

# Sustainable Energy-efficient Microgrid – A Case Study on Local Energy System Design

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Elahe Doroudchi



# Sustainable Energy-efficient Microgrid – A Case Study on Local Energy System Design

**Elahe Doroudchi**

A doctoral dissertation completed for the degree of Doctor of Science (Technology) to be defended, with the permission of the Aalto University School of Electrical Engineering, at a public examination held at the hall Jeti of A Grid (Otakaari 5A) on 26 September 2018 at 12:00.

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**Abstract**

Increasing environmental concerns about the use of fossil fuels have generated great interest in emerging technologies to produce clean energy. Current research aims to mitigate this concern by proposing solutions for applying clean energies in residential buildings. This thesis focuses on microgrids, small energy grids to generate, consume and share energy among producers within their own networks. Microgrids can come in different sizes and be based on various electricity generation sources. This research modelled and designed a microgrid solution that is sustainable, energy-efficient, economically viable and easily implemented. To achieve these goals, the design of a community of residential buildings is reverse-engineered in order to scale down the microgrid model into smaller segments for simplifying the management of energy in individual and groups of dwellings.

This research presents a sequence of approaches to optimally utilise distributed energy resources, such as PV systems, battery energy storage, thermal storage and electric vehicles, with the aim of minimising imports from utility electricity grids, as well as helping houses, buildings, and communities to reduce energy bills. The optimisation algorithms are also tested in a hardware-in-the-loop environment to validate their performance. Furthermore, the research includes economic assessments to provide a complete picture of the real value of such an approach, incorporating the cost of the new assets (e.g. batteries) and the effects of different pricing strategies. The research starts with the design of a DC microgrid for single-family homes, leading to the development of a community model consisting of eight dwellings in a neighbourhood. The model is implemented for daily, monthly and yearly time spans to verify that the proposed approach works across different time scales.

The results of this thesis, which are extended from a small dwelling model to a community model, from one-day energy management analysis to a year-long energy sharing assessment, would benefit researchers, grid utilities, power companies and city planners in order to provide better solutions for a future carbon-free environment.

**Keywords** Community energy network, demand response, electrical storage, microgrids, renewable energy systems, residential building energy management system, sustainability, thermal storage

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I started as a doctoral candidate in 2014. I had the chance to work in an international multidisciplinary working environment under the supervision of Professor Jorma Kyyrä and Professor Matti Lehtonen. I would like to appreciate Professor Jorma Kyyrä for his continuous support and guidance during the whole work and Professor Matti Lehtonen for all the scientific comments and discussions. I would like to thank my co-authors Dr. Kari Alanne and Dr. Sudip Pal at Aalto University (Department of Mechanical Engineering); and Dr. Xian-yong Feng, Ms. Shannon Strank and Professor Robert Hebner from the University of Texas at Austin, USA, where I was a visiting researcher, for their great cooperation. I would also like to thank all my former and present colleagues and the department staff for their interesting conversations, help with the research topic and experimental measurements, as well as a great working environment. I am also grateful to the participants in the Energy-efficient Townhouse project for the discussions on my work that we held during the research project meetings.

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Espoo, August 16<sup>th</sup>, 2018

Elahe Doroudchi



# Contents

Acknowledgements .....	5
List of Abbreviations .....	9
List of Symbols .....	11
List of Publications .....	14
Author's Contribution .....	16
1. Introduction .....	19
1.1 Aim of the research .....	20
1.2 Scientific contributions .....	20
1.3 Dissertation outline .....	22
2. Local energy system design .....	24
2.1 System modelling .....	24
2.1.1 Building model .....	24
2.1.2 Energy system model .....	25
2.2 Comparison of the AC and DC microgrids efficiency .....	28
2.3 Conclusion .....	29
3. Microgrid electricity and energy systems analysis .....	30
3.1 Electrical storage sizing optimisation .....	30
3.1.1 Monthly energy costs analysis .....	31
3.1.2 Annual energy savings .....	33
3.2 Demand response control of thermal storage .....	34
3.2.1 Demand response control by greedy variable neighbour- hood algorithm .....	35
3.2.2 Results and discussion .....	36
3.3 Conclusion .....	37
4. Validation of the proposed models via hardware-in-the-loop tests... .....	38
4.1 Real-time testing including PV and electrical storage .....	39
4.1.1 Time of use pricing .....	40
4.1.2 Dynamic pricing .....	42

4.2	Real-time testing including solar collector and thermal storage .....	43
4.2.1	Storage size 7 kW .....	45
4.2.2	Storage size 10.5 kW .....	47
4.2.3	Storage size 14 kW .....	47
4.2.4	Results comparison .....	48
4.3	Conclusion .....	49
5.	Temporal and spatial escalation of the proposed microgrid model ..	50
5.1	Microgrid model expanded to a calendar year .....	50
5.1.1	Results discussion, district heating (DH) scenario .....	52
5.1.2	Results discussion, ground source heat pump (GSHP) scenario .....	54
5.1.3	Economic assessment .....	55
5.2	Microgrid model expanding to a community area .....	56
5.2.1	Community area model and analysis .....	56
5.2.2	Economic assessment .....	59
5.3	Conclusion .....	59
6.	Conclusions .....	60
	References .....	62

# List of Abbreviations

Abbreviations	Description
AC	Alternating current
DC	Direct current
DH	District heating
DHW	Domestic hot water
DR	Demand response
EMS	Energy management system
ESC	Energy storage capacity
ESS	Energy storage system
EV	Electric Vehicle
GSHP	Ground-source heat pump
GVNA	Greedy variable neighbourhood algorithm
HIL	Hardware-in-the-loop
HVAC	Heating, ventilation and air-conditioning
IGBT	Insulated-gate bipolar transistor
LPSP	Loss of power supply probability
MILP	Mixed-integer linear programming
nZEB	nearly-zero energy building
NZEB	Net-zero energy building
OEF	On-site energy fraction
OEM	On-site energy matching
PMV	Predicted mean vote
PPD	Predicted percentage of dissatisfied
PV	Photovoltaic

RMS	Root mean square
SOC	State of charge
ToU	Time of use
V2H	Vehicle to home

# List of Symbols

Symbols	Description
$f_{sw}$	IGBT switching frequency
$h$	Number of houses
$i$	Index of house number
$r$	Discount rate
$r_{on}$	IGBT on-state resistance
$t$	Index of time in hours
$w_{exp}$	Export power electricity price
$w_{imp}$	Import power electricity price
$x$	Imported energy
$A$	EV availability at home
$BP$	Electricity purchasing price
$C_{air}$	Air heat capacity
$CE$	Imported power
$C_{mass}$	Building fabric heat capacity
$C_n$	Dynamic capacitance
$DE$	Exported power
$E_{in}$	Momentary input energy
$E_{loss}$	Energy losses
$E_{off}$	IGBT turn-off energy losses
$E_{on}$	IGBT turn-on energy losses
$E_{out}$	Momentary output energy
$E_{RR}$	Diode reverse-recovery energy

$H_e$	Virtual thermal conductance between internal and external temperature node points
$H_g$	Thermal conductance between ground temperature and ambient temperature
$H_m$	Heat conductance of solid wall material
$H_M$	Heat convection on the surfaces
$H_s$	Thermal conductance controlling the ventilation air heat capacity flow having temperature $T_s$
$I$	Current
$I_{nom}$	Rated current
$I_{rms}$	RMS value of the actual current
$N$	Planning intervals
$P_t^{hvac}$	Electrical power supplied to HVAC unit at time $t$
$P_t^{sth}$	Heat power provided from the solar thermal collector at time $t$
$P$	Price of electricity at hour $t$
$P_{EV-}$	EV charging power
$P_{EV+}$	EV discharging power
$P_{EXP}$	Exported power
$P_{HVAC}$	HVAC load demand
$P_{IMP}$	Imported power
$P_{loss}$	Wiring losses
$P_{loss,cond}$	Conduction losses
$P_{loss,su}$	Switching losses
$P_{max}$	Maximum allowed imported power
$PMV_t$	Predicted mean vote at hour $t$
$PPD_t$	Predicted percentage dissatisfied at hour $t$ , units of %
$P_{STO-}$	Charging power of the stationary storage
$P_{STO}$	Storage charging/discharging power
$P_{STO+}$	Discharging power of the stationary storage
$Q_t^{hvac}$	HVAC thermal output power at time $t$

$R$	Wiring resistance
$R_o$	Ohmic resistance
$R_n$	Dynamic resistance
$S$	Cumulated cost savings
$S_a$	Annual savings
$SOC$	State of charge
$SP$	Electricity selling price
$T^*$	Desired room temperature
$T_{amb}$	Ambient temperature
$TDHD$	Total daily heat demand
$T_e$	Outdoor temperature
$T_g$	Ground temperature
$T_{mass}$	Building fabric temperature
$T_s$	Ventilation air heat temperature
$V_{on}$	IGBT on-state voltage drop
$w_{EXP}$	Electricity price for export power
$w_{IMP}$	Electricity price for import power
$\alpha$	Storage loss coefficient/penalty factor
$\beta$	Temperature dead-band
$\eta$	Efficiency
$\lambda_t$	Power price at hour $t$
$\Pi$	Maximum thermal storage capacity
$\Delta t$	Decision time interval

# List of Publications

This doctoral dissertation consists of a summary and of the following seven publications that are referred to in the text by their Roman numerals.

- I.** Doroudchi, Elahe; Kyrrä, Jorma; Lehtonen, Matti. Battery energy storage effect on AC/DC microgrids efficiency. The 18<sup>th</sup> IEEE European Conference on Power Electronics and Applications (EPE'16 ECCE Europe). Karlsruhe, Germany, Sep. 5-9, 2016. DOI: <https://doi.org/10.1109/EPE.2016.7695659>.
- II.** Doroudchi, Elahe; Pal, Sudip K.; Kyrrä, Jorma; Lehtonen, Matti. Optimizing energy cost via battery sizing in residential PV/battery systems. The 2015 IEEE Innovative Smart Grid Technologies - Asia (ISGT ASIA). Bangkok, Thailand, Nov. 3-6, 2015. DOI: <https://doi.org/10.1109/ISGT-Asia.2015.7387155>.
- III.** Doroudchi, Elahe; Lehtonen, Matti; Kyrrä, Jorma. Demand response control of a townhouse thermal storage by greedy variable neighbourhood algorithm. International Review of Electrical Engineering (IREE), vol. 11, no. 6, pp. 654-662, 2016. DOI: <https://doi.org/10.15866/iree.v11i6.9951>.
- IV.** Doroudchi, Elahe; Feng, Xianyong; Strank, Shannon; Hebner, Robert E.; Kyrrä, Jorma. Hardware-in-the-loop test for real time economic control of a DC microgrid. The 2018 IET 9<sup>th</sup> International Conference on Power Electronics, Machines and Drives (PEMD). Liverpool, UK, Apr. 17-19, 2018.
- V.** Doroudchi, Elahe; Kyrrä, Jorma; Lehtonen, Matti. Hardware-in-the-loop test for a residential partial thermal storage space heating demand response control. Submitted to a peer-reviewed journal, 2018.
- VI.** Doroudchi, Elahe; Alanne, Kari; Okur, Özge; Kyrrä, Jorma; Lehtonen, Matti. Approaching net zero energy housing through integrated EV. Sustainable Cities and Society (SCS), vol. 38, pp. 534-542, 2018. DOI: <https://doi.org/10.1016/j.scs.2018.01.042>.

- VII.** Doroudchi, Elahe; Lehtonen, Matti; Kyyrä, Jorma. Optimizing residential energy costs through community energy network. Submitted to a peer-reviewed journal, 2018.

# Author's Contribution

The author of this thesis is the main contributor to all the publications [I] - [VII]. The author had the lead role in all the manuscripts and was responsible for developing the concepts, performing the simulations, analysing the results, and writing the papers. The contributions from the co-authors are indicated in the following paragraphs.

## **Publication [I]:**

### **Battery energy storage effect on AC/DC microgrids efficiency**

The co-authors of this article contributed to the manuscript through discussions and comments.

## **Publication [II]:**

### **Optimizing energy cost via battery sizing in residential PV/battery systems**

S. Pal contributed by providing the energy consumption data for the example single-family house in the publication. J. Kyyrä and M. Lehtonen contributed to the manuscript through discussions and comments.

## **Publication [III]:**

### **Demand response control of a townhouse thermal storage by greedy variable neighbourhood algorithm**

The co-authors of this article contributed to the manuscript through discussions and comments.

## **Publication [IV]:**

### **Hardware-in-the-loop test for real time economic control of a DC microgrid**

X. Feng contributed by preparing the simulation model for this publication and applying the proposed model in the real-time simulator. S. Strank and R.E. Hebner contributed to this publication through their continuous comments and discussions. J. Kyyrä contributed to the manuscript through discussions and comments.

