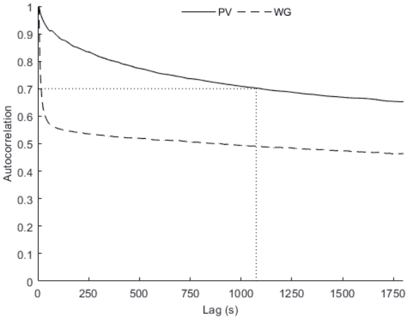

Fig. 8. Autocorrelation functions of PV and WG output data with 5-second integration periods [38].

Fig. 8 shows that the maximum autocorrelation lag, during which the PV output has a strong autocorrelation (≥ 0.7), is 1040 s. As a comparison for WG output, the maximum lag with the same autocorrelation threshold (≥ 0.7) is 40 s. The decrease in the strength of the autocorrelation for WG is faster than for the PV. On the basis of Fig. 8 and Fig. 9 can be concluded that building integrated PV installations have in this case higher stability of output than building integrated WGs. The periods of fast changes in the WG output are probably caused by wind turbulence in the surroundings. PV panels are not as much affected by the local microclimate. Fig. 8 shows that the fastest decrease of the autocorrelation values occurs on time lags up to 1000 s, which is most likely caused by wind speed and direction changes that affect the WG output short term. 250 ms data from a sample day (Fig. 9) shows a similar situation the autocorrelation function as 5 s data from a whole year (Fig. 8).

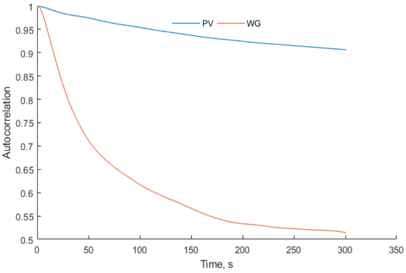

Fig. 9. Autocorrelation functions of a PV array and WG output data with 250 ms integration period [38].

By comparing the standard deviations of the normalized PV and WG outputs in Table III it is also evident that the standard deviation of PV output is higher. The analysis of daily averages shows that deviations between days are highest in the month of March. The highest intraday standard deviation of output occurs from the PV panels on days with active cloud movement but on average the PV output is more stable than the output from the wind generator. The WG output is in direct relation to wind speed, and in the case of the analysed building-integrated WG the rotor inertia had no significant effect on the output stability. The output stability of building-integrated WG is strongly correlated to the wind conditions in the area [38].

4. Discussion

The above-stated hypothesis was confirmed to be true that PV panels have higher output stability than wind generators in the same geographical location. Furthermore, the consumption power of the building has a much higher stability than the production power of the energy generation on the building. This issue is especially important in regard to the direct consumption and storage of locally produced renewable electricity.

There are several possibilities to cope with output fluctuations like shown in Fig.1 and Fig. 2. These are capacitors [39], demand management with power electronics [40], increase transmission capability of distribution grid [41], [42] or batteries [43], [44].

Each of these methods has advantages and disadvantages for the mitigation of short-term fluctuations. The use of demand management of electronic applications or white goods in residential buildings (Table 3) is not feasible for the utilization of local peak power production (Fig. 1 to Fig. 3), because the output peaks of small renewable energy systems are generally too short in duration for this (Fig. 8).

Table 3. Work cycle durations of household appliances [45]

Appliance	Cycle duration (min)
Refrigerator	30
Heat pump	15
Dish washer	60
Washing mashine	120

Storage devices in cooperation with demand-side management are needed to overcome the problem that appliances have longer working cycles (Table 3) than the fluctuations of energy generation devices.

5. Conclusion

The study shows with the application of ramp rates that the electricity consumption power in building based energy systems is generally more stable than the production power of renewable energy generation devices that may be installed on the same buildings. It was also concluded that the output power of small PV panels had higher stability than the output power of a wind generator with comparable capacity in the same location. The stability of energy flows is an important factor for local energy management or energy storage optimization.

The maximum autocorrelation lag with a strong correlation coefficient (≥ 0.7) is for the PV system 1050 s and for the WG 40 s. The fastest changes can be observed in the output power of the WG and the normalized annual standard deviation is also higher for the WG.

The fluctuations are dependent of weather conditions and the daily standard deviations can vary profoundly for both of the compared technologies, the WG and PV. Especially in springtime, on days with active cloud movement and gusty winds. The findings from the article can be used for the optimization of data acquisition, short-term energy storage and demand management.

Acknowledgements

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III

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Case Study for Battery Bank Subsidization

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***Abstract*— The purpose of this study is to investigate how government subsidies for purchasing battery banks would affect the production of renewable energy. The Republic of Estonia, like many other countries supports investments into solar panels and the selling of renewable energy. At the same time, the cost of solar panels has been falling, and this in turn raises the question if it's reasonable to support solar panel installations? In the same time, it is extremely important that the energy supply is continuous and uniform from the grid operator's point of view. Selling electricity produced by solar panels or wind generators without an intermediate storage device is extremely chaotic and does not provide the consumer with the necessary uninterrupted energy flow. Due to the high cost of battery banks, small energy producers also find it economically difficult to install battery banks in order to ensure uninterrupted energy supply. The article focuses on finding the optimal subsidy system for support to installing a battery bank for a prosumer. The hypothesis is that an installation subsidy of 100 € per 1 kWh of energy storage capacity of a battery bank makes the investment feasible for renewable energy producers and, in this context, also increases energy security.**

Keywords*— *battery storage, subsidies, renewable energy, energy storage system (ESS), solar energy

I. INTRODUCTION

There are three types of productivity cycles for photovoltaic (PV) power plants: first short time disturbances caused by cloudy weather or shadows on the panels, a daily cycle, and then there is the annual cycle when production is dictated by the sunlight duration and intensity of the seasons. Also, the angle of the PV panel affects the productivity of electricity [1]. In Estonia, the time with minimal daylight is approximately three months long in wintertime when there is only insignificant output from PV power stations. For wind generators, productivity cycles are harder to predict - weather forecasts can foresee windy weather, but wind outbreaks are impossible to predict for 24 hours of time. In order to cover the need for electricity for a nearly zero energy building, when there is no wind and sunlight, it is possible to connect it to the utility grid, install an internal combustion engine with electrical generator, or install a battery bank to the system. As of 2019 the Estonian national electricity company produces nearly 86% electricity from oil shale, a non-renewable resource. Generally, most auxiliary generators also use fossil diesel or gasoline. This shows that the share of fossil fuels in the electricity production is high and that the uptake of renewables is still to come. When the independence of a private house from fossil fuels is targeted, it is not expedient to buy electricity from the grid or use a generator to generate electricity. To ensure the supply security of electricity in a system that produces energy with PV power stations or wind generators, it is reasonable to install some sort of energy storage system like boiler[2], a battery bank [3]–[5], boiler combined with battery bank[6], real time tariffs applications[7] or some other system to increase self-consumption[8]–[12] in the system.

