TALLINNA TEHNIKAÜLIKOOL
TALLINN UNIVERSITY OF TECHNOLOGY

School of Engineering

MODELLING AND TECHNICAL-ECONOMIC ANALYSIS OF POWER SUPPLY SYSTEM FOR AN OFF-GRID APARTMENT BUILDING

VÕRGUÜHENDUSETA KORTERMAJA ELEKTRIVARUSTUSLAHENDUSE MODELLEERIMINE JA TEHNILIS-MAJANDUSLIK ANALÜÜS

MASTER THESIS

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Tallinn, 2018

AUTHOR’S DECLARATION

Hereby I declare, that I have written this thesis independently.
No academic degree has been applied for based on this material. All works, major viewpoints and data of the other authors used in this thesis have been referenced.

“29” May 2018

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Accepted for defence

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THESIS TASK

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Study programme, KAYM; Materials and Processes for Sustainable Energetics

main speciality: Processes for Sustainable Energetics

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Thesis topic:

Modelling and Technical-Economic Analysis of Power Supply System for an Off-Grid Apartment Building

Võrguühenduseta kortermaja elektrivarustuslahenduse modelleerimine ja tehnilis-majanduslik analüüs

Thesis main objectives:

1. To provide an overview of main definitions and elements related to the study;
2. To study and analyse electrical load data of apartment buildings in Estonia;
3. To model the elements and electrical loads with HOMER Pro software;
4. To provide recommendations on the capacity and technology of electro-chemical energy storage; the sizing and direction of the solar array; the sizing of the diesel generator in the on-site power system for an average apartment building in Estonia.

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Composing the topic and main objectives of thesis	21.12.17
2.	Compiling an overview of relevant literature and research	01.03.18
3.	Modeling of the proposed power system in HOMER Pro	15.04.18
4.	Drawing conclusions on the modeling results: main objective 4	30.04.18

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PREFACE

Determining the topic this thesis was a lengthy process for which I had to put in a lot of thought. As my studies have mainly focused on solar energy and during my internship in Spain I researched the field of energy storage, I wanted to include both in my thesis. My wish was also to make my thesis useful and to provide something new on the way. The final topic was proposed by my supervisor, professor Argo Rosin, without whom this work wouldn't have become a reality. I'm sincerely grateful for his trust, patience and valuable thoughts during writing of this thesis.

To my closest ones – Liisi, Andres, Siiri, Karl Joonas, Simo Anders – your unconditional love and support have driven me to strive towards perfection in what I do. You have put up with me when times have been challenging and without you I wouldn't be anywhere near where I am today. I can't thank you enough for being my inspiration and guiding lights.

This thesis has 95 pages in total. The principal aims of this thesis are to model and analyse the technical and economical feasibility of an off-grid electrical power system for a modern apartment building in Estonia; to find the optimal configuration and component sizes for an off-grid power supply system for the studied building and to analyse if off-grid power supply for apartment buildings is financially competitive against grid electricity prices.

First, overviews of energy performance of buildings, sustainable energy supply in cold climate, hybrid power systems and off-grid systems' components are presented. Second, electrical load demand data of an average 18-flat apartment building was modelled in HOMER Pro software. Six different off-grid power system configurations were developed and analysed with actual load data and shifted loads. The studied components in the systems included solar PV panels, Lithium ion and Lead Acid energy storage and a diesel generator. The thesis provides the means for improving the profitability of off-grid power systems and potential benefits depending on the system's configuration. Based on the modelling results, a technical-economic analysis was carried out. It was concluded that optimal off-grid power systems for apartment buildings are currently not justified, but thanks to decreasing component prices, off-grid solutions for apartment buildings can become the preferred choice of electricity supply in the coming years.

Keywords: energy efficiency, renewable energy, nearly zero energy building, energy storage, solar energy, off-grid, master thesis

INTRODUCTION

This thesis addresses the topic of sustainable electricity generation in off-grid apartment buildings in cold climates. A new tendency in electricity supply is distributed energy generation that comprises small production units in distribution networks in electricity grid. Distributed energy is closely related to off-grid and nearly-zero energy buildings as they need to have on-site electricity production to achieve a lower net energy demand. Therefore, one of the aims of this work is to determine if sizing the on-site power systems so that they can meet the electrical loads in apartment buildings at all times is economically justified.

The feasibility and operation of small residential buildings in various off-grid scenarios has been thoroughly researched and analysed in known literature. However, larger apartment buildings in off-grid conditions have been studied significantly less. In addition, off-grid installations can prove to be viable in remote locations where grid connections can be non-feasible technically and financially.

The European Commission has issued the Energy Performance of Buildings Directive, which states the following: "Member States shall ensure that (a) by 31 December 2020 all new buildings are nearly zero- energy buildings; and (b) after 31 December 2018, new buildings occupied and owned by public authorities are nearly zero-energy buildings". Therefore, this work is to analyses the technical and economical feasibility of apartment buildings in off-grid conditions in cold climate, essentially making them zero energy buildings. The scope of current work involves all-year electricity demand and supply in residential apartment buildings in Estonia. As thermal energy is not addressed in this work and the building's thermal energy needs are added to electrical energy needs, the off-grid apartment buildings are analyzed in the context of nearly-zero energy buildings.

From 2020, the energy demand associated with a typical use of new buildings shall drop significantly and meet the energy performance class A. To meet these requirements, the buildings constructed from 2020 have meet nearly-Zero Energy Building (nZEB) requirements. In addition to low energy demand of nZEB's, much of it should be met with energy from renewable sources. Generally the renewable energy that is consumed in nZEB's is at least partially produced on-site or nearby. The proposed off-grid power installation is composed of solar PV panels, a battery storage system and a diesel generator. A reference building in Estonia will be used for detailed modeling with HOMER Pro and PVsyst softwares in off-grid conditions. To the knowledge of the author, no works on off-grid apartment buildings have been conducted in Estonia.

The distributed energy systems including solar photovoltaic components are feasible in Southern Europe with life cycle costs equal or lower than conventional fossil fuel-based energy. The task of developing a feasible on-site power system model is challenging and novel because the climatic conditions and relatively low solar irradiation in Northern Europe along with rising fossil fuel costs for diesel generators are the main limiting factors. Due to a large energy demand in cold climates, it is challenging to meet the electrical loads with on-site generation. On the opposite, mild and cold temperatures can at least partially compensate for the natural limits. In addition, the properties of building envelopes become especially vital to achieve a low net energy demand in cold climate. The building envelopes and overall energy demand are not further discussed in this work.

It has been concluded after previous research that in northern regions (including Estonia) small fluctuing power sources can only be economically justified in off-grid solutions where establishing a grid connection is not feasible and there is a controllable generation unit (such as a diesel generator) available nearby. One of the aims of this thesis is to provide an update on the topic of off-grid systems and present the situation in Spring 2018.

Previous research on nZEB's has provided mixed results about the buildings reaching cost-optimal levels. In 2013, Kurnitski et al noted that the cost-optimal level of construction and renovation of apartment buildings does not allow meeting nZEB standards. In 2017, Zangheri et al found that the cost optimal construction and renovation levels in Helsinki can be considered equal to nZEB requirements. Therefore, a clear improvement in the field of energy efficiency and total energy demand of buildings can be noted. However, research specialized on distributed electricity supply and demand in apartment buildings still has to be conducted.

This thesis begins with a literature overview and description of zero and nearly-zero energy buildings and energy efficiency. The work continues with a general overview of the installation's main components: solar PV, energy storage and diesel generator. The balance of system (BoS) between AC and DC sides of the system is described in the discussion about solar PV. The final part of this work addresses the development, sizing and simulation on-site power systems in various configurations to supply electricity to an apartment building in Estonia. Generally the known and available technological possibilities enable to reach the requirements of zero and even negative energy standard. The complicated part of the analysis is to reach a cost-effective system that would also be able to supply the building's electricity demand and reach the zero energy level while being competitive against grid electricity prices. After determining the technical feasibility of the system by simulating and optimising, a simple economical analysis is carried out to present financial considerations related to building and operation of the system. Simulations and analysis are carried out for an off-grid scenario.

1. LITERATURE OVERVIEW

1.1 Definitions

Energy performance of a building, EP – the calculated or measured amount of energy needed to meet the energy demand associated with a typical use of the building, which includes energy used for heating, cooling, ventilation, hot water and electricity. [1]

Nearly Zero-Energy Building, nZEB – A building that has a very high energy performance; the level of performance is defined individually by each country. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby. [1]

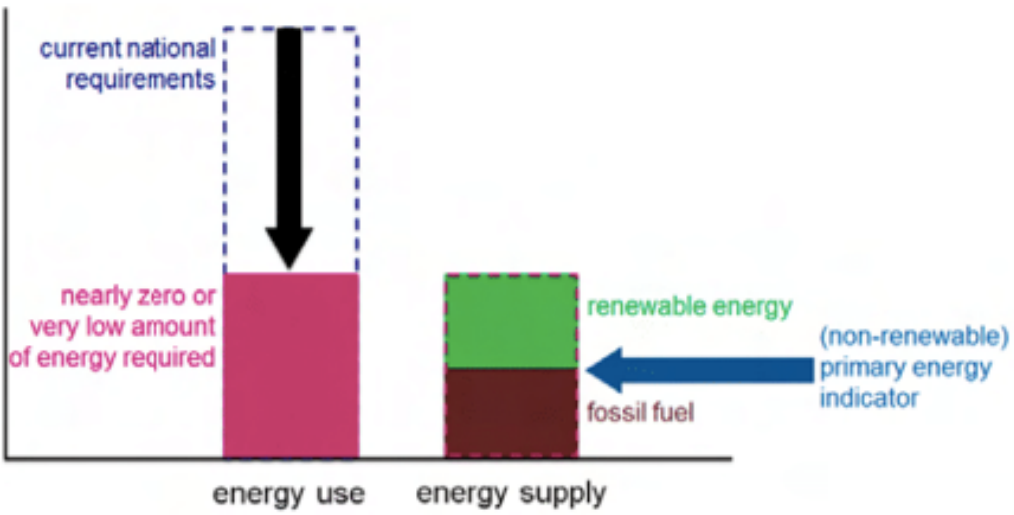

Figure 1.1. Graphical expression of a nZEB definition according to EPBD article 2 [2]

The definition of "nearby" renewable energy is not clearly defined in the Energy Performance of Buildings Directive. The European Union (EU) member states have developed their individual definitions for "nearby" energy production. Thus, the definition of "nearby" varies from being at the building (the UK, France), the same site (Austria, Slovenia, Slovakia), anywhere in the country (Malta, Lithuania) or is based on the owner's economical interests in the power generation system (Denmark). More than half of the EU member states (including Estonia) don't have a definition of nearby energy generation. [2]

For the previous reason it is assumed here that the electricity generation system is located next to the building and no electricity distribution losses occur. Furthermore, **an off-grid apartment building is considered here as a nearly-zero energy building**, because electricity is produced on site and the following assumptions are made:

- thermal energy is being locally produced according to the requirements of nZEB,
- the building envelope meets nZEB requirements.

"Zero" within the nearly zero-energy building definition typically means net zero over a certain period of time. The period of time expresses a certain time interval within which a nearly zero energy aim should be achieved. The agreed period according to EPBD is one year. Typically, in nearly-zero energy buildings there is a net surplus energy balance in summer and a net deficit of energy in winter, especially in cold climate zones where the energy demand increases greatly during winter. [1]

Zero energy building – a building with a net energy consumption of 0. Energy can be delivered to the building if it's compensated with exported energy [3]

Delivered energy – electric energy drawn from the grid; diesel fuel transported to the building.

Net primary energy – is the primary energy that would be consumed in one year by the building if renewable generation was absent, minus the primary energy equivalent of renewable energy generated.

Prosumers – grid-connected electricity end-consumers who also produce electricity with on-site generation units such as small-scale solar PV, making them electricity producers and consumers at the same time.

Costs – capital costs, cost of energy, operating and maintenance costs, replacement costs, residual value at end of life, all discounted to year zero with a given discount rate (except electricity bought from the grid). Indirect financials like environmental or health costs or the benefits from reduced emissions and better productivity of residents are not addressed for end-consumers. However, indirect benefits from avoided greenhouse gas emissions are briefly discussed separately.

1.2 Energy efficiency in buildings

European Commission's Energy Performance of Buildings Directive states that all new buildings have to meet the nZEB demands by 2020 [1]. It is important to understand that the techniques and approaches for constructing nearly-zero energy buildings are highly dependent on the climate zones. One of the most suitable and widely accepted classifications of climate zones is the Köppen-Geiger climate classification. The European climate classification is presented on the Figure below. [3]

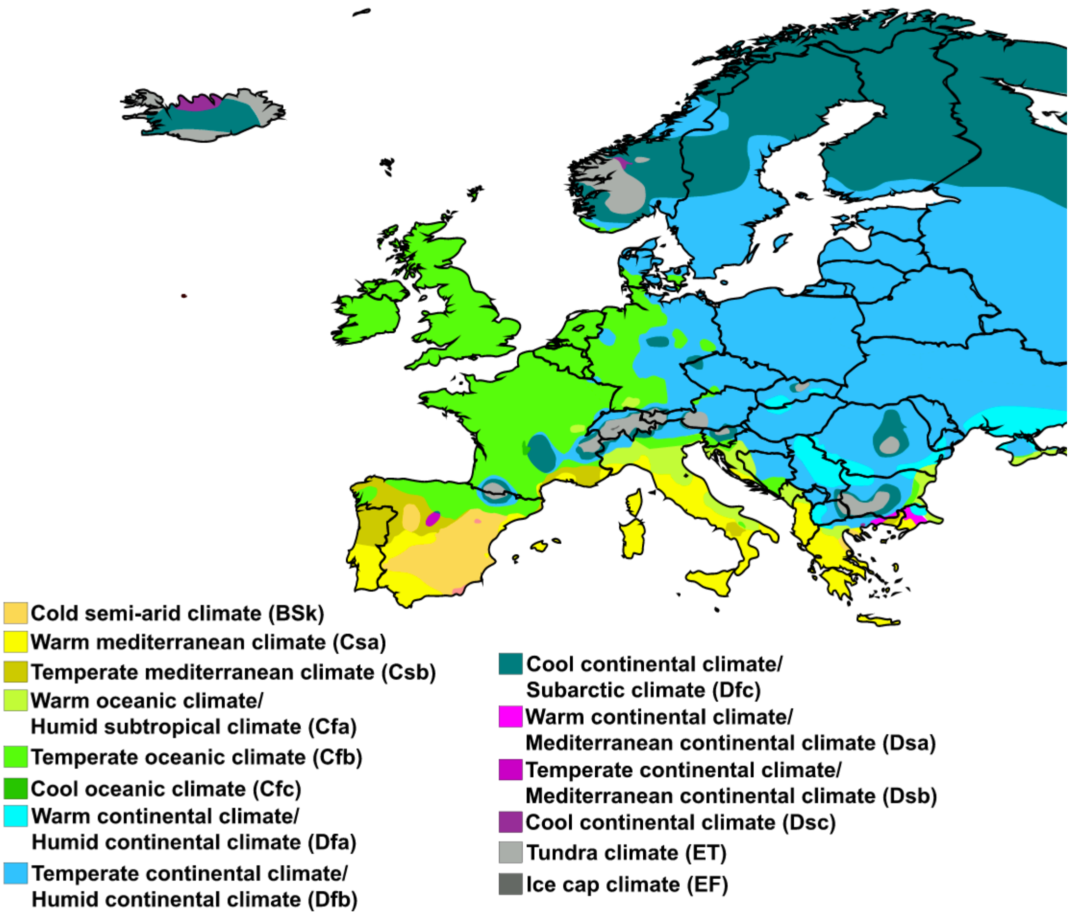

Figure 1.2. Köppen-Geiger climate classification of Europe [3]

As seen from the previous Figure, the Southern parts of Europe enjoy a warm mediterranean climate (Csa), while the majority of Western and Eastern Europe hava been divided between Temperate oceanic climate (Cfb) and Temperate continental climate (Dfb), respectively. The climate of Northen Europe is mostly Cool continental or Subarctic (Dfc). According to Energy Performance of Buildings Directive (EPBD) in Europe, the Köppen Climate Classification of Tallinn, Estonia, is Dfb. As part of the actions related to EPBD, a list of Key Implementation Decisions has been compiled to determine the reference statuses and progress in the field of energy performance of buildings in all EU countries. [1] [2]

The energy performance of buildings is presented in seven energy performance classes rated from A to H, where A stands for low energy consumption and H stands for high. The reference point is energy class C that corresponds to a new building that meets the energy performance requirement. In the year of reference in Estonia (2016) the number of buildings with an Energy Performance Certificate (EPC) was 16 869. Out of the total amount of 300 000 buildings in Estonia, the share of buildings with an EPC was just 5%. The energy performance requirements are mandatory for all new buildings since January 2008, including residential, non-residential and public buildings. It is mandatory to have EPCs for new buildings built after July 2009. For existing buildings, it is mandatory to have an EPC for renting or selling property. [4]

The minimum energy performance requirements are expressed as a primary energy performance according to the building's normal use. In addition, the whole building has to meet the minimum energy performance requirements. Data for standardized use includes a description of occupants, small power equipment and lighting usage profiles, operation times, as well as indoor climate requirements. The energy performance calculation takes into account the energy needs for space heating, Domestic Hot Water (DHW), cooling, lighting, ventilation, and electrical appliances [5]. In this work only the electrical appliances (including lighting and other electricity consumers) are under detailed view. The minimum energy performance value characterizes the net primary energy use of the building. As thermal energy is also included in energy performance calculations, but not addressed by this work, it is assumed that thermal energy is imported to the building (district heating). Due to this, the off-grid building is considered as a nearly-zero energy building in this work.

The number of issued certificates and energy classes in new and existing residential buildings is presented on figures 1.3 and 1.4, respectively.

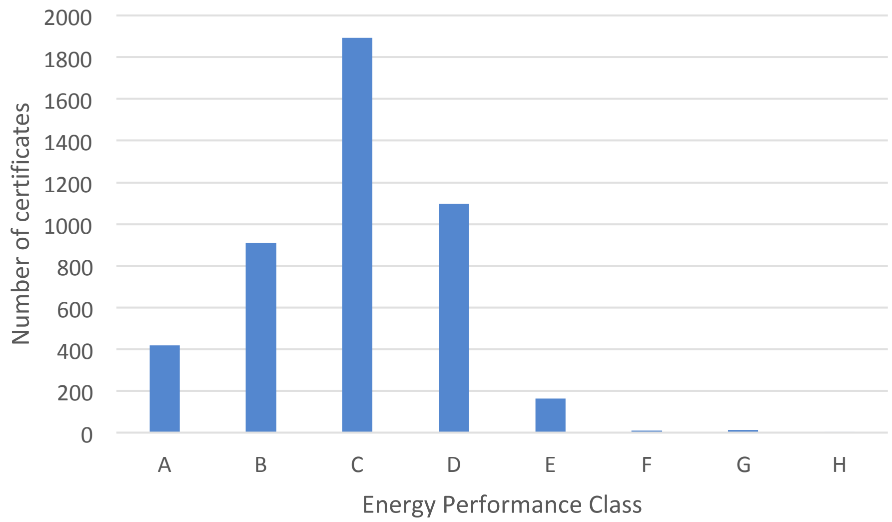

Figure 1.3. Energy performance classes of new residential buildings in Estonia [4]

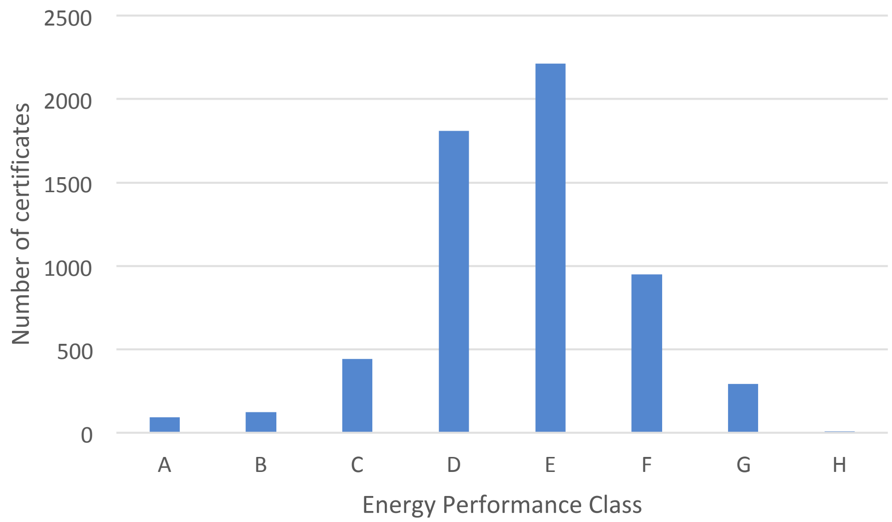

Figure 1.4. Energy performance classes of existing and renovated residential buildings in Estonia [4]

As seen from the figures above, the majority of existing buildings in Estonia are certified for energy performance classes D and E. The bigger part of Estonian residential buildings are panel buildings that were constructed during the Soviet era from 1960s to early 1990s with a design lifetime of 50 years. The Soviet panel buildings were initially constructed as permanent housing facilities until an improvement in housing stock could be afforded. The technology was bought from a French company Camus and it allowed quick and robust panel production and construction. [6]

According to Statistics Estonia there were 700 512 housing rooms in 2017 in total, 255 309 of which were built in 1961-1980 and 151 464 of which were built in 1981-2000. Therefore, approximately a half of Estonian housing rooms are in panel buildings. A panel building from 1-464 series, built in 1960s, can be seen in the photo below. [7]

Figure 1.5. 1-464 series reinforced concrete apartment building in Tallinn, Estonia [8]

The panel buildings, such as the one seen above, were designed for a low electricity demand. Thus, the heat load demand is met with district heating and the apartments have gas stoves.

In Estonia there are approximately 3000 reinforced concrete buildings with just under a tenth of these renovated. Recent energy performance audits in these buildings have shown that without major renovation the panel buildings typically meet the energy performance classes E or F. First, a slight correlation between Estonian housing stock and EPC statistics can be seen. Second, a considerable part of panel buildings, and total housing stock, in Estonia is near the end or past its design lifetime. [9]

Due to this, concerns have risen regarding the panel buildings' lifetime, present performance and durability. It has been noted that while the main bodies of buildings are generally in a satisfactory state, the protruding parts such as balconies and overhangs may pose a safety threat due to their unsatisfactory condition. Therefore, the need for reconstructing or renovation of existing reinforced concrete housing stock has risen considerably.

Kuusk et al. [10] noted that rebuilding would be about four times more expensive than a major renovation of panel buildings. The target of the study was to seek cost-effective solutions for improving energy performance of apartment buildings. It was pointed out that in 2014 the cost-optimal renovating solution over a 20-year project duration was reaching energy performance class B with an investment cost of 150-170€/m^2. The total area of a typical five-floor panel building with four compartments of staircases and 60 apartments is approximately 3900 m^2. Therefore, the renovation cost would reach an amount of approximately 619 000 €. In 2008, a panel building with the same properties went through a major refurbishment with a total budget of 403 035 €. As a result, the heat energy demand decreased from 527 MWh/y to 296 MWh/y, but an energy performance certificate was not issued [11]. Since the beginning of 2017, the construction costs in Estonia have grown about 20%, reaching 1400 €/m^2 for new apartment buildings [12]. The construction expenditure of a new 3900 m^2 apartment building would reach 5 460 000 €. The price growth is caused by the supply of new apartment buildings that is exceeded by the demand.

In 2013, Kurnitski et al. [13] reported that the cost optimal energy performance in apartment buildings in Estonia is 145 kWh/m^2 y primary energy. Additionally, they pointed out that compared to cost optimal level nZEB performance can be achieved with an additional investment of 19 €/m^2, that would account for an additional investment of 74 100 € (12%) for the five-floor building mentioned above.