## **Publication [V]:**

### **Hardware-in-the-loop test for a residential partial thermal storage space heating demand response control**

The co-authors of this article contributed to the manuscript through discussions and comments.

**Publication [VI]:**

**Approaching net zero energy housing through integrated EV**

K. Alanne contributed to the publication by providing the energy matching indices and duration curve models, as well as through his continuous discussions. In addition, he proposed the EV inside the building's energy system boundary. Ö. Okur contributed by providing the EV energy consumption pattern in Finland by studying the Finnish National Travel Survey. The other co-authors contributed through their feedback and comments on the manuscript.

**Publication [VII]:**

**Optimizing residential energy costs through community energy network**

The co-authors of this article contributed to the manuscript through discussions and comments.



# 1. Introduction

Electrical power generation, transmission and distribution have traditionally been the main route for providing electric energy to customers. Residential, commercial and industry customers pay the utilities for the electricity they receive, and are often not concerned with the environmental effects of fossil fuel-based energy production [1]-[5]. Nevertheless, due to the adverse effects of global warming, there is an increasing awareness of the disadvantages of using fossil fuels. Global warming, the rise in seawater levels, and droughts constitute the main impacts of increased CO<sub>2</sub> levels in the Earth's atmosphere. Therefore, renewable energy sources could offer reasonable replacements for traditional energy sources, since they produce no CO<sub>2</sub>. For over two decades, the most widely used renewable resources have been solar, hydro and wind energy, as well as geothermal energy and bioenergy [6]-[11].

These renewable resources have not only enabled energy to be generated in small-scale power plants but also distribute its production. Distributed energy generation is a benefit of renewable energy systems, thereby making it possible to generate and consume energy without the need for long transmission lines. However, achieving distributed energy generation will require smaller grids. These smaller grids, known as microgrids, can be as large as a college campus or a military base or as small as an individual house (often dubbed a "nanogrid") [12]. Operating microgrids poses a challenge due to varying regulations and standards in each country. Microgrids can be grid-connected or islanded, can consist of one or more renewable energy resources, and can be operated in numerous buildings of different types, or even a single-family home. These factors need to be considered when designing a microgrid in order to produce a layout that would be productive and safe, as well as applicable to varying locations.

When defining a microgrid, it is not only important to apply renewable energy systems, but also vital to consider the energy efficiency of future electrical power networks. Therefore, the design should be carefully studied to increase the energy efficiency and sustainability of these future power systems. In order to design a microgrid, three challenges must be overcome: finding an optimal method for increasing efficiency in the microgrid, ensuring the sustainability of the models designed, and determining methods for enhancing the reliability of the system. However, the third challenge is beyond the scope of this research, as reliability assessment would require a separate extensive study. Although the first and second challenges have attracted the attention of many researchers, there is currently no widely accepted standards or models for designing microgrid.

The study of microgrids is very wide-ranging and varies from case to case and country to country. In Europe, countries have focused on different aspects of the microgrid. For example, Denmark and the Netherlands have mainly studied wind energy, Germany and Spain have concentrated on solar energy, whereas Switzerland and Austria have examined the benefits of hydropower [13]-[16]. In Finland, the emphasis has been on both wind and solar energies. The EU Directive 2010/31/EU demands that European Union countries achieve nearly-zero energy in all new buildings from the beginning of the year 2021 [17]. Therefore, many countries including Finland there has been a concerted focus on this issue, thus affecting the design of new buildings and electrical power systems.

## **1.1 Aim of the research**

Due to the lack of applicable standards for microgrids, this research develops and validates models for microgrids equipped with the DC electricity distribution system that are integrated with the PV systems, battery energy storage, thermal storage and electric vehicles. Because designing microgrids on a large scale would pose a challenging task, this research reverse-engineers the design of an energy generation and distribution system in order to scale down the design of a microgrid into smaller segments for simplifying energy management. This allows a large microgrid consisting of a number of buildings and two or three possible renewable energy sources to be scaled down to one building. This building, located in the city of Helsinki, is a single-family dwelling, a townhouse, designed to satisfy the requirements of EU Directive 2010/31/EU in terms of architectural features [18, 19]. However, nearly-zero energy buildings (nZEB) specified in the directive also require changes in the energy and electricity distribution systems. Therefore, this research concentrates on designing an electricity and energy system for the development of a microgrid model that would be sustainable, energy-efficient, economically viable and easily implemented.

To achieve these goals, this research proposes a microgrid model for integrating renewable energy sources as well as electrical and thermal storage systems into the design phase of residential, single-family homes. To validate the proposed model, hardware-in-the-loop (HIL) tests are applied to examine its accuracy. Finally, the model is extended to include a community consisting of eight homes in order to test the proposed model on a wider scale.

## **1.2 Scientific contributions**

This dissertation consists of seven publications [I] - [VII]. A brief overview of the major contributions in each publication is given in this section.

The first three publications [I]-[III] develop the microgrid model for a single-family house that is iteratively improved in these publications. The model proposed in this research for a DC microgrid considers two DC voltage levels of 380 V and 48 V. The model is designed to be operational according to Finnish housing standards. The model will be implemented in future townhouse dwellings in the Helsinki region of Finland. Therefore, these three publications develop a

working model for a local energy system, which in Publications [IV]-[V] is validated, and later in Publications [VI]-[VII] further extended for a small residential community.

Publications [IV] and [V] develop and test the designs for an electrical and a thermal storage system, respectively. These two publications also propose hardware-in-the-loop tests for the microgrid models developed in Publications [I]-[III]. The microgrid model as well as the optimisation models for the demand response and building energy management system are applied to test the two building energy designs. However, since directly using the model and the energy management system in a real plant poses the risk of destroying the physical system, it is considered more reliable to first test the model and the control system on a virtual system rather than on a real physical plant. The hardware-in-the-loop test allows real-time testing of the control system and provides validation for the proposed energy management algorithms. On the other hand, for the real-time test, it is considered safe to test the model on an actual system. These publications provide a comparison between the off-line and the real-time simulation tests, demonstrating that the off-line simulation models can be effectively validated using real-time simulation tests.

In order to ensure the sustainability of the generation and distribution system, Publications [I]-[V] study electrical and thermal storage systems under different conditions for a single-family home. To complete the design and determine the productivity of the proposed building energy management models, the model is expanded temporally and spatially. These publications focus on a single day, while publication [VI] studies the two storage systems for one calendar year, as well as integrating an electric vehicle into the building system boundary. The model proposed in this publication aims to meet the requirements of an nZEB building and evaluates the feasibility of the proposed energy management model in attaining this goal. Publication [VII] spatially expands the model in Publication [VI]. To achieve this goal, a community network consisting of eight nZEB single-family homes are modelled and simulated as one entity in two cases. The first case involved allocating separate storage units for each community member. In the second case, the whole community benefits from one storage facility. This publication provides results that would be useful in future research for power utilities contemplating the creation of sustainable independent communities.

Overall, the series of aforementioned publications provide solutions for the utilities, home owners, city planners and even architects in terms of the requirements for sustainable, energy-efficient buildings and offers an approach for reducing electricity consumption in an nZEB perspective. This research applies new methods and real-time simulation tests that have not previously been implemented for such case studies. The studies in this research pave the way for integrating solar energy, storage systems and EVs into individual homes and residential communities in Finland as well as elsewhere in the world.

### 1.3 Dissertation outline

Understanding the operation of the microgrid is a starting point before undertaking a detailed analysis of the system. Therefore, Publication [I] studies the microgrid design in AC and DC distributions, and compares the structure of each of the microgrids when an electrical energy storage is added to the system. The design of the microgrid in this publication forms the basis for this thesis. The model is energy-distribution template for a single-family dwelling for further publications in this research. Publications [II] and [III] concentrate on an energy analysis of the model in different scenarios applying electrical and thermal storage systems to the design. Storage systems are reasonable balancing solutions when applying renewable energy sources or using electricity dynamic pricing. Furthermore, renewable systems offer intermittent sources of energy that do not provide full productivity without storage facilities. The first type of facility, electrical storage, provides a good means for preserving electricity, whereas the second type, thermal storage, is excellent for maintaining hot water. Therefore, both of these should be applied with their strengths in mind: electrical storage for providing electricity; thermal storage for heating, ventilation and air-conditioning (HVAC) systems. Depending on the electricity and energy consumption of the building, the size of these storage systems can vary. Finding the optimal size and analysing the charging/discharging operation of the storage are discussed in Publications [II] and [III]. Due to the stochastic nature of the renewable energy systems (PV systems in this case) and the dynamic pricing, a demand response (DR) control system benefits the building energy system. This minimises the energy costs for the building owner. Throughout the dissertation, different time spans are considered to study the usefulness and the effectiveness of the proposed methods applied in different articles. In addition, longer time scales provide better economic viability justifications compared to daily scale studies. Publications [I] and [III] mainly focus on daily operations, while Publication [II] concentrates on monthly operation. Publications [IV] and [V] apply one day analysis, while time and space escalation are considered in Publications [VI] and [VII] for year-long operation.

To assess the model proposed in this research, a hardware-in-the-loop test is applied to validate the results of the model. Publication [IV] compares the results of the demand response model in the offline simulation against HIL simulations. This study examines the way in which the real-time simulation modelling works as well as the accuracy of the proposed model. In this publication, electrical storage consists of a storing device with photovoltaic (PV) solar panels. Publication [V] explores the validity of the DR model when applying thermal storage and solar thermal collectors in real-time and offline simulations.

This research cannot be finalised without expanding the model in terms of temporal and spatial escalation. The proposed microgrid model is tested throughout one year while integrating an electric vehicle (EV) in the building system boundary in Publication [VI]. The results are analysed to assess the success of the model in achieving a net-zero energy building (NZEB). This publication considers the EV as an active component in the energy system boundary of the building providing energy to the building. To assess spatial escalation, a

number of houses are considered on a larger scale microgrid to study the impact of the buildings' energy sharing on each other. Publication [VII] compares the energy sharing and savings in a community with a common larger storage facility for all the buildings versus the case of each building owning its own individual smaller storage unit.

## 2. Local energy system design

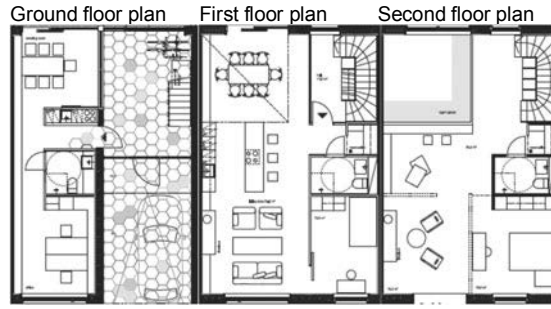
Studying microgrids of any size raises challenges that should be carefully answered, regardless of whether it is a large microgrid or a single-family dwelling. In this chapter, the electricity distribution system for a single-family home is designed to meet both AC and DC requirements. Electrical storage is considered in the microgrid model, and minute resolution data are applied in order to take into account the energy consumption peaks of some appliances.

### 2.1 System modelling

Most of buildings around the world are consumers of electricity and do not contribute to the energy production chain. Such buildings are known as passive houses. The focus of attention in such houses is the amount of the required energy received. The owners of passive buildings receive monthly invoices of their energy consumption without understanding the means or source of the energy provided. However, with the ongoing change in people's life habits, society has become more aware of its energy consumption and concerned about CO<sub>2</sub> emissions into the atmosphere, especially in developed countries. One solution to the carbon emissions reduction is to adapt each house to become an active player in the electrical power network. Although owners are aware of the possibility of onsite energy generation, they may not be aware of the benefits of utilising these systems in their houses.

#### 2.1.1 Building model

The single-family house used for the case study in this thesis is a generic three-storey conceptual townhouse, the architecture and geometry of which is based on German townhouse design [20], as Finland does not have any widespread architectural traditions of this particular building type. Figure 2.1 shows the floor plan of the house. The house is located in Helsinki (60°N, 25°E), and has a heated area of 259.6 m<sup>2</sup>.



**Figure 2.1.** Plan of the three-storey townhouse

The building is modelled and simulated using IDA-ICE whole building simulation software [21]. The software was originally developed by the Division of Building Services Engineering, Royal Institute of Technology (KTH) and the Swedish Institute of Applied Mathematics (ITM) [22]. The software offers a suitable tool for simulating thermal comfort, energy consumption and renewable energy in complex buildings.