Since 2007, the sale of electricity from the renewable sources to the grid has been subsided in Estonia. This includes the sale of electricity produced from efficient biofuel-based cogeneration to the grid. As of 2019 the subsidy for renewable energy is 5.3 s/kWh and subsides for efficient cogeneration are 3.2 s/kWh [13]. The subsidy is guaranteed for twelve years from the start of production under the current scheme. Thus, support is geared towards production and sales and not for self-consumption. Therefore, small producers have not invested in adding storage capacity in installation of solar and wind farms. Therefore, small-scale manufacturers use the utility grid as a battery bank and in a situation when there insufficient production of electricity, they buy electricity from the grid.

Previous similar studies on the feasibility of storage in cooperation with residential photovoltaic power plants have found that battery storage is still not a profitable solution under market conditions [14]. Therefore, the aim of this study is to determine the theoretically necessary additional subsidies to make electricity storage for residential applications a profitable solution.

II. MATERIALS AND METHODS

A. Prices and existing subsidies

Subsides for installing a battery bank to the system should be aimed for the most efficient and long-term storage of electricity. Selecting only one parameter of the battery bank for assigning the subsidy may lead to a situation where the subsidy is used inefficiently. This is because the battery bank may only have selected aimed for the maximum subsides possible and not for a long-term effective energy storage device. At the same time, a large financial investment does not always guarantee the longevity and suitability of the acquired device.

A battery or a battery bank can be characterized by several different values. This can be the nominal voltage, predicted lifetime, battery weight, charging voltage, number of charge cycles, depth of discharge, recommended temperature or electrical capacity.

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In order to identify the most effective method for determining the battery bank subsidy system, it is important to compare the different parameters of the battery banks and find the most suitable formula.

The proposed subsidation scheme is compared in this context to the presently paid feed-in tariffs for renewable energy. In Estonia, renewable energy producers with a nominal capacity of up to 15 kW are eligible for subsidization.

Photovoltaic (PV) powerplants in Estonian climate conditions have approximately a capacity factor of 11% [2]. Therefore a 15 kW_p plant produces 14.45 MWh/a (on average 39.6 kWh per day). The average self-consumption share of PV electricty in residential applications is 25 %, which means 75 % of the energy will be sold to the grid [15]. Derived from the inputs the currently paid subsidy is calculated by using equation (1). Where S_a is the calculated annual subsidy for the powerplant (€/a), W_a is the calculated annual electricity production (MWh/a), η_1 represents the energy sold to the grid (%) and M_a is the feed-in tariff (€/MWh).

$$S_a = W_a \cdot \eta_1 \cdot M_a \tag{1}$$

S_a=16.5·0.75·53=655.88 €/a.

The levelized cost for 1 kWh of electricty storage capacity per year is for residential applications between 569 $ to 594 $ (503 € to 525 €) [16].

According to the Statistics Estonia, the average household electricity demand in 2016 was 1913 kWh/a [17] and European average is about 10 kWh/d.[18] Based on this information, there can be an assumption, that in 24 hours period a medium size household in Estonia uses 5.24 kWh of electrical energy. When all the electrical energy used in a household is from renewables, then it is possible to calculate the capacity of the required battery bank for the average household. It is assumed that the battery bank should supply the household with electricity for 24 hours.

There are many conditions that must be met to extend the lifetime of the battery bank. For example: temperature of battery environment, temperature of the battery, charging/discharging time, charging/discharging voltage and current, the depth of discharge. To design a battery bank, the depth of discharge determines the capacity of a battery bank. As illustrated in Fig. 1, a lower usage percentage of a battery ensures a longer lifetime of it. Therefor to ensure required electrical power supply for 24 hours and to guarantee a battery long lifetime it is necessary to overdose the battery capacity. To calculate needed battery bank capacity for output of 5.24 kWh and depth of discharge 30% the equation (2) and equation (3) must be used. Where C_A is battery output capacity (Ah), C_W is battery capacity in kWh, capacityV_bV_{b12} is battery voltage (V), C_Σ is total battery output capacity (Ah), DoD is depth of discharge (%).

$$C_A = \frac{1000 \cdot C_W}{V_b} \tag{2}$$

$$C_A = \frac{1000 \cdot 5.24}{12} = 436.7 \text{ Ah}$$

$$C_\Sigma = \frac{C_A \cdot 100}{DoD} \tag{3}$$

$$C_\Sigma = \frac{436.7 \cdot 100}{30} = 1456 \text{ Ah}$$

The calculation show that the battery bank should be at least 1456 Ah when the depth of discharge is 30%.

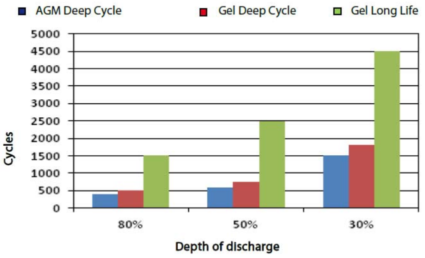

Fig. 1 Depth of discharge of AGM batterys [19]

As shown in Fig. 1, the depth of discharge affects the battery usable charging cycles. If discharged only 30% of capacity, the charging cycles goes up to three times compared to 80% of discharge.

B. *Technical aspects*

The demand for electricity is mostly higher in the morning and evenings in the households. It is related to the people's daily proceedings: after wake up and after business day till bedtime they usually use more electricity. The rest of the time is a fairly constant demand for electricity. Therefore, battery banks consists of several batteries and there may be situations according to the length of daylight and demand for electricity, when some batteries in the battery bank are not used for power consumption for several days. For example a summertime: in the daytime, electricity consumption may be directly covered by solar energy and the other elements of the battery bank in the morning, in the evening and at night.

III. RESULTS

The actual sales prices of batteries have been used in this work [20] and the data sheets of these batteries [21]. The system's own needs and natural losses have not been taken into account. The results obtained are included in the tables 1, 2 and 3. Battery BTL 12-200 AMG capacity is 200 Ah and size is 2.4 kWh. Battery BTL 12-150 AMG capacity is 150 Ah and size is 1.8 kWh, and battery BTL 12-100 AMG capacity is 100 Ah with size of 1.2 kWh.

To calculate useful power for one charging cycles (W_U, kWh) of battery according to depth of discharge, equation (4) is used. Battery capacitance is P_W.

$$W_U = P_W \cdot DoD \tag{4}$$

$$W_{U30} = 2.4 \cdot 0.3 = 0.72\ kWh$$

To calculate the cost of 1 kWh, the battery useful charging cycles must be taken into account and the cost of the battery. The cost of 1 kWh is calculated using equation (5). Where M_K is the cost of 1 kWh storage (€/kWh), M_B is the cost of battery (€), W_U is useful power of the battery (kWh) and η_c is battery useful cycles.

$$M_K = \frac{M_B}{W_U \cdot \eta_c} \tag{5}$$

$$M_{K30} = \frac{364{,}22}{0.72 \cdot 1100} = 0.4599\ \text{€/kWh}$$

The hypothesis of this paper is that an installation subsidy of 100 € per 1 kWh of energy storage capacity of a battery bank makes the investment feasible for renewable energy producers. The BTL 12-200 battery is capacity of 2.4 kWh. So, the subsidies for this battery should be 240 €. This means that the storage cost of 1 kWh power is also lesser and is calculated by the equation (6). Where M_{KS} is the cost of 1 kWh storage with subside (€/kWh), B_S is the value of the subside (€)

$$M_{KS} = \frac{M_B - B_S}{W_U \cdot \eta_c} \tag{6}$$

$$M_{KS30} = \frac{364{,}22 - 240}{0.72 \cdot 1100} = 0.1568\ \text{€/kWh}$$

Calculations for the three different battery series and their different conditions of depths of discharges were made and the results are shown in Tables 1, 2 and 3.