In 2017, Zangheri et al. [14] analysed various building types in several different climate zones in Europe to determine cost-optimal and and nZEB renovation levels. As a relevant location for Estonian conditions Helsinki, Finland, was addressed in the study. The research found that all parts of cost optimal building envelope – i.e. walls, roof, basement and windows – already meet the thermal transmittance levels to meet the nZEB requirements. Typically a nZEB building has a well-insulated envelope, an efficient heating system (can be district heating) and a solar energy installation. Therefore, it can be concluded that presently nZEB requirements are achievable reasonably through a major renovation. Furthermore, it can be noted that the cost-optimal and nZEB energy efficiency levels in buildings are increasingly correlating.

The primary energy requirements for apartment buildings in Estonia are presented in table 1.1 below.

Table 1.1. Energy performance requirements for apartment buildings in Estonia [5] [15]

	Energy performance, kWh/m^{2}y	**Energy performance class**
New building	150	C
Major renovation	180	D
Low energy	120	B
Nearly-zero energy	100	A
(Net) zero energy	0	

According to energy efficiency requirements in Estonia, a low energy building is constructed in conformity with the best available building practice and equipped with resonable energy efficient and renewable energy solutions. However, it is not assumed that renewable energy would be produced on-site. A nearly-zero energy building meets the same description as a low energy building, but it is additionally assumed that the building includes on-site renewable energy generation. The principle of a zero energy building is similar to a nearly-zero energy building, but the amount of energy that is produced on-site and exported, compensates for the imported energy. [5]

Therefore, the principal difference between low energy, nearly-zero energy and zero energy buildings lies in renewable energy produced on-site. The common choice of technology for such renewable energy installations are solar PV and solar thermal. The general order of preferences in energy efficiency are summed up on the figure below. [5]

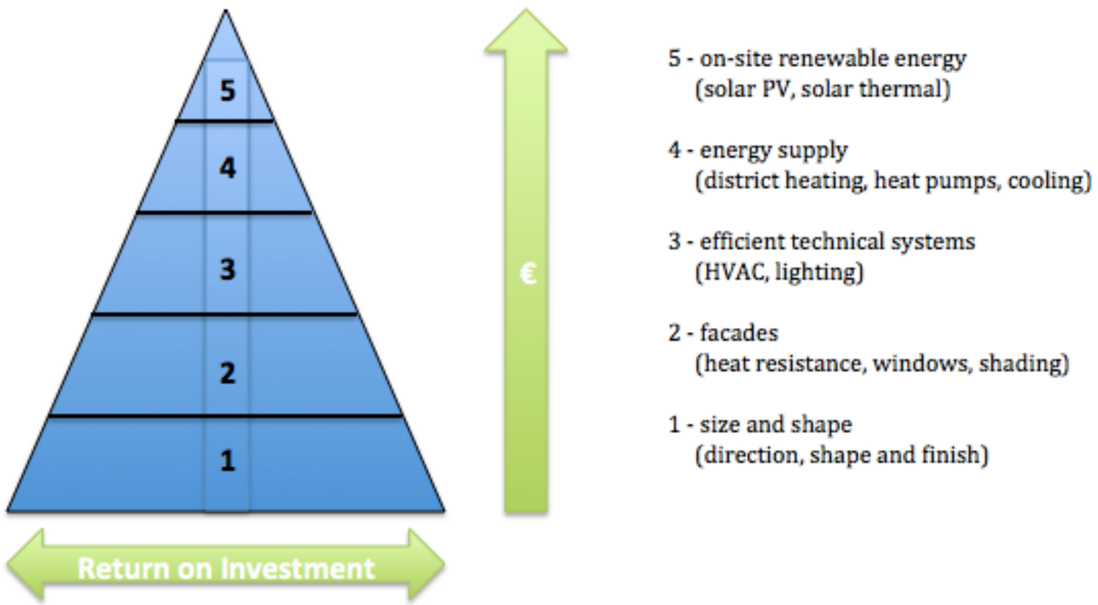

Figure 1.6. Priorities of energy efficiency planning in buildings [16]

As for renovation, insulating external walls has the highest effect (up to 30%) on the reduction of the primary energy consumption. Adding different elements improves the energy performance of a building further. For instance, additional thermal insulation on the facade, replacing the windows and installing a ventilation system with heat recovery will allow meeting the energy efficiency requirements for new apartment buildings. Solar collectors for domestic hot water supply are needed in addition to the previous aspects to reach full technical energy savings potential (up to 70% compared to non-renovated buildings) and fulfil the criteria of low-energy buildings. To further improve energy efficiency and meet the nZEB standard, solar PV panels should be added. As confirmed by numerous research results, reaching low-energy and nZEB energy performance levels is both technically feasible and economically reasonable to apartment owners. However, as the total up-front cost needed for cost-optimal renovation is a major barrier to deep renovation. [2]

As of Spring 2018, there is only one reinforced concrete apartment building that has been renovated to meet nZEB rquirements in Estonia. It is located in Tallinn (Akadeemia tee 5a) and is used as a student dormitory of Tallinn University of Technology. The five-floor building was constructed in 1986 and its heated area is 4318 m^2. The building includes the following elements with their respective capacities and U-values [17]:

- building envelope: walls – 0,11 $W/m^2 \cdot y$; roof – 0,1 $w/m^2 \cdot y$; concrete fillings 0,7 $W/m^2 \cdot y$;
- ventilation system with heat recovery;
- solar thermal collectors and waste water heat recovery for domestic hot water;
- solar PV panels – 14,3 kW.

The entire on-site solar installation is located on the roof of the building, a preferential placement for densely populated areas due to limited land availability.

Estonia has not set minimum requirements for U-values. However, the current Estonian requirements include the definition of cost-optimal buildings:

- a cost-optimal building must ensure the lowest lifecycle cost over a period of 30 years for residential, and 20 years for non-residential buildings [18].

As stated before, the locally produced energy by Renewable Energy Sources (RES) has a positive effect on the energy performance ratio. The median U-values of nearly-zero energy apartment buildings in the European Union are following [19]:

- walls – 0,14 $W/m^2 \cdot K$;
- roof – 0,12 $W/m^2 \cdot K$;
- floors – 0,16 $W/m^2 \cdot K$;
- windows – 1,0 $W/m^2 \cdot K$;
- ground/basement ceiling – 0,33 $W/m^2 \cdot K$.

The most dominant technologies for achieving nearly-zero energy performance are increased insulation and high energy performance windows, mechanical ventilation systems with heat recovery, heat pumps and PV applications. The building service systems are often connected to the district heating network, sometimes with solar support. Domestic hot water (DHW) is mostly generated centrally. [2] [19]

The most frequently applied renewable energy systems are on-building solar thermal and PV systems. In all cases with district heating systems, the district heating generation also includes renewable energy sources such as biogas or biomass. [2]

Most of the completed nZEB projects have reported that the renovation and operating costs were affordable or financially attractive to the tenants. Additional costs compared to conventional buildings have been reported as 0 €/m² in Croatia, 20 €/m² in Denmark, 27 €/m² in Spain and 25 €/m² in Finland [14] [19]. Several projects have reported user satisfaction and improved quality of life. That includes apartment building renovations in Estonia where the renovated building hasn't reached nZEB performance levels [11].

1.3 Energy supply and consumption in apartment buildings in cold climate

As the scope of current work is limited to cold climate in Northern Europe, Estonia was chosen as the region for a detailed study. Single-family houses have been thoroughly analysed in the contexts of nZEB and on-site or nearby energy production. Research addessing single-family houses is widely available in scientific journals and other sources. This work examines apartment buildings in Estonia as there hasn't been much research about their on-site energy production and off-grid operation. Furthermore, this topic is relevant in Estonian context as approximately 70% of the residential buildings are apartment buildings [9] [6]. In addition, the majority of the current building stock has been built during the Soviet era and there is considerable interest in improving the energy performance of these buildings.

In cold climate zones the biggest energy demand in buildings is associated with space heating, followed by energy demand for domestic hot water (DHW). It is worth noting that as energy performance of buildings as an issue is widely addressed and the energy demand for space heating is expected to gradually drop. Therefore, the importance of energy demand for DHW and electrical appliances will grow [16] [20]. The rest of the energy demand comes from electrical appliances. As this work addresses the electricity demand of apartment buildings, the aspects regarding heat energy supply and demand are not further discussed. It is worth noting that the share of renewable energy sources for nZEB is not fixed. With that taken into consideration, the aim of this work is to minimise the use of fossil fuels to meet the building's energy demand.

During the implementation of EPBD, the EU Member States had to develop and determine their own definitions of nZEBs. Across the EU there are various energy performance indicators and targets set by the Member States. These may be related to building insulation, energy demand, consumption covered by renewables etc. In Estonia, the main reference documents have been the Governmental Act No 68:2012 "Energiatõhususe miinimumnõuded" ("The Minimum Requirements of Energy Efficiency") and the Governmental Act No 55:2015 "Hoone energiatõhususe miinimumnõuded" ("The Minimum Requirements for Energy Efficiency in Buildings") for which maximum primary energy demand is the main indicator. It is stated that a very high energy performance of a building is equivalent to building class A (nearly-zero), with a primary energy demand of 50 kWh/m^{2}y for single-family houses, 100 kWh/m^{2}y for apartment and office buildings, for example. The minimum energy performance requirements for each building type in Estonia is presented in Table 1.2 below. Energy performance class A (nZEB) is also assumed for the analysis in this thesis. There isn't a requirement for the share of renewable energy supply in nZEBs, but generally nZEB requirements can't be met without on-site or nearby renewable energy production in Dfb climate zone of Köppen Classification [2].

Table 1.2. Nearly-zero energy performance requirements for each building type in Estonia

Building type	**Energy performance (kWh/m^{2}y)**
single-family house	50
apartment building	100
offices, libraries and science facilities	100
business buildings	130
public buildings	120
commercial buildings and terminals	130
education buildings	90
kindergartens	100
medical buildings	270

The energy performance calculations are carried out according to the standard EN 15603:2008 "Energy performance of buildings – Overall energy use and definition of energy ratings". Determining the share of renewable energy in nZEB's is being developed by Technical Committee CEN/TC 371 "Energy performance of Buildings Project Group" for updating EN 15603.

For the energy performance calculations, EN 15603:2008 states the following: "Inside the boundary the system losses are to be taken into account explicitly, outside they are taken into account in the conversion factor (=primary energy factor). Technical building systems located partly outside of the building envelope are considered to be inside the system boundary. /.../ The assessment can be made for a group of buildings serviced by the same technical systems. /.../ For active solar and wind systems only the energy delivered by the generation devices and auxiliary energy are taken into account in the energy balance (i.e. kinetic energy of wind is not)."

Achieving the values presented in Table 1.2 is challenging due to the location and climate zone of Estonia. As winters are usually cold and the solar energy production is limited at that time, meeting the electrical load demand with on-site renewable energy can prove to be not feasible. The on-site power production possibilities are analysed in chapter 2 of this work. As energy efficiency also includes the building's thermal energy consumption, a high energy performance of the building envelope is even more important than in regions with milder climate. For complementing solar energy, an electrochemical energy storage system, i.e. battery, is introduced to the on-site system. Energy storage enables to prolong the daily (and yearly) hours of on-site solar energy consumption.

Net primary energy consumption was described among the definitions in the beginning of this work. Compared to shorter time frames, yearly nearly-zero energy consumption in off-grid buildings is easier to achieve due to the energy surplus in summer and a higher demand in winter. This can also be expressed with a Load Match Index, which in this work is defined as the simultaneity of energy demand and supply. Different load match indexes for apartment buildings are presented on Figure 1.7 below.

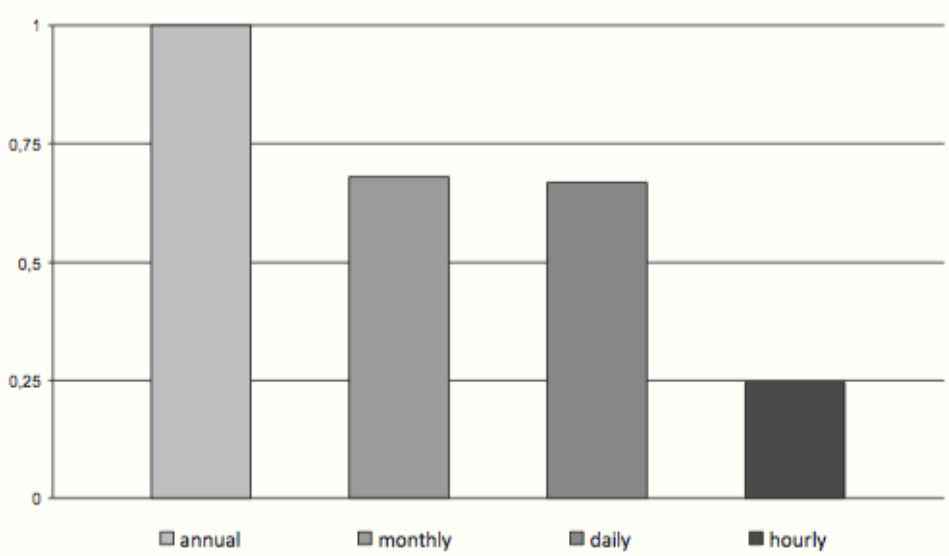

Figure 1.7. Load match index in residential apartment buildings [21]

The low hourly Load Match Index value again presents a necessity for energy storage in off-grid systems, which also has a potential to increase monthly and daily values. To meet a higher load demand in winter with lower irradiation, a large solar system is needed to meet the electrical energy demand. Energy storage can be one of the tools to limit the size of the solar system, in turn reducing the cost of electricity in off-grid power generation installations. In addition, a diesel generator will be used as a back-up power source in the simulation part of this thesis.

1.4 Electricity supply in rural and low population density areas

Flat landscape and natural conditions in Estonia are fairly favourable for building power transmission and distribution lines. Thanks to this there are only a small number of customers (distant farms, family houses) who are not connected to the grid. The electricity demand in rural and low population density areas often varies across the seasons. In addition, there are many connection points with no or a negligible demand. According to Valtin et al. [22] about 60% of Estonian distribution grid supplies 13% of customers with only 4% of total consumption. Due to demographic reasons the consumption in rural areas in Estonia will continue to decrease. There are approximately 722 000 grid connection points in Estonia [23]. It was estimated that in 2013 about 487 000 grid connection points were not profitable for the Distribution System Operator (DSO) due to low consumption [22].

Generally the grids in densely populated areas are well protected and prepared against extreme natural conditions, high variable energy (solar, wind) penetration and other factors. That is usually ensured with higher voltage levels and underground lines. The majority of low- to middle-voltage distribution lines are built on smaller wooden, steel or concrete poles. 86% and 66% of distribution lines in rural and low density areas in Estonia are of such overhead type. This makes distribution lines more vulnerable to extreme climate conditions, falling trees etc. Due to that, there are often problems with energy resiliency in distribution networks. A considerable improvement in energy resiliency can be noted with a 75-80% share of underground lines. The share of underground lines in Estonian distribution grid is considerably lower. However, reinforcing the distribution grid by taking the distribution lines under ground may not be economically feasible for the DSO. [22]

It can be concluded that due to the previously named aspects all of the required investments for improving resiliency in the majority of the distribution grid can't be made when needed. However, during the recent years substantial investments have been made to improve and renew the distribution grid. As of Spring 2018 approximately 65% of Estonian distribution lines were well protected from climatic and environmental affectors. The biggest Estonian DSO Elektrilevi has set a target to make 75% of the distribution grid resilient by 2025. [24]

A high penetration of variable energy sources like solar and wind can adversely affect low-voltage distribution grids. A solution for grid components to withstand reverse power flows, higher peak loads, maintain the required frequency etc is replacing them. However, such method can again be too costly for the DSO. Hybrid power systems in off-grid or microgrid applications can help to overcome some of these issues as these occasionally include energy storage and operate on smart grid principles, enabling better application of demand side management methods. With local energy storage the excess electricity produced in off-grid hybrid power systems is not wasted, but stored and consumed later, instead. Hybrid power systems are studied in further detail in Section 1.5.

In rural and low-density areas the distances between consumers and the nearest substations are remarkably longer than in densely populated regions. The required number and locations of low-voltage substations to provide the quality of service is an issue that is addressed in several works addressing optimization of distribution grids. Since 2015, customers in Estonia have to cover 80% of the grid connection expenses if they are located more than 400 meters from the closest LV substation and the location has not been connected to the grid before [25]. About 25% of the customers live outside of that radius. The cost of establishing a grid connection depends on any location's environmental conditions. The general methodology for calculating the connection fees is presented in the Grid Code [26]. Estonian DSO Elektrilevi estimated that connecting a consumer located 660 meters from the nearest existing substation would cost 13 042.73 € for the customer, which accounts for approximately 80% of the total connection costs [27]. By applying this method, the majority of expenses on building new substations or replacing existing electricity lines are avoided by the DSO. [28]

1.5 Hybrid power systems for distributed energy production

Individual customers in residential buildings such as apartment buildings and private houses are generally connected to the electricity grid. Therefore, the consumers are supplied with energy through low- and medium-voltage distribution networks. As the distribution networks were initially intended for only supplying energy, the increasing amount of prosumers (especially in rural areas) sets an additional stress on the networks with frequency problems, higher possibility of short circuit currents etc [29].

As this work proposes an off-grid hybrid power system model and simulates its operation in Estonia, it is necessary to point out that because of the country's relatively small area and flat landscape, connecting rural areas to the grid has not been a complex task historically. Therefore, operational off-grid installations or separate micro-grids are uncommon in Estonia. Currently there are two known separate micro-grids in Estonia, which are located on small islands of Prangli and Ruhnu, respectively. However, the trend is expected to change and the Electricity Market Act states that new micro-grids shall be constructed in a way that ensures the quality of service and supply is not worse than in the big electricity grid [25].

The soon-to-be implemented nZEB standard requires local energy generation in cold climate. Assuming that all nZEB's that will be built from 2020 will include their own electricity generating installation (as required by [5]), several off-grid scenarios for electricity production will be analysed in the current work. These power production installations are also called hybrid power systems as they combine multiple energy sources such as renewables (solar and wind among others), energy storage and often include diesel generators as a back-up source. Before simulations and financial analysis is carried out, the components of the proposed hybrid power system will be described in more detail. A basic conceptual scheme of a typical residential-scale hybrid power system is presented on figure 1.8 below.

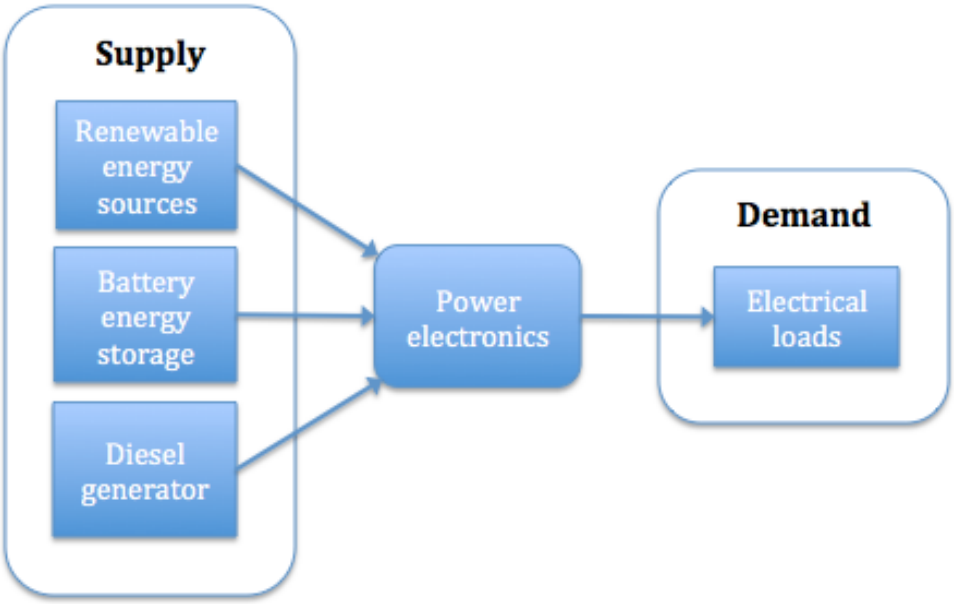

Figure 1.8. Conceptual scheme of a hybrid power system (author's drawing)

1.5.1 Solar photovoltaic panels

Solar radiation can be converted into electricity with photovoltaic panels that are assembled of solar cells. Photovoltaic (PV) panels in turn can be joined to form a solar PV array. Solar power installations with desired capacities can be formed with several arrays, varying from small residential to large utility scale solar power plants. According to International Energy Agency, solar PV is the fastest-growing source of electricity. At the same time, the cost of solar PV is rapidly decreasing, making it increasingly appealing for both energy producers and customers. In certain locations and conditions solar PV is the cheapest power source. [31]

Solar PV installations are common in hybrid power systems, micro-grids and off-grid installations. In the context of off-grid and nearly-zero energy buildings, solar PV is the most popular choice of generation units. PV panels can be integrated into the façade or installed on the roof of the building without further land use, for instance. A study found that solar PV panels are used at about 70% of all nZEBs included in the samples, followed by various means of renewable thermal energy generation: solar thermal, ground source heat pumps, biomass and renewable district heating. [2]

A graphical explanation of solar radiation and solar energy consumption is presented in figure 1.9 below.

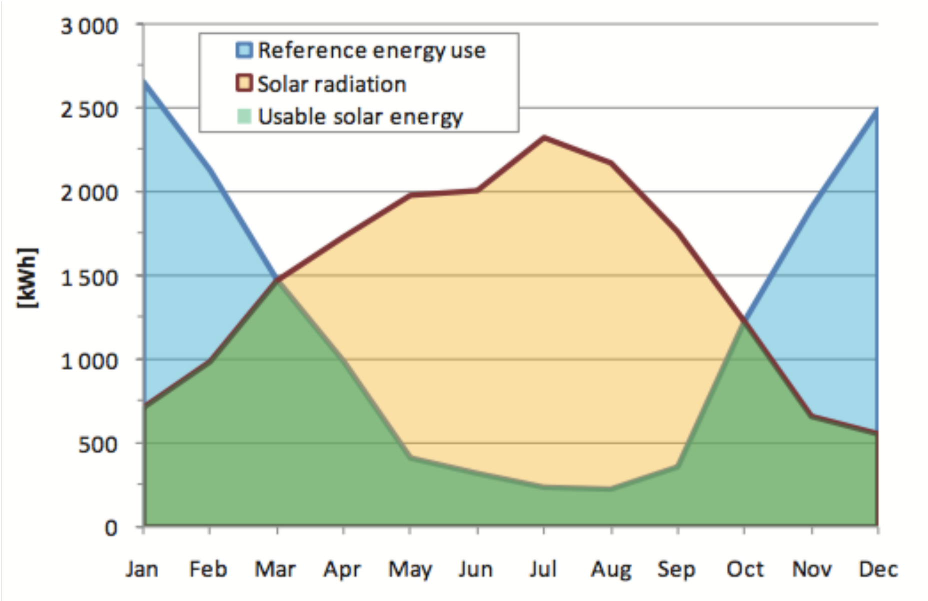

Figure 1.9. Monthly residential energy use and solar radiation [21]

As presented in the figure, the usable solar energy and the reference domestic energy use do not match neither during a given day or during the year. The figure shows that the amount of usable solar energy peaks in March and October. For an analogous intraday graph, the amount of usable residential energy typically peaks before the noon and in the late afternoon. When the solar radiation is higher than the reference energy use, the excess solar energy needs to be stored for later use, otherwise it will be unused and wasted. During wintertime the amount of stored renewable electricity is lower due to lower solar radiation and elevated electrical load demands. In addition, using energy storage or managing the electricity demand allows reducing the net electricity consumption daily and yearly.