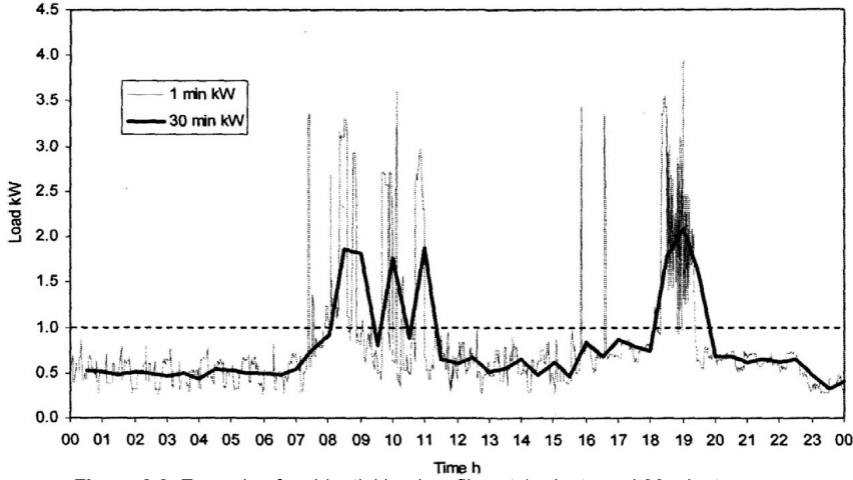
In the building simulation, the energy performance level of the building envelope and building systems has been chosen to satisfy the requirements of the Finnish Building code D3 2012 [23]. Furthermore, the dynamic profile of lighting, electrical appliances and occupants is based on statistical information gathered through questionnaires and the hourly measured kWh consumption of 1630 Finnish households over a year [24]. This study assumes district heating for domestic hot water and space heating.

### **2.1.2 Energy system model**

For residential buildings, solar energy is one of the most common options for easily applying onsite energy generation. In contrast to wind turbines, purchasing and installing PV panels seems more reasonable. Thus, the model in this research applies solar energy as the main source of onsite generation. All the models considered are grid-connected as well as possess the capability of exporting power to the grid.

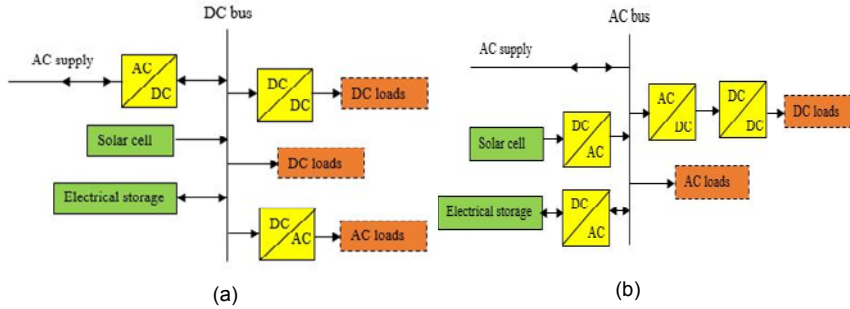
Electrical storage is a sufficient energy-saving device that is required in systems aiming at achieving the net-zero energy theorem [25], [26]. Significant parameters examined include the size of the system, and modelling its losses.

To design an accurate model, it is necessary to determine the appliances present in a house and to know their energy consumption. Thus, the energy consumption of the devices is studied in minute resolution to observe high frequency cyclic loads. Figure 2.2 compares the load profiles of one-minute and 30-minute resolution to highlight the load spikes that disappear in lower resolution data averaging.



**Figure 2.2.** Example of residential load profiles at 1 minute and 30 minutes time resolutions [27].

It is possible to integrate all appliances, PV panels, and electrical storage in a residential building into conventional AC distribution systems as well as in newly proposed DC distribution systems. Figure 2.3 illustrates the simple design for these two distribution systems.



**Figure 2.3.** Scheme of the applied residential building power systems  
(a) DC system (b) AC system

As can be seen in Figure 2.3, there are less conversions in a DC microgrid, resulting in a higher overall efficiency for the designed model. However, to prove this hypothesis, the efficiency is calculated for the proposed systems. Furthermore, the losses over the distribution system, the losses of the converters and the storage charging/discharging losses should be considered to calculate the overall efficiency of each of the distribution systems.

The wiring losses are calculated based on the wiring length in the building. Equation (2.1) calculates the wiring losses,  $P_{loss}$ , while  $R$  denotes the wiring resistance and  $I$  the current.

$$P_{loss} = RI^2 \quad (2.1)$$

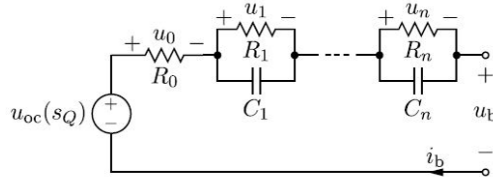
Considering the converters, the losses are calculated through detailed equations of conduction losses,  $P_{loss,cond}$ , and switching losses,  $P_{loss,sw}$ , that are represented as follows:

$$P_{loss,cond} = \frac{2\sqrt{2}}{\pi} V_{on} I_{rms} + r_{on} I_{rms}^2 \quad (2.2)$$

$$P_{loss,sw} = \frac{2\sqrt{2}}{\pi} \frac{I_{rms}}{I_{nom}} (E_{on} + E_{off}) f_{sw} + E_{RR} f_{sw} \quad (2.3)$$

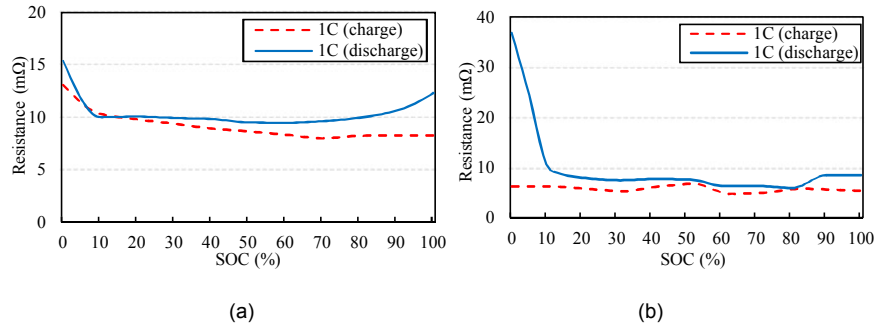
In Equation (2.2),  $I_{rms}$  is the rms value of the actual current through the converter,  $r_{on}$  represents the IGBT on-state resistance and  $V_{on}$  displays the IGBT on-state voltage drop. In addition, the switching frequency of the IGBT is  $f_{sw}$ , its rated current is  $I_{nom}$ , and  $E_{on}$  and  $E_{off}$  are assigned for the energy losses during turn-on and turn-off of the IGBT, while  $E_{RR}$  represents the diode reverse recovery energy. These equations provide the losses based on the current flow in the system, thus allowing the losses to be momentarily obtained.

In order to model the storage charging/discharging losses, a Thevenin-equivalent circuit battery model is applied, as depicted in Figure 2.4. A lithium-ion 7 kW, 3.3 kWh battery is used as the storage. The model consists of parallel RC branches and corresponding dynamic resistors,  $R_n$ , capacitors,  $C_n$ , and a series resistor,  $R_o$ , which represents the ohmic resistance.



**Figure 2.4.** Electrical equivalent circuit of a Li-ion battery [28]

Figure 2.5 illustrates the derived parameter mappings for  $R_o$  and  $R_i$ . As the time resolution in this study is minute and the dynamic capacitance variations happen in milliseconds, the model is simplified to  $R_o$  and  $R_i$  in the series. The resistance values are mainly dependent on the state of charge (SOC), the aging effect, and self-discharge of the storage; in addition, they vary at different dis/charging rates [28].



**Figure 2.5.** Parameter mappings. (a)  $R_o$  (b)  $R_i$

In the loss calculations for the storage, SOC is determined at each minute and the related charging or discharging resistance value is selected at 1C rate.

Equation (2.4) is applied to calculate the efficiency of the model in order to compare its value in the AC and DC microgrids. Efficiency,  $\eta$ , is dependent on the  $E_{out}(t)$  and  $E_{in}(t)$ , which represent the momentary output and input energy, respectively. The lost energy at each moment is expressed as  $E_{loss}(t)$ . The efficiency equation numerator and denominator are the total energy exchange within the microgrid for a full day, corresponding to 1440 minutes.

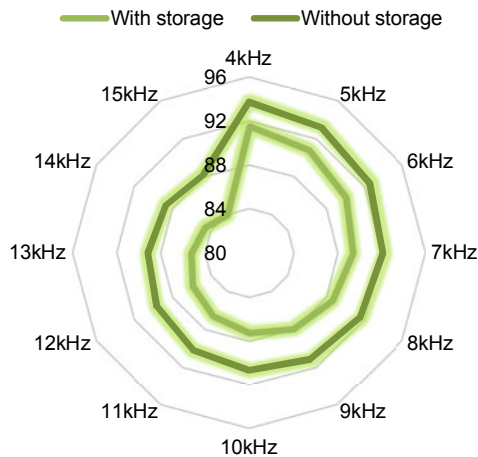
$$\eta = \frac{\sum_{t=1}^{1440} E_{out}(t)}{\sum_{t=1}^{1440} E_{in}(t)} \quad (2.4)$$

$$E_{out}(t) = E_{in}(t) - E_{loss}(t) \quad (2.5)$$

## 2.2 Comparison of the AC and DC microgrids efficiency

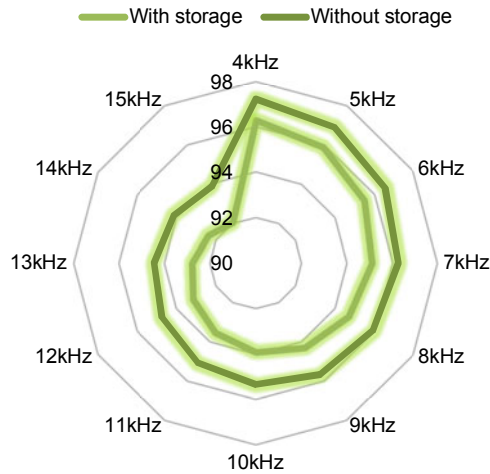
The designed AC model applies 230 V, 50 Hz as the bus voltage and the designed DC model has 380 V DC as the main bus voltage. In both models, the loads are studied and divided into two groups, the appliances operating with AC voltage, and those operating with DC voltage. Their nominal consumption in minute resolution is studied to clearly highlight every single energy consumption spike. In the DC microgrid model, the devices working with DC are also categorised into two groups, devices working with 380 VDC and those operating with lower DC voltage 48 VDC.

The efficiency of the system is dependent on bus voltage variations and the switching frequency of the converters. Thus, when calculating efficiency, variable switching frequency is considered within the range of 4 kHz to 15 kHz. The voltage variation is between 225 VAC to 235 VAC for the AC bus voltage and 370 VDC to 390 VDC for the DC bus voltage.



**Figure 2.6.** AC microgrid efficiency schema

Figure 2.6 represents the efficiency schema of the AC microgrid. The numbers in the centre represent the efficiency value and change based on the frequency, with the efficiency being higher at lower switching frequency. However, due to the size of the components of the converter and the power rating, it is not advisable to operate the system at the lowest frequency level. As shown in the figure, there are two rings in the figure: the outer ring represents the efficiency of the system without including the storage, and the inner one has storage in the system. The overall efficiency is lower when the storage is included due to the charging/discharging losses of the battery.



**Figure 2.7.** DC microgrid efficiency schema

Figure 2.7 compares the efficiency at different switching frequencies in the DC microgrid. A comparison between the AC and DC microgrids illustrates that the reduction in the overall efficiency of the system in the DC microgrid is less than that of the AC microgrid when the storage is added to the system boundary.

## 2.3 Conclusion

When comparing AC and DC electricity distributions in the single-family home, the DC microgrid displays a higher overall efficiency. This difference is valid in both cases with and without the storage. In addition, less reduction in microgrid efficiency can be reached in a DC system compared to the AC system when the energy storage is added to the microgrid boundary. Thus, considering the fast developments in power conversion devices, switching to DC distribution seems promising when attempting to meet the requirements of EU Directive 2010/31/EU.

### 3. Microgrid electricity and energy systems analysis

When designing the microgrid for this study, the effect of storage cannot be overlooked. Storage can collect the excess power produced by the renewable energy sources for hours or even days. It is also financially beneficial in terms of dynamic pricing considered as the utility power tariff. Therefore, the storage device can greatly increase the potential flexibility of the microgrid, resulting in the advantages outweighing the disadvantages. Chapter 2 discussed the issue of storage addition leading to a decrease in the overall efficiency of the microgrid; this chapter highlights the reasons for retaining the storage for the same case study as introduced in Chapter 2.