TABLE I *Battery data at 30% depht of discharge .*

Battery	Useful electricity, kWh	Battery price, €	Battery useful cycles	1 kWh storage cost, €	1 kWh storage cost (with subsides), €
BTL 12-200 AGM	0.72	364	1100	0.450	0.1568
BTL 12-150 AGM	0.54	300	1100	0.506	0.2026
BTL 12-100 AGM	0.36	198	1100	0.501	0.1972

TABLE II *Battery data at 50% depht of discharge.*

Battery	Useful electricity, kWh	Battery price, €	Battery useful cycles	1 kWh storage cost, €	1 kWh storage cost (with subsides), €
BTL 12-200 AGM	1.2	364	550	0.552	0.1882
BTL 12-150 AGM	0.9	300	550	0.607	0.2431
BTL 12-100 AGM	0.6	198	550	0.601	0.2366

TABLE III *Battery data at 100% depht of discharge.*

Battery	Useful electricity, kWh	Battery price, €	Battery useful cycles	1 kWh storage cost, €	1 kWh storage cost (with subsides), €
BTL 12-200 AGM	2.4	364	290	0.523	0.1785
BTL 12-150 AGM	1.8	300	290	0.575	0.2305
BTL 12-100 AGM	1.2	198	290	0.569	0.2244

As seen in the table I, II and III, the storage cost for 1 kWh of electrical energy without and with subsides differs 2.5 to 3 times.

The average electrified household consumes 3600 kWh per year [22].

In the Estonian electricity system, the fee for consumed electricity from the utility grid consists of several components: consumed electricity – the electricity cost rate depends on the contract; network service fee – depends on the network service provider; renewable energy fee and electricity excise. The fee for consumed electricity apportioned approximately as follows: 38% for consumed electricity, 49% for network service charge and 13% for renewable energy and electricity excise. It shows that more than a half of the cost for electricity is not for electricity itself but for supportive purpose. In the 2017 the fee for network service and renewable energy together was 8.12 s for consumed 1 kWh and in the 2018 it was 7.93 s/kWh. In 2019 the fee remains at same level as in 2018.In Tables I, II and III can be seen that battery BTL 12-200 AMG at depth of discharge 30% is the most cost effective for storing the energy in this case. It point out that storing 1 kWh energy cost 0.4599 € and with subsidy 100 €/kWh it is 0.1568 €. But it is still about two times higher than the fee for network service and renewable energy together.

To untie the renewable energy producers from the utility grid it is necessary to bring the cost of the battery bank to the level where it is comparable to the network fee. In this case – 0.0793 €/kWh. Using equation 7 the subsidy for 1 kWh in battery can be calculated. M_{sub} is subsidy (€/kWh), N_{fee} is the fee for network service and renewable energy (€/kWh)

$$M_{Sub} = \frac{M_B - (N_{Fee} \cdot \eta_c \cdot W_u)}{P_W} \text{ €/kWh} \qquad (7)$$

Calculations shows, that subsidy for battery BTL 12-200 AMG at depth of discharge 30% is 129.95 €/kWh and for batteries BTL 12-150 AMG and BTL 12-100 AMG it is 145.04 and 143.26 €/kWh. In table IV is shown the amount of needed batteries when depth of discharge is 30% and daily energy need is 10 kWh (average European household) [22].

TABLE IV *Cost of battery bank and subsidy comparaison*

Battery	Useful electricity, kWh	Battery price, €	Needed amount of Batteries	Cost of batteries, €	Subsides, €	Percentage of the subsidy, %
BTL 12-200 AGM	0.72	364	14	5099	4220	83
BTL 12-150 AGM	0.54	300	19	5706	4811	84
BTL 12-100 AGM	0.36	198	28	5546	4667	84

As shown in table IV the subsidies for batteries covers more than 80% of the cost of the batteries.

Although, it has been previously pointed out that 15 kW is the maximum capacity for renewable energy parks eligible for subsidization, but normally there are lower capacity PV parks for private households [18]. In this case, a 3.3 kW PV panel park will be used. Calculations for 3.3 kW PV panel parks has been made and results are in table V.

TABLE V *PV panel park capacity and output*

PV panel park capacity, kW	Period, h	Capacity factor, %	Annual output, kWh	Average self-consumption, (25%), kWh/a	Sold to the grid (75%), kWh/a	75 % Subsidization, €
3.3	8760	11	3179.9	795	2385	126.41

In table V it is pointed out, that yearly subsidition for renewable energy is 126.41 € if the PV park is at capacity 3.3 kW and 75% of produced energy is sold to the utility grid. Battery lifetime is about 10 years, that means that yearly subsidition to the battery bank is about 422-481 €. This is roughly 3.3-3.8 times more than subsiditon to the PV panels produced energy sold to the grid.

IV. DISCUSSION

Energy storage devices are needed to ensure the household independents of weather conditions and the periodicity of renewable energy production. There are three types of periodicity: short term, middle and long term cycles [23]. On the scale of time it varies from seconds and days to seasons.

In Estonia, about 86% electricity is from oil shale, a non-renewable resource. That means the renewable energy producers who uses PV panels and wind generator and uses utility grid as a battery bank, indirectly support non renewable energy usage.

Adding battery bank to the renewable energy production system rises locally produced energy usage onsite and therefore, in this case, may lower the use of oil shale energy usage. It is because the renewable energy can be use when there is no production at the time. Locally produced energy usage may rise, depend on weather conditions, from 25% to 100%.

The necessary subsidation covers about 83% of the battery bank value, and this includes only batteries without any control devices and inverter. Also, there are any losses in the system not taken into account.

The hypothesis of this article is that an installation subsidy of 100 € per 1 kWh of energy storage capacity of a battery bank makes the investment feasible for renewable energy producers and, in this context, also increases energy security. The calculations shows, that 100 € per 1 kWh may be too low to reach that objective. It is because at the time it will not cover the gap between network service fee and the cost of the battery. The calculations shows subsidies should be in these conditions 83…84% of the cost of the battery bank. That rises the subsidy from 100 to 125 €/kWh.

For effective use of this method, there must be some sort of method to ensure the use of high quality batteries in the system. The calculations show, that the depth of discharge is effective way to guarantee the useful lifetime of the battery. In this case the 30% DoD is the most effective for battery lifetime capacity.

V. CONCLUSION

By subsidizing electricity storage capacity with 100 €/kWh, the energy stored by the battery banks will cost 2.5-3 times less in comparison to a situation where the batteries are installed without subsidy. Thus, it can be assumed that by subsidizing battery banks rather than subsidizing the sold electricity increases the establishment of battery banks. This will also increase the households local self consumption and energy security. Although, calculations shows that 100 € per 1 kWh capacity may not be enough to untie electricity self consumption from the utility grid, it may have a positive effect.