Solar yield

In order to maximize the yield of solar PV installation, Global Horizontal Irradiance (GHI) is of most interest as it takes both Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DHI) into account. DNI accounts for solar radiation that is received by a surface that is always at 90° compared to the Sun's rays. DHI includes the radiation that a surface does not receive directly, but is scattered and received from any undetermined direction. GHI is determined with Formula 1.1 below [31]:

$$GHI = DNI \times \cos\theta + DHI \qquad (1.1)$$

where θ – zenith angle, which is the angle between the Sun's rays and the horizontal plane, °.

GHI is directly impacted to the varying declination of the Earth. Declination is the angle between the Sun's rays and the Earth's equator. The yearly declination fluctuates between +23,45° and -23,45°, which means that the amplitude of yearly declination is over 46°. The declination is calculated with Formula 1.2 [31]:

$$\delta = 23{,}45 \sin\left[\frac{360}{365}\times(284+n)\right] \tag{1.2}$$

where δ – declination, °,

n – the day of the year.

The highest solar declination values are can be witnessed in Summer, which in Northern Hemisphere means that there are more hours of daylight during Summer. This in turn ensures that the maximum solar yields in Northern hemisphere are during Summer and the lowest during Winter. The previously mentioned phenomenon is also seen in Figure 1.9. As the latitude of Estonia is approximately 59°, the Sun's path is noticeably lower during Winter months. During that time, maintaining the optimum tilt angle of PV panels is of particular importance as the electricity demand is the highest and available solar radiation at its lowest.

Tilt angle is defined as the angle between a horizontal (or a vertical) line and the PV panels. The optimum tilt angle generally positions the PV panels perpendicularly to the Sun. According to Agrawal and Tiwari [31], depending upon the season, the PV system should be tilted towards equator at an angle of ±15° of the latitude of the site. Qiu and Riffat [32] found that the tilt angle should be set at ±10° of the latitude of the location. Some other scientific studies determined the optimum angle value in the ranges of ±8° (Lewis) [33] and ±5° [34], respectively. Soulayman [35] found that the energy gains from daily and monthly tilt angle adjustments are not significant. Therefore, seasonal angle adjustment can be considered acceptable as it counts for 1% losses when compared to monthly angle adjustment [35]. In order to increase the yield from the solar array with limited extra effort, it is recommendable to change the tilt angle of PV panels at least twice a year.

Similar recommendations are presented in other sources. Compared to a tracking system (optimal yield), a fixed installation receives 28,9% less energy while adjusting the tilt angle twice or four times a year yields 24,8% and 23,3% less energy. Due to climatic conditions and high latitude, close to 90% of the annual solar output could be produced from March till October in Estonia. Therefore, it is preferable to set the tilt angle so that the energy yield would be greater in summer. As the solar trackers are notably more expensive than fixed or adjustable frames, the cost optimal solution for residential- or microgrid-scale PV would be adjusting the tilt angle twice (in March and September) or seasonally (in April, August, October and March). [36]

As PV panels generate electricity from sunlight, shadows cast on them should be avoided to the greatest reasonable extent. In order to maximise the energy yield from solar PV installations, a sufficient distance between module rows shall be kept. By this method shading losses in module rows are avoided. If a solar cell in a panel is shaded, the electrical current through the entire string (cells connected with one wire) is obstructed. This can be partially avoided with the use of bypass diodes. Without sufficient distance between module rows, the energy loss in shaded arrays can measure up to 100% [38]. When available area on the site is limited, this also sets a limit on the number of module rows that can be installed. The placement of solar arrays in a PV system is presented in Figure 1.10.

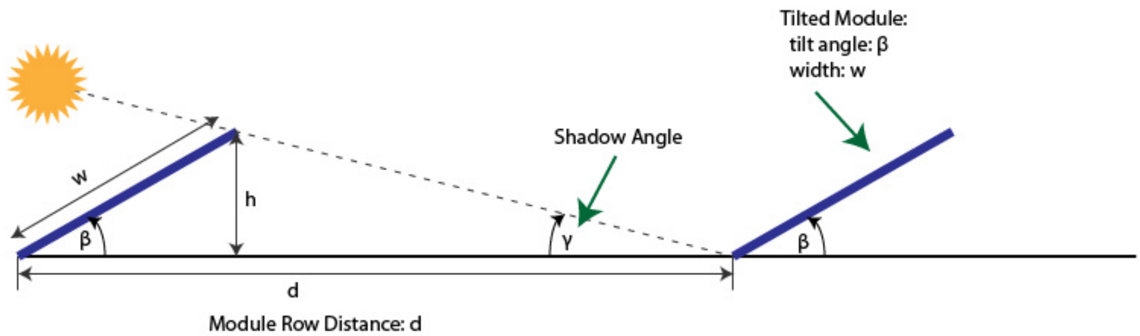

Figure 1.10. Placement of PV panels in a solar array [37]

The distance between solar arrays can be found with formula 1.3 [31]:

$$d = \sin(\beta + \gamma) \times \frac{w}{\sin \beta} \qquad (1.3)$$

where d – module row distance, m,

β – PV module tilt angle, °,

γ – shadow angle, °,

w – length of PV module's vertical side, m.

However, the formula above is only precise when determining the shadow distance between arrays, meaning that the values obtained are correct at solar noon only. Solar noon is the point in the Sun's daily path when it's located directly in the south. Therefore, the shadow distance value needs to be corrected with azimuth angle. The shadow length d_{shadow} and minimum solar array spacing d_{arrays} can be calculated with formulas 1.4 and 1.5 [31] [39]:

$$d_{shadow} = \frac{h}{\tan \gamma} \quad (1.4)$$

where h – heigth from the ground to the top of arrays, m.

and

$$d_{arrays} = d_{shadow} \times \cos \psi \quad (1.5)$$

where ψ – azimuth, °.

The heigth of solar arrays is calculated with formula 1.6:

$$h = \sin \beta \times w \quad (1.6)$$

In order to determine the distance between solar arrays in Estonia, it should be done based on the wintertime tilt angle, because the shadows are the longest then. It is assumed that 60-cell PV panels will be used in the installation. According to the PV panel database compiled by the author of this thesis, w value for 60-cell panels is generally 0,990 meters. To determine the shadow angle γ with a sufficient confidence level, sun height at solar noon on December 21st (the shortest day of the year) was simulated using PVsyst ver 6.7.0; PVGIS [40] and University of Oregon's Sun Path Chart program [41]. As a result, a sun path chart for Estonia was compiled. The chart can be seen in Figure 1.11 below. Note that there are no gaps in Sun path chart as it is assumed here that there are no high objects around the solar field and as a result, no shadows are cast on the solar arrays.

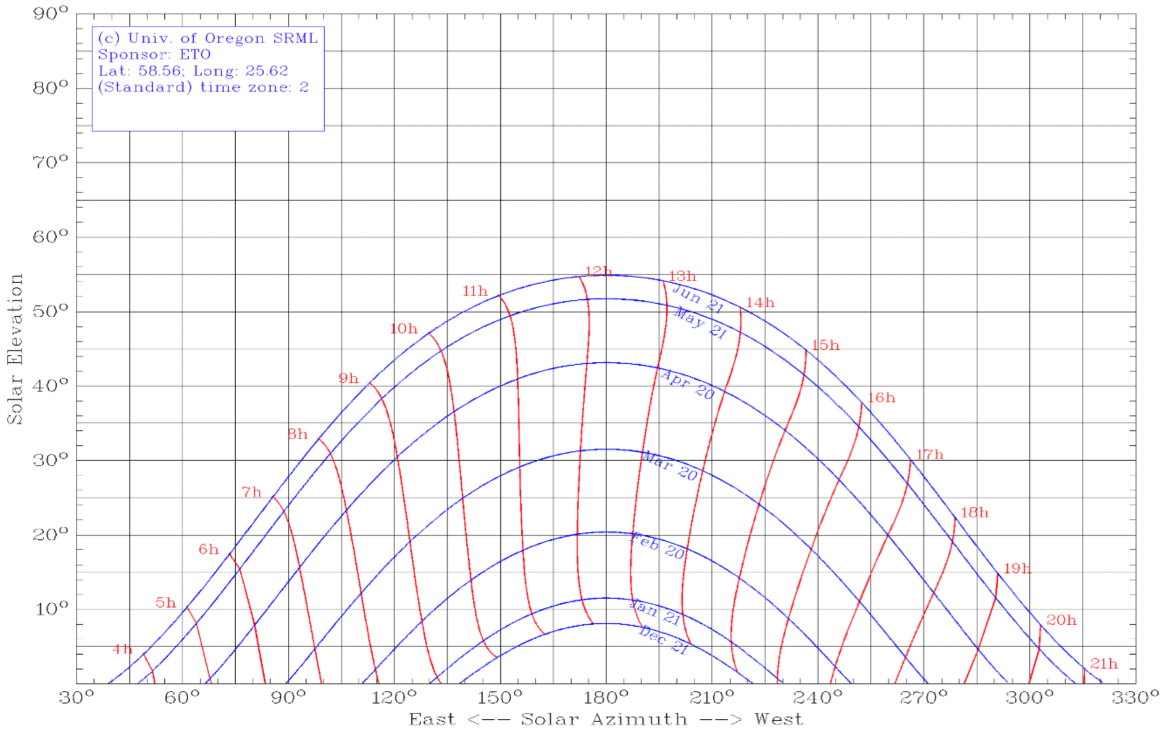

Figure 1.11. Sun path chart for a given location in Estonia [41]

The results of simulations were approximately equal with all programs used: γ = 8°. According to Soulayman's methodology [35], the optimal PV module tilt angle β for December in Estonia is: β = 82°. To simplify the solar array distance calculation, an optimisation of the tilt angle for the whole winter season in Estonia was carried out with PVsyst (ver 6.7.0) software. From October to March β = 66°. With these data the shadow length of solar arrays can be found with formula 1.7:

$$d_{shadow} = \frac{\sin 66° \times 0{,}990}{\tan 8°} \approx 7{,}18 \qquad (1.7)$$

To calculate the minimum distance between solar arrays, it is necessary to know the angle between direct South and the Sun at the start and end of expected energy production. The chosen times were 9:30 in the morning and 15:00 in the afternoon, which are shortly after sunrise and before sunset on December 21st. From the previously composed sun path chart it can be seen that ψ at chosen times is approximately 35°. As both shadow length of 7,18 meters and azimuth of 35° are known, the distance between solar arrays (in meters) can be found with formula 1.8 as follows:

$$d_{arrays} = 7{,}18 \times \cos 35° = 5{,}88 \qquad (1.8)$$

After the azimuth correction it was found that the minimum distance between solar arrays shall be at least 5,88 meters, which is about 18% less than shadow length. It is common to set the array distance equal to the shadow length. Therefore, this correction enables the owner to install up to 18% more PV modules on the same area or decrease the PV installation's land use by 18% at most.

The solar panel tilt angles were optimised with simulation software PVsyst. Based on solar irradiance data gathered in Tõravere observatory, the optimal tilt angle during April-September is 34° and from October to March the optimal value is 66°. The recommendable azimuth in both cases was found to be 0° (facing south). The annual measured GHI in Southern Estonia is 963,8 kWh/m^2y. For a fixed tilt angle the optimal annual value is 42°. However, increasing the tilt angle for wintertime will help mitigate the strain from snow load on the PV panels in addition to increased energy yield. Therefore, a fixed tilt angle is not used in current work.

In the off-grid models proposed in this work it is assumed that the only shadows in the PV installation are cast by PV panels. Therefore, shadows from other surrounding objects e.g. trees, buildings are neglected in the model. It is also assumed, that there are no limitations to the area of the installation. On one hand, it is recommendable to install as many PV modules on the roof of the building to minimize the ground area that is occupied by the PV installation and to effectively use the roof of the building that otherwise might not have a practical application. On the other hand, it should be considered that ground-mounted PV installation total cost is likely lower than a building-mounted installation, as the construction works and mechanical parts (i.e. PV array racks) can be more robust on ground-mounted installations, making them cheaper. Simplifying the installation is an efficient solution for lowering the capital cost of the installation.

The other components that are considered to be a part of the PV installation are inverters and cables. Inverters are an important part of the PV installation as the electrical appliances generally consume electricity in the form of alternating current (AC), but the PV panels produce electricity in direct current (DC), which is not suitable for the majority of household appliances. Then, inverters are used to convert PV array's DC production to a more suitable AC form. Similarly to PV panels and other components, inverters are produced for different operating conditions, voltages, intended applications etc. Therefore, various options and aspects should be addressed in order to choose an optimal inverter for the system.

The main aspects to be considered when choosing a suitable inverter for the PV installation are as follows [42]:

- If the inverter is undersized and the available solar power exceeds the inverter's maximum power, the system's efficiency decreases. This phenomenon occurs because all of the available power can't be converted from DC to AC when the inverter is undersized. However, the inverter can be overloaded for a small amount of time as peak solar irradiances occur for a very limited amount of time.
- Generally, inverters' efficiency is high – about 98% for residential-scale string inverters. Inverters use a small amount of energy for own-consumption. Therefore, the system losses due to inverters are proportionally larger when there is little available solar power and the inverter is operating at low loads.
- High solar irradiance and warm ambient temperatures result in a higher PV panel temperature, which in turn decreases the efficiency of the PV panel. According to the database of PV panels (including top 15 Tier 1 manufacturers of Bloomberg New Energy Finance) compiled by the author of this thesis, the temperature coefficient of most Silicon-based PV panels on the market is in the range of -0,3...-0,4%/°C. In this context, colder temperatures are favourable for solar power production which is one of the main benefits for solar PV in cold climate zones.
- The output of PV panels drops during exploitation. Typically, manufacturers provide a warranty of PV degradation, rated at 80% of nameplate power at the end of panel's operational life. Silicon-based PV panels reach the previously mentioned degradation level after 25-30 years. According to the author's PV database the power output of PV panels degrades approximately 2-3% in the first year of operation. From the research conducted by Edwin [43], Goswamy [44] and NREL [45] it can be concluded that PV panels' effective operating life can exceed well beyond the warranted period and the degradation rate is slower than presented in warranties.

Zürn et al. found that oversizing of the inverter is justified for on-grid applications where a higher amount of energy fed to the grid produces a higher revenue in form of a feed-in tariff. On the contrary, undersizing the inverter limits the amount of usable solar power to the maximum power of the inverter. As one of the hypotheses of this thesis is related to profitability of off-grid operation, an undersized inverter will be chosen for the simulation. This is also recommended by well-known inverter manufacturers. It should also be taken account that the input solar power to the inverter is expected to drop for the reasons previously mentioned in this chapter. It should be kept in mind that the inverter's size should at least match the highest supplied loads that are supplied from the system's DC side in off-grid scenarios. [42] [46]

The maximum recommendable powers of the solar field and inverter are in the following relation 1.9:

$$P_{PV} = \frac{P_{AC}}{\eta \times k_P} \quad (1.9)$$

where P_{AC} – AC output of the inverter, W,

η – efficiency of the inverter, %,

k_p – power coefficient between P_{PV} and P_{AC}, value chosen here is 1,1.

The proposed off-grid systems are parallel hybrid system, meaning that the power flows on parallel AC and DC buses. AC generating units and loads are connected to the AC bus, while PV panels and the battery storage system are connected to the DC bus. It should be noted that if the storage system has an integrated inverter, it can be connected directly with the AC bus. In order to maintain the quality of electricity, the voltage and frequency on both buses have to be kept within the required amplitude. In off-grid systems, the DC-bus voltage is regulated by batteries, solar arrays or a generator. When the voltage of the DC-bus is stable and no power is absorbed from the inverter, all of the DC power is fed to the AC-bus via the inverter. Dong et al. found that the required amount of power to maintain the stability of the DC-bus is marginal. Thus, it is assumed that no power is consumed exclusively for maintaining the stability of the system. [47]

Cables

Solar cables connect the PV panels with the rest of the components in the PV installation such as inverters, charge controllers etc. It is recommendable that the PV system losses from cabling don't exceed 1-2%. It is recommended to oversize the cabling to increase reliability, long term savings and reduce losses. When the cabling is substantially undersized, it can lead to adverse consequences due to lower voltage and overheating. In addition, smaller cables make the system vulnerable to solar power surges. Using aluminum cables with a cross-sectional area less than 16 mm^2 is restricted with standards in Estonia. Therefore, when choosing aluminum cables, the cross-sectional area shall be at least 16 mm^2. [48]

The optimal cable cross-section area is found with formula 1.10 [49]:

$$S = L \times \varrho \times \frac{P}{U^2 \times E_{loss}} \quad (1.10)$$

where S – cross-section area, mm^2,

L – length of the cable, m,

ϱ – resistance (copper) 1,7 x 10^{-8} ohm·m,

P – power in cables, W,

U – system voltage, V,

E_{loss} – energy losses in wires, %.

PV panels can be installed in arrays in both portrait (wider side vertically) and landscape (wider side horizontally) orientation. The number of panels in a given area can be calculated with formula 1.11 as follows [39]:

$$n = \frac{S}{d \times l} \tag{1.11}$$

where n – number of panels in a given area,

S – the site area, m^2,

d – module row distance, m,

l – length of PV module's horizontal side, m.

When replacing the equation for module row distance (formula 1.3) to formula 1.11 the following equation 1.12 is presented [39]:

$$n = \frac{S}{d \times l} = \frac{S}{\sin(\beta+\gamma) \times \frac{w}{\sin\beta} \times l} = \frac{S \times \sin\beta}{\sin(\beta+\gamma) \times w \times l} \tag{1.12}$$

Therefore, the number of PV modules that can be installed in a given area does not depend on the orientation (portrait or landscape) of the modules.

The typical wire length from PV panels' junction boxes is approximately 1 meter to allow for connecting the modules in landscape orientation if needed. During the planning phase when choosing the PV panels' orientation it should be kept in mind that all PV panels can't be installed in landscape orientation. [39]

Generally the panels in PV arrays are connected with cables using daisy chain wiring method, where adjacent panels are connected in series for the whole length of the solar array. However, applying such wiring method on vertically oriented panels results in longer wiring than necessary. When connecting the panels in strings, the excess wiring can be coiled together for a tidy finish, but when that step is skipped, it might lead to major faults with junction boxes and grounding due to hanging excess wires. Furthermore, cable in the length equal to the width of the array is additionally needed to connect the array to other system components. The probability of such risks occurring can be considerably limited with leapfrog wiring method, where the panels aren't connected in series but every other panel is connected instead. By this method the cables are used optimally, ensuring savings in material and labor costs. [50]

The relation between wiring methods and panels' orientation can be concluded as follows [50]:

- Vertical (portrait) orientation – leapfrog wiring;
- Horizontal (landscape) orientation – daisy chain wiring. This orientation can't be used for all PV panels.

Graphical expressions of daisy chain and leapfrog wiring are presented on Figures 1.12 and 1.13 below.

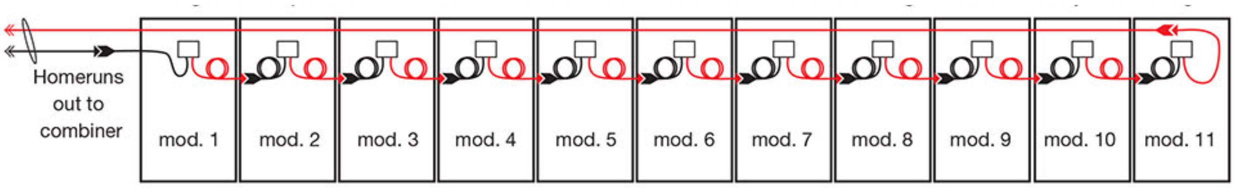

Figure 1.12. PV module array connected with daisy chain wiring method [50]

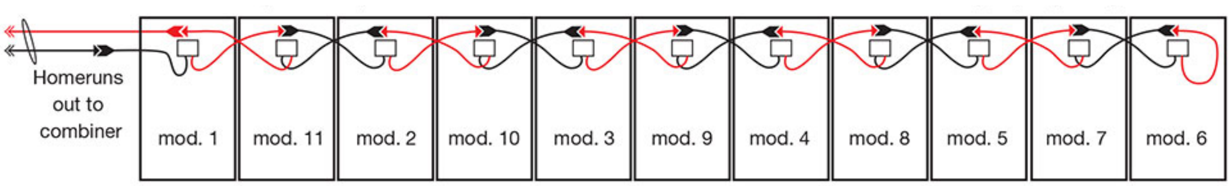

Figure 1.13. PV module array connected with leapfrog wiring method [50]

1.2.2 Electrochemical energy storage

Energy storage has become an important part of modern power systems by addressing several power system issues. Energy storage systems have had various applications historically, including storing low-price electricity for peak-time consumption, providing back-up power during supply failures and improving power quality by balancing power supply and demand. More recently energy storage technologies have also mitigated problems related to power fluctuations and inflexible power supply. [51]

A vast majority of installed energy storage systems are based on pumped-hydro technology, which is similar to conventional hydro power plants. Pumped-hydro power plants (PHPP) enable bulk energy storage by pumping water between an upper and a lower reservoir. When the electricity prices are low, the higher reservoir is filled with water. During peak-load periods with high electricity prices, PHPPs work like conventional hydro power plants with water flowing towards the lower reservoir. Despite being a mature technology, the usage of pumped-hydro is generally limited to large utility-scale applications with other constraints including a limitation to possible sites. [54]

The main downside of solar energy production is intermittency, meaning that it fluctuates uncontrollably. As an opposite, during extensive periods of favorable conditions solar energy production can exceed the consumption. The consequences of the previously mentioned factors can effectively be addressed with energy storage systems. Energy storage systems enable to mitigate the intermittent nature of power output when paired with variable energy sources like solar, improving the quality of energy. In addition, energy storage makes electrical load following with variable energy sources (i.e. solar and wind) possible and improves the usage rate and competitiveness of variable energy sources against conventional power production. The economical aspects of the proposed hybrid power system models will be discussed in Chapters 2 and 3 of this work. [52] [53]

The current work focuses on electrochemical storage technologies, i.e. batteries, as they can be easily combined into storage systems with an optimal capacity for various applications, ranging from residential end-consumers to utility-scale services. As high altitudes and extreme temperatures generally have an adverse effect on batteries, such conditions would not be limiting factors in Estonia. In this paper smaller residential-scale off-grid storage systems are analysed in detail. The principal types of applications and purposes of storage systems for end-consumers in micro-grid and off-grid locations are presented in Table 1.3 below.

Table 1.3. Applications of energy storage for end-consumers in on-grid and off-grid conditions [56]

Application	On-grid/microgrid	Off-grid/islanded microgrid
Load leveling		
Load following	The storage system follows the load curve to ensure that only enough power is fed to the consumers to meet the demand. Excess (renewable) power is stored for later when demand exceeds production.	
Demand side management: distributed energy	Storing low-cost power for use during peak demand and improving security of supply	-
Peak shaving	Reducing demand charges from the utility grid by discharging the storage during peak load	-
Renewables grid integration	Changing the net load shape and improving energy quality	-

Depending on the application, use and site conditions, the most common battery technologies include Lithium-ion, Sodium-Sulfur, Lead-Acid, Vanadium Redox Flow etc. Each of the technologies has its limitations and strengths, with the major aspects related to cost and technical parameters (energy density, cycle-life, efficiency etc). In the current work Lithium-ion and Lead Acid batteries are analysed in detail as these represent the most common battery technologies. Lead Acid has been the most common and mature electrochemical energy storage technology to date. Thanks to its maturity, Lead Acid technology has been studied and installed in micro-grid and off-grid solutions for a long time. Lithium-ion technology is currently in a state of rapid development and has lately been the fastest improving battery storage technology, with a great potential to soon achieve a lower specific cost than Lead Acid technology. Based on the previous facts it is assumed that these two technologies are most reliable in long term. The principle of both technologies is similar – the two electrodes are placed in an electrolyte which enables an electrochemical reaction in the battery cell to occur.