Storage can consist of either an electrical storage or a thermal storage unit. Although their application and operation differ, both are applied for common purposes. Approaching the NZEB target and providing clean energy might be seen as the benefits of these storage units. Section 3.1 examines the impact of electrical storage on microgrid energy costs, and Section 3.2 explores the ways that a thermal storage unit can benefit the building owner's energy costs when considering day-ahead and real-time scheduling of the thermal storage unit.

#### 3.1 Electrical storage sizing optimisation

The electrical storage model in this research is a lithium-ion battery [26]. Lithium-ion batteries work efficiently for short and long periods, ranging from a few hours to a few days, without losing an excessive amount of stored energy. Thus, whether operating in DC or AC, the microgrid model consists of storage, PV panels, lighting and electrical appliances. Article II investigates the effect of different storage sizes on the monthly energy costs of the building.

The case study model is a minimisation problem that is solved by applying GAMS software [29]. The objective equation (3.1) is a cost function that minimises the cost of the imported power and maximises the value of the exported power. Since a dynamic pricing model is applied, the storage is charged during not only sunny hours, but also when the energy price is low. The price of selling the power is about one-third of that for purchasing electricity in Finland. Hourly imported power,  $BP(t)$ , exported power,  $SP(t)$ , and hourly energy purchasing price,  $CE(t)$ , and the selling price to the utility,  $DE(t)$ , are used to form the Equation (3.1) for minimising the building owner's monthly energy bill.

$$F = \min \sum_{t=1}^{N \cdot 24} CE(t)BP(t) - DE(t)SP(t) \quad (3.1)$$

The time frame is one month for the optimisation problem, with  $N$  representing the number of days within a month. This allows a longer period for observing the consumption of the stored energy. In addition, it increases the functionality of the model, as the energy stored on a sunny day could be used, for instance, two days later.

Based on the monthly energy consumption of the building, three storage sizes are suggested, 10 kWh, 20 kWh and 30 kWh with a nominal power output of 3.3 kW. Four scenarios for the area of the PV panels and their installation locations are summarised in Table 3.1. The panel area refers to the total area covered by the PV panels including the spaces between the panels. Onsite solar PV generation represents the amount of power produced per year for each square meter of the PV area in different scenarios.

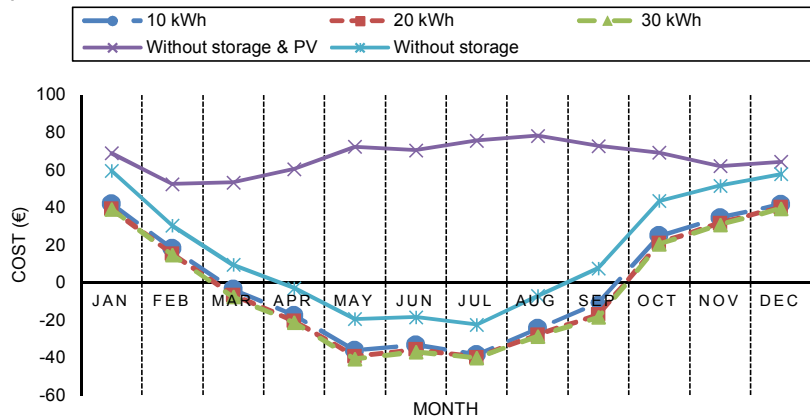
**Table 3.1.** PV installation scenarios

PV installation scenario	Specifications	Yearly onsite solar PV generation
Scenario 1	80 m <sup>2</sup> of PV on roof	21.5 kWh/m <sup>2</sup>
Scenario 2	80 m <sup>2</sup> of PV on roof + 40 m <sup>2</sup> of PV on south facade	24.7 kWh/m <sup>2</sup>
Scenario 3	80 m <sup>2</sup> of PV on roof + 40 m <sup>2</sup> of PV on south facade + 40 m <sup>2</sup> of PV on north facade	26.5 kWh/m <sup>2</sup>
Scenario 4	80 m <sup>2</sup> of PV on roof + 40 m <sup>2</sup> of PV on south facade + 40 m <sup>2</sup> of PV on north facade + 15 m <sup>2</sup> of PV as solar roadways	26.9 kWh/m <sup>2</sup>

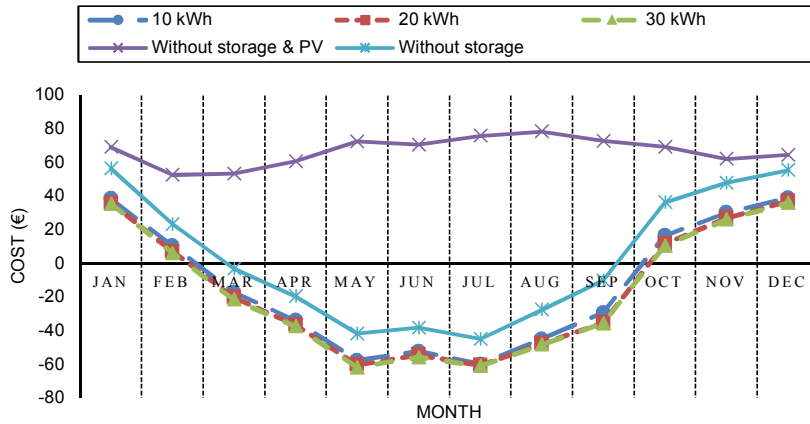
The results of the optimisation model are divided into two categories. In Section 3.1.1, the monthly energy cost to the household owner is examined by considering three storage sizes and the aforementioned PV installation scenarios. Section 3.1.2 explores the annual energy cost savings in these cases.

### 3.1.1 Monthly energy costs analysis

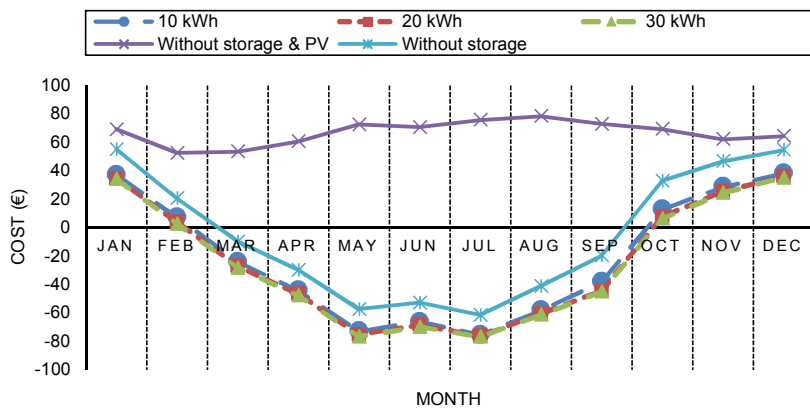
The monthly energy cost of the designed microgrid is compared in Figures 3.1 - 3.4.



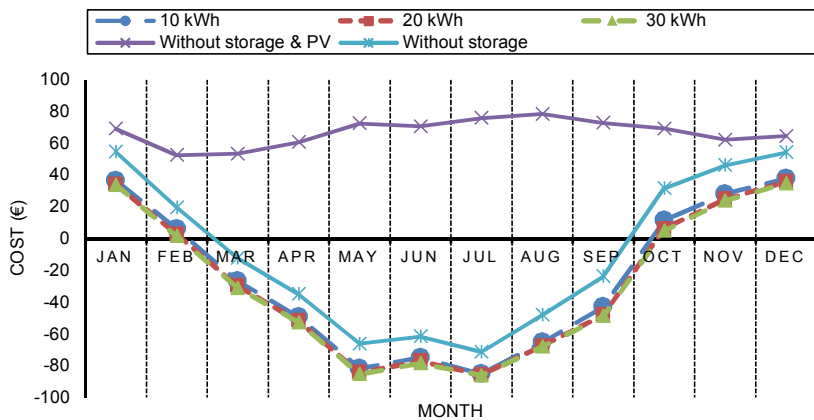
**Figure 3.1.** Cost analysis applying Scenario 1



**Figure 3.2.** Cost analysis applying Scenario 2



**Figure 3.3.** Cost analysis applying Scenario 3



**Figure 3.4.** Cost analysis applying Scenario 4

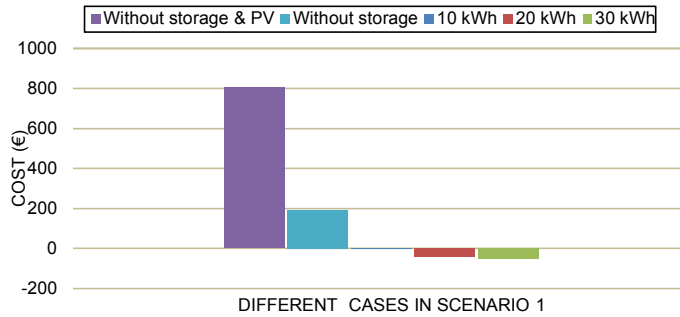
As can be observed from the figures, all four PV installation scenarios offer a noticeable reduction in the monthly cost of the electricity for the building owner.

Comparison between the case without any PV installation or storage and the case with PV available in the microgrid model shows significant cost variations.

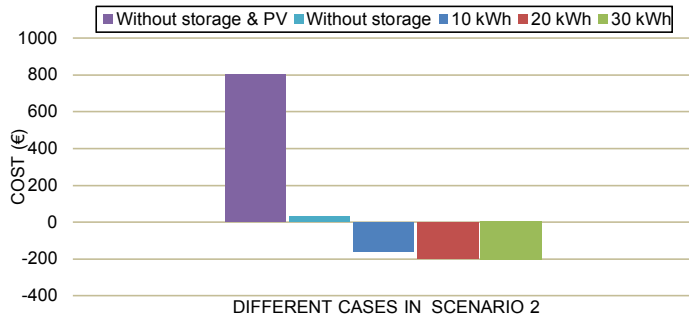
Although applying storage increases cost savings, the study shows that the discrepancy between monthly energy savings is not remarkable when changing the storage size. PV generation and load consumption are fixed, ensuring that any change in the storage size will not significantly affect the savings, as there is no more power to be saved. Nevertheless, the results show that storage would influence energy savings, and that a storage capacity of 10 kWh is suitable for the model proposed in this research.

### 3.1.2 Annual energy savings

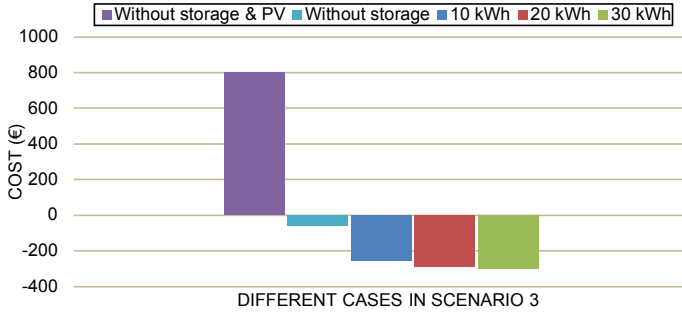
This section studies the annual energy savings by calculating the revenue accrued to the building owner from the installed system excluding the investment costs. This study is extended in Chapter 5 by considering the investments and calculating the payback period. The results in Figures 3.5 - 3.8 illustrate the annual energy costs for Scenarios 1 to 4.



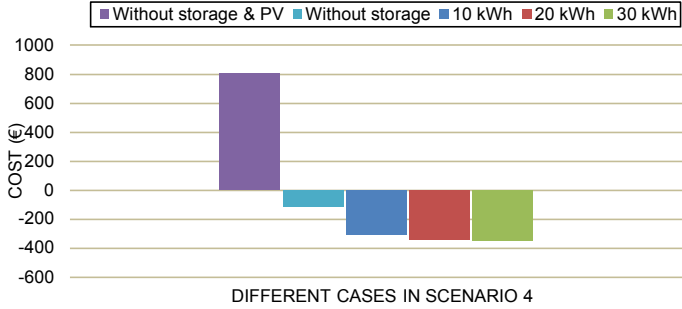
**Figure 3.5.** Annual energy cost for Scenario 1



**Figure 3.6.** Annual energy cost for Scenario 2



**Figure 3.7.** Annual energy cost for Scenario 3



**Figure 3.8.** Annual energy cost for Scenario 4

The costs in the figures consist of positive and negative values. The positive values represent the money that the owner of the building should pay, while the negative values show the payback for the exported energy that provides the owner with some income. As displayed in all four scenarios, the owner receives a profit when installing the PV panels. In Scenarios 1 and 2, the benefit is less than that obtained in Scenarios 3 and 4. Furthermore, the case with no storage installation in Figure 3.5 has a positive value for the annual costs.