To give to the renewable energy producers the same electricity storage cost as they are using the utility grid. This leads to the conclusion that subsidies should be approximately 125…130 €/kWh of installed battery capacity at the current price levels.

To avoid subsidies misuse and put it in long term purpose, the batteries depth of discharge and useful charging cycles must be compered. The greater amount of energy that can be stored to the battery over it´s lifetime, the better the battery is.

ACKNOWLEDGMENT

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IV

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Integrated Smart Heating System in Historic Buildings

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***Abstract*— In Estonia, wood-based heat accumulating stove heating is the traditional method of keeping houses warm during the cold period. Over time, district heating has started to replace local heating systems in urban areas. Different heating systems, based on different kind of combustion materials, have been introduced for heating private houses. Solar, earth and air heating have also been introduced in recent decades. At the same time, wood burning stove heating have still an important role in heating private homes as a traditional way. This, in turn, causes a reduction in air quality in urban areas during the heating season. Due to the decline in air quality, an idea of banning the wood-burning stove heating systems in urban areas rises. In historic buildings of architectural value, as well as heritage sites and buildings seeking of cultural authenticity, the preservation of stoves is required. In order for stoves to remain more than just decorative furnishings, it is wise to find possibilities of using stoves for their intended use using modern and non-polluting options. For example, by installing electric heating elements in furnaces or by supplying heat to the furnaces through preheated water. The aim of this study is that by using smart control element and heating the furnace with an electric heater during periods when electricity is cheap, it ensures the suitability of the indoor climate of the building and reduces the air pollution. At the same time, it balances the demand response ratio in electricity market.**

Keywords*— *historic buildings, heating system, demand response, heat storage.

I. INTRODUCTION

The integration of energy and communication networks enables ever more possibilities for the controlling of processes [1]. One of the most available controllable loads are heating loads. In Estonia, the active heating season usually starts in October and ends in April. Traditionally, wood-based solid fuel is used as heating in private homes in rural as well as urbanized areas. Depending on the size of the household, the house has at least one stove, but there may be more. The heat generated by the burning process of combustion material in the furnace is stored in the furnace stones, which then slowly spreads into the living quarters. The combustion gases are discharged from the furnace through the chimney. After the combustion process is completed, the furnace flaps are closed to prevent the heat stored in the furnace from escaping through the chimney to the outside. The heat energy distribution of the furnace over time is shown in Fig. 1.

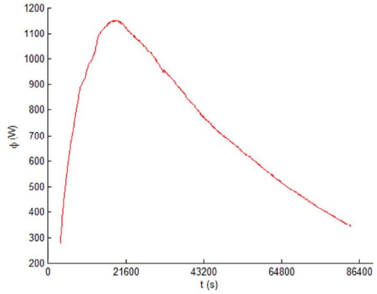

Fig. 1. Stove output power during an example heating cycle, April 15, 2014 - [2].

From Fig. 1. it can be seen that up to about 6 h the amount of energy emitted by the furnace increases with time, then the amount of heat in time begins to decrease until after (86400 s) 24 h it reaches the same level as before heating. Although stove heating is traditional in Estonia, there are problems with air quality in urban areas, as shown in Fig. 2. To improve air quality, homeowners are directed to select other types of heating than solid fuel stove heating. There are many air polluting components, but fine particles are considered to be the most dangerous to human health [3]. Fine particles can be classified into three: fine particles PM10, especially fine particles PM2.5 and ultra-fine particles PM0.1, with sizes of less than 100 nm, 100 nm to 2.5 micrometers and 2.5 to 10 mm. The finer the particles, the more dangerous they are to health [4]. Measurements have confirmed that one of the main causes of the deterioration of air quality in Tartu is local heating. At the same time, 16 TWh of heat was used for heating in Estonia in 2012, of which 40% e. 6.5 TWh originated from different types of local heating. About 70% of this was biofuel. This means that 30% of locally used fuels were fossil fuels [5]. The city of Tartu is located in a valley near the river Emajõgi, and the dispersion of exhaust gases due to wind conditions is not always good [6]. Therefore, modernization or, and switching to district heating is planned to improve the air quality in Tartu [7]. The air quality in the city worsens with the decrease of temperatures (Fig. 2).

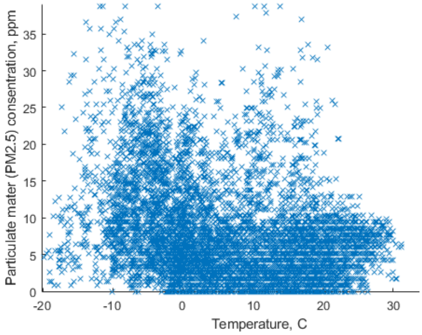

Fig. 2. Annual air quality in Tartu and temperature in 2018 [8].

The air quality, indicated above (Fig. 2) with the concentration of PM2.5 particles deteriorates especially when the outside temperature falls below 0 C.

Switching to district heating in private homes can be problematic due to the lack of communication near the house, and the economic aspect of the merger also plays a role. In addition, district heating can also change the indoor climate of a dwelling to an extent that does not satisfy its occupants (air dryness). At the same time, different heritage conservation requirements restrict changes both the exterior and interior design of buildings. There may be situations where the entire building is converted to use the district heating system, but the furnaces remain as the important architectural elements in the building. In order to preserve historically used heating systems even today, electric heating elements heating elements can be installed in them. Wind-generated electricity can lead to a situation where there is a large amount of electricity produced but no demand to use it (at night). Therefore, in such a case, the sale of electricity at a negative price is applied

II. MATERIALS AND METHODS

1.1. Electricity prices

Estonia joined Nord Pool Spot electricity sales area in 2010. Nord Pool Spot is a Nordic power exchange that sells electricity produced in Norway, Denmark, Sweden, Finland, Estonia, Latvia and Lithuania. Electricity produced in Estonia is predominantly of fossil origin, while electricity produced in Denmark, for example, is produced from renewable sources. Fig. 3 and Fig. 5 show the incidence of electricity prices in the Estonia and DK1 region of Denmark in 2018. Electricity prices in DK1 are also lower than in Estonia. The prices from the Nord Pool Spot electricity market are used in this article [9].

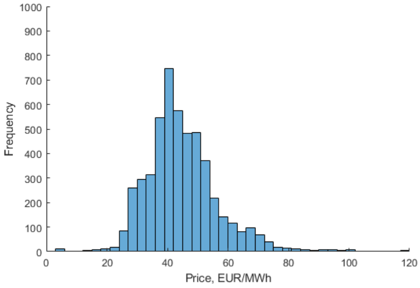

Fig. 3. Electricity market prices during the heating period in Estonia

An important factor in the price distribution is the relation to the outside temperature (Fig. 4).