In the proposed power system modesl the entire battery storage system is made up of same battery units from the same supplier. Therefore, the characteristics, chemistry and properties of the battery units are assumed to be identical. Under these conditions it can be determined that behaviour of the units across the proposed storage system are in conformity. It is also assumed that the storage system is used according to the supplier's recommendations by remaining within the limits of recommendable states of charge (SOC) and not exploiting the batteries in other ways that might have an adverse effect on their properties and operational life. However, degradation of the system over its operational life in business-as-usual scenario is taken into account. [55]

The principal variables determining the suitability of different battery technologies with different applications are the cost and cycle life (number of charge-discharge cycles in a batterys lifetime), allowed depth of discharge, charge/discharge current and time and environmental conditions of the installation site. [56]

The optimal capacity of the battery can be calculated with formula 1.13 [57]:

$$E_{g,i} \leq E_{C,i} \rightarrow E_{res} = \sum_{i=1}^{n} E_{res,i} = \sum_{i=1}^{n} E_{c,i} - E_{g,i} \quad (1.13)$$

where $E_{res,i}$ – required capacity in hour *i*, Wh,

E_{res} – daily average required capacity, Wh,

$E_{g,i}$ - generated electricity in hour *i*, Wh,

n – 24 (hours in a day),

$E_{c,i}$ – electricity consumption in hour *i*, Wh.

Li-ion batteries

Li-ion has become the technology of choice in portative devices and applications thanks to its high energy density and relatively low mass-production price. With intensive research and development the cost of Li-ion batteries has rapidly fallen, which makes the technology more desirable. Li-ion batteries have a high charge/discharge cycle efficiency of up to 98%. The energy density of Li-ion batteries is 120-180 Wh/kg. The calendar and cycle life of Li-ion batteries are 15 years and 5000 cycles, respectively. The main advantages of Li-ion technology include wide market availability, a steady discharge current and low stand-by losses. However, Li-ion batteries are sensitive to over-discharge and can not always withstand deep discharging. The other disadvantages of Li-ion batteries are relatively high capital cost and standby degradation. [56] [57]

The working principle of a typical Li-ion battery is presented in Figure 1.14 below.

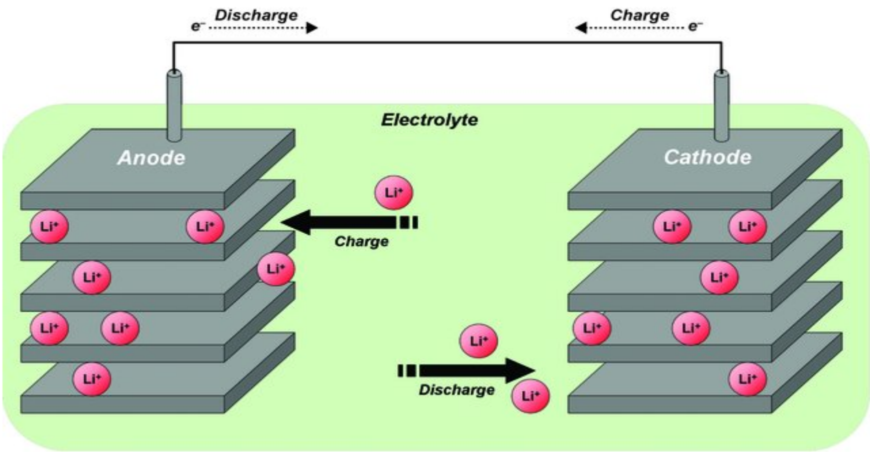

Figure 1.14. Working principle of a typical Li-ion battery [58]

The structure of a typical Li-ion battery is similar to capacitors. The three layers – Lithitum anode, separator and Graphite cathode – are wrapped around each other. All the layers are placed in an electrolyte which enables an electrochemical reaction to occur.

Lead Acid batteries

Lead Acid-based batteries are the most common energy storage devices to date. It can be considered the only mature electrochemical energy storage technology, which has made it relatively cost-effective, with a long operating life and a low self-discharge. Lead Acid (LA) batteries can be used in applications that require deep discharging as they can withstand a deep State of Charge (SOC) well. Therefore, LA batteries are technologically well-suited for off-grid and residential applications. The electrodes are generally made of Lead Oxide (positive) and porous Lead (negative) and sulphuric acid is used as an electrolyte. [57]

The principle of a typical Lead Acid battery is presented in Figure 1.15 below.

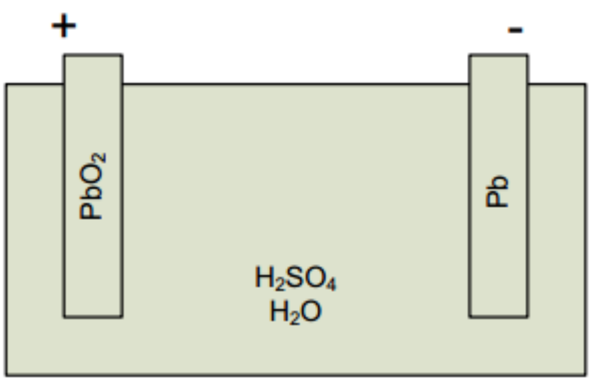

Figure 1.15. Principle schematic of a Lead Acid battery [57]

LA batteries are more sensitive to high tempearatures than Li-ion batteries. That does not have a great importance in cold and mild climatic conditions in Estonia, but should be kept in mind when planning an energy storage system in a hot region. The average roundtrip efficiency of LA batteries ranges between 75-85%, which is lower than Li-ion batteries. The specific energy of LA batteries is about 30 Wh/kg, which is several times lower than that of Li-ion batteries. The calendar and cycle life of LA batteries is similar with Li-ion: 15 years and 3000 cycles. Therefore, LA technology is not as well suited to portable applications where the weight and dimensions of the energy storage system are important. In this work a stationary application is studied and it is assumed that the available space for batteries is not limited. Therefore, a lower energy density and bigger occupied area by the battery bank are not considered as limiting factors. [57] [59]

1.2.3 Diesel generators

Diesel generators can be used in distribution networks, microgrids or off-grid applications to improve the system's reliability. Sometimes the faults or the lack of available renewable power in grids or off-grid systems can cause blackouts. This means that the electrical load demand can't be satisfied. For these reasons diesel generators are used, as the electricity production can then be controlled to ensure the security of electricity supply at all times. Diesel generators generally make a lot of noise when operating. Thus, the generator is sometimes surrounded by a noise shield or placed inside another building to avoid disturbing the nearby residents. The generator room should be located at least 60 meters away from the residential buildings to reduce the noise to an acceptable level of 30-40 dB [60] [61].

The principal variables related to diesel generators are fuel consumption, fuel prices, operating speed and maintenance intervals. As fossil fuel prices are expected to grow in long term, operating a diesel generator will become more expensive over time and needs replacing with other fuels in the future. Generally the producers present a data sheet along with the generator to show its operation speed and fuel consumption. The generators that operate at or below 1800 rpm have a longer lifetime and have longer maintenance intervals. Most of the generators require minor maintenance works (oil change, replacement of filters and coolant etc) after every 500 or 1000 operating hours. In off-grid solutions these maintenance times should be considered as potential times of power outage when no other generation units are actively producing electricity. Bigger generators operate on three phases and generally use liquid coolants instead of smaller one phase generators which can often be air cooled. For the studied installation a three-phase generator with liquid coolant should be preferred. As one of the aims of the installation is to reduce fossil fuel consumption, the generator would only be used as a back-up power source if possible. [30]

2. SIMULATION AND MODELLING OF HYBRID POWER SYSTEMS

HOMER Pro software is used as a simulation tool to determine the technical and economical feasibility of different power system configurations for an off-grid apartment building. HOMER is one of the most common microgrid simulation programs. The inputs to HOMER simulation include load data, climate data, economical data and data about the simulated components. Based on these inputs and its own library data, HOMER finds the optimal sizes of the system components and calculates the costs for each simulated scenario. HOMER is a user-friendly software that can be used for free during a trial period. After the trial, a subscription has to be made to continue using HOMER. The detailed description of the working principle and an exhaustive user manual of HOMER can be found on the webpage of HOMER Energy [62].

2.1 Building's energy flows

In this work it is assumed that the studied building is connected to the district heating system. In addition, due to the cold climate conditions the cooling energy needs for the studied building can be neglected. In fact, air conditioners are not commonly used by individual residents in apartment buildings. Therefore, it is assumed that the energy needs for heating and cooling are not covered by the on-site energy supply installation. The data about the simulated building is presented in Table 2.1.

Table 2.1. Data of the simulated building

Parameter	Value
Construction year	2006
Floors	5
Apartments	18
Dimensions (heigth, length, width), m	17 x 17,9 x 17
Closed area , m^2	1317,7
Heated area, m^2	1220,6
Usable roof area, m^2	230

The building's specific electricity consumption can be considered average. Most of the modern apartment buildings have electrical stoves, electrical water heaters (boilers) etc. It has been found that the share of electrical boilers in household consumption can be up to 50% [57]. For example, in most Soviet-era apartment buildings the specific electricity consumption is low because the heating, hot water and cooking do not require electricity, but are provided from central distribution points (heating and water) or burn natural gas for producing heat (gas stoves).

The overall energy efficiency calculations of buildings include other types of energy besides electricity, too. These can be heating and cooling energy, energy for ventilation etc. A building's energy needs are determined with a specific analysis. The principal schematic of an off-grid building's energy flows is presented in Figure 2.1 below. The off-grid power system is highlighted in a light blue field and electrical energy flows are presented as pink arrows. The principle scheme is illustrative and has no complete relation to the building concerned in this study.

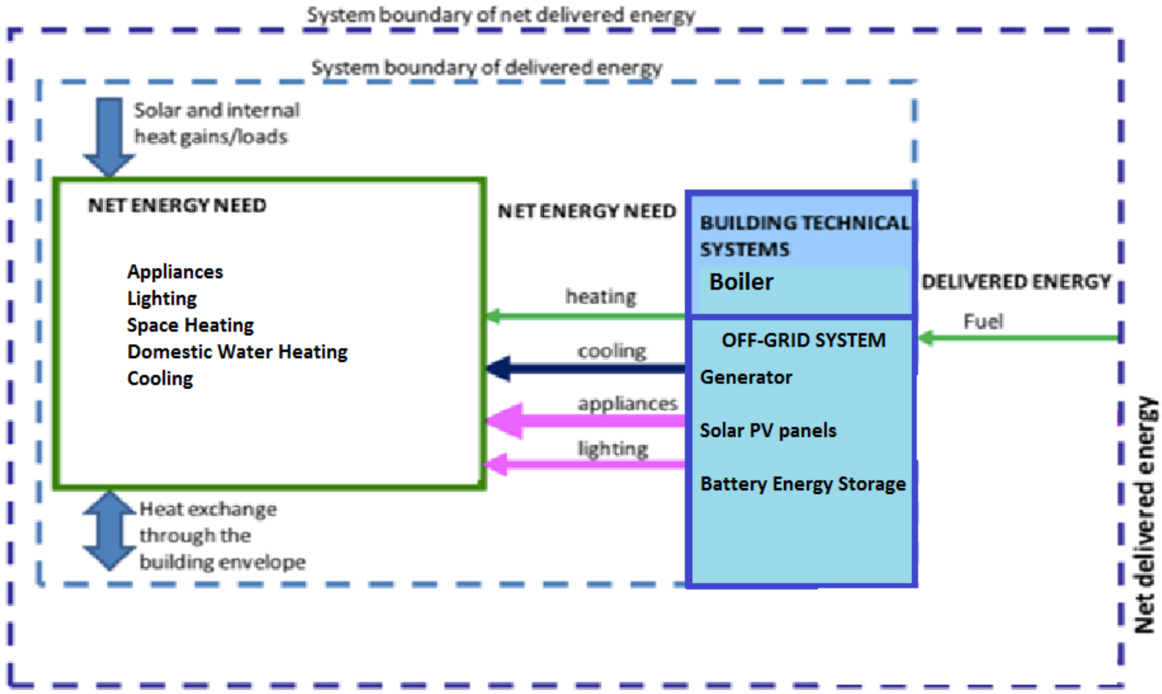

Figure 2.1. Schematic of a building's net energy flows [63]

The studied building will be simulated in off-grid scenarios, meaning that electricity is neither delivered to the site or exported to the grid – all the electricity flows within the system boundary of delivered energy (Figure 2.1). Electricity is produced directly for the building's technical systems and excess electricity is stored for supplying the technical systems or energy needs later. The electrical energy need of the simulated apartment building is 62,1 kWh/m^{2}y, all of which is produced on-site. Based on the author's calculations, the same value for Soviet-era apartment buildings designed for low electrical loads can be estimated at 15 kWh/m^{2}y.

2.2 Inputs to the simulation

HOMER Pro requires various inputs for carrying out the simulation. The main inputs include the electrical load profile (hourly load data preferrable), installation operation strategies (Load Following, Cycle Charging, Combined Dispatch etc) and data about generating units. HOMER software is able to autosize the generating units such as PV, diesel generator, wind and others. In addition, HOMER Pro library includes several system components available on the market. [64]

2.2.1 Controller strategies

Load Following is a strategy which enables the generator to produce only enough power to meet the electrical load at a given moment. Therefore, charging the energy storage system with a generator is not a priority. Batteries in the system are mainly charged by PV panels. A generator is used to charge the batteries only when a low State of Charge (SOC) becomes harmful to the battery. Generally, Li-ion batteries are more vulnerable to deep discharging.

Cycle Charging control strategy enables the generator to operate at full power when it needs to supply the base load demand. When the generator produces any excess power, it is used for charging the energy storage system.

When Combined Dispatch strategy is applied, HOMER decides whether Load Following or Cycle Charging is the cheapest strategy for any hour during the year.

Controller strategies are added and removed on the Components page in HOMER. The Controller menu view with three different strategies chosen is presented in Figure 2.2 below.

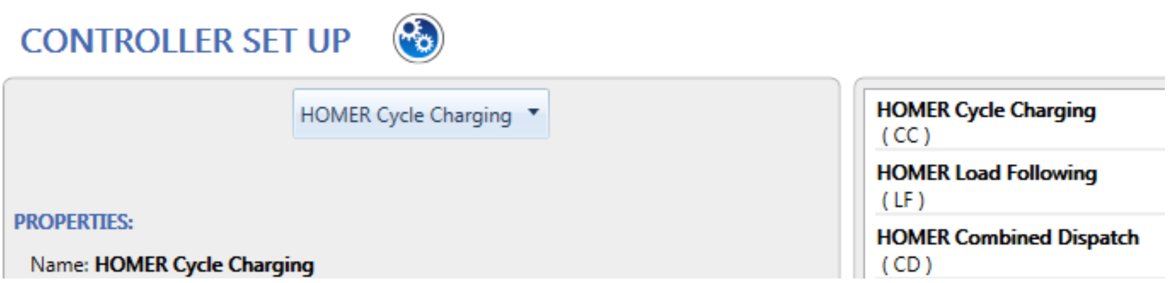

Figure 2.2. Controller strategy set up in HOMER (author's picture)

2.2.2 Hourly electrical load data

The electrical loads fluctuate during the day and also throughout the year, depending on peak consumption periods. Typically the peak load demands occur in winter in cold climates, but brief load surges can occur at any time. HOMER Pro library includes typical load profiles for several different consumers such as residential buildings, communities (villages, apartment buildings), commercial and industrial enterprises etc. However, due to a highly fluctuating nature of each consumer's load profile, a measured load profile should be imported to the simulation in order to obtain better results that can be trusted for a specific site. The same is also suggested by Cervantes et al [55]. In the analysed apartment building the peak load reached 29 kW in January. The yearly electricity consumption was 81 796,5 kWh, accounting for an average hourly and daily loads of 9,34 kW and 224,1 kWh, respectively. The electrical load data with 8760 data fields (hours in a year) was imported to HOMER in .csv format. The described electrical load chart can be seen in Figure 2.3.

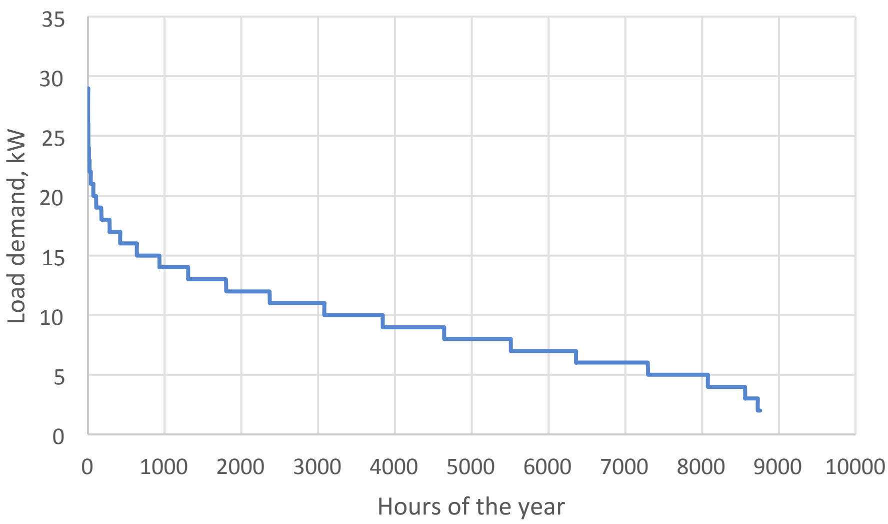

Figure 2.3. Hourly electrical load chart of the simulated building

When the electrical load data is imported to HOMER, the daily, seasonal and yearly load profiles are automatically pictured. The load view in HOMER is presented in Figure 2.4.

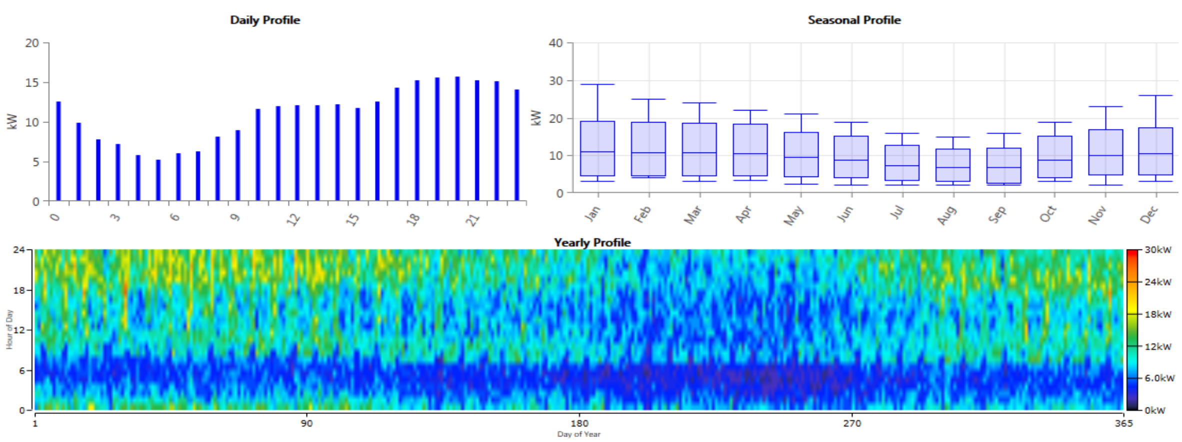

Figure 2.4. Daily (January), seasonal and yearly electrical load profiles in HOMER Pro

The average daily load profile (Figure 2.4, upper left) shows that in January there is one clear load peak from 17:00–22:00, when the electrical load demand is between 14,35-15,65 kW. Hourly electrical loads in the morning and during daytime are approximately level at 11,65-12,57 kW, meaning that there is no distinctive morning peak load that can be noticed for small residential buildings.

The hourly electrical load profiles on weekdays (Monday-Friday) in winter and summer are presented in Figure 2.5.

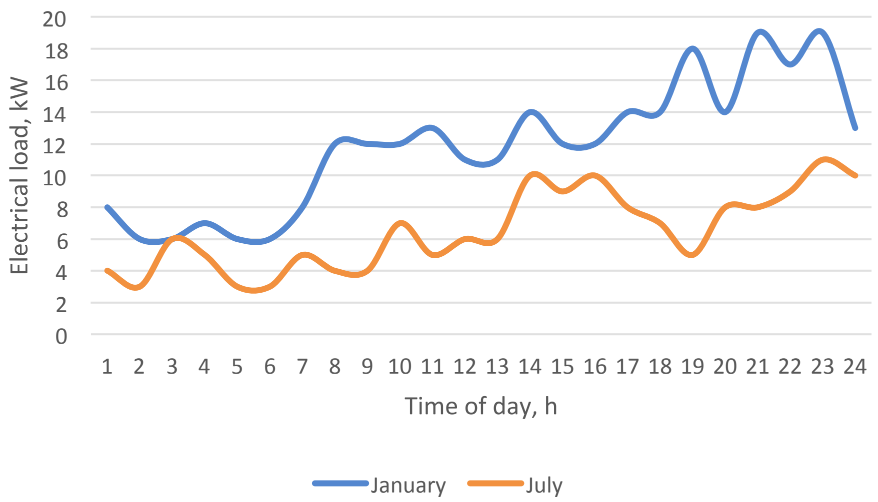

Figure 2.5. Hourly loads on weekdays in winter (January 26th) and summer (July 17th)

The hourly electrical load profiles on weekends in winter and summer are presented in Figure 2.6.

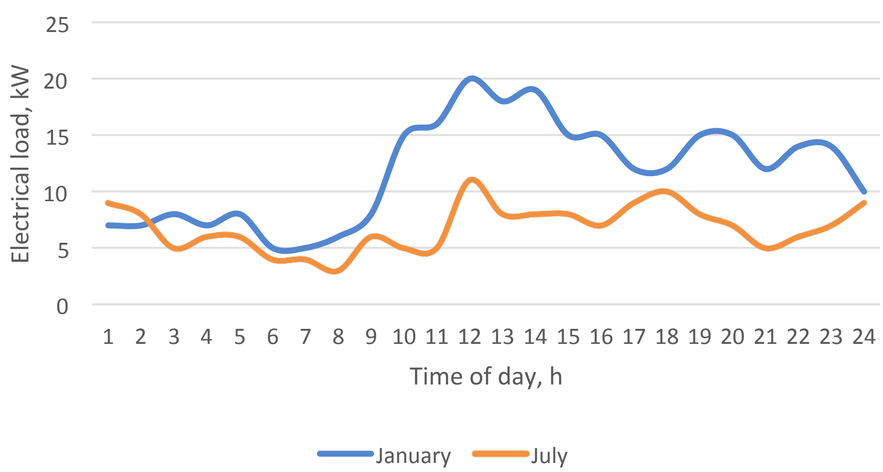

Figure 2.6. Hourly loads on weekends in winter (January 21st) and summer (July 15th)

It can be seen from the figures that the peak electrical loads on weekdays occur in the evenings while during weekends the load demand peaks at noon. The load demand during weekends in winter correlates with hourly solar irradiation (Figure 1.9) fairly well, but the same can't be concluded about loads during weekdays. This in turn means that a higher share of load demand can be supplied by solar PV during weekends. However, the electrical loads have to be met by using energy storage and a diesel generator in winter and nighttime.

In comparison, the yearly electricity consumption of an average five-floor Soviet-era concrete panel building with 60 apartments is 56 859,7 kWh, the peak load reaches 23,18 kW and the average daily elecricity load is 158,77 kWh.

2.2.3 Solar radiation and temperature data

As the solar installation is comprised of PV panels, GHI resource data was needed for the simulation. GHI hourly solar resource data from Tõravere Observatory was used in the simulation. The data was imported from PVsyst 6.7.0 resource library, where the production simulation of the PV installation was carried out. The imported file included 8760 rows of data, each representing every hour of the year. The peak daily radiation is received in Estonia from May to July (5,2-5,53 kWh/m^2/day). On the opposite, the radiation in January and December ranges between 0,18-0,32 kWh/m^2/day. The annual average radiation in Estonia is 2,63 kWh/m^2/day. The annual PV production of 963,8 kWh/m^{2}y was obtained as a result of PVsyst simulations. The monthly GHI data from Tõravere Observatory is presented on Figure 2.7.