Overall, the grid-connected PV/battery system benefits the microgrid owner by saving money and energy when attempting to meet the requirements specified in the EU Directive 2010/31/EU.

### 3.2 Demand response control of thermal storage

Space heating and domestic hot water (DHW) are the main heating loads in a residential home. There are different ways of providing the heating. District heating, direct electric heating, and ground source heat pumps (GSHP) are possible solutions to heat a building and provide the required hot water [30]. This section applies direct electric heating and an electric thermal storage. Thus, electricity is used to heat the water of the storage. Section 3.2.1 explains the implementation of the demand response model for warming the storage. Section 3.2.2 presents the results as well as discusses the advantages and disadvantages of the applied methodology.

### 3.2.1 Demand response control by greedy variable neighbourhood algorithm

The demand response control for the microgrid model, the townhouse in this research, is designed to be simple with little computation burden. There are many different ways to implement the demand response; however, they are complicated models that require considerable memory space and time to generate results. Therefore, we suggest a simple model that operates in very little time and does not occupy excessive memory capacity.

This metaheuristic approach enables both day-ahead and real-time scheduling of the residential thermal storage. This method, called greedy variable neighbourhood algorithm (GVNA), performs two layers of optimisation. First, the day-ahead optimisation solution is generated through linear programming. Then, in the second layer, the greedy variable neighbourhood algorithm explores distant neighbourhoods for the current incumbent solution, and moves from there to a new one, only in the case of a clear improvement.

The objective function considered is presented in (3.2).

$$\text{Minimise } \sum_{t=1}^n P(t)x(t) \text{ subject to } \sum_{t=1}^n x(t) = TDHD \quad (3.2)$$

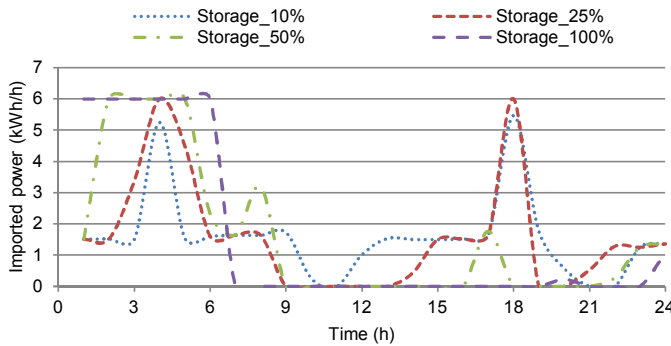
Where,  $P(t)$  is considered as the price of electricity for hour  $t$ ,  $x(t)$  is the amount of power that will be bought at hour  $t$ , and  $x(t) \in [0, P_{max}]$  and the  $TDHD$  are the total daily heat demand for the building.  $P_{max}$  defines the maximum allowable power that is purchased from the grid for heating purposes. The problem is modelled as a multi-dimensional knapsack problem that could first be solved through linear programming to provide the day-ahead data. A problem can be considered a multi-dimensional knapsack problem if there is more than one constraint for the objective function when in operation [31], [32]. Regarding the problem of charging the thermal storage, the owner of the building is eager to gain financial benefit from the control system model. Therefore, not only the price, but also the amount of power is important when charging the storage. This causes the problem to be simulated as a multi-dimensional knapsack problem. This problem could be solved by applying linear programming; however, the results cannot be updated.

The greedy variable neighbourhood algorithm enables the control system to be updated in real-time as well. This algorithm allows the programme to consider a local neighbourhood around each hour, consisting of a few hours before and after the hour in question. Then, a local optimisation is implemented to provide updated power sharing in the building energy system. This type of locally optimised solution is called a variable neighbourhood search. When the result for the hour under study is updated, the algorithm moves to the next hour and again implements the same procedure.

This methodology combines the greedy algorithm and variable neighbourhood search to create the greedy variable neighbourhood algorithm (GVNA). This metaheuristic method simplifies the real-time decision-making for residential building energy management systems. To study the productivity of this approach, the results are discussed in Section 3.2.2.

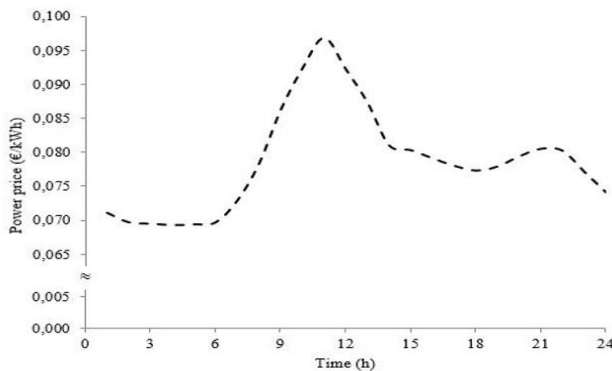
### 3.2.2 Results and discussion

The programme composed using the strategy presented in the previous section, GVNA, results in a scheduling scheme that contributes to a decrease in the total monthly energy cost for the household owner. Figure 3.9 displays the effect of different storage sizes on the daily energy purchase from the grid. In this study, four sizes are considered for the storage unit, 10 %, 25 %, 50 % and 100 % of the total daily heat demand. As the storage price increases with increasing storage capacity, home owners would have a chance to choose the storage that best suits their own conditions. This study considers a typically cold weekday of the year in Finland to evaluate the success of thermal storage in reducing the monthly energy cost for the household owner.



**Figure 3.9.** Effect of thermal storage on required power from the supply

Figure 3.10 presents the electricity spot prices for a sample day. The figure shows the electricity price increases in the morning, followed by a smaller rise around 9 pm in the evening. Comparing Figures 3.9 and 3.10 shows that storage discharges mainly occur during peaks in the energy price. The comparison demonstrates that the energy purchased from the grid is minimised when the price of the electricity is higher when the dynamic pricing model is applied in this study.



**Figure 3.10.** Electricity spot prices

To evaluate the effect of thermal energy storage on the energy consumption pattern of a single-family home over a month, the optimisation is implemented for a typically cold month in Finland. The results are shown in Table 3.2.

**Table 3.2.** Monthly heating energy costs

Different storage sizes	Heating cost (€/month)	Monthly saving
<i>No thermal storage</i>	78,075	-----
10 %	71,040	9,01 %
25 %	67,788	13,18 %
50 %	64,317	17,62 %
100 %	62,553	19,88 %

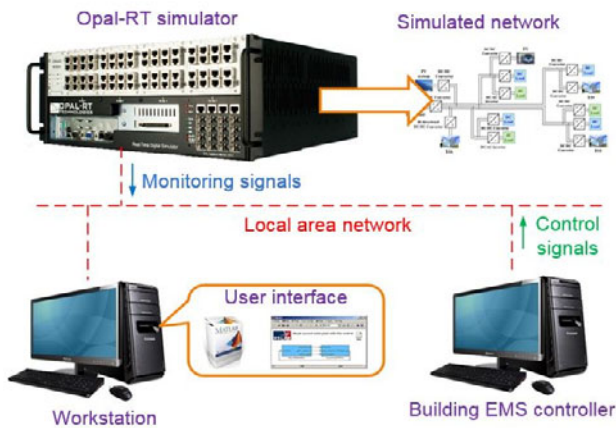
As expected, there are more savings when applying a larger storage unit. However, installing a larger storage is not always a good solution. The payback time for every investment is very important, and a larger thermal storage causes higher initial investments and a longer payback time. Therefore, finding an optimum size for the storage is important and directly impacts costs and energy savings.

### 3.3 Conclusion

This chapter closely investigated electric and thermal storage application in residential buildings. Applying each of the storage units has its own advantages and perhaps even disadvantages. However, with the proper design and demand response control model, owners could benefit from their initial investment within a reasonable payback time. Therefore, the economic viability of the proposed control system is assessed in Chapter 5.

## 4. Validation of the proposed models via hardware-in-the-loop tests

Chapters 2 and 3 mainly concentrated on the design of the microgrid, the methodologies and solutions of applying electrical storage and thermal storage in building systems while integrating renewable sources of energy. The proposed models for integrating these devices were tested through simulations. These simulations provided good and justified solutions. However, when these models are applied in real cases, the results might differ from the offline simulation models. Therefore, it is important to determine an approach to validate the proposed solutions. One way to validate is to implement the simulation models in real-time [33]. Real-time simulation allows a comparison between the results of the offline and real-time simulations. In this research, the real-time simulation is implemented through hardware-in-the-loop (HIL). HIL testing is a viable substitute compared to typical testing systems [34]. In HIL methodology, the physical plant is replaced by a precisely designed computer model. Therefore, the designed control models can be tested without the need for the real system.



**Figure 4.1.** High-level diagram of the real-time HIL simulation test platform.

Figure 4.1 presents the operation of the HIL system. The Opal-RT simulator is used to implement the real-time simulation. The Simulink model, which provides the building simulation model, is uploaded to the simulator. The real-time simulation results are transferred to the building energy management system (EMS) controller to visualise and update the initial conditions for the next optimisation routine. This technique is applied in this chapter to test the proposed

models in real-time. Section 4.1 considers an electrical storage and photovoltaic panels when implementing the HIL test. In this section, the decision time interval of the EMS is chosen to be 20 sec in order to reduce the total algorithm testing time. Section 4.2 studies the real-time simulation results of a building model that integrates solar thermal collectors and a thermal storage unit. In Section 4.2, one hour is used as the decision time interval to allow dynamic variations to stabilise. Thus, the following two sections complement the proposed idea together..

#### 4.1 Real-time testing including PV and electrical storage

This study applies two pricing systems for the electricity purchased from the grid: the time of use (ToU) tariff and the dynamic pricing tariff. In each of the pricing systems, the building EMS model is tested in offline and real-time simulations with the results and then compared. In the real-time simulation, the system clock is used to run the models. However, in this section, a smaller time resolution is used to reduce the total algorithm testing time.

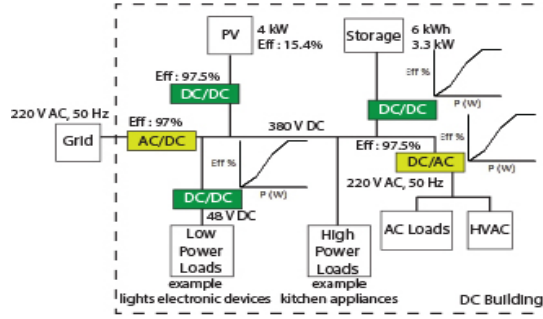


Figure 4.2. DC building model.

This study applies two pricing systems for the electricity purchased from the grid: the time of use (ToU) tariff and the dynamic pricing tariff. In each of the pricing systems, the building EMS model is tested in offline and real-time simulations with the results then being compared. In real-time simulation, the system clock is considered to run the models. However, in this section, a smaller time resolution is considered to reduce the total algorithm testing time.

$$F = \text{Min} \sum_{t=1}^N w_{IMP}(t)P_{IMP}(t) + w_{EXP}(t)P_{EXP}(t) + \alpha P_{STO}(t) \quad (4.1)$$

The objective function (4.1) minimises the energy exchange with the grid. It also involves the storage charging/discharging cycles and limits this number to increase the battery lifetime. Equations (4.2) and (4.3) consider the effect of the temperature and building insulation parameters on the heat required from the HVAC system.

$$C_{air} \frac{T_{amb}(t+1) - T_{amb}(t)}{\Delta t} = H_e(T_e(t) - T_{amb}(t)) + H_m(T_{mass}(t+1) - T_{amb}(t)) + H_g(T_g - T_{amb}(t)) + H_s(T_s - T_{amb}(t)) + P_{HVAC}(t), \quad 0 \leq t \leq N-1 \quad (4.2)$$

$$C_{mess} \frac{T_{mess}(t+1) - T_{mess}(t)}{\Delta t} = H_m(T_{amb}(t) - T_{mess}(t)) + H_M(T_e(t) - T_{mess}(t)), \quad 0 \leq t \leq N-1 \quad (4.3)$$

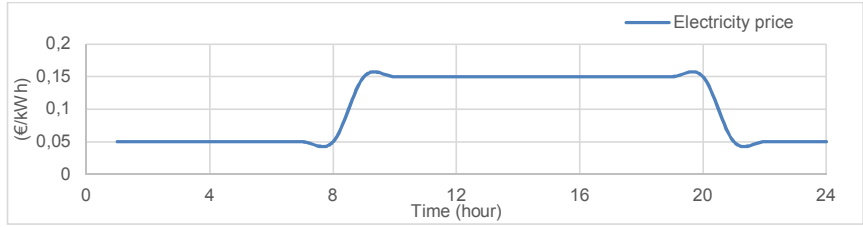
$$T^* - \frac{\beta}{2} \leq T_{amb}(t) \leq T^* + \frac{\beta}{2}, \quad 1 \leq t \leq N \quad (4.4)$$

In Equation (4.4), the room temperature is set within a defined dead-band that could be determined by the residents of the building or by the electricity company. This dead-band allows optimisation of the HVAC system operation. The EMS model of the building considers a temperature dead-band for the room temperature,  $\beta$ , which also allows for optimising operation of the HVAC system. The symbols used in Equations (4.1) to (4.4) are defined as follows.