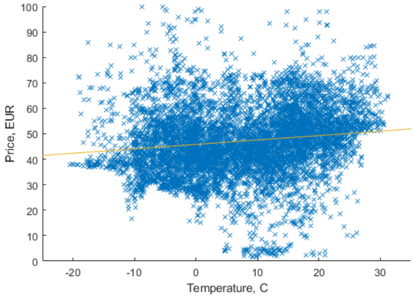

Fig. 4. Electricity market prices in relation to the outside air temperature in Estonia

There is a negative correlation between electricity price and temperature in the Estonian price region, which is caused by wind energy generation, and is beneficial for the implementation of the here described concept. This negative correlation could be even more pronounced in the future, as there are plans to install significant wind power capacities in the region. The graphs show, that the electricity sold in the Estonian price area has never been less than 0 €, but this has occurred in the Danish DK1 region (Fig. 5), which has more wind power production.

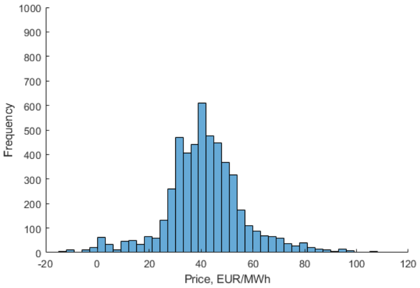

Fig. 5. Electricity market prices during the heating period in the Danish price region DK1.

It has to be noted that the price in the figures above (Fig. 3 and Fig. 5) is only the price for the electrical energy. Additionally, to that, the customer has also to pay the transmission fees and taxes. These fees and taxes are in the range of 50 €/MWh, which is equal to the cost of energy produced from solid biofuel. This result in a situation, where it is economically better for the customer to heat with electricity when the price of electrical energy is below 0 EUR/MWh.

1.2. Modernized furnace heating system

Solid fuel is commonly used for furnace heating. However, by replacing heat-producing combustion process in the stove with electric heating system inside the stove, hazardous flue gases with fine particles are no longer released into the environment. At the same time, the outfit and purpose of the stove are preserved.

Electric heating elements can be easily installed in to the furnace fireplace. Correct heating elements must be selected, according to the stove output power. However, solid fuel can not be used at the same time when the electric heating elements are installed into the furnace fireplace. The fire can damage the connection wires.

When the furnace is amortized, it need to be refurb. During the refurbish, it is possible to install electric heating elements in the furnace so that the fire will not damage the connection cables.

The simplest way to add electric heating elements is when building a new furnace or completely disassembling and renovating an old furnace.

1.3. The energy capacity of the furnace

Solid fuel furnace in Estonia have an average mass of 2000 kg. Usually there is one furnace in the household, which provides the necessary heat for the dwellings. Furnace is made out of stone. The stone specific heat capacity is 1 $kJ \cdot kg^{-1} \cdot K^{-1}$. During the active heating period, the furnace minimal temperature is 40 ^{0}C and maximal temperature is about 80 ^{0}C.

$$Q = \Delta t \cdot m \cdot c \qquad (1)$$

Using equation 1, the energy, stored to one furnace can be calculated.

1.4. Furnace heating control system

The proposed furnace heating system requires an integrated control system. The control system must take into account a number of different real-time variables. These include outdoor and indoor temperature, change in outside air temperature (weather forecast) and power exchange price. As seen in Fig. 6, the control system decision, whether to use electrical heating elements for furnace heating begins with measuring the room temperature. If the room temperature is at or below the desired level, the logic process goes to the next step. If not, it repeat itself.

The second step for the control logic is to measure the heater temperature. If the heater is not warm enough, the logic process goes to next step. If the heater is warm enough to heat the household, it is not wise to overheat the furnace and the logic process goes to the loop and repeats itself after delay time.

The third step for the controller is obtaining the weather forecast data. The weather conditions change over time and the indoor temperature is directly dependent on the outside temperature. If the change in the outdoor temperature is known in advance, it can also be used to infer the change in the indoor temperature. Falling outside temperature also causes the indoor temperature to drop. The indoor temperature change occurs with a time shift compared to the outdoor temperature. So, if the weather forecast informs the system of the falling temperature the control system goes to the next step. If the weather forecast shows a rise of outside temperature, it goes to the loop and repeats itself after delay time.

The forth step is obtaining the electricity price information. User must set the maximum electricity price level, when it is expedient to heat with electricity. It is due to local peculiarities and is related to the cost of other heating sources. When the electricity price is below economically feasible threshold level for heating, the system goes to the next step. In addition, when it is not economically feasible to use electricity for heating the control logic goes to loop and repeats itself after delay time.

The fifth and the final step is to switch the heater on for the next time step. Because of the variability of the system, it needs to control all the input parameters. If parameters are suitable for heating then the system will continue to use electricity to heat the furnace.

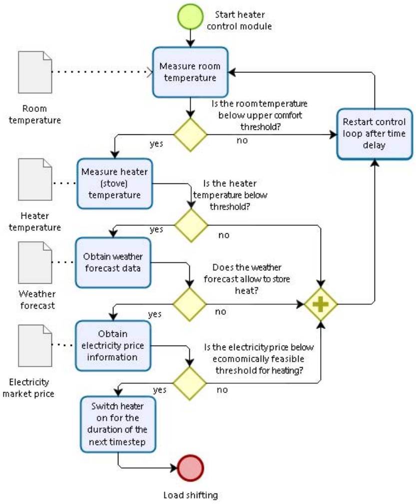

Fig. 6. Control logic of the demand response method.

1.5. Demand response

Electrical systems, in general, consist of three parts: the production units, transmission lines, transformers and the consumers. The production unit, like wind generators, supply consumers with electricity. In many cases, the production units cannot change the power generation on demand. The reason is the inertia of the production units or, in this case, caused by the intermittency of the wind. It is necessary, that the electricity productivity and consumption in a system are in balance. If the load exceeds the produced power or vice versa, voltage problems in the grid occur, which can lead to the shutdown of generating installations, the deterioration of electricity consumers and, in the worst case, power outages. In an open market situation, the price of electricity is indicative of over- and under-production. Low electricity prices attract to consume the electricity. At the same time, the high electricity prices does not favor the use of electricity. It is called demand response (DR) [10][11]. At the moments of low consumption, where the wind generators produce more electricity than consumers need, the additional load will be turned on and that way the stability of the utility grid is guaranteed [12][13].

III. RESULTS

Since the generation and consumption of electricity transmitted through the electricity grid must be balanced in order to maintain stability, the additional load must be applied to the system. Additional load i.e. electrical heating elements in the furnace, consume relatively large amounts of electricity in a short period of time and can be controlled by the control device connected to the internet.

The proposed system enables additional balancing reserves for the electricity grid operator. According to the Statistics Bureau of Estonia, 172 446 households of 30% used furnaces as a heating source for their living space. Therefore, it can be calculated, how much energy can be stored by all the furnaces in Estonia. Calculations show, that for an average furnace the heat capacity is 80 MJ. By scaling this number up, the heat capacity for all Estonian furnaces, it is 13.79 TJ.

Considering, that an average heater element for such an application could be in the range of 2 kW, the theoretical total controllable load could be 345 MW. In comparison, the maximum load of the Estonian electricity grid is 1560 MW, which occurs during winter.

The control system for the modernization of the stove heating system is described in Fig. 6. Depending on the following factors, the control unit will decide whether the heaters will be turned on: indoor temperature; stove temperature; weather forecast; electricity price prognosis.