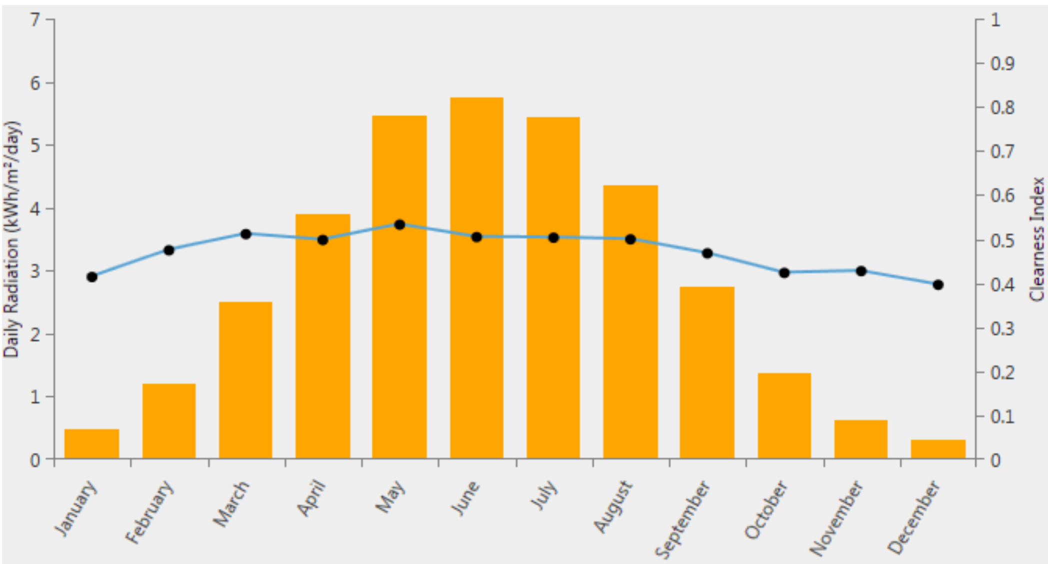

Figure 2.7. Solar GHI data from Tõravere Observatory (author's picture from HOMER, data from PVsyst)

Ambient temperature is the second major climatic condition that affects the performance of the majority of the studied off-grid power systems. The effect of temperature on the PV components is presented in Table 2.2 in this work. The annual average temperature measured in Tõravare Observatory is 5,8 ^{o}C with the coldest month being February at -5,3 ^{o}C and the warmest being July at 17,6 ^{o}C.

2.2.4 Finance inputs

The objective of this simulation model was to seek the optimal size of generating units for the lowest possible cost of electricity. The effect of nominal discount rate, expected inflation rate, diesel fuel price and electricity price on the prices and feasibility of the Project were analysed by changing these variables. Until 2015, specially marked diesel fuel, which is priced at about 35% lower than regular diesel fuel, could be used for heat and electricity production [67]. The requirement for using regular diesel fuel in generators in considerably more expensive and elevates the operation costs of diesel generators by a third. It is assumed in this work that diesel is bought in large amounts at wholeThe wholesale price of diesel fuel is rated at about 1,15 €/l in Estonia in March 2018. However, fossil fuel prices in Estonia have rapidly grown due to rising crude oil prices and political and taxation factors both globally and locally. Therefore, several higher fuel prices were used in the sensitivity analysis in HOMER. [68]

The following values were used:

- nominal discount rate – 0%,
- expected inflation rate – 1,5%,
- diesel fuel price – 1,2 €/l; 1,4 €/l.

The nominal discount rate applied by the Central Bank of Estonia has been 0% since 1. July 2016 [68]. The inflation rate in Eurozone fluctuated between narrow margins near 1,5% in 2017. However, it was close to 0 in 2014-2016. Based on the previous data, simulations at nominal discount rate of 0% and inflation rate of 1,5% are used (data inserted in Economics page). Based on these values, HOMER Pro determined the real discount rate: -1,48%. The Economics view in HOMER is presented in Figure 2.8.

Figure 2.8. Economics input data in HOMER simulations (author's picture)

In the simulation the costs are discounted over the planned project lifetime. For this reason, the the interest rate, inflation rate and components' expected lifetime were taken into account. It was also assumed that the batteries have an initial state of charge of 100% when installed.

2.2.5 System components

Solar PV panels

As the usable roof area of the building is 230 m^2, the distance between arrays is 5,88 m and the horizontal side of the PV panels (landscape orientation) is 1,66 m, according to Formula 1.11 the amount of solar panels installed on the roof is n = 23. The actual sizing of the PV installation can be expected to be larger, meaning that the rest of the panels would be mounted on the ground. The actual need will be determined with the simulations. Table 2.2 presents different PV panels that were considered as possible options for simulations.

Table 2.2. Comparison between PV panels that were considered for simulations

Parameter	HANWHA Q.PLUS-G4 280 [69]	SolarEst SE260-3BB-W [70]	JinkoSolar JKM270PP-60 [69]	Canadian Solar CS6P-270P [72]
STC Power, W	280	260	270	270
Power per area, W/m^2	167,7	159,8	164,3	167,9
Efficiency, %	16,8	15,9	16,5	16,8
Short Circuit Current, A	7,58	9,22	9,09	9,32
Open Circuit Voltage, V	36,37	37,3	38,8	37,9
Temperature Coefficient of power, %/K	-0,4	-	-0,4	-0,41
Capital Cost, €/W	0,401	0,497	0,556	0,459

All of the compared PV panels are similar in their technical specifications. Therefore, the price and local availability were the principal factors influencing the choice of PV panels. Hanwha PV panels were chosen for their cheapest price and a local distributor Taastuvenergia OÜ. In addition, Hanwha has a Tier 1 certificate issued by Bloomberg New Energy Finance, which ensures that the panels are of high quality and durable. With 280W panels the power of the roof-mounted PV installation is 6,44 kW and the rest of the installation has to be installed on the ground. The PV panels' specifications as seen in HOMER are presented in Figure 2.9 below.

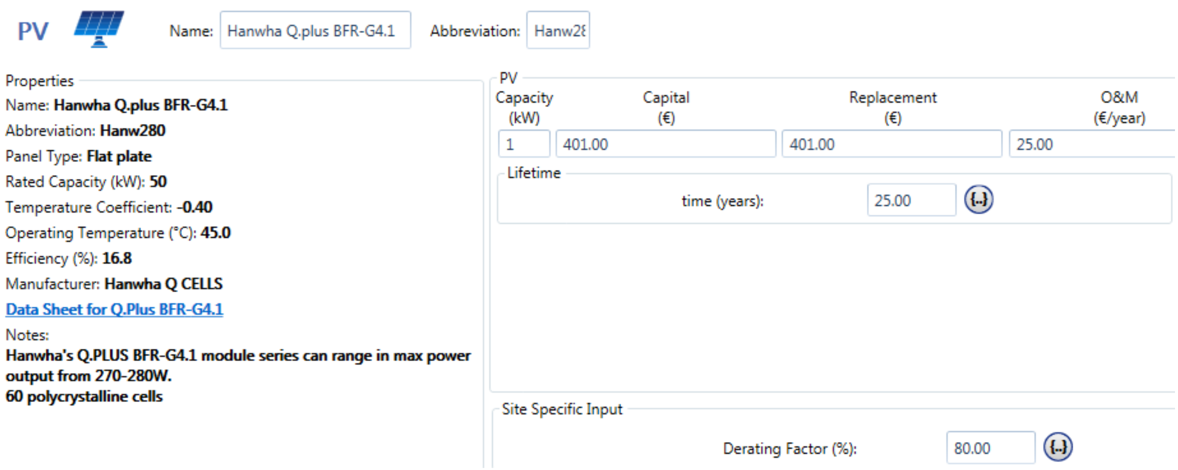

Figure 2.9. Hanwha PV panels' specifications in HOMER (author's picture)

For the simulations monthly adjustment of tilt angle was applied and ambient temperature effects were taken into account.

Energy storage

For energy storage two Lead Acid and two Li-ion batteries were viewed in detail. The batteries that were considered as inputs to the simulation are presented in Table 2.3 below.

Table 2.3. Comparison of batteries for the simulation

Parameter	**Tesla Powerwall 2.0 [73]**	**sonnenBatterie eco 8.0/16** [74]	**Trojan T-145**	**Zap 100 Ah ENERGY Plus**
Technology	Li-ion	Li-ion	Lead Acid	Lead Acid
Capacity, kWh	13,5	16	1,56	1,2
Capacity, Ah	60	66,67	260	100
Voltage, V	220	240	6	12
Roundtrip efficiency, %	90	86	86	-
Lifetime, cycles	5000	10 000	1200	-
Lifetime, years	10 (warranty)	10 (warranty); 20 (designed)	1 (warranty); 20 (designed)	-
Depth of Discharge, %	100	100	50	-
Capital cost, €	5525,42	8295,81	144	99
Capital cost, €/kWh	409,3	518,49	92,3	82,5

All of the chosen batteries are widely available on the market. From Li-ion technology Tesla Powerwall 2.0 was chosen for its price and cycle life advantages. Systems with Powerwall 2.0 are analysed to determine the most suitable battery choice for the simulated system. Tesla's strengths are also their customer support and maintenance services. In the simulations, a minimum state of charge of 30% was set for Li-ion batteries. An overview of Tesla Powerwall's specifications in HOMER are seen in Figure 2.10 below.

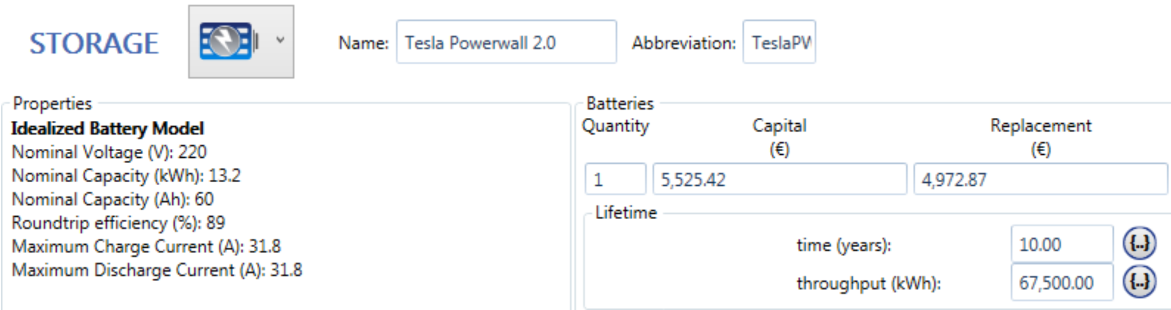

Figure 2.10. Tesla Powerwall 2.0 specifications in HOMER (author's picture)

Trojan T-145 deep-cycle battery was chosen from Lead Acid batteries. T-145 has a lower voltage than other LA batteries, but it is compensated with a larger capacity. Lead Acid batteries have to be connected in several strings to achieve a necessary storage capacity. In the simulations, a 20% minimum state of charge was set for Lead Acid batteries. An overview of Trojan T-145 specifications in HOMER are seen in Figure 2.11 below.

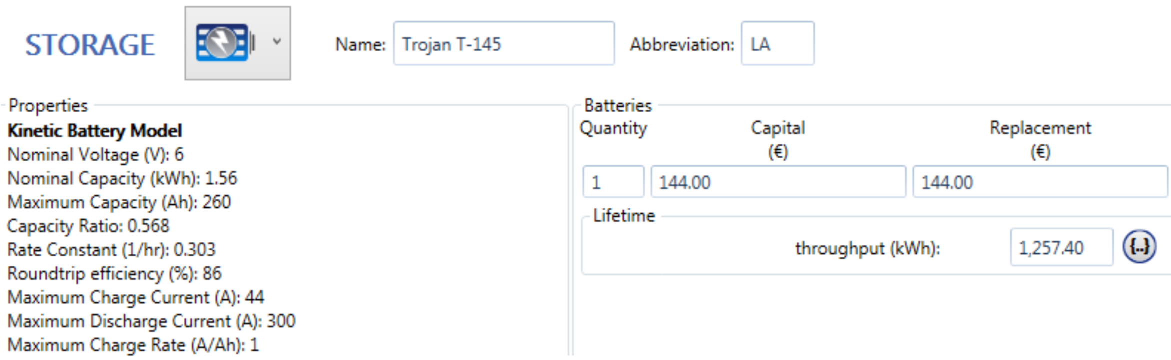

Figure 2.11. Trojan T-145 specifications in HOMER (author's picture)

Diesel generator

A diesel generator operates as a back-up power source in the system. First, the size of the generator will be optimized according to the electrical load by HOMER. Later, the generator's size will be manually limited so that it would only supply the base load in the building. In other words, the generator alone does not have to be able to meet the peak loads. This enables to use the resources more efficiently as a larger generator would be underloaded for the most of the time. It is also recommended for the generator not to be loaded below 40% of nominal power [76]. Therefore, the same minimum load ratio of 40% is applied in HOMER simulations. In addition, it will be determined if a diesel generator makes the system more feasible. Table 2.4 presents the diesel generators that were considered for the system.

Table 2.4. Comparison of diesel generators for the simulation

Parameter	**SDMO T22K [76]**	**Caterpillar DE22E3 [78]**	**Cummins C28 D5 [79] [80]**
Power, kW	18	16	20
Engine RPM	1500	1500	1500
Fuel consumption, l/h	3,4 (half load); 6,2 (full load)	2,9 (half load); 5,3 (full load)	3,5 (half load); 6 (full load)
Enclosure	Yes	Optional	Optional
Warranty	5 years	5 years	?
Coolant	Liquid	Liquid	Liquid
Capital cost, €	9586,6 [81]	8652 [81]	8700

1500 RPM generators were chosen for their durability, lower capital costs and lower operating costs (including lower maintenance needs) compared to high RPM generators that operate at over 1800 RPM. Cummins C28 D5 generator was chosen for the installation for several advantages:

- the best price per power ratio,
- there is an official importer and distributor in Estonia – Baltic Industrial OÜ, which also offers on-site maintenance and customer support,
- it is able to serve higher loads than other generators in Table 2.4.

HOMER Energy Support suggests that the operating and maintenance cost of diesel generators is about 0,017 €/kWh. For the Cummins generator it is then assumed that the O&M cost is 0,34 €/h regardless of the power output. The replacement cost of the generator is assumed to account for 90% of the initial capital cost – 7830 €. The lifetime of the generator is estimated at 15 000 operating hours.

The generator's specifications as seen in HOMER are presented in Figure 2.12 below.

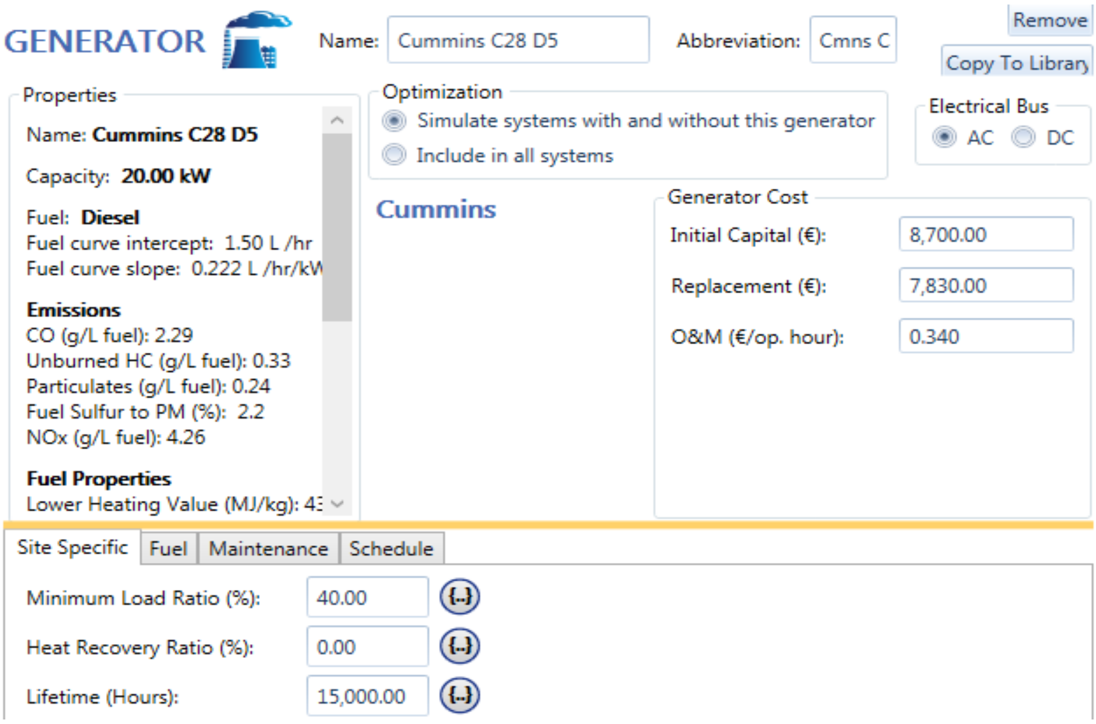

Figure 2.12. Cummins C28 D5 specifications in HOMER (author's picture)

HOMER optimizes the generator so that it would be able to serve the peak electrical loads in emergency situations, e.g. when the storage system is depleted and the PV system produces no electricity. Therefore, **the generator's size only depends on the simulated peak electrical loads.**

Components summary

For an easier overview, all the capital costs, replacement costs and O&M costs that were used for simulating and sizing the power system components are presented in the following table.

Table 2.5. Costs of the proposed power system components

Component	Capital cost	Replacement cost	O&M cost
Solar PV (Hanwha Q.PLUS 280W Poly)	401 €/kW	401 €/kW	18,2 €/kW/y
Diesel generator (Cummins C28 D5)	8700 €	7830 €	0,34 €/h
Energy storage: Li-ion (Tesla Powerwall 2)	409,3 €/kWh	368,4 €/kWh	
Energy storage: Lead Acid (Trojan T-145)	92,3 €/kWh	92,3 €/kWh	
Balance of System	57,0 €/kW	57,0 €/kW	

Renovation and building costs to meet nZEB performance were not applied as inputs to the HOMER simulation. Only the electrical power system was studied in detail in HOMER. The expenses of renovation and construction works are several times higher than the power system costs and are discussed in Chapter 3 in this work.

2.3 Off-grid power system simulations

When the consumers and their electricity generation units are not connected to the utility grid, the customers rely 100% on local off-grid generation to meet their electrical load demand. This means that the consumption is limited to the maximum output of available generation units. When no on-site electricity supply is available, it essentially means that there is a blackout. In off-grid applications energy is consumed directly on site or in an islanded microgrid. Generally it is most practical to combine different power generation units to ensure the security of supply at the lowest costs. Such hybrid power systems have been previously described in this work. [30]

The overall structure of the off-grid power system model is presented in Figure 2.13.

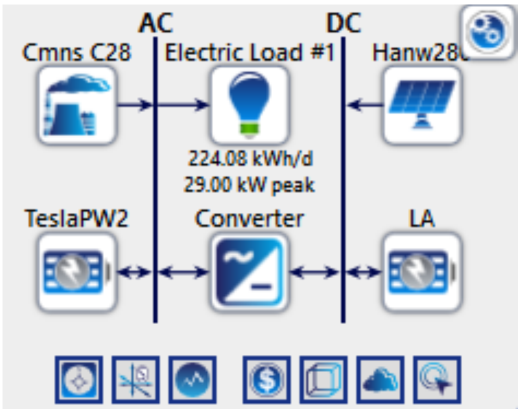

Figure 2.13. Schematic of the power system's structure (author's picture from HOMER)

Various system configurations were analysed and the size of each component was optimized to determine the most suitable system configuration and component sizes for the studied building. The following system topologies were chosen for the analysis:

- System 1 – PV + generator + Lead Acid storage,
- System 2 – PV + generator + Li-ion storage,
- System 3 – PV + Lead Acid storage,
- System 4 – PV + Li-ion storage,
- System 5 – generator + Lead Acid storage,
- System 6 – PV + generator.

With the absence of a grid connection, the importance of energy storage and especially generator components grows due to the need for a controllable generation unit and for maintaining the system's stability. This section aims to find numerical values to back this claim.

First, the simulations are carried out using HOMER Optimizer function for all components. Later, the simulations are done with chosen specific components available on the market. In addition, deferrable loads are applied to see the effects on the system's profitability. Later, an analysis is carried out to see how the sizing of system components affects the optimal size of other components, for example how the storage capacity changes when installed PV power is increased.

From Figure 2.13 it could be noticed that the LA battery is on the DC side of the system while the Li-ion battery is on the AC side. The reason for this is that Tesla Powerwall includes an integrated inverter, meaning that the battery produces AC output. To model AC-output batteries in HOMER, a free (0 cost) and large (at least equal to the storage capacity) dedicated converter with 100% efficiency has to be included in the model. This can be added by choosing a Dedicated Converter under the battery's Site Specific Input. Here, a capacity of 10 000 kW was chosen for the dedicated converter. The Dedicated Converter view from HOMER can be seen in Figure 2.14 below.

Figure 2.14. Dedicated Converter settings for Tesla Powerwall batteries (author's picture)

2.3.1 Simulation of different off-grid system configurations

Optimization of the whole system with HOMER Optimizer

First, the simulation was carried out using the inputs referred to above and all of the system's components were optimized by HOMER i.e. no specific products were used in component inputs. The size of the generator is constant at 33 kW for all configurations because HOMER optimizes the generator according to the worst case scenario where PV and storage units can not be used and peak electrical loads occur simultaneously. All the other components are sized depending on the configuration. In addition, a most suitable operation strategy is chosen for each configuration. System 1 can be considered as the system with the most suitable architecture. An optimally sized system for each configuration by COE is presented in Table 2.6. The systems' numbering is found in section 2.3.

Table 2.6. System architectures with lowest COE values

No. of system	**System Component Sizes, kW (ES: kWh)**					**Strategy**	**COE, €/kWh**
	Solar PV	**Generator**	**ES: Li-ion**	**ES: LA**	**Converter**		
1	163	33	-	524	25,4	LF	0,236
2	133	33	180	-	28.8	CD	0,294
3	414	-	-	1078	32,1	CD	0,317
4	540	-	773	-	194	CD	0,611
5	-	33	-	218	25,3	CC	0,546
6	131	33	-	-	24,3	CD	0,569

Capital costs, operating costs and Net Present Costs of the systems are presented in Table 2.7 below.

Table 2.7. NPC, Operating cost and Capital cost of systems 1-6

No. of system	**NPC, €**	**Operating cost, €/y**	**Capital cost, €**
1	588 102	15 043	129 066
2	734 096	19 381	142 706
3	761 313	16 195	267 152
4	1 470 000	30 408	544 004
5	1 360 000	43 504	35 485
6	1 420 000	44 295	67 936

From the tables it can be seen that the lowest COE is achieved with system 1 that includes PV, generator and Lead Acid energy storage. The system's Capital and lifetime costs are 129 066 € and 588 102 €, respectively, which makes it the most feasible system configuration. Systems 3 and 4 are greatly oversized for the studied electrical load due to an absence of a generator in the system. **Without a controllable generation unit in the system, the PV and storage components have to be oversized to meet a high load demand during winter** with low solar irradiation level.

System no. 6 that comprises only solar PV and a generator is not technically recommendable as the renewable penetration in this case is high enough to cause stability issues in the system. All of the presented system architectures have a high renewable penetration, meaning that they require energy storage to maintain required stability.

Optimization of the system with specific components in HOMER

The specifications of specific components used in the simulations are presented above in item 2.2.5. Optimization with real components was carried out to see the results with actual products currently available on the market and to see the differences between a fully optimized off-grid system and an off-grid system where products with given specifications have to be used. The storage and PV units can be joined together to form larger systems with a desired size and capacity. On the opposite, the only fixed element in the system is the Cummins generator at 20 kW, because **the system was limited to include only one generator.**

An optimized system with real-world components for each configuration by COE is presented in Table 2.8.