$C_{air}$	Air heat capacity
$C_{mass}$	Building fabric heat capacity
$H_e$	Virtual thermal conductance between internal and external temperature node points
$H_g$	Thermal conductance between ground temperature and ambient temperature
$H_m$	Heat conductance of solid wall material
$H_M$	Heat convection on the surfaces
$H_s$	Thermal conductance controlling the ventilation air heat capacity flow having temperature $T_s$
$N$	Planning intervals
$P_{EXP}$	Exported power
$P_{HVAC}$	HVAC load demand
$P_{IMP}$	Imported power
$P_{STO}$	Storage charging/discharging power
$SP$	Electricity selling price
$T^*$	Desired room temperature
$T_{amb}$	Ambient temperature
$T_e$	Outdoor temperature
$T_g$	Ground temperature
$T_{mass}$	Building fabric temperature
$T_s$	Ventilation air heat temperature
$w_{EXP}$	Electricity price for export power
$w_{IMP}$	Electricity price for import power
$\alpha$	Storage penalty factor

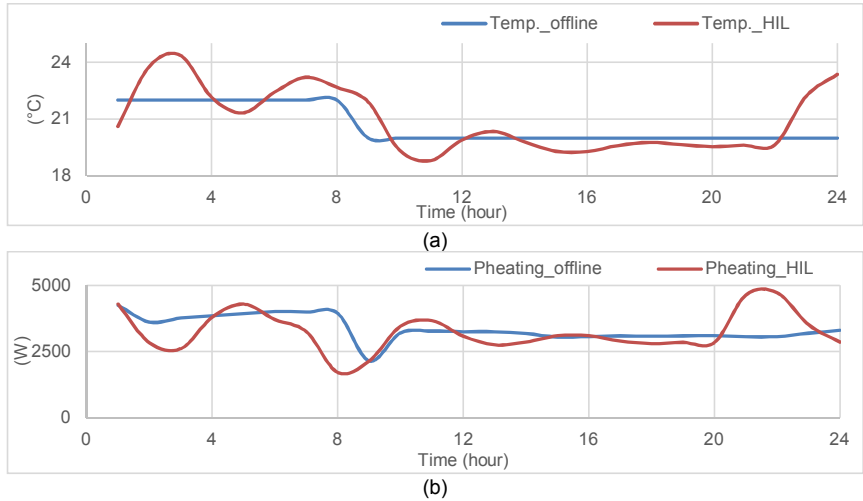
#### 4.1.1 Time of use pricing

In this case, a two-step price signal is used to test the performance of the developed EMS algorithm. The electricity price is relatively high from hour 9 to 20, with the price being lower during the rest of the time, as shown in Figure 4.3.



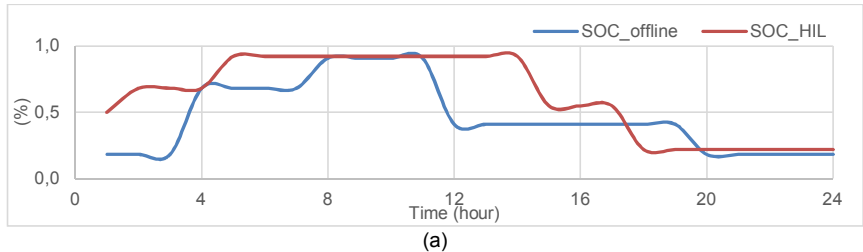
**Figure 4.3.** Time of use (ToU) pricing model

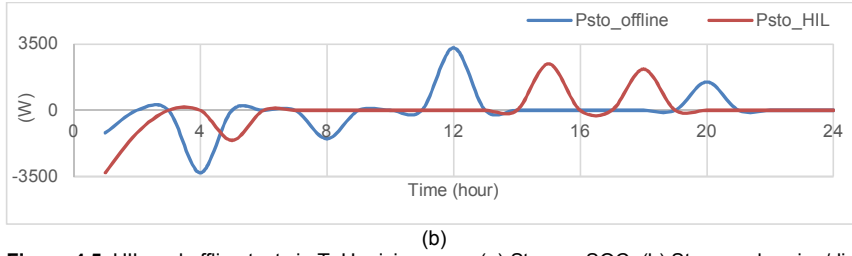
A comparison between the results in Figures 4.4 (a, b) shows more variation for the heating power consumption and room temperature in the HIL test. As explained, the time allocated for each time step in the HIL test is more realistic and thus renders more precise results. The differences between the HIL and the offline test results are less significant in both the heating power consumption graph as well as the temperature diagram, with variations representing the real room air conditions.



**Figure 4.4.** HIL and offline tests in ToU pricing case, (a) Temperature, (b) Heating power

Figure 4.5 illustrates SOC and storage power behaviour. As can be seen, the charging and discharging pattern of the HIL and offline simulation tests are slightly different. In the HIL test, the control system decides the power sharing flow hour by hour, which causes current hour parameters to be taken into effect for the next hour.

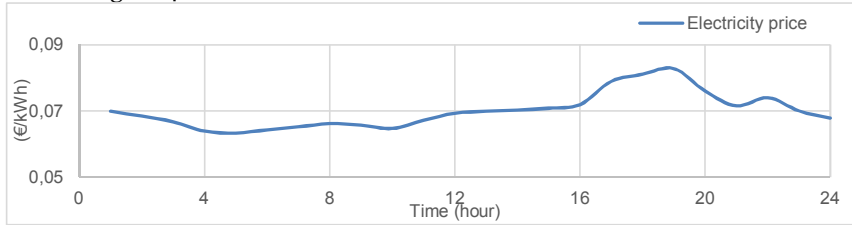




**Figure 4.5.** HIL and offline tests in ToU pricing case, (a) Storage SOC, (b) Storage charging/discharging power

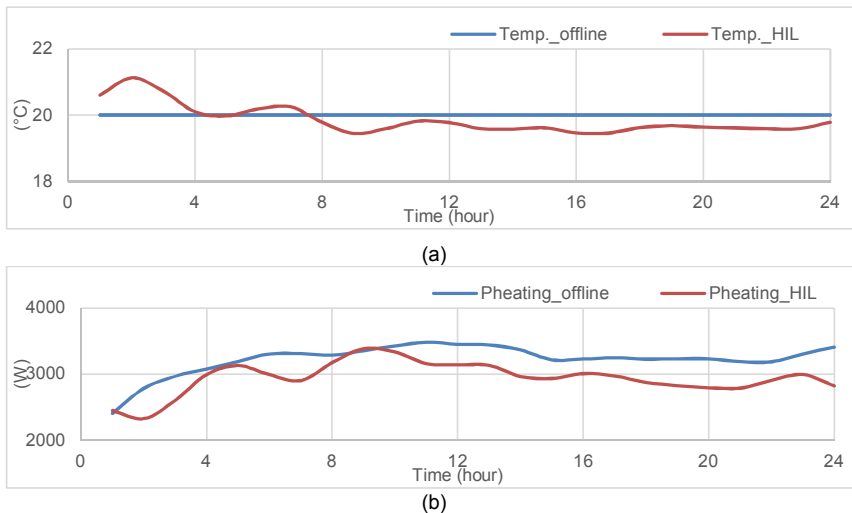
#### 4.1.2 Dynamic pricing

In this subsection, the dynamic pricing tariff is applied to the optimisation model. All parameters, except the pricing model, are the same as those in the time of use pricing. In the dynamic pricing model, the electricity price changes hour by hour, and is usually higher in the evening around 16 to 20, as can be seen in Figure 4.6.



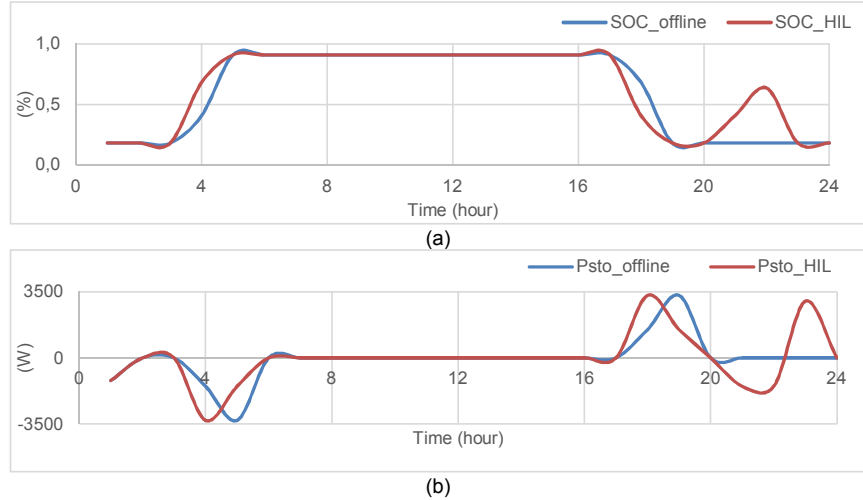
**Figure 4.6.** Dynamic pricing model

Figure 4.7 illustrates the heating load that is smaller in the HIL test, with more oscillations being evident compared to the offline test. This shows that the real-time simulator provides more realistic data. Comparing Figure 4.7 (a) and (b) shows that whenever the room temperature is low, more power is provided to keep the temperature at a desirable level and vice versa.



**Figure 4.7.** HIL and offline tests in dynamic pricing case, (a) Temperature, (b) Heating power

The offline simulation test shows that the storage unit is charged during the daytime and is discharged only in the evening, as shown in Figure 4.8 (b). However, the HIL test charges and discharges the storage once more during the evening in comparison to the offline test. This is caused by the capability of the real-time test, which enables an online decision based on the hourly updated conditions of the room.

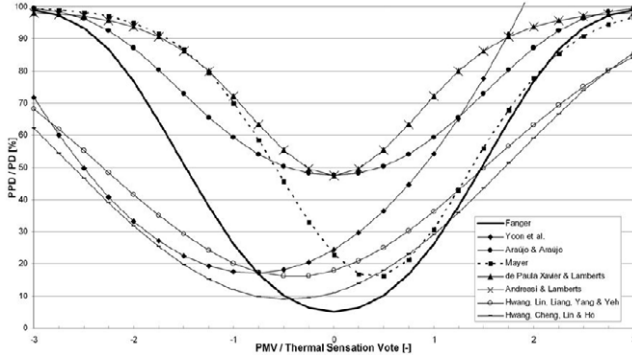


**Figure 4.8.** HIL and offline tests in dynamic pricing case, (a) Storage SOC, (b) Storage charging/discharging power

## 4.2 Real-time testing including solar collector and thermal storage

The Simulink model in this part consists of solar thermal collectors and thermal storage. The case study uses a typical winter day to examine the heating condition of the building. For optimising the consumption of the HVAC system in the building, the viability of using solar thermal collectors and thermal storage is also important. The HVAC system operates using AC power, thus directly affecting energy consumption in the building. When optimising the HVAC system, not only should the consumption be optimised, but also the comfort level should be desirable for the residents. Thus, Franger's curve is applied to include the residents' comfort level.

As shown in Figure 4.9, Franger's curve represents the most satisfactory situation. Although studies of the Franger model all approve its validity, field studies have revealed that Franger's curve under-predicts the real situation [35]. Thus, some standards are used to consider thermal comfort: the European countries use ISO 7730 standard [36], while North America uses ASHRAE Standard 55 [36].



**Figure 4.9.** Relations between predicted percentage of dissatisfied (PPD) and predicted mean vote (PMV) in different methods [37]

As explained earlier, two variables should be optimised in the model: HVAC consumption and comfort level. Equation (4.5) is the objective function that consists of two terms. The first term minimises the house heating consumption; the second term optimises the PPD to provide the optimum comfort level.

$$F = \min \sum_t \lambda_t P_t^{hvac} + \sum_t PPD_t \quad (4.5)$$

Two main constraint equations in this model are (4.6) and (4.7).