Applying proposed technology to all existing furnaces in Estonia, the balancing capacity may rise to 13.79 TJ. At the same time, using this technology in rural areas, it reduces the air pollutions and gives back the purpose to the furnaces in historic houses.

IV. DISCUSSION

The storage of energy in the form of heat could partially replace the need for battery storage which is needed in smaller energy systems [14],[15].

For urban environment, it is critical to lower the air pollution. In this case, abandoning the solid fuels in heating systems, it can be done. For architectural and heritage reasons it is expedient to maintain the stoves purpose.

During the observed period, in 2018, the electricity price was below (including) 0 €/kWh 49 hours in DK1 price area. Cases where the price of electricity was less than 0 €/kWh were all within the heating season. In that period, it is reasonable to heat houses with electricity.

From an economic point of view, electrically heated furnaces must be studied wider scale than below zero price level for electricity. It is because solid fuels also have a value that has to be paid. The optimal electricity price, when the control logic should switch on, is higher than 0 €/kWh and it depends of the local solid fuel price used in heating stove.

V. CONCLUSION

The current research studied the option for retaining the heating purpose of historic stoves by using smart grid technology. For that purpose, a smart control system was modelled. In this model, real-life data must be use: indoor temperature, stove temperature, weather forecast and electricity price prognosis.

ACKNOWLEDGMENT

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Professor Andres Annuk
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CURRICULUM VITAE

Contact information

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Education

2017 – 2021	PhD studies, Estonian University of Life Sciences,
2015 – 2017	Master's degree, Estonian University of Life Sciences, Energy use (*cum laude*). Master's thesis: Raspberry Pi Based Datalogger
2010 – 2013	Bachelor's degree, Estonian University of Life Sciences, Energy use
1997 – 2000	Võru Kreutzwald Gymnasium

Work experience

2021 – …	Estonian University of Life Sciences, Tartu Technology College. Junior Research Fellow.
2017 – …	Estonian Trade Union Confederation. Regional Manager.
2014 – …	Estonian University of Life Sciences, Tartu Technology College. Program Leader.
2016 – 2017	Estonian Defence League. Guard.
2007 – 2016	Tartu Prison, Inspector.
2011 – 2012	Tartu University Hospital, Caregiver.

Software skills

Planning: AutoCad
Modeling: R, Scicoslab
Office software: MS Office, Mendeley
Communication: Outlook, Skype, Teams, Dropbox, GoogleDocs

Languages

Estonian	Native speaker.
English	Good in spoken and written language.
Russian	Basic skills.

Participation in academic organisations

2019 – 2020	Member of board at Institute of Technology in Estonian University of Life Sciences
2015 – 2017	Member of Teaching Methodology Committee in Institute of Technology in Estonian University of Life Sciences

Training Courses

2019	Training of Evaluation Experts, Estonian Quality Agency for Higher and Vocational Education
2016	Occupational Safety and Personal Protection, CPR - New Building Regulations, SLO Eesti AS
2013 – 2015	Teaching subjects in the field of natural sciences, exact sciences and technology, Tallinn University of Technology
2015	First aid in case of shooting injuries, The Estonian Academy of Security Sciences
2014	Emergency vehicle driver training, The Estonian Academy of Security Sciences

Supervised theses

2020	Kenneth Alto, PV Panels Production in Underdimensioning of Inverter, bachelors thesis
2019	Kristjan Loite, Cost-Benefit Analysis of PV Panels and Battery Bank System for a Single Family Hous, bachelors thesis
2019	Juhani Almers, Remote Weapon Station Integration With an Unmanned Ground Vehicle, applied higher education thesis
2018	Anti Samasonov, Explosive Forming Device, bachelors thesis

Presenetations at international conferences

8th International Scientific Conference "RURAL DEVELOPMENT 2017: Bioeconomy Challenges", (23-24.11.2017, Kaunas Lithuania), Presentation title: Optimal Wind/Solar energy Mix For Residental Net Zero-Energy Buildings. Based on the same titled article, authored by: Janar Kalder, Alo Allik, Hardi Hõimoja, Erkki Jõgi, Mart Hovi, Maido

Märss, Jarek Kurnitski, Jevgeni Fadajev, Heiki Lill, Algridas Jasinskas, Andres Annuk.

24th ICE IEEE ITMC 2018 Conference, (17-20.06.2018. Stuttgart Germany). Presentation title: Capacitor and Battery Energy Storage System Sizing Ratio for Wind Microgenerators. Based on the same titled article, authored by: Heiki Lill, Alo Allik, Erkki Jõgi, Mart Hovi, Hardi Hõimoja, Andres Annuk.

7th International Conference on Renewable Energy Research and Applications, (14.-17.10.2018. Paris France). Presentation title: Augmentation of Self-Consumption of Electricity by Using Boilers and Batteries for Residential Buildings. Based on the same titled article, authored by: Annuk, Andres; Jõgi, Erkki; Lill, Heiki; Kalder, Janar; Hovi, Mart; Pihlap, Heino; Jasinskas, Algirdas; Härm, Mihkel; Trashchenkov, Sergei; Allik, Alo.

8th International Conference on Renewable Energy Research and Applications, (03-06.11.2019 Brasov Romania). Presentation title: Case study for battery bank subsidization. Based on the same titled article, authored by: Lill, Heiki; Allik, Alo; Annuk, Andres.

7th International Conference on Smart Grid, (09-11.12.2019 Newcastle Australia). Presentation title: Integrated Smart Heating System in Historic Buildings. Based on the same titled article, authored by: Lill, Heiki; Allik, Alo; Mart Hovi; Kristjan Loite; Annuk, Andres.

Presentations at local conferences

Seminar of the Energy Department of the EMU Institute of Technology, Tartu. 02.02.2018. Possibilities of storing electricity produced by a wind generator.

Conference of Knowledge-Based Construction, 26.02.2018, Sokos Hotel Viru, Tallinn. Possibilities of electricity storage in a power supply system with a wind generator and PV panels.

Doctoral Conference of Natural Sciences "The Art of a Popular Science Talk". 05.13.2018, Võrtsjärv Limonology Center. Capacitor and Battery Energy Storage System Sizing Ratio for Wind Microgenerators.

Cooperation Festival "At the Right Time in the Right Place". 01.11.2018, Tallinn University, Tallinn. Capacitor and Battery Energy Storage System Sizing Ratio for Wind Microgenerators.

Overview of publications

Classification	1	3				6	
Number of publications	1	6				7	
Subclassifier	1.1.	3.1.	3.2.	3.4.	3.5.	6.3.	6.7.
Number of publications	1	6	-	-	-	-	7

1.1. Scholarly articles indexed by Thomson Reuters Web of Science (excluding articles indexed in Thomson Reuters Conference Proceedings Citation Index) and/or published in journals indexed by ERIH (European Reference Index of the Humanities) categories INT1 and INT2 and/or indexed by Scopus (excluding chapters in books)

Allik, Alo; **Lill, Heiki**; Annuk, Andres (2019). Ramp Rates of Building-Integrated Renewable Energy Systems. International Journal of Renewable Energy Research-IJRER , 9 (2), 572−578.