Table 2.8. System architectures with lowest COE values

No. of system	System Component Sizes, kW (ES: kWh)					Strategy	COE, €/kWh
	Solar PV	Generator	ES: Li-ion	ES: LA	Converter		
1	141	20	-	836,2	20,1	CD	0,204
2	132	20	158,4	-	22,1	CD	0,303
3	295	-	-	2475,7	62,3	CD	0,193
4	617	-	673,2	-	99,0	CD	0,644
5	-	20	-	842,4	9,9	CC	0,465
6	127	20	-	-	19,8	CD	0,472

Capital costs, operating costs and Net Present Costs of the same systems are presented in Table 2.9 below.

Table 2.9. NPC, Operating cost and Capital cost of systems 1-6

No. of system	NPC, €	Operating cost, €/y	Capital cost, €
1	505 581	11 702	148 497
2	751 945	20 236	134 457
3	446 400	3303	365 599
4	1 550 000	33 042	558 827
5	1 160 000	35 069	89 429
6	1 170 000	36 132	65 389

From the tables it can be seen that a lower COE is achieved with systems that include PV, generator and energy storage. However, the lowest COE is obtained for a PV + LA storage system (system 3) with a capacity that is considerably higher than that of other systems. In spite of the lowest NPC of 446 400 €, the main obstacle for installing system 3 is a high capital cost of 365 599 €. Furthermore, system 3 is greatly oversized for the studied electrical load due to an absence of a generator in the system. Without a controllable generation unit in the system, the PV and storage components have to be large enough to meet a high load demand during winter with low solar irradiation level.

Again, system no. 6 that comprises only solar PV and a generator is not technically recommendable as the renewable penetration in this case is high enough to cause stability issues in the system. All of the presented system architectures have a high renewable penetration, meaning that they require energy storage to maintain required stability. It can be concluded here that off-grid systems without energy storage are not suitable for stable and reliable operation.

When comparing simulation results of fully optimized systems and of systems with specific components it can be concluded that lower COE and NPC values were achieved with real-world systems. The biggest differences can be noticed in case of system 3, which yielded about 30% better results than a fully optimized system of the same configuration. Despite that, systems 1 and 2 are of biggest interest in this work as these can be considered the most complete configurations. While system 1 obtained better results with real-world components (COE 0,204 €/kWh) than in a fully optimized scenario (COE 0,236 €/kWh), a great difference was not seen between the two simulation results for system 2 – COE values found were 0,294 €/kWh and 0,303 €/kWh, respectively. A technical comparison between these three-component systems is done in section 2.5.

2.4 Simulations with deferrable loads

In order to try and further reduce the COE, the simulations were carried out with deferrable loads. HOMER considers regular electrical loads as a priority, which means that deferrable loads are serviced when the electrical load demand is met and the storage system is not discharged to a minimum SOC (20% for LA and 30% for Li-ion).

It is generally assumed that electrical water heaters in residential buildings operate as thermal energy storage units and don't have to be heated at the exact time of hot water consumption. Therefore, electrical water heaters are simulated in HOMER as deferrable loads. The simulated building has 18 apartments and each apartment has a 2 kW electrical boiler for domestic water heating. The boilers usually operate at 8-10 o'clock in the morning and at 17-19 o'clock in the evening. The total installed power of the electrical water heaters is 36 kW. According to an expert opinion by the supervisor of this work, the share of water heaters in the building's total electricity demand is 40%.

HOMER Pro requires daily average deferrable load data for simulations. The monthly average deferrable loads were determined by deducting 40% from the hourly load data of the building. After hourly deferrable load was obtained, the data was converted into average daily deferrable load (kWh/d), a suitable format for HOMER. The average daily values for each month do not correspond with the actual daily water heating loads. However, the annual deferrable load can be considered accurate. The average daily deferrable load for each month is presented in figure 2.15 below.

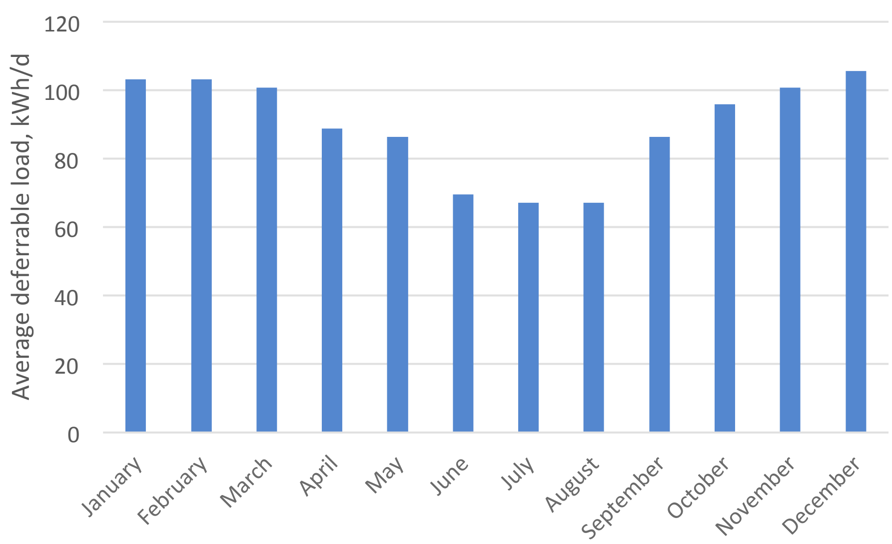

Figure 2.15. Daily average deferrable loads in the apartment building (data from HOMER)

The scaled average deferrable load of the building is 89,6 kWh/d. The simulation was carried out with previously chosen components and financial variables for Spring 2018:

- Nominal Discount Rate – 0%,
- Inflation Rate – 1,5%,
- diesel fuel price – 1,2 €/l.

The new system architecture with a deferrable load in HOMER is presented in Figure 2.16 below.

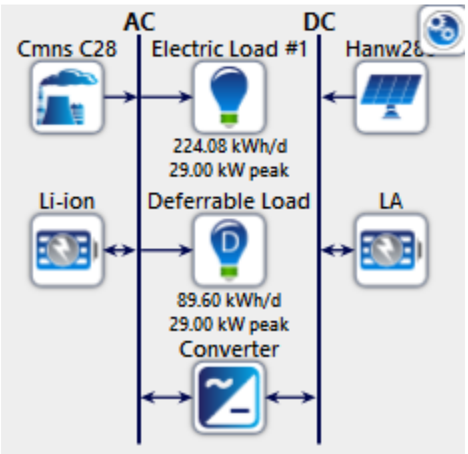

Figure 2.16. System scheme with a deferrable load (electric water heating)

The simulations with deferrable load component in HOMER did not yield any better results than before. Therefore, it is not discussed further and a manual method for shifting electrical loads was used instead.

The main target for deferring the loads was to increase the direct utilisation of solar energy and potentially reduce the generator's operating hours. Ideally, all of the loads should be moved towards noon because the load demand could be met with the solar PV component more than without deferred loads. However, as discussed before, the water heaters need to be used at 8-10 o'clock and at 17-19 o'clock, meaning that only the evening water heating load can be supplied directly by solar PV as solar energy production before the morning load is minimal. The manual load deferring was done by moving all of the electrical loads in a year 3 hours forward. The author of this work proposes the following:

- by moving the electrical loads forward, a larger part of the evening peak load can be supplied directly by solar PV.

An exemplary graphical expression of manually deferred load and actual electrical load on January 28th is presented in Figure 2.17 below.

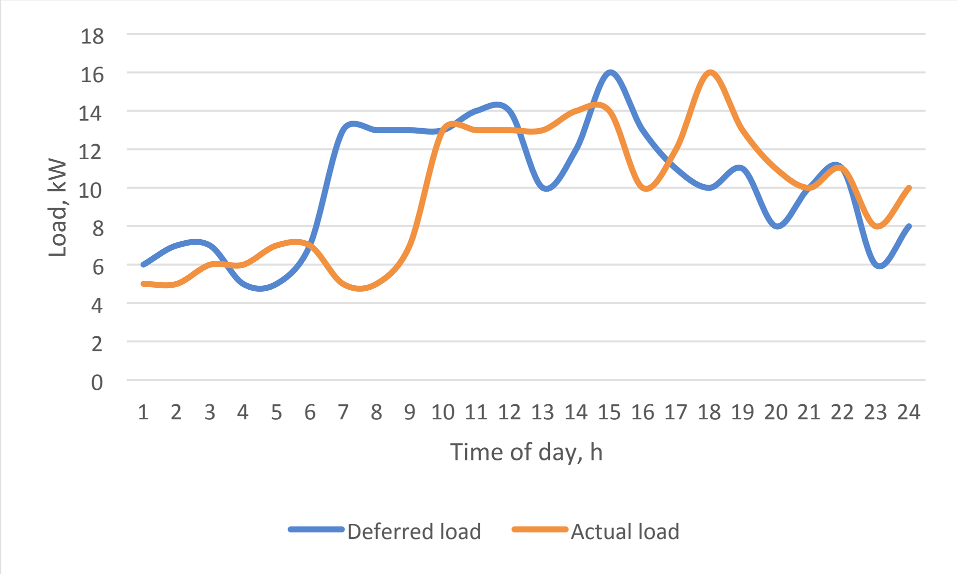

Figure 2.17. Deferred load (shifted 3 hours forward) and actual load (base case) in the studied building

It can be seen from Figure 2.17 that the peak deferred load demand (blue) is moved more towards the noon. The obtained deferred load profile was used for simulating the installation once more. The simulation was again carried out by using the same components and financial variables as previously described in this work. The proposed system architectures with lowest COE values are presented in Table 2.10 below.

Table 2.10. System architectures with lowest COE values – load 3 hours forward

No. of system	**System Component Sizes, kW (ES: kWh)**					**Strategy**	**COE, €/kWh**
	Solar PV	**Generator**	**ES: Li-ion**	**ES: LA**	**Converter**		
1	156	20	-	842,4	24,3	CD	0,194
2	139	20	171,6	-	27,6	CD	0,304
3	283	-	-	2472,6	43,9	CD	0,186
4	562	-	752,4	-	119,0	CD	0,660
5	-	20	-	842,4	9,9	CC	0,465
6	120	20	-	-	21,1	CD	0,462

Compared to undeferred loads, systems 1, 3 and 5 obtained lower COE values by about 0,01 €/kWh. The optimal component sizes in this case do not differ much from the base case. However**, the operating hours of the generator were reduced and renewable energy fraction was increased for system 1**. The generator's annual operating time was 996 hours in the base case, but was slightly reduced to 967 hours when the load is deferred by 3 hours. In addition, renewable fraction of the system grew from 80% to 83,5%.

The simulation was carried out for a scenario when the electrical loads are moved forward by 2 hours. The simulation results are presented in Table 2.11.

Table 2.11. System architectures with lowest COE values – load 2 hours forward

No. of system	System Component Sizes, kW (ES: kWh)					Strategy	COE, €/kWh
	Solar PV	Generator	ES: Li-ion	ES: LA	Converter		
1	149	20	-	842,4	20,9	CD	0,206
2	138	20	184,8	-	33,2	CD	0,304
3	263	-	-	2513,2	32,0	CD	0,174
4	540	-	726	-	86,1	CD	0,630
5	-	20	-	817,4	7,3	CC	0,515
6	110	20	-	-	20,2	CD	0,461

The final simulation with deferrable loads was carried out for a scenario, where the electrical loads are moved forward by 1 hour. The simulation results are presented in Table 2.12.

Table 2.12. System architectures with lowest COE values – load 1 hour forward

No. of system	System Component Sizes, kW (ES: kWh)					Strategy	COE, €/kWh
	Solar PV	Generator	ES: Li-ion	ES: LA	Converter		
1	157	20	-	842,4	24,3	CD	0,209
2	132	20	211,2	-	36,0	CD	0,310
3	274	-	-	2466,4	35,2	CD	0,182
4	523	-	752,4	-	86,1	CD	0,635
5	-	20	-	817,4	7,3	CC	0,515
6	123	20	-	-	20,4	CD	0,460

It is interesting to note that despite moving the electrical loads forward, it favoured larger energy storage capacities. This is on the opposite with studies which show that load deferral can reduce the needed storage capacity up to 30%. Based on that, it can be concluded that **the main limiting factor which does not allow smaller storage capacities is the need for overnight energy storage during winter**. A conclusive graph with the effect of load deferral on COE is presented in Figure 2.18 below.

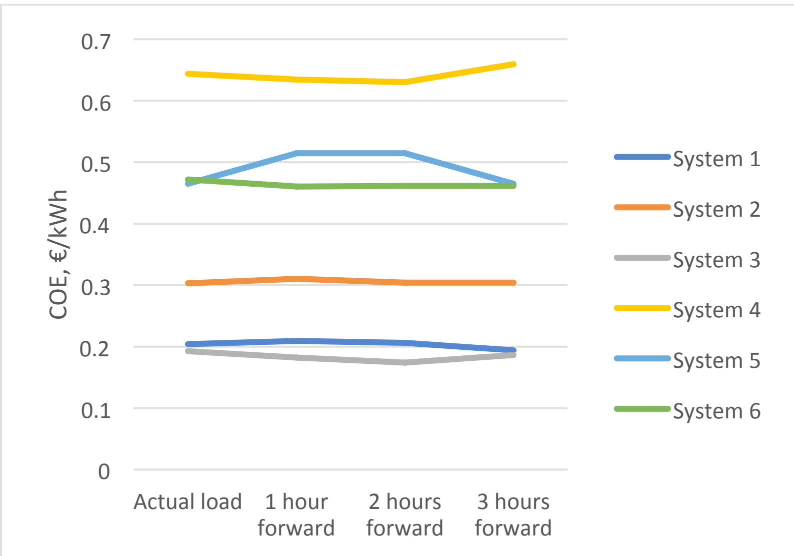

Figure 2.18. COE values of systems 1-6 depending on the time shift of load deferral

It can be seen that the COE of systems 1, 2 and 6 are not majorly affected by electrical load time shifts. Systems 3 and 4 present the best results in this context. The simulation results show that **systems without a diesel generator are more positively affected by shifting electrical loads forward**, with a 2-hour time shift presenting the lowest COE values. Despite the fact that no great benefit from load deferral can be seen, generally slightly lower COE is achieved by moving the loads forward up to 3 hours.

2.5 Technical comparison between three-component systems

Here, a more detailed comparative analysis is carried out for three-component systems including solar PV, energy storage and a generator.

2.5.1 PV, generator and storage: systems 1 and 2

The COE comparison between systems 1 and 2 show that the capital cost of an optimized system including Li-ion energy storage is 10% lower than an optimized LA system, but has a 33% higher COE and a 42% higher operating cost. In addition, the capacity of an optimal Li-ion storage is limited to 158,4 kWh, which allows for 11,9 hours of autonomy. On the other hand, the optimal Lead Acid storage capacity is 836,2 kWh and enables to have 71,6 hours of autonomy. The comparison between simulated storage technologies is presented in Table 2.13.

Table 2.13. Optimal energy storage system specifications depending on the technology

Storage Technology	Autonomy, h	Annual throughput, kWh/y	Nominal Capacity, kWh	Usable Capacity, kWh
Li-ion	11,9	34 758	158	111
Lead Acid	71,6	40 678	836	669

The simulation results show **that the best operating strategy for an off-grid system is Combined Dispatch**. The optimal system with real-world components that comprises solar PV as well as energy storage and a generator is system 1 – 141 kW solar PV, 20 kW generator and 836 kWh Lead Acid storage. The generator and storage system complement each other in providing reliability and stability in the power system by having a controllable generation unit and a unit for smoothing solar power output. Both systems have enough storage capacity to supply the electrical load demand over night from Spring to Autumn. This means that without emergency, the systems are capable of running without a generator from February to October (system 1) and from March to Spetember (system 2). A graphical expression of overnight electricity supply from energy storage in system 1 during summer can be seen on Figure 2.19 below.

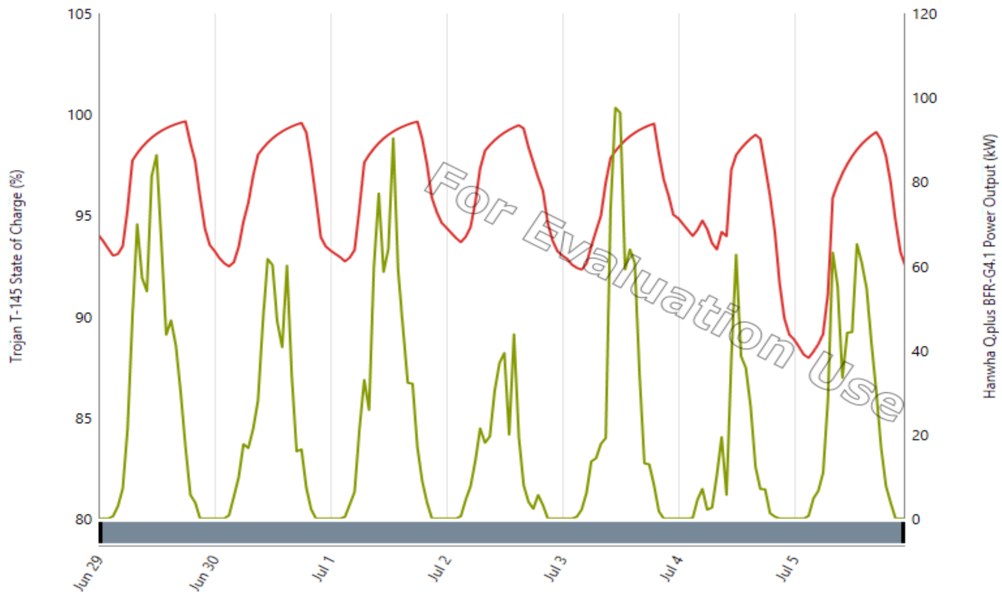

Figure 2.14. SOC of LA storage and solar power output in summer – system 1 (author's picture from HOMER)

In addition to Figure 2.14, the zero output of diesel generator on the same days can be seen in Figure 2.15.

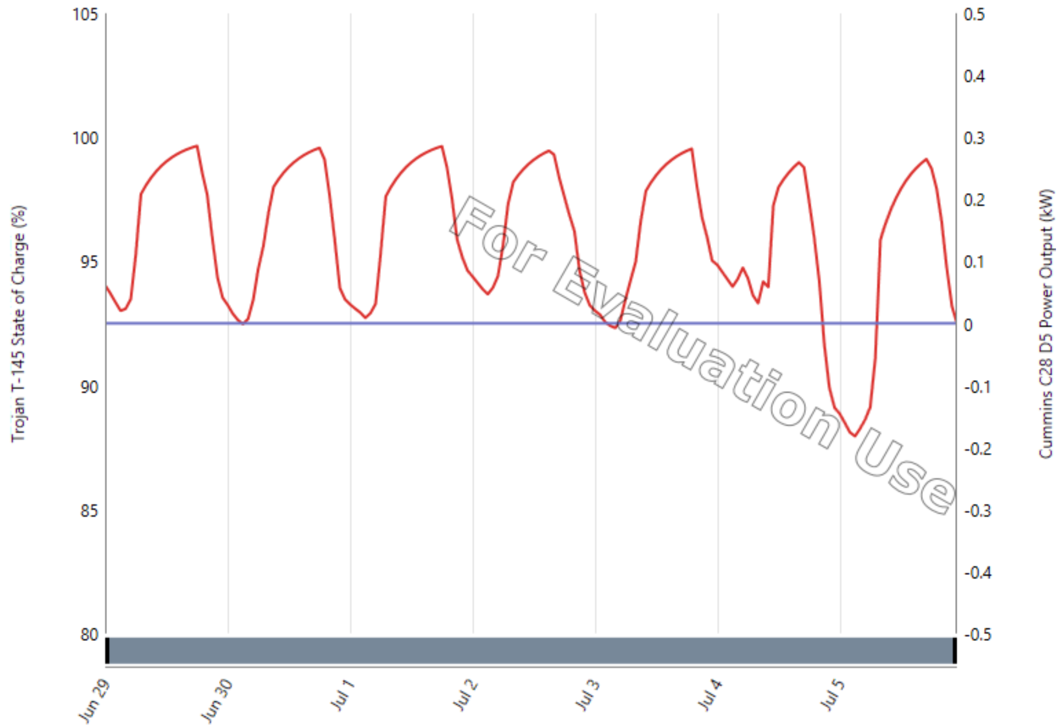

Figure 2.15. SOC of LA storage and generator output in summer – system 1 (author's picture from HOMER)

In system 1, the generator is regularly operated from October 29th till February 7th for supplying evening peak loads and charging the storage system during nighttime. In winter, the storage system's SOC drops to 20% in about 4 days. Then the storage system is charged to SOC=80% in 4 days when there is no excess solar energy produced. When there is abundant excess solar energy produced, the storage system is charged considerably faster – at up to 10%/h, which is near the limit of charge current of the storage system. On average, the storage system is discharged by 5-6% during nighttime when all the loads are supplied by the battery bank (Figures 2.14 and 2.15).

To compare the SOC of two battery storage systems during overnight electricity supply, the relation between Li-ion storage SOC and solar energy production in system 2 is presented in Figure 2.16 below.

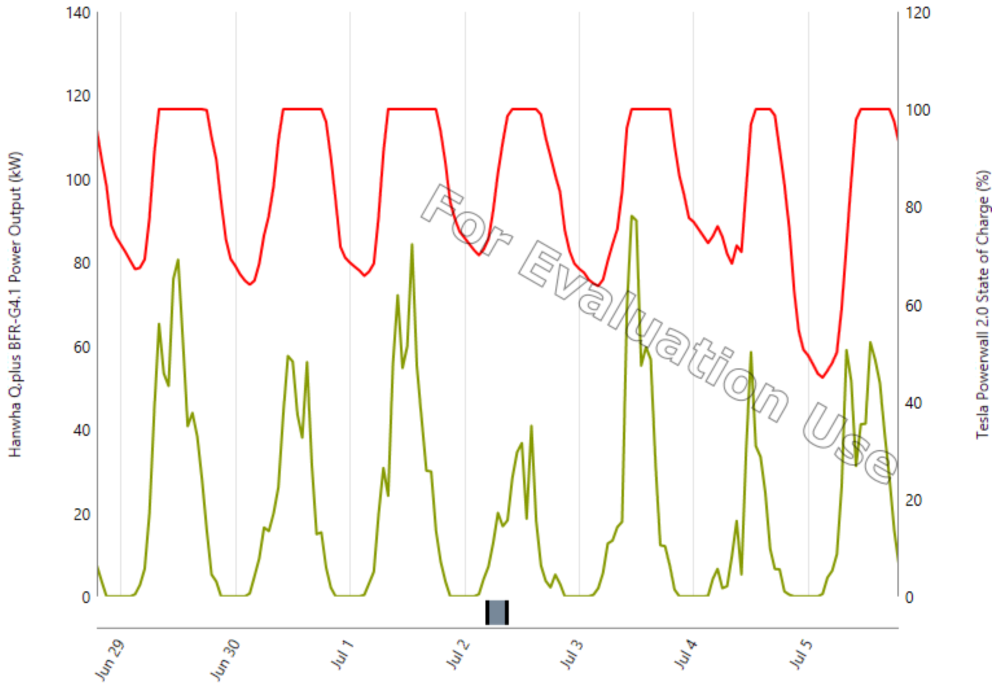

Figure 2.16. Relation between SOC of Li-ion storage and solar power output in summer – system 2 (author's picture from HOMER)

It can be seen that the Depth of Discharge (DoD) of Li-ion storage (Figure 2.16) for nighttime electricity supply is approximately 20% (80% SOC), which is four times deeper than that of LA storage (Figure 2.14). This increases annual operating hours of the generator to 1788 h/y in system 2. The same value for system 1 is 996 h/y, which is 45% less. **It is preferential to minimise the generator's operating hours** as this is the biggest cause for high operating costs. The annual operating cost of the generator alone is 608 € and 339 € in systems 2 and 1, respectively. As the project lifetime is 25 years, the cost savings from minimising generator use in system 1 reach 6725 € (maintenance cost excluded). When considering that generator's expected lifetime is 15 000 operating hours, in system 1 (LA) the generator's lifetime is 15,1 years while in system 2 (Li-ion) the lifetime is 8,4 years. The generator's daily output power during the year in system 1 is presented in Figure 2.17.