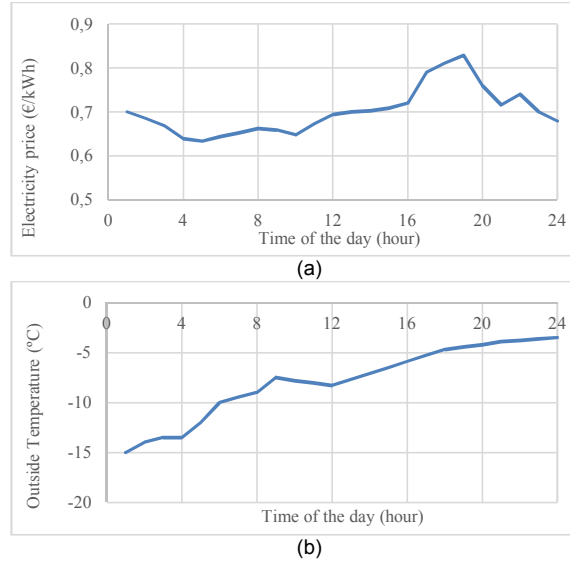
$$PPD_t = 100 - 95 e^{-(0.03353 PMV_t^4 + 0.2179 PMV_t^2)} \quad (4.6)$$

$$(SOC_{t+1} - SOC_t) \Pi = (P_t^{hvac} + P_t^{sth} - Q_t^{hvac}) \Delta t - \alpha SOC_{t-1} \quad (4.7)$$

Equation (4.6) provides a satisfactory Franger's curve for the optimisation model and Equation (4.7) affords the balance equation between the thermal storage, the load, and the energy generated from the solar collectors. In these equations

$P_t^{hvac}$	Electrical power supplied to HVAC unit at time $t$ (kW)
$P_t^{sth}$	Heat power provided from the solar thermal collector at time $t$ (kW)
$Q_t^{hvac}$	HVAC thermal output power at time $t$ (kW)
$\lambda_t$	Power price at hour $t$ (€/kWh)
$PMV_t$	Predicted mean vote at hour $t$
$PPD_t$	Predicted percentage dissatisfied at hour $t$ , units of %
SOC	State of charge
$\alpha$	Storage loss coefficient (%)
$\Pi$	Maximum thermal storage capacity (kWh)

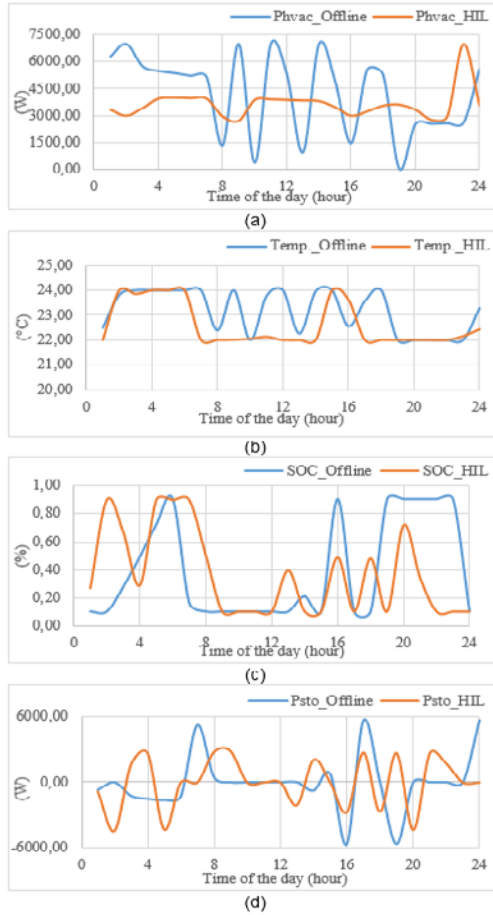
In this study, three scenarios are tested and explained based on the three storage sizes used in the following subsections. In all the case studies, electricity spot prices, and outside temperature are applied as shown in Figure 4.10.



**Fig. 4.10.** A typical winter day (a) Electricity price, (b) outside temperature.

#### 4.2.1 Storage size 7 kW

The 7 kW, 3.3 kWh storage size is considered as the minimum size to partially provide the heating demand of the building. Figure 4.9 compares the storage SOC, charging/discharging power, heating demand and room temperature in the HIL and offline simulations.

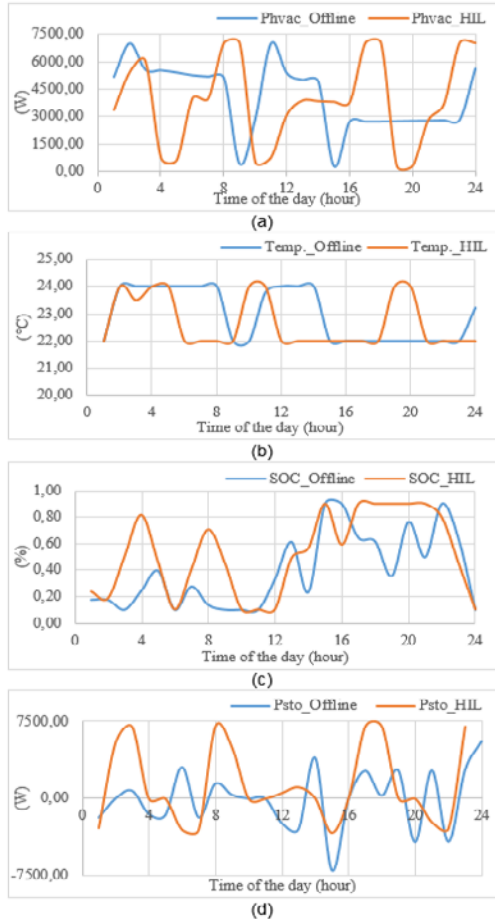


**Fig. 4.11.** HIL and off-line simulation results comparison for the 7 kW storage, (a) HVAC power consumption, (b) Inside temperature, (c) SOC of the storage, (d) Battery charging/discharging power.

In Figure 4.11 (a), the comparison between the HIL and offline test results shows lower HVAC power consumption. This is caused by the room temperature being maintained at a lower bound for a longer time period, Figure 4.11 (b). In the HIL system, the pace of the change in temperature and HVAC power are more realistic. These parameters change at a lower speed in real models than in the offline simulation. HIL provides a model closer to the real system than the offline simulation, since the simulation curves are not as steady as in the offline simulation test. Moreover, in the real case, the change in temperature occurs gradually, which can be seen better in the HIL test results. Storage SOC shows a nearly similar pattern to that of the offline simulation, Figure 4.11 (c). However, the SOC does not reach 90 % in the evening hours as in the offline model; this is due to the room temperature, which is maintained at a lower bound during those hours. In Figure 4.11 (d), the storage charging/discharging power shows some differences between the offline and real-time simulation results, as the need for power to keep the room temperature within the defined comfort range is different in the two tests due to the aforementioned reasons.

#### 4.2.2 Storage size 10.5 kW

As the storage size increases, the flexibility of the system becomes higher regarding the storage power flow. In this section, the size of the storage is 10.5 kW, 3.3 kWh, allowing storage SOC to be maintained at 90 % for a longer number of hours, with the need for fewer charging/discharging cycles, as can be seen in Figure 4.12 (c). Figures 4.12 (a) and (b) show a different behaviour for the heating consumption and its related temperature in the real-time system compared to the offline test. The differences between the HIL and the offline test results can be attributed to temperature changes in the building in order to maintain the temperature within a desirable range. The results from the real-time simulator are more realistic, because the model reflects the results for real one-hour operation of the system.

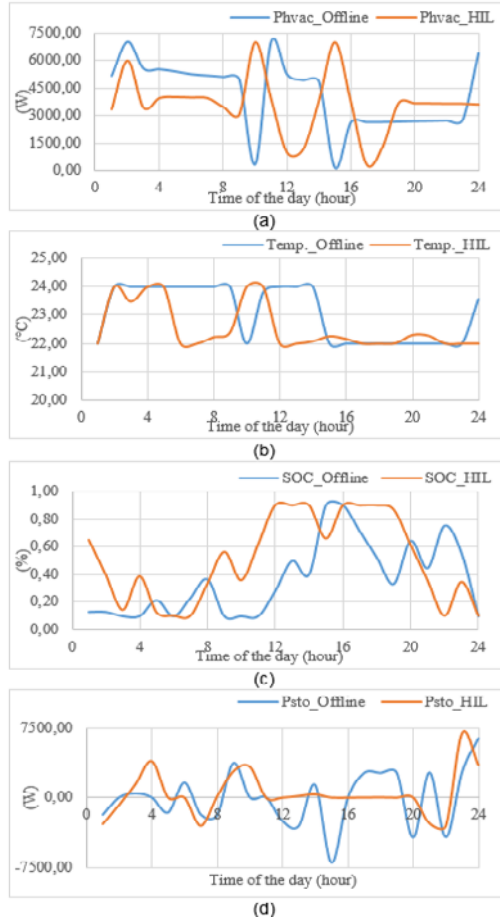


**Fig. 4.12.** HIL and off-line simulation results comparison for the 10.5 kW storage, (a) HVAC power consumption, (b) Inside temperature, (c) SOC of the storage, (d) Battery charging/discharging power.

#### 4.2.3 Storage size 14 kW

The storage size of 14 kW, 5 kWh is selected to study the effect of a larger storage size on energy savings and system behaviour. Fig. 4.13 (a), (b), (c) and (d) present the results from both HIL and offline simulation tests showing that a larger

storage could maintain power for a greater number of hours, and economises on energy. The temperature could be set at a lower bound for a longer period as more heating power is provided by the storage unit during on-peak hours. The charging/discharging cycles follow the change in the SOC of the storage unit and provide results that are more reasonable, as can be observed in the HIL test. The difference between the real-time and offline test results are due to the slightly lower variation in temperature and less need for power to keep the room temperature within the desired range. This causes the battery SOC and charging/discharging cycles to behave differently in the two tests.



**Fig. 4.13.** HIL and off-line simulation results comparison for the 14 kW storage, (a) HVAC power consumption, (b) Inside temperature, (c) SOC of the storage, (d) Battery charging/discharging power.

#### 4.2.4 Results comparison

The cost savings results in the three scenarios of storage size for offline simulation test and the HIL test are summarised in Table 4.1. The table shows the energy cost savings for the heating load in a day for the building model of this study. A comparison between the HIL and offline results shows higher than expected savings in the HIL test. In addition, the larger storage size results in more

savings than the smaller storage systems, as it could provide more energy for heating.

**Table 4.1.** Comparison of wholesale energy cost savings in different case studies

Case studies	Energy cost savings (%)	
	Offline test	HIL test
7.0 kW storage	21.08	29.12
10.5 kW storage	29.48	35.84
14.0 kW storage	35.26	41.84

### 4.3 Conclusion

This chapter introduced the hardware-in-the-loop simulation test operation and its application for testing the control systems in real-time. The tests were implemented for two different case scenarios: the building model including photovoltaic panels and an electrical storage system, and the model integrating solar thermal collectors and a thermal storage system. The results from the real-time simulation tests were compared with the offline simulation tests in the case scenarios. Real-time simulation tests showed results that are more realistic, thus paving the way to improving the control systems before applying them to the real physical plants.

## 5. Temporal and spatial escalation of the proposed microgrid model

Chapters 1 - 4 studied the microgrid design in a single-family home, including its integration with photovoltaic panels and solar thermal collectors, as well as electrical and thermal storage units. Chapter 4 applied a real-time simulator to validate the models proposed in Chapters 2 and 3. In all these chapters, the case study was a single-family house and the time scale was a 24-hour period. Therefore, to further validate the proposed models, Chapter 5 expands the models in terms of time and space. Section 5.1 provides an energy analysis for a single-family home over a one-year period while also integrating an electric vehicle into the model. This section aims to evaluate the model energy indices for a year, and examines whether the proposed methodology enables the system to approach the requirement of a net-zero energy building. Section 5.2 considers a spatial escalation for the proposed model, which involves studying the energy flow of a greater number of houses in a community. This part expands the model to include a community of eight homes and compares the energy exchange flow when each home has its own individual storage against the case when a common storage facility is supplied to the community.

### 5.1 Microgrid model expanded to a calendar year

The building boundary model introduced in Chapter 2 contained the loads, heating system and the storage. In this section, an electric vehicle is added to the building system boundary. Integrating EV into the building system boundary causes the vehicle to act as an active load. Thus, the EV storage can also be used as a backup for energy consumption in the home.

In the dynamic pricing model, charging of the EV occurs during off-peak hours, with the cheapest electricity price period usually being in the early morning. Thus, when the car returns home in the evening on a weekday, the remaining energy stored in the EV battery could be used for the home energy consumption until midnight.