3.1. Articles/chapters in books published by the publishers listed in Annex (including collections indexed by the Thomson Reuters Book Citation Index, Thomson Reuters Conference Proceedings Citation Index, Scopus)

Lill, Heiki; Allik, Alo; Annuk, Andres (2019). Case study for battery bank subsidization. In: 8th International Conference on Renewable Energy Research and Applications (234−238). ICRERA 2019, Brasov: IEEE. DOI: 10.1109/ICRERA47325.2019.8996602.

Allik, Alo; **Lill, Heiki**; Annuk, Andres. (2019). Effects of Price Developments on Photovoltaic Panel to Inverter Power Ratios. 8th International Conference on Renewable Energy Research and Applications: ICRERA 2019, Brasov. Ed. Ilhami Colak. IEEE, 371−376. DOI: 10.1109/ICRERA47325.2019.8997104.

Lill, Heiki; Hovi, Mart; Loite, Kristjan; Allik, Alo; Annuk, Andres (2019). Integrated Smart Heating System in Historic Buildings. In: 7-th International Conference on Smart Grid (92−96). Newcastle, Australia: IEEE. DOI: 10.1109/icSmartGrid48354.2019.8990833.

Annuk, Andres; Jõgi, Erkki; **Lill, Heiki**; Kalder, Janar; Hovi, Mart; Pihlap, Heino; Jasinskas, Algirdas; Härm, Mihkel; Trashchenkov, Sergei; Allik, Alo (2018). Augmentation of Self-Consumption of Electricity by Using Boilers and Batteries for Residential Buildings. Proceedings of 7th International Conference on Renewable Energy Research and Applications: 7th International Conference on Renewable Energy Research and Applications, Paris, 14.-17.10.2018. Ed. Ilhami Colak. Paris: ICRERA, 256−260.

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Kalder, Janar; Allik, Alo; Hõimoja, Hardi; Jõgi, Erkki; Hovi, Mart; Märss, Maido; Kurnitski, Jarek; Fadejev, Jevgeni; **Lill, Heiki**; Jasinskas, Algirdas; Annuk, Andres (2017). Optimal wind/solar energy mix for residential net zero-energy buildings. 8th International Conference: Rural Development, 23.-24.11.2017. Kaunas: Aleksandras Stulginskis University, 621−626. DOI: 10.15544/RD.2017.020.

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Haridustee

2017 – 2021	Doktoriõpe, Eesti Maaülikool, Tehnikainstituut, doktoritöö teema: Erinevad energia salvestustehnoloogiad liginullenergihoonetes.
2015 – 2017	Magistriõpe, Eesti Maaülikool, energiakasutus (cum laude). Magistritöö teema: Raspberry Pi baasil valmistatud andmeloger.
2010 – 2013	Bakalaureuseõpe, Eesti Maaülikool, energiakasutus.
1997 – 2000	Võru Kreutzwaldi Gümnaasium, reaalainete õppesuund.

Töökogemus

2021 – …	Eesti Maaülikool Tartu tehnikakolledž, nooremteadur.
2017 – …	Eesti Ametiühingute Keskliit, lõuna osakonna juht.
2014 – …	Eesti Maaülikool, tehnotroonika õppekava juht.
2016 – 2017	Kaitseliit, valvur.
2007 – 2016	Tartu Vangla, inspektor-korrapidaja abi.
2011 – 2012	SA Tartu Ülikooli Kliinikum, hooldaja.

Arvutioskused

Projekteerimine: AutoCad
Modelleerimine: R, Scicoslab
Kontoritarkvara: MS Office, Mendeley
Suhtlus: Outlook, Skype, Teams, Dropbox, GoogleDocs

Keeled

Eesti keel	Emakeel
Inglise keel	Väga hea nii kõnes kui kirjas. Praktika tööalase rahvusvahelise suhtluse kaudu.
Vene keel	Algtase.

Teadusorganisatsiooniline tegevus

2019 – 2020	Eesti Maaülikooli tehnikainstituudi nõukogu liige
2015 – 2017	Eesti Maaülikooli tehnikainstituudi õppemetoodika komisjoni liige

Täiendkoolitus

2019	Hindamisekspert, korraldaja: Eesti Kõrg- ja Kutsehariduse Kvaliteediagentuur
2016	Tööohutus ja isikukaitse, CPR – uus hoonete ehitusmäärus, korraldaja: SLO Eesti AS
2013 – 2015	Loodus-, täppisteaduste ja tehnikavaldkonna õppeainete õpetamine, korraldaja: Tallinna Tehnikaülikool
2015	Esmaabi laskevigastuste korral, korraldaja: Sisekaitseakadeemia
2014	Alarmsõiduki juhi koolitus, korraldaja: sisekaitseakadeemia.

Juhendatud lõputööd

2020	Kenneth Alto, PV paneelide elektrienergia tootlus inverteri aladimensioneerimise korral, Bakalaureusetöö;
2019	Kristjan Loite, PV paneelide ja akupanga süsteemi tasuvusanalüüs eramule, Bakalaureusetöö;
2019	Juhani Almers, Kaugjuhitava relvasüsteemi integreerimine mehitamata roomiksõidukiga, Rakenduskõrghariduse lõputöö;
2018	Anti Samasonov, Plahvatuslehtvormimise seade, Bakalaureusetöö.

Suulised ettekanded rahvusvahelistel konverentsidel

8th International Scientific Conference "RURAL DEVELOPMENT 2017: Bioeconomy Challenges", (23-24.11.2017, Kaunas Leedu Vabariik). Suuline ettekanne: Optimal Wind/Solar energy Mix For Residental Net Zero-Energy Buildings. Artikli autorid: Janar Kalder, Alo Allik, Hardi Hõimoja, Erkki Jõgi, Mart Hovi, Maido Märss, Jarek Kurnitski, Jevgeni Fadajev, Heiki Lill, Algridas Jasinskas, Andres Annuk.

24th ICE IEEE ITMC 2018 Conference, (17-20.06.2018. Stuttgart Saksamaa Liitvabariik). Suuline ettekanne: Capacitor and Battery Energy Storage System Sizing Ratio for Wind Microgenerators. Artikli autorid: Heiki Lill, Alo Allik, Erkki Jõgi, Mart Hovi, Hardi Hõimoja, Andres Annuk.

7th International Conference on Renewable Energy Research and Applications, (14.-17.10.2018. Pariis Prantsusmaa). Suuline ettekanne: Augmentation of Self-Consumption of Electricity by Using Boilers and Batteries for Residential Buildings. Artikli autorid: Annuk, Andres; Jõgi, Erkki; Lill, Heiki; Kalder, Janar; Hovi, Mart; Pihlap, Heino; Jasinskas, Algirdas; Härm, Mihkel; Trashchenkov, Sergei; Allik, Alo.

8th International Conference on Renewable Energy Research and Applications, (03-06.11.2019 Brasov Rumeenia). Suuline ettekanne: Case study for battery bank subsidization. Artikli autorid: Lill, Heiki; Allik, Alo; Annuk, Andres.