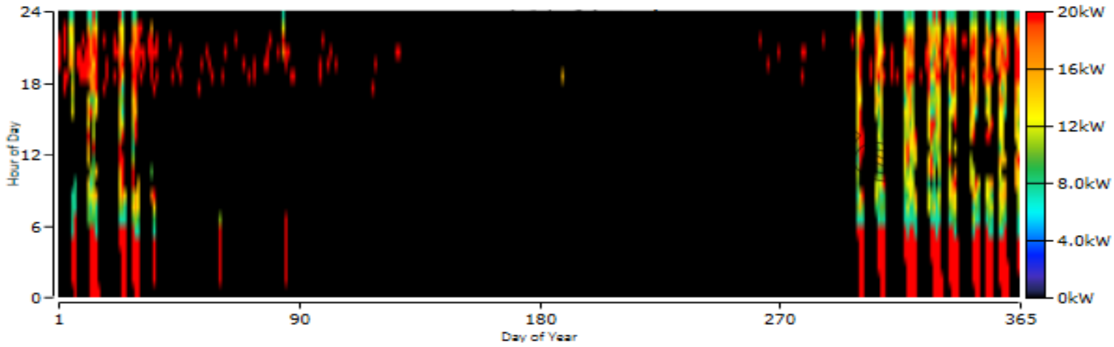

Figure 2.17. Generator's annual power output with LA storage – system 1 (author's picture from HOMER)

The generator's daily output power during the year in system 2 is presented in Figure 2.18.

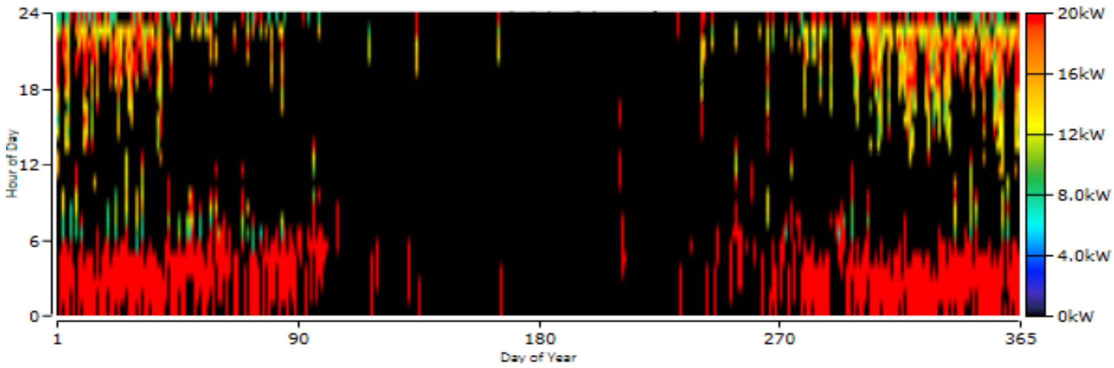

Figure 2.18. Generator's annual power output with Li-ion storage – system 2 (author's picture from HOMER)

For further considerations it is assumed here that the separate batteries in the storage system are charged and discharged evenly e.g. the SOC of the whole storage system is equal to the SOC of each battery unit. As the Li-ion storage generally has a deeper DoD than LA (Figures 2.14 and 2.16), the useful life of the storage system is reduced in comparison with LA storage. In systems 1 and 2, the expected lifetime of LA and Li-ion storage systems is 16,6 years and 10 years, respectively. Based on these operating data about energy storage and a generator it can be concluded that the main price growth driver for system 2 are high capital costs and a smaller optimal capacity of Li-ion batteries.

As one of the principal targets for off-grid and nearly-zero energy buildings in EPBD is to reduce fossil primary energy consumption, system 1 is the one to be preferred with considerable non-renewable energy production occuring in November, December and January and the system's total renewable fraction is 83,5%. In system 2, diesel generator has a big role in electricity supply from October to March and the system's renewable fraction is 60,9%. A schematic distribution between renewable and non-renewable energy in system 1 is presented in Figure 2.19.

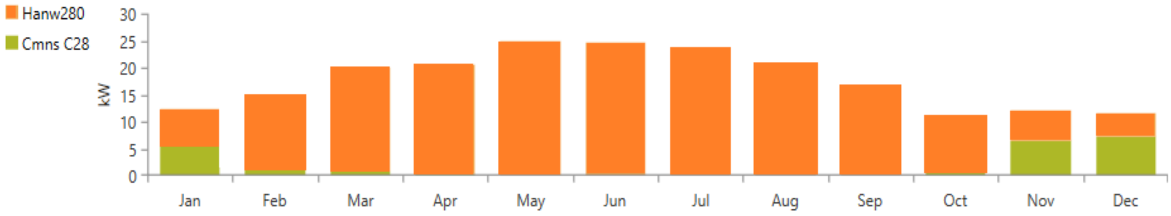

Figure 2.19. Monthly electricity production of system 1 (LA) (orange – renewable energy; green – generator) (author's picture from HOMER)

A schematic distribution between renewable and non-renewable energy in system 2 is presented in Figure 2.20.

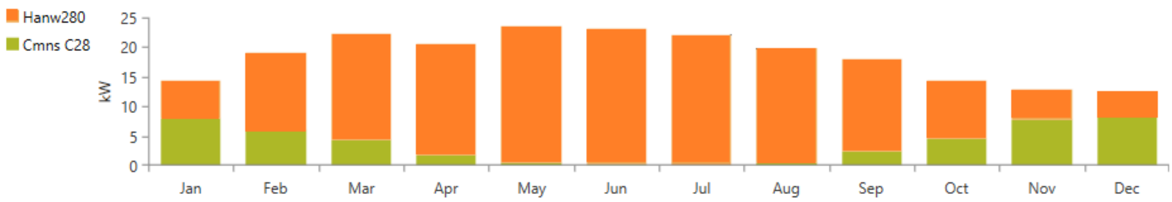

Figure 2.20. Monthly electricity production of system 2 (Li-ion) (orange – renewable energy; green – generator) (author's picture from HOMER)

The simulation data about annual electricity production, consumption, excess electricity and storage of systems 1 and 2 are presented in Table 2.14 below.

Table 2.14. Electricity production, load and storage data in systems 1 and 2

No. of system	Annual production, kWh	Annual load, kWh	Annual excess electricity, kWh	Storage energy in/out, kWh
System 1	155 405	81 781	64 257	43 223/37 723
System 2	162 044	81 781	73 392	36 743/32 790

2.6 Relation between component sizes in different system topologies

As part of the technical analysis, the relations between component sizes in the systems were addressed. Such simulations help to better understand how changing the parameters of each component affects the whole system and its feasibility. The simulations were carried out so that the size of each component was changed manually and all the other components were automatically optimized by HOMER Optimizer (see more in Item 2.3.1). Conclusive remarks explaining the components' relations are provided for each simulation case separately.

All of the system topologies were analysed and the size of each component was separately varied to see how the optimization results of the other components were affected. Again, the same system topologies were used:

- System 1 – PV + generator + Lead Acid storage,
- System 2 – PV + generator + Li-ion storage,
- System 3 – PV + Lead Acid storage,
- System 4 – PV + Li-ion storage,
- System 5 – generator + Lead Acid storage,
- System 6 – PV + generator.

All of the simulation data and obtained financial values should be considered with a reservation as the prices of the analysed components are rapidly changing. Furthermore, it is important to note that it can be technologically challenging to maintain the stability of system 6.

The data that was unchanged through all of the simulations was the following:

- Solar PV – capital cost: 401 €/kW; replacement cost: 401 €/kW; O&M cost: 25 €/kW/y; lifetime 25 years; ground reflectance 20%; monthly tilt angle adjustment,
- Generator – capital cost: 435 €/kW; replacement cost: 391,50 €/kW; O&M cost: 0,017 €/h; minimum load ratio 35%; lifetime 15 000 hours; fuel price 1,2 €/l,
- Li-ion storage – capital cost: 418,59 €/kWh; replacement cost: 416,67 €/kWh; initial SoC: 100%; minimum SoC: 30%; integrated inverter,
- Lead Acid storage – capital cost: 92,31 €/kWh; replacement cost: 92,31 €/kWh; initial SoC: 100%; minimum SoC: 20%,
- Converter – capital cost: 57 €/kW; replacement cost: 57 €/kW; lifetime 15 years; efficiency 95%,
- Nominal discount rate – 0%,
- Inflation rate – 1,5%,
- Project lifetime – 25 years.

Note that the **generator's size is again constant** (33 kW) when using automatic optimization, as it is calculated to supply peak loads and **all the other variables are neglected**.

2.6.1 Effect of PV component size on the storage capacity and generator size

The simulations were carried out using the same system components and financial inputs as previously presented. The system components were simulated in HOMER so that a fixed PV size was manually chosen and all the other components were optimized accordingly. PV sizes of 50 kW, 100 kW, 200 kW, 300 kW and 500 kW were chosen for the analysis to see the changes in other components' sizes. System 5 was not analysed as this topology does not include solar PV. Systems 1 and 6 were not analysed due to their unfeasibility with given component sizes and capacities. The effect of installed PV power on LA storage capacity and generator in system 1 is seen in Table 2.15 below.

Table 2.15. Effect of installed PV power on LA storage and generator – system 1

System Component Sizes, kW (ES: kWh)					Strategy	COE, €/kWh
Solar PV	Generator	ES: Li-ion	ES: LA	Converter		
50	33	-	839,3	20,8	CC	0,308
100	33	-	833	29,9	CC	0,235
200	33	-	841	28,3	LF	0,220
300	33	-	842	28,4	LF	0,241
500	33	-	842	30,2	LF	0,313

It can be seen that the other **components' sizes are not greatly affected by the installed PV power in system 1**. The lowest obtained COE with the given inputs was 0,220 €/kWh for a system with 200 kW installed PV. When further increasing the PV size, the capacities of other components remains unchanged as the building's energy needs are already fulfilled with the best throughput for each component, but the costs are higher because of an oversized PV system. Systems with 50 kW and 100 kW of PV have a higher COE due to a **bigger share of generator's production, which is triggered by a capacity shortage of the PV component**. This can also be seen from the difference in operating strategies, as in the first two scenarios the generator is needed more for charging the battery bank, while the last three scenarios are operated with Load Following strategy where the PV size is mostly sufficient for both electricity supply and charging the storage system.

The effect of installed PV power on Li-ion storage capacity and generator in system 2 is seen in Table 2.16 below.

Table 2.16. Effect of installed PV power on Li-ion storage and generator – system 2

System Component Sizes, kW (ES: kWh)					Strategy	COE, €/kWh
Solar PV	Generator	ES: Li-ion	ES: LA	Converter		
50	33	118,8	-	19,6	CD	0,338
100	33	171,6	-	22,4	CD	0,309
200	33	184,2	-	29	CD	0,315
300	33	184,8	-	23,4	CD	0,348
500	33	224,4	-	29,2	CD	0,428

Again, in system 2 the optimal generator size is not affected by the changes in other components, because the power of the generator is determined by the building's peak loads and a 10% margin for an operating reserve (assumptions made by HOMER optimization algorithm). It is easy to note that **Li-ion capacity is affected by the PV size much more than was observed for Lead Acid** storage. Li-ion storage is about 4 times more expensive than Lead Acid, which is the reason why the optimal storage capacities are much smaller than in system 1. **In system 2, with the increase in PV size, the storage capacity is increased as well.** The operating strategy for all cases is Combined Dispatch, as LF and CC strategies have no clear advantage over one another.

The effect of installed PV power on the generator in system 3 is seen in Table 2.17 below.

Table 2.17. Effect of installed PV power on generator's nominal power – system 6

System Component Sizes, kW (ES: kWh)					Strategy	COE, €/kWh
Solar PV	Generator	ES: Li-ion	ES: LA	Converter		
50	33	-	-	19,8	CD	0,607
100	33	-	-	19,8	CD	0,566
200	33	-	-	21,6	CD	0,565
300	33	-	-	22,1	CD	0,590
500	33	-	-	22,4	CD	0,660

No changes can be seen in system 6 with a change in solar PV power. Similarly to system 1, the COE is higher for smaller systems due to PV capacity shortages, so the generator needs to be run more to meet the load demand in the building. On the opposite, **300 kW and 500 kW PV systems are oversized for the building's electricity needs, so the PV's capital and O&M costs elevate the COE despite a smaller number of generator's operating hours**. However, due to the absence of energy storage, the system is likely to be unstable and this along with a high COE are the main barriers for using such system architecture in off-grid applications.

2.6.2 Effect of generator's nominal power on the storage capacity and solar PV size

The simulations were carried out using the same system components and financial inputs as previously. The system components were simulated so that a fixed generator size was manually chosen and all the other components were optimized accordingly. Generator sizes of 10 kW, 25 kW, 30 kW and 50 kW were chosen for the analysis. Systems 3 and 4 were not analysed as these topologies do not include a generator. A minimum load ratio of 35% and a 15 000-hour lifetime was applied for all generator sizes.

The effect of generator's nominal power on LA storage capacity and installed PV power in system 1 is seen in Table 2.18.

Table 2.18. Effect of generator's nominal power on LA storage and installed PV power – system 1

System Component Sizes, kW (ES: kWh)					Strategy	COE, €/kWh
Solar PV	Generator	ES: Li-ion	ES: LA	Converter		
185	10	-	2527,2	29,3	LF	0,161
157	25	-	841	27,6	CC	0,206
169	30	-	842	27,6	LF	0,217
295	50	-	2475,7	62,3	LF	0,193

Out of all the simulations, **the lowest COE – 0,161 €/kWh** – was achieved for system 1 which was compiled of 185 kW PV, a 10 kW generator and 2527,2 kWh of LA energy storage. As the building's base load demand is 9,34 kW, the generator's nominal power is just enough for supplying the base load with the peak loads supplied by the storage system or PV. System 1 with a 25 kW generator can also be recommended as the capital cost of this system is about a half of the system cost with a 10 kW generator (153 127,02 € against 313 670,83 €, respectively). A high upfront cost of the 10-kW generator system is the main challenge for installing it in practice.

The effect of generator's nominal power on Li-ion storage capacity and installed PV power in system 2 is seen in Table 2.19.

Table 2.19. Effect of generator's nominal power on Li-ion storage and installed PV power – system 2

System Component Sizes, kW (ES: kWh)					Strategy	COE, €/kWh
Solar PV	Generator	ES: Li-ion	ES: LA	Converter		
111	10	158,4	-	26	CD	0,288
126	25	158,4	-	22,4	CD	0,306
145	30	184,8	-	27,4	CD	0,323
136	50	145,2	-	24,4	CD	0,310

It can be seen that the **changing the generator's size has a much smaller effect on the storage capacity in system 2 when compared to changing the PV size**. The COE is fairly level across all sizes – the generator's higher capital cost is balanced by slightly smaller PV and storage sizes.

The effect of generator's nominal power on LA storage capacity in system 5 is seen in Table 2.20.

Table 2.20. Effect of generator's nominal power on LA storage capacity – system 5

System Component Sizes, kW (ES: kWh)					Strategy	COE, €/kWh
Solar PV	Generator	ES: Li-ion	ES: LA	Converter		
-	10	-	803	8,3	CD	0,461
-	25	-	842	8,9	CC	0,493
-	30	-	808	11,4	CD	0,558
-	50	-	274,6	39,5	CC	0,589

In system 5 the converter sizes are considerably lower because the PV component is not used. Therefore, **the converter is only needed when the storage system is charged or discharged**. In system 5 the converter size also determines the maximum amount of electrical loads that move between storage and generator/demand sides of the system. System 5 is economically not justified due to high operating costs of generators and converter/storage losses, which means that **by storing only the generator's produced electricity, it becomes even more expensive**. The importance of storage in system 5 is supplying electricity with low or high loads, when the generator would be underloaded (harmful for the hardware) or the demand exceeds the generator's nominal power.

The effect of generator's nominal power on installed PV power in system 6 is seen in Table 2.21.

Table 2.21. Effect of generator's nominal power on installed PV power – system 6

System Component Sizes, kW (ES: kWh)					Strategy	COE, €/kWh
Solar PV	Generator	ES: Li-ion	ES: LA	Converter		
-	10	-	-	-	-	-
127	25	-	-	19,8	CD	0,485
175	30	-	-	22,1	CD	0,575
175	50	-	-	22,1	CD	0,768

In system 6 the optimal solution would be using a 25 kW generator coupled with 127 kW of PV, which is sufficient for satisfying the building's electricity needs. A system with a 10 kW generator was not analysed as it would be unable to meet the given electrical load demand. Using larger generators is not justified because the generator's resources would not be optimally used (underloading), which results in a higher COE. In addition, due to the absence of energy storage the system is likely to be unstable and this along with a high COE are the main barriers for using such system architecture in off-grid applications.

2.6.3 Effect of Li-ion storage capacity on the generator and solar PV size

The simulations were carried out using the same system components and financial inputs as previously. The system components were simulated so that a fixed Li-ion capacity was manually chosen and all the other components were optimized accordingly. Li-ion storage capacities of 50 kWh, 100 kW, 200 kWh, 500 kWh and 1000 kWh were chosen for the analysis. Systems 1, 3, 5 and 6 were not analysed as these topologies do not include Li-ion energy storage.

The effect of Li-ion storage capacity on installed PV and generator power in system 2 is presented in Table 2.22.

Table 2.22. Effect of Li-ion storage capacity on PV and generator's nominal power – system 2

System Component Sizes, kW (ES: kWh)					Strategy	COE, €/kWh
Solar PV	Generator	ES: Li-ion	ES: LA	Converter		
92,4	33	50	-	18,2	LF	0,345
111	33	100	-	25,5	CC	0,324
131	33	200	-	27,1	CD	0,275
124	33	500	-	30,2	CC	0,321
139	33	1000	-	28,6	CC	0,443

As noted before, the generator's nominal power is not affected by the other components but the electrical load demand. When increasing the storage capacity in system 2, the size of PV is also increased because more solar power can be consumed and utilised, reducing the need for running the generator. **The larger the storage size, the fewer generator operating hours are needed**. The reasons for COE trends are similar to previous system 3 analyses – with a smaller storage capacity the generator has to be run to meet evening peak loads and only a small share of electricity can be supplied from the battery bank; with higher capacities the generator has to be used to charge the batteries as PV output is not sufficient for charging the storage and meeting the load demand.

The effect of Li-ion storage capacity on installed PV power in system 4 is presented in Table 2.23.

Table 2.23. Effect of Li-ion storage capacity on installed PV power – system 4

System Component Sizes, kW (ES: kWh)					Strategy	COE, €/kWh
Solar PV	Generator	ES: Li-ion	ES: LA	Converter		
-	-	50	-	-	-	-
-	-	100	-	-	-	-
-	-	200	-	-	-	-
-	-	500	-	-	-	-
450	-	1000	-	78,9	CD	0,541

System 4 was analysed but can't be considered feasible because when coupled with solar PV, Li-ion capacity of under 1 MWh is not sufficient to supply the building's electricity needs, essentially eliminating the chance for a comparative analysis. In addition, a heavily oversized 450 kW solar installation would be required, meaning that the total capital cost reaches 603 540 €, which is more than a deep renovation budget for an apartment building with a similar area.

2.6.4 Effect of Lead Acid storage capacity on the generator and solar PV sizes

The simulations were carried out using the same system components and financial inputs as previously. The system components were simulated so that a fixed Lead Acid storage capacity was manually chosen and all the other components were optimized accordingly. Lead Acid storage capacities of 500 kWh, 1000 kW, 1500 kWh, 3000 kWh and 5000 kWh were chosen for the analysis. Systems 2, 4 and 6 were not analysed as these topologies do not include Lead Acid energy storage.

The effect of LA storage capacity on installed PV and generator power in system 1 is presented in Table 2.24.

Table 2.24. Effect of LA storage capacity on installed PV and generator power – system 1

System Component Sizes, kW (ES: kWh)					Strategy	COE, €/kWh
Solar PV	Generator	ES: Li-ion	ES: LA	Converter		
173	33	-	500	27,6	LF	0,226
157	33	-	1000	28,1	CC	0,212
175	33	-	1500	32,3	CC	0,233
214	33	-	3000	24,5	CD	0,309
172	33	-	5000	29,4	LF	0,409

For system 1 it can be seen that when LA storage capacity is increased from 500 kWh to 5000 kWh in five steps, the generator and PV sizes are not greatly affected. Again, the generator's nominal power remains unchanged. The PV installation size in system 1 can not be reduced with a larger storage capacity as it is needed (along with the generator) to charge the battery bank while **only a minor share of solar power is directly fed to the AC bus and electrical loads**. Overall, the first two storage capacities can be considered sufficient while the last two capacities are oversized to see the changes in components' capacities.

The effect of LA storage capacity on installed PV power in system 3 is presented in Table 2.25.

Table 2.25. Effect of LA storage capacity on installed PV power – system 3

System Component Sizes, kW (ES: kWh)					Strategy	COE, €/kWh
Solar PV	Generator	ES: Li-ion	ES: LA	Converter		
-	-	-	500	-	-	-
413	-	-	1000	26,1	CD	0,265
334	-	-	1500	25,8	CD	0,255
288	-	-	3000	26,6	CD	0,322
232	-	-	5000	26,6	CD	0,415

By increasing the storage size in system 3, the installed PV size is reduced. As there is no generator, a **large storage capacity can provide stable power supply, whereas a small storage capacity has to be balanced with a large PV system** to be able to meet the peak load demand. However, it should be kept in mind that with a large PV size the share of excess electricity is increased, as all of the peak solar power can't be utilised by consuming and storing it. The main obstacle for system 2 is a high upfront cost, mainly due to a large storage capacity.

The effect of LA storage capacity on installed generator power in system 5 is presented in Table 2.26.

Table 2.26. Effect of LA storage capacity on installed generator power – system 5

System Component Sizes, kW (ES: kWh)					Strategy	COE, €/kWh
Solar PV	Generator	ES: Li-ion	ES: LA	Converter		
-	-	-	500	-	-	-
-	33	-	1000	32,6	CC	0,546
-	33	-	1500	32,7	CC	0,563
-	33	-	3000	31,8	CC	0,647
-	33	-	5000	30,7	CC	0,759

System 5 in all studied component sizes is considered unfeasible. First, when a 500 kWh storage is used, it is not enough to meet the electricity needs of the building. However, when compared to system 5 where generator sizes were changed, the storage and converter sizes here are much bigger and a much larger part of electricity is supplied from the battery bank. The downside is that **the storage system is only charged by the generator, which is expensive** to run and the COE for the end-consumer is further increased by the converter and storage losses. Again, the importance of storage in system 5 is supplying electricity with low or high loads, when the generator would be underloaded (harmful for the hardware) or the demand exceeds the generator's nominal power (not expected in analysed scenarios).

2.7 Conclusions from the simulation results

In conclusion, it was clearly seen that **the main upfront cost component in the systems is energy storage**, whereas **the O&M costs are the highest for diesel generators.** The simulation results showed that the optimal off-grid installation has to be comprised of at least three components – a renewable energy unit (here: PV), a controllable generation unit (here: diesel generator) and an energy storage unit (here: Li-ion or LA battery storage). While the PV is used as the main energy source in the system, a generator is needed as a back up to ensure the electricity supply when the demand can't be met with the PV unit. The energy storage unit allows for more solar energy to be used by storing it for later use instead of running the generator. Furthermore, energy storage stabilizes the system by smoothing out an otherwise fluctuing production of solar energy.