7th International Conference on Smart Grid, (09-11.12.2019 Newcastle Austraalia). Suuline ettekanne: Integrated Smart Heating System in Historic Buildings. Artikli autorid: Lill, Heiki; Allik, Alo; Mart Hovi; Kristjan Loite; Annuk, Andres.

Ettekanded kohalikel konverentsidel

EMÜ Tehnikainstituudi Energeetika osakonna seminar. 02.02.18. EMU Tehnikainstituut. Tuulegeneraatori toodetud elektrienergia salvestusvõimalused.

Teadmistepõhine ehitus 2018. 26.02.18. Sokos Hotell Viru. Elektrienergia salvestamise võimalused tuulegeneraatori ja PV paneelidega energiavarustussüsteemis.

Reaalteaduste doktorantide konverents 2018 The Art of a Popular Science Talk. 13.05.18. Võrtsjärve Limonoloogiakeskus. Capacitor and Battery Energy Storage System Sizing Ratio for Wind Microgenerators.

Koostööfestival õigel ajal õiges kohas. 01.11.2018 Tallinna Ülikool. Ülikondensaatori ja akupanga suhe tuulegeneraatori elektri salvestussüsteemis.

Publikatsioonid vastavalt ETIS-e klassifikaatorile

Klassifikaator	1	3				6	
Publikatsioonide hulk	1	6				7	
Alamklassifikaator	1.1.	3.1.	3.2.	3.4.	3.5.	6.3.	6.7.
Publikatsioonide hulk	1	6	-	-	-	-	7

1.1. Teadusartiklid, mis on kajastatud Thomson Reuters Web of Science andmebaasis (v.a. Thomson Reuters Conference Proceedings Citation Index poolt refereeritud kogumikud) ja/või Euroopa Teadusfondi humanitaarteaduste loendi ERIH (European Reference Index of the Humanities) kategooriates INT1 ja INT2 ja/või andmebaasis Scopus (v.a. kogumikud)

Allik, Alo; Lill, Heiki; Annuk, Andres (2019). Ramp Rates of Building-Integrated Renewable Energy Systems. International Journal of Renewable Energy Research-IJRER , 9 (2), 572−578.

3.1. Artiklid/peatükid lisas loetletud kirjastuste välja antud kogumikes (kaasa arvatud Thomson Reuters Book Citation Index, Thomson Reuters Conference Proceedings Citation Index, Scopus refereeritud kogumikud)

Lill, Heiki; Allik, Alo; Annuk, Andres (2019). Case study for battery bank subsidization. In: 8th International Conference on Renewable Energy Research and Applications (234−238). ICRERA 2019, Brasov: IEEE. DOI: 10.1109/ICRERA47325.2019.8996602.

Allik, Alo; **Lill, Heiki**; Annuk, Andres. (2019). Effects of Price Developments on Photovoltaic Panel to Inverter Power Ratios. 8th International Conference on Renewable Energy Research and

Applications: ICRERA 2019, Brasov. Ed. Ilhami Colak. IEEE, 371−376. DOI: 10.1109/ICRERA47325.2019.8997104.

Lill, Heiki; Hovi, Mart; Loite, Kristjan; Allik, Alo; Annuk, Andres (2019). Integrated Smart Heating System in Historic Buildings. In: 7-th International Conference on Smart Grid (92−96). Newcastle, Australia: IEEE. DOI: 10.1109/icSmartGrid48354.2019.8990833.

Annuk, Andres; Jõgi, Erkki; **Lill, Heiki**; Kalder, Janar; Hovi, Mart; Pihlap, Heino; Jasinskas, Algirdas; Härm, Mihkel; Trashchenkov, Sergei; Allik, Alo (2018). Augmentation of Self-Consumption of Electricity by Using Boilers and Batteries for Residential Buildings. Proceedings of 7th International Conference on Renewable Energy Research and Applications: 7th International Conference on Renewable Energy Research and Applications, Paris, 14.-17.10.2018. Ed. Ilhami Colak. Paris: ICRERA, 256−260.

Lill, Heiki; Allik, Alo; Jõgi, Erkki; Hovi, Mart; Hõimoja, Hardi; Annuk, Andres (2018). Capacitor and Battery Energy Storage System Sizing Ratio for Wind Microgenerators. IEEE Xplore, 940−945. DOI: 10.1109/ICE.2018.8436338.

Kalder, Janar; Allik, Alo; Hõimoja, Hardi; Jõgi, Erkki; Hovi, Mart; Märss, Maido; Kurnitski, Jarek; Fadejev, Jevgeni; **Lill, Heiki**; Jasinskas, Algirdas; Annuk, Andres (2017). Optimal wind/solar energy mix for residential net zero-energy buildings. 8th International Conference: Rural Development, 23.-24.11.2017. Kaunas: Aleksandras Stulginskis University, 621−626. DOI: 10.15544/RD.2017.020.

VIIS VIIMAST KAITSMIST

KAIRE LOIT
PATOGEENSED JA ARBUSKULAARMÜKORIISSED SEENED EESTI KARTULIPÕLDUDEL
PATHOGENIC AND ARBUSCULAR MYCORRHIZAL FUNGI IN POTATO FIELDS IN ESTONIA
Professor Alar Astover, dokor Maarja Öpik ja doktor Leho Tedersoo
22. juuni 2021

NASIME JANATIAN GHADIKOLAEI
HÜDROMETEOROLOOGILISTE JA KLIIMATEGURITE MÕJU JÄRVEDE FÜTOPLANKTONILE: AJASKAALADE OLULISUS
HYDROMETEOROLOGICAL AND CLIMATIC CONTROL OVER LAKE PHYTOPLANKTON: THE IMPORTANCE OF TIME SCALES
Juhtivteadur Peeter Nõges, Biel Obrador, vanemteadur Fabien Cremona, vanemteadur Alo Laas
27. august 2021

KRISTIINA AUN
RAIETE LÜHIAJALINE MÕJU SÜSINIKU VOOGUDELE JA VARUDELE ERINEVATES EESTI METSAÖKOSÜSTEEMIDES
SHORT-TERM EFFECT OF FELLING ON CARBON FLUXES AND STORAGES IN DIFFERENT ESTONIAN FOREST ECOSYSTEMS
Professor Veiko Uri
27. august 2021

PRIIT KARIS
TOITUMUSE, LIPOMOBILISATISOONI JA INSULIINIRESISTENTSUSE SEOSED PIIMALEHMADEL
RELATIONSHIPS BETWEEN BODY CONDITION, LIPOMOBILIZATION AND INSULIIN RESISTANCE IN DAIRY COWS
Doktor Hanno Jaakson, doktor Katri Ling, doktor Meelis Ots
31. august 2021

HARES KHAN
KALTSIIDI AVAVEELINE SADENEMINE: PÕHJUSED JA TAGAJÄRJED GLOBAALSES JA KOHALIKUS VAATES
PELAGIC CALCITE PRECIPITATION IN LAKES: FROM A GLOBAL TO A LOCAL PERSPECTIVE ON ITS DRIVERS AND IMPLICATIONS
Doktor Biel Obrador (University of Barcelona, Hispaania), doktor Alo Laas
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