The main takeaways from the simulations are:

- without a PV unit, the Cost of Electricity is increased twice due to increased generator operation time and using only the generator to charge the storage system,
- without a generator, the size of PV and the capacity of storage have to be be greatly oversized for an all-year electricity supply, elevating both the capital and O&M costs,
- without energy storage, the excess electricity in the system is wasted; maintaining the system's stability is challenging during daytime and; the generator always runs during nighttime,
- the two-component systems set a lot of extra stress on the used components, increasing wear and shortening their lifetime, thereby increasing the system's operating costs,
- in three-component systems consuming renewable energy should be maximised; a generator should be sized to meet the base load demand; PV and stored electricity are recommended to use for meeting peak loads,
- deferring loads and managing the load demand should be considered – moving the peak loads towards noon maximises direct consumption of solar energy and prolongs the lifetimes of storage and generator units.

Off-grid electricity supply can only be feasible when establishing a grid connection is not justified or there is an absolute necessity to have a control over the COE and supply. However, the simulation results show that technically and technologically there are no constraints to building an off-grid installation. The system's stability should be kept in mind when choosing a suitable system architecture. For example, a PV + generator system with a PV capacity over 5 times larger than the generator might face stability issues as there is not balancing power to mitigate solar energy fluctuations. On islands or remote locations with no grid connection possibility, off-grid systems can prove to be a justified substitution to an electricity grid.

3 FINANCIALS OF THE SIMULATED SYSTEMS

A simple financial analysis was carried out to find the effects of different economical variables on the systems and their cost-effectiveness. Effect of Nominal Discount Rate (NDR), Inflation Rate (IR) diesel fuel price on the system's prices and components' sizes for all 6 systems are presented in the following tables. For the financial analysis, systems composed of real-world components were used. More details about the components' specifications are seen in Item 2.2.5.

The effect of financial parameters on the size and feasibility of system 1 is presented in Table 3.1.

Table 3.1. Effect of financial parameters on the system's size and feasibility - system 1

NDR, %	IR, %	Diesel, €/l	COE, €	NPC, €	Capital cost, €	Op. cost, €/y	PV, kW	ES (LA), kWh	Generator, kW
0	1,5	1,2	0,204	505 581	148 497	11 703	141	836	20
0,5	1,5	1,2	0,209	483 183	151 265	11 644	146	842	20
2	1,5	1,2	0,225	429 300	153 638	11 746	153	841	20
0	0,5	1,2	0,214	464 519	147 773	11 867	139	836	20
0	2	1,2	0,200	529 162	151 433	11 562	147	842	20
0	1,5	1,4	0,215	533 091	153 690	12 434	154	836	20

The effect of financial parameters on the size and feasibility of system 2 is presented in Table 3.2.

Table 3.2. Effect of financial parameters on the system's size and feasibility - system 2

NDR, %	IR, %	Diesel, €/l	COE, €	NPC, €	Capital cost, €	Op. cost, €/y	PV, kW	ES (Li), kWh	Generator, kW
0	1,5	1,2	0,303	751 945	134 457	20 236	132	158	20
0,5	1,5	1,2	0,307	713 222	125 113	20 631	107	158	20
2	1,5	1,2	0,320	611 287	95 405	21 983	106	92	20
0	0,5	1,2	0,311	675 876	127 344	20 551	116	158	20
0	2	1,2	0,298	793 274	134 771	20 156	132	158	20
0	1,5	1,4	0,325	808 931	161 932	21 203	168	185	20

The effect of financial parameters on the size and feasibility of system 3 is presented in Table 3.3.

Table 3.3. Effect of financial parameters on the system's size and feasibility - system 3

NDR, %	IR, %	Diesel, €/l	COE, €/kWh	NPC, €	Capital cost, €	Op. cost, €/y	PV, kW	ES (LA), kWh	Generator, kW
0	1,5	1,2	0,193	466 400	365 599	3303	295	2476	-
0,5	1,5	1,2	0,209	471 733	358 030	3989	295	2379	-
2	2	1,4	0,232	458 351	320 847	5500	303	2059	-
0	0,5	1,2	0,214	452 931	359 832	3488	295	2502	-
0	2	1,2	0,179	462 553	365 797	2962	294	2485	-
0	1,5	1,4	0,209	471 733	358 030	3989	295	2379	-

The effect of financial parameters on the size and feasibility of system 4 is presented in Table 3.4.

Table 3.4. Effect of financial parameters on the system's size and feasibility - system 4

NDR, %	IR, %	Diesel, €/l	COE, €	NPC, €	Capital cost, €	Op. cost, €/y	PV, kW	ES (Li), kWh	Generator, kW
0	1,5	1,2	0,644	1 550 000	558 827	32 546	617	673	-
0,5	1,5	1,2	0,663	1 490 000	558 827	32 740	617	673	-
2	1,5	1,2	0,716	1 330 000	554 544	32 872	592	686	-
0	0,5	1,2	0,682	1 440 000	558 827	32 904	617	673	-
0	2	1,2	0,626	1 610 000	558 827	32 327	617	673	-
0	1,5	1,4	0,644	1 550 000	558 827	32 546	617	673	-

The effect of financial parameters on the size and feasibility of system 5 is presented in Table 3.5.

Table 3.5. Effect of financial parameters on the system's size and feasibility - system 5

NDR, %	IR, %	Diesel, €/l	COE, €	NPC, €	Capital cost, €	Op. cost, €/y	PV, kW	ES (LA), kWh	Generator, kW
0	1,5	1,2	0,465	1 160 000	89 429	35 069	-	842	20
0,5	1,5	1,2	0,467	1 090 000	89 219	35 102	-	839	20
2	1,5	1,2	0,476	913 397	34 488	37 452	-	246	20
0	0,5	1,2	0,472	1 030 000	53 645	36 583	-	454	20
0	2	1,2	0,462	1 230 000	89 507	35 025	-	842	20
0	1,5	1,4	0,529	1 320 000	89 219	40 360	-	839	20

The effect of financial parameters on the size and feasibility of system 6 is presented in Table 3.6.

Table 3.6. Effect of financial parameters on the system's size and feasibility - system 6

NDR,%	IR, %	Diesel, €/l	COE, €	NPC, €	Capital cost, €	Op. cost, €/y	PV, kW	ES, kWh	Generator, kW
0	1,5	1,2	0,472	1 170 000	65 389	36 132	127	-	20
0,5	1,5	1,2	0,474	1 100 000	65 389	36 144	127	-	20
2	1,5	1,2	0,480	914 320	65 389	36 175	127	-	20
0	0,5	1,2	0,476	1 030 000	65 389	36 156	127	-	20
0	2	1,2	0,470	1 250 000	65 389	36 118	127	-	20
0	1,5	1,4	0,529	1 310 000	71 099	40 581	139	-	20

The economics of each system configuration that achieved the lowest NPC (Tables 3.1-3.6) is summarized in Table 3.7.

Table 3.7. All system configurations that achieved the lowest Net Present Costs.

Syst.	NDR,%	IR, %	Diesel, €/l	COE, €	NPC, €	Capital cost, €	Op. cost, €/y	PV, kW	ES, kWh	Generator, kW
1	2	1,5	1,2	0,225	429 300	153 638	11 746	153	841	20
2	2	1,5	1,2	0,320	611 287	95 405	21 983	106	92	20
3	0	0,5	1,2	0,214	452 931	359 832	3488	295	2502	-
4	2	1,5	1,2	0,716	1 330 000	554 544	32 872	592	686	-
5	2	1,5	1,2	0,476	913 397	34 488	37 452	-	246	20
6	2	1,5	1,2	0,480	914 320	65 389	36 175	127	-	20

The tables indicate that **systems including energy storage are generally more affected by changes in Nominal Discount Rate and Inflation Rate**. For example a rise in Nominal Discount Rate reduces the optimal storage capacity considerably. A 2% rise in NDR reduces the storage capacity by 15% in system 3; by 40% in system 2; and by 70% in system 5. Storage capacity in systems 1 and 4 is almost not affected by 2% fluctuations in NDR. This should definitely be considered when planning an off-grid power system with one of the architectures presented above. Analysing the NDR trends can help to determine the optimal energy storage capacity over the system's expected lifetime.

In addition, a higher NDR results in a higher COE and a lower NPC. A 2% rise in NDR elevates the COE by 16% in system 3; by 7% in system 1; by 6% in system 2; by 1,5% in system 5; by 1% in system 6 and; by 9% in system 4. At the same time NPC is reduced by 2% in system 3; by 15% in system 1; by 19% in system 2; by 21% in systems 5 and 6; by 14% in system 4. It can be concluded here that both COE and NPC should be addressed when planning off-grid installations of different topologies.

Inflation rate mainly affects the expenditure during operation of the systems. A higher inflation rate reduces the operating costs as well as COE. On the opposite, NPC grows along with the inflation rate. **IR does not affect the optimal size of system's components** much. A higher IR occasionally rises the optimal size of the PV component (systems 1 and 2), but no regularity was found between the optimal component sizes and IR.

For further reducing the COE, a simulation was carried out for system 1 architecture with a 10 kW generator. With the actual electrical load the system's COE was 0,161 €/kWh (Item 2.6.2). When moving the loads 3 hours forward, the system's COE cna be further reduced to 0,151 €/kWh, which is the lowest achieved value that was achieved in the simulations.

One of the principal targets for nZEBs and Energy Performance of Buildings Directive is to reduce primary energy consumption and to support renewable energy production. For further consideration the renewable fractions of three-component systems 1 and 2 were addressed. It was found that renewable energy fraction of system 1 (PV+generator+LA storage) is 83,5%, while the same value for system 2 (PV+generator+Li-ion storage) reaches 60,9%. Therefore, system 1 complies better with nZEB and EPBD targets and requirements.

It has been found that for building a new nZEB, the average additional investment compared to the current national requirements is 208 €/m^2 across the EU [2]. As of Spring 2018, most of the new apartment buildings in Estonia meet the low energy building standard (or energy performance class B). According to the biggest construction companies and banks in Estonia, the building cost of apartment buildings reached 1400 €/m^2 in 2017. With the two values summed, the average building cost of a nZEB is 1608 €/m^2. For a 1317 m^2 (simulated) or a 3900 m^2 (average five-floor concrete) apartment building that meets the nZEB standard, the total building cost for the construction company would reach 2 117 736 € or 6 271 200 €, respectively. A deep renovation cost for buildings with the same areas is estimated at 209 000 € or 619 000 €, respectively. Based on these estimations, a deep renovation of existing apartment buildings is a much cheaper solution than building new apartment buildings.

As discussed previously, the installation with the lowest COE would cost 129 650 € without labour and installation costs. The installation was sized (and priced) according to the load profile of a small apartment building constructed in 2006, which has a relatively high specific electricity demand with electrical water heaters consuming about 40% of the electricity. The installation and programming costs of the simulated generation system can be higher than the total price of the components. A study conducted by NREL in 2017 showed that the total installed cost of a residential-scale PV and storage system reached 29 568 USD while the components cost just 14 101 USD of that amount. Generally the costs for installing, marketing, profit and supply chain can be multiplied by the amount of components in the system. For instance, these additional costs can be roughly three times higher for a PV-storage-generator system when compared to a PV-only system. [72] Therefore, it is assumed that the total installed cost of the power system is approximately 200 000 €, which can be lower in practice but such possibility should be considered with reservation.

As the proposed installation enables to improve a low energy building's performance class to nearly-zero performance class, the residents in the apartment building will consume 100% renewable energy from March to September and the share of renewable energy is 95% or more in February and October as well. Therefore, the generator is mainly relied upon from November to January. The main takeaway from these esimations is that compared to the building or deep renovation costs, building an on-site electricity generation unit does not require a vast additional investment and it is economically justified to build electricity generation units for nZEB's already today.

For different scenarios, the economical analysis results are presented in table 3 below. The calculations were carried out using the simple cost analysis methodology. For the COE value, the LCOE (levelised cost of electricity) of energy storage was converted into LCOS (levelised cost of storage), which accounts for the round-trip efficiency and losses of batteries. Literature on LCOS can be found from [53] and [76]. The installed capital costs are rough estimations based on known literature and may not correspond with actual prices that should be considered individually for every location addressed. The values were obtained using actual load data and without deferred loads. It can be assumed that the COE can be reduced by approximately 0,01 €/kWh when shifting some of the loads forward. Further reductions in COE and storage capacity are possible with a more detailed analysis addressing load deferral and demand side management.

The summary economics of systems 1-6 and modified „system 1 deferred" is presented in Table 3.8 below.

Table 3.8. Economics for optimally sized power systems 1-6 (interest rate 2%; inflation rate 2%)

Structure	**Figure**	**Value**
System 1: 141 kW PV + 20 kW generator + 836,2 kWh Lead Acid storage	Capital cost (installed)	200 000 €
	Operating cost	11 702 €/y
	COE (Cost of Electricity)	0,204 €/kWh
System 2: 132 kW PV + 20 kW generator + 158,4 kWh Li-ion storage	Capital cost (installed)	200 000 €
	Operating cost	20 236 €/y
	COE (Cost of Electricity)	0,303 €/kWh
System 3: 295 kW PV + 2475,7 kWh Lead Acid storage	Capital cost (installed)	500 000 €
	Operating cost	3303 €/y
	COE (Cost of Electricity)	0,193 €/kWh
System 4: 617 kW PV + 673,2 kWh Li-ion storage	Capital cost (installed)	750 000 €
	Operating cost	33 042 €/y
	COE (Cost of Electricity)	0,644 €/kWh
System 5: 20 kW generator + 842,4 kWh Lead Acid storage	Capital cost (installed)	120 000 €
	Operating cost	35 069 €/y
	COE (Cost of Electricity)	0,465 €/kWh
System 6: 127 kW PV + 20 kW generator	Capital cost (installed)	100 000 €
	Operating cost	36 132 €/y
	COE (Cost of Electricity)	0,472 €/kWh
System 1 deferred: 138 kW PV + 10 kW generator + 1094 kWh Lead Acid storage*	Capital cost (installed)	210 000 €
	Operating cost	10 507 €/y
	COE (Cost of Electricity)	0,151 €/kWh

*- the lowest achieved COE, the loads were shifted 3 hours forward

Except for a system comprising only PV and Li-ion storage, a relation between capital expenditure and operating expenditure can be seen – generally, capital cost and operating cost are inversely related. The principal problem for end-consumers is that the high upfront costs are difficult to overcome, even if renewables and the studied off-grid systems are profitable over their estimated lifetime. Furthermore, many residents in apartment buildings are not motivated to invest in deep renovation projects as the financial gains from energy efficiency and undone by long-term loans for financing the projects. To address this issue, KredEx in Estonia launched a new support mechanism for apartment buildings to install PV panels. The financial support can amount up to 30% of the installed PV costs. As the PV component capital cost in the lowest-COE model (system 1 deferred) reaches 56 700 € and the total installed cost can reach 100 000 €, about 30 000 € can be reimbursed by KredEx in the simulated case. The new support mechanism for apartment buildings is welcome, but more should be done to motivate the residents to invest in deep renovation with on-site electricity generation. [73] This work has shown that in off-grid systems, energy storage is the main contributor to a high capital cost that is considered as an obstacle for widespread implementation of off-grid or other on-site power systems. Therefore, it is recommendable to introduce similar support schemes for energy storage systems or off-grid power systems as a whole.

3.1 Indirect benefits of off-grid systems and competitiveness against grid electricity

3.1.1 Avoided costs of CO_2 emission allowances under the EU Emission Trade System

In addition to direct cash flows, there are indirect benefits for installing off-grid systems that don't directly affect the end-consumer, but may benefit other parties on the macroeconomic level. To determine these benefits related to nZEB and hybrid power systems' implementation, an analysis shall be conducted.

From the state's perspective, the main benefit can be the reduced CO_2 emissions. The price of CO_2 allowances under the EU Emission Trade System (ETS) is about 13,50 €/tCO_2 [74]. The greenhouse gas emissions from electricity production in Estonia amount to 1,19 t_{CO2}/MWh [75]. As the yearly renewable energy consumption in the simulated model is 68 881,2 kWh, approximately 82 tonnes of CO_2 emissions are avoided, equaling 1108 € on the EU ETS market every year per one apartment building. The estimated indirect benefits for Soviet-era concrete buildings are about 950-1000 €. The 10 kW diesel generator analysed in system 1 with load shifting produces 12,908 MWh of electricity annually, while the annual CO_2 emissions are 11,502 t, meaning that the specific CO_2 emissions of the system reach 0,89 t_{CO2}/MWh. As the CO_2 allowance price is expected to grow, the indirect benefits will increase as well.

3.1.2 Competitiveness against grid electricity

For analysing the off-grid system's competitiveness against electricity bought from the grid, the cost of grid electricity was found. The real time grid electricity price was calculated with formula 3.1:

$$C_{el,grid} = C_{NPS} + C_{fee} \tag{3.1}$$

where $C_{el,grid}$ – grid electricity price for end-consumer, €/kWh,

C_{NPS} – Nord Pool Spot hourly electricity price, €/kWh,

C_{fee} – total fees and taxes included in the electricity bill, 0,0636 €/kWh.

The hourly sellback price of electricity was calculated with formula 3.2:

$$C_{el,sell} = C_{NPS} + C_{subsidy}$$
(3.2)

where $C_{el,sell}$ – electricity sellback price, €/kWh,

$C_{subsidy}$ – renewable energy subsidy, 0,0537 €/kWh [25].

Since 2005 the consumer price index (CPI) has grown 49% in Estonia. At the same time the network fees in distribution grid have risen by 19%. Based on these values it can be concluded that grid services have become more affordable and the service cost has fallen for about a third compared to the CPI. As seen from formula 3.1, the total taxes and fees of grid electricity are 0,0636 €/kWh. [66]

The average NPS electricity price in 2017 was 0,0332 €/kWh, meaning that the average price for the end-customer was 0,0968 €/kWh. At the same time the average electricity sellback price was approximately 0,0869 €/kWh.

If no grid connection is present and the building is located more than 400 meters away from the nearest substation, additional investments into establishing a connection are needed. The actual expenses vary, but costs of approximately 13 000 € should be taken into account. When the distance is below 400 meters, establishing a connection with a 63 A main fuse costs 9828 € [71].

The off-grid project lifetime of 25 years was used in HOMER. It was assumed that the building is connected to the grid, the building's energy consumption remains constant at 81 789,2 kWh/y and the grid electricity price will be affected by a 2% yearly inflation rate. The total consumed electricity over 25 years is 2 044 730 kWh, the total expenditure on electricity over 25 years is 253 590,1 € and the estimated average COE for the next 25 years is 0,124 €/kWh. In comparison, the lowest obtained off-grid COE is 0,151 €/kWh.

Overall, the financial considerations show that from the end-consumers' interests it is not justified to build an off-grid installation that would be able to meet the electrical loads of an average apartment building for the whole year, if a feasible solution for establishing a grid connection is available. However, the prices of PV and especially energy storage are expected to drop, meaning that off-grid power systems may become feasible in Estonia in the coming years. Furthermore, introducing load management and deferral in off-grid systems can bring the expected profitability time forward.

SUMMARY

This thesis studied the technical and economical aspects of on-site electricity supply models for off-grid and nearly-Zero Energy Buildings in Estonian conditions. As the European Union has set long term targets of reducing primary energy consumption and energy consumption in buildings, this work provides insight to the current situation and non-exhaustive solutions for moving towards these strategic targets. For drawing conclusions on the topic, simulations with HOMER Pro and PVsyst softwares were carried out for a hybrid power system consisting of solar PV panels, energy storage (Lithium-ion and Lead Acid technologies) and a back-up diesel generator. This work is novel for addressing off-grid power supply of apartment buildings with more sophisticated electrical loads than single-family houses that have been thoroughly studied in this context.

The simulations were perfomed for a modern apartment building with a heated area of 1317 m^2 and a yearly electricity demand of 81 789 kWh. As a comparison, the annual electricity demand of a Soviet-era concrete building with a heated area of 3900 m^2 reaches approximately 57 000 kWh.

The main takeaways from this work are the following:

- the lowest achieved off-grid electricity price of 0,151 €/kWh can not yet compete with average expected spot prices of grid electricity and taxes of 0,124 €/kWh;
- the cost of electricity can be reduced by increasing the Load Match Index and maximising direct consumption of solar energy;
- supplying energy from the storage system should be preferred over operating a diesel generator in all scenarios;
- for increasing the share of renewable energy consumption, on-site solar PV should be preferred over any other electricity source;
- three-component off-grid power systems – including energy storage, renewable energy production and controllable generation unit – are most reliable and advantageous,
- the best system configuration is composed of a solar PV system, Lead Acid battery energy storage and a back-up diesel generator,
- without a PV unit, the Cost of Electricity is increased twice due to increased generator operation time and using expensive generator electricity to charge the storage system,
- without a generator, the size of PV and the capacity of storage have to be be greatly oversized for an all-year electricity supply, elevating both the capital and O&M costs,

- without energy storage, the excess electricity in the system is wasted; maintaining the system's stability is challenging during daytime and; the generator always has to run during nighttime,
- the two-component systems set a lot of extra stress on the used components, increasing wear and shortening their lifetime, thereby increasing the system's operating costs,
- in three-component systems consuming renewable energy should be maximised; a generator should be sized to meet the base load demand; PV and stored electricity are recommended to use for meeting peak loads,
- deferring loads and managing the load demand should be considered – moving the peak loads towards noon maximises direct consumption of solar energy and prolongs the lifetimes of storage and generator units.

When operating the best proposed power system (PV, Lead Acid storage and a generator) in Estonian climatic conditions, the nZEB and energy efficiency targets are met. It can be estimated that the optimal power system is able to supply the studied apartment building with **100% renewable energy from the beginning of February to the end of October**. The diesel generator has to be used to meet the building's load demand in winter. HOMER simulations show that the share of renewable energy consumption for the off-grid power system is 83,5%.

The most feasible system configuration can be comprised with two preferred component sizing options:

- 141 kW solar PV, 20 kW diesel generator and 836,2 kWh Lead Acid energy storage with an estimated installed cost of 200 000 € (including cost of components – 130 000 €), offering an average Cost of Electricity of 0,204 €/kWh over its lifetime,
- 138 kW solar PV, 10 kW diesel generator and 1094 kWh Lead Acid energy storage with an estimated installed cost of 210 000 € (including cost of components – 140 000 €), offering an average Cost of Electricity of 0,151 €/kWh over its lifetime, if load shifting and management methods are applied.

The construction cost of a 1317 m^2 nearly-zero energy apartment building is estimated at 2,1 M€, while a deep renovation of an old apartment building with an equal area is estimated to cost from 0,2 M€ upwards. It can be seen that the price of the on-site electricity generation unit is several times lower than the costs of renovation and construction. Therefore, adding any of the simulated power systems to a building, that is constructed according to the current best practice and cost-optimal methods is likely to elevate the building's energy performance to a nearly-zero level required from 2020.

The indirect benefits for installing on-site power systems include avoided investments into improvements of distribution grids and avoided CO_2 emissions. It was estimated in this work that the each simulated on-site generation unit may reduce the country's expences on CO_2 allowances by 1000 € every year. Considering the number of apartment buildings in Estonia and the lifetime of the simulated systems, the indirect benefit potential is considerable.

In conclusion, this thesis has shown promising initial results for on-site electricity production for off-grid apartment buildings. Much further research is needed on the topic to possibly develop a cost-effective off-grid power generation model. The cost-effectiveness of off-grid power systems is expected to improve rapidly with improvements in solar energy and energy storage technologies. Off-grid power systems for apartment buildings in Estonia are currently not competitive against low grid electricity prices, but this is likely to change in the coming years. In future research, the effect of widespread implementation of apartment buildings' on-site power systems on the power quality in grids needs to be addressed.

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