To manage the power balance between different loads and sources in the building, a control system is suggested to monitor and decide on the power sharing in the building. The objective function (5.1) minimises the need for using energy from the grid, while maximising the use of energy for an electric vehicle. In this equation, energy cost is a weighting factor that helps in decision-making concerning power sharing. The EV discharged power weight factor,  $w_{EV}$ , is also

used to prioritise the power from the EV compared to the grid power. Constraints to limit the grid import/export power, battery and EV charging/discharging power are considered for formulating the problem. Detailed information about these constraints can be found in Publication [VI].

$$F = \min \sum_{t=1}^T w_{IMP}(t)P_{IMP}(t) + w_{EXP}(t)P_{EXP}(t) - Aw_{EV}(t)P_{EV+}(t) \quad (5.1)$$

The optimisation problem is subject to the following constraint:

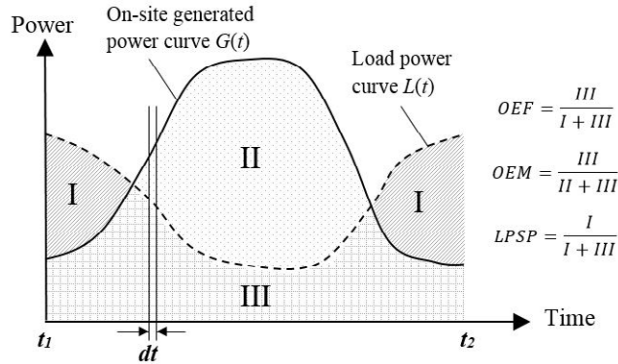
$$P_{PV}(t) + P_{IMP}(t) + P_{STO+}(t) + AP_{EV+}(t) = P_L(t) + P_{EXP-}(t) + P_{STO-}(t) + AP_{EV-}(t); \quad \forall t \in T \quad (5.2)$$

where

$A$	EV availability at home
$w_{IMP}$	Imported energy price
$w_{EXP}$	Exported energy price
$w_{EV}$	EV discharged power weight factor
$P_{IMP}$	Imported power from the grid
$P_{EXP}$	Exported power to the grid
$P_{EV+}$	EV discharging power
$P_{EV-}$	EV charging power
$P_{STO-}$	Charging power of the stationary storage
$P_{STO+}$	Discharging power of the stationary storage

The optimisation model is a mixed-integer linear program (MILP) that is tested in two different heating scenarios. In one scenario, heating for the building is provided through district heating (DH); in the second scenario, the heating is provided via a ground source heat pump (GSHP) system.

To compare the results of the DH and GSHP scenarios, the energy matching indices are obtained from an on-site energy fraction (OEF), on-site energy matching (OEM), and loss of power supply probability (LPSP). Figure 5.1 shows the general principle of the explained energy matching indices.



**Figure 5.1.** General principle of energy matching indices [38,39,40]

The objective function (5.1) is applied in four case studies using the following adjustments.

Case 1) This is the reference case in which the residential building supplies its demand from roof-installed photovoltaic panels and the grid utilities. An electric vehicle is considered to be an electric load on the building, but it does not contribute to the vehicle-to-home (V2H) mode in this case (without V2H mode + without ESS).

In this case, the power balance Equation (5.2) is simplified by removing the terms related to the storage exchange power,  $P_{STO+}$  and  $P_{STO-}$ , and EV discharging power,  $P_{EV+}$ . Furthermore, the last term in the objective function is omitted as there is no V2H mode in case 1.

Case 2) The effect of V2H mode is studied in this case, meaning that the EV contributes to providing the household demand while it is available at home and before midnight, after which it is charged (with V2H mode + without ESS).

In Case 2, as the storage is not yet added to the system, (5.2) does not have the  $P_{STO+}$  and  $P_{STO-}$  terms, though the rest of the equations remain unchanged.

Case 3) This case investigates the effect of the stationary battery on the energy balance at home. Case 3 does not consider V2H mode discharge, but EV is just a consumer in this case (without V2H mode + with ESS).

Case 3 has the storage added to the system, but the term  $P_{EV+}$  is removed, as the EV discharging mode is not active in this case. In addition, the term related to the EV discharging power in (5.1) is omitted.

Case 4) Both stationary battery and V2H mode discharge of the EV are considered in this case. This combination investigates the effect of applying both stationary and EV batteries to the energy indices of the building compared to the other cases (with V2H mode + with ESS).

### 5.1.1 Results discussion, district heating (DH) scenario

As explained earlier, two building heating scenarios are compared in this study while considering the four cases of energy management system. Table 5.1 summarises the energy matching indices results of the DH scenario.

**Table 5.1.** Energy matching indices of DH scenario

Summary (Year)	Case 1	Case 2	Case 3	Case 4
Imported energy (kWh)	8250	6614	6936	5811
Exported energy (kWh)	3415	3072	2094	1682
OEF	0,256	0,325	0,375	0,440
OEM	0,454	0,509	0,665	0,731
LPSP	0,744	0,675	0,625	0,560
MAX import (W)	2753	3967	5000	5000
MAX export (W)	5078	5078	5000	5000

As can be seen from Table 5.1, the total imported and exported energy throughout the year has been significantly reduced from Cases 1 to 4. This shows that the V2H mode and stationary battery has a remarkable impact on achieving the NZEB levels for a residential building. In addition, the OEF and OEM have

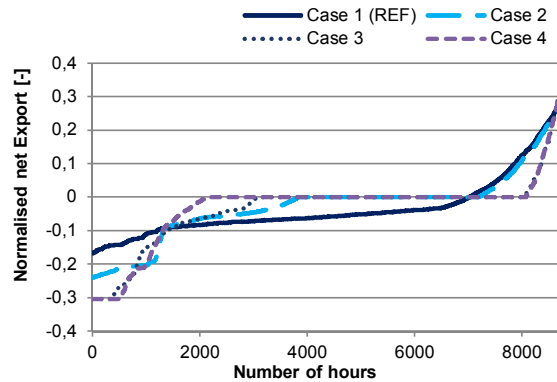
increased by Case 4, which reflects the impact of adding the EV and stationary battery. Comparing Cases 2 and 3, the amount of imported power for Case 3 is higher than that of Case 2. However, the other energy indices have improved. This is caused by the difference in the battery capacity of EV and the stationary battery. The EV has a capacity of 24 kW, 3.3 kWh, while the capacity of the stationary battery is 7 kW, 3.3 kWh; thus, the EV can provide more power during the evening (5pm-12am) depending on its available SOC compared to the stationary storage. The other parameter checked and controlled in the study is the maximum imported and exported power. In Cases 1 and 2, which lack storage in the system, the transferable power does not exceed 5 kW; however, when the storage is added, this power exceeds 5 kW and needs to be limited in order to not exceeding the maximum export power constraint, as can be seen in Table 5.1. The power starts passing the 5 kW, as the objective function in this study minimises the energy costs as well as the imported/exported power; therefore, without limiting the power to some value, it increases to enable a saving of energy at off-peak hours for later consumption. This limitation maintains the price at a reasonable range and simultaneously improves the energy indices.

Table 5.2, compares the annual savings achieved by the owner of the building by investing in each of the above cases.

**Table 5.2.** Annual saving of DH scenario in respect to the reference case (case 1)

District heating scenario	Case 2	Case 3	Case 4
Annual saving (%)	29	24	38

Comparing Tables 5.1 and 5.2, it can be concluded that improving the energy matching indices and decreasing the energy costs is attained when the energy storage and V2H mode are included in the building system boundary. To examine the changes in the magnitude of peak power and its duration by the new system boundary, normalised net export curves are derived for different cases, as shown in Section 5.1. Figure 5.2 illustrates the length of time during which the duration curve remains closer to zero in Cases 1 to 4.



**Figure 5.2.** Normalised net export of DH scenario

In a duration curve, the normalised exports are ranked by magnitude. Thus, the hours are representative of the number of hours that power is imported or exported. Figure 5.2 explains the advantage of having the storage and V2H

mode in the system boundary, as demonstrated by the duration curve that follows the zero axis for most of the period during the year. This figure also illustrates the strong seasonal variation in Finland.

### 5.1.2 Results discussion, ground source heat pump (GSHP) scenario

This subsection compares the results for the case when the heating is provided through a ground-source heat pump scenario. Tables 5.3 and 5.4 summarise the results and compare them for the different cases. In this scenario, as the amount of energy consumption rises significantly, two storage sizes are compared to examine the ways in which a larger storage with 10 kW, 3.3 kWh capacity will effect energy matching indices and the duration curve with respect to the case with a 7 kW, 3.3 kWh storage capacity.

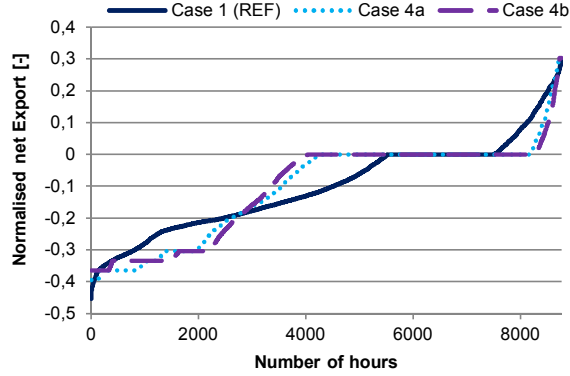
Table 5.3. Energy matching indices of GSHP scenario			
Summary (Year)	Case 1	Case 4a (ESC=7 kW)	Case 4b (ESC=10 kW)
Imported energy (kWh)	17015	16545	16150
Exported energy (kWh)	2419	1360	1006
OEF	0,184	0,228	0,245
OEM	0,613	0,783	0,839
LPSP	0,816	0,772	0,755
MAX import (W)	7487	6500	6000
MAX export (W)	4871	5000	5000

Comparing the energy matching indices of the GSHP scenario with similar ones in the DH scenario reveal a significant increase in imported power due to the demand for ground source heat pump energy. Therefore, there is a need for the storage and V2H mode to be applied in order to reduce the high amount of imported power. Comparing Cases 4a and 4b indicates the effect of a larger storage on reducing both imported and exported powers. In addition, OEF, OEM and LPSP are improved and the maximum imported power could be declined when applying a larger energy storage capacity (ESC). It is important to analyse the amount of savings that Cases 4a and 4b will provide for this system boundary of the GSHP scenario. Therefore, Table 5.4 compares the amount of annual saving for each scenario with respect to the reference case (Case 1).

**Table 5.4.** Annual saving of GSHP scenario in respect to the reference case (Case 1)

Ground source heat pump scenario	Case 4a	Case 4b
Annual saving (%)	8	11

The data in Table 5.4 implies that the amount of savings is much lower compared to the DH scenario that poses a high burden for both the grid utility and the building owner in the form of energy costs. However, duration curves (Figure 5.3) show that the new system boundary improves the NZEB concept, although highly significant changes have not been achieved. Figure 5.3 illustrates the normalised net export parameters and presents a comparison between the curves towards zero axes.



**Figure 5.3.** Normalised net export of GSHP scenario

### 5.1.3 Economic assessment

This paper [Publication VI] expands the building system boundary and considers the V2H mode within the boundary of the building. The management system must track energy transfers at home and between the home and the grid, home and EV, as well as home and storage. Moreover, due to the proposed changes, the need to install a bidirectional converter and energy storage system raises the question of the economic viability of this system. Table 5.5 presents a summary of the required equipment prices. It also compares the annual savings provided by different cases in each scenario (DH and GSHP) when using Nordpool spot prices [41]. Table 5.5 provides a reference for calculating the payback time of the investments for the aforementioned scenarios based on Equation (5.3).

**Table 5.5.** System costs and annual savings compared to the reference case

System costs	Stationary battery 415 €/kWh	Bi-directional con- verter ~2000 €	Control system & other costs ~1000 €
Annual saving (€)_DH	Case 2 166	Case 3 138	Case 4 217
Annual saving (€)_GSHP	Case 4a 108	Case 4b 142	

To evaluate the economic viability of the advanced system, the net present worth of the cumulated cost savings,  $S$  (over a given analysis period), is calculated from

$$S = \frac{(1+r)^n - 1}{r(1+r)^n} \cdot S_a \quad (5.3)$$

where  $r$  is the discount rate,  $n$  is the length of the analysis period in years and  $S_a$  is the annual saving in euros (€) [42]. The discount rate is calculated based on the cost of the capital employed in the innovation. A typical discount rate ranges between 10 and 30 percent depending on the risky nature of the ventures. The net present worth of the cumulated savings indicates the maximum allowable capital cost of the advanced power management system for each analysis period. In other words, the analysis period is an indicator of the period by

the end of which the investment pays for itself. The economic viability is assessed by comparing the cumulated cost savings with the known prices of the system components.

In Finland, the electricity price is one of the cheapest found in the European Union countries [43]. This also causes the payback time to increase. For example, as shown in Table 5.6, when considering electricity prices in Germany for the same study, the payback time  $n$  in Equation (5.3) could be reduced from 14 years to 3 years when  $r = 0.2$ , and from 25 years to 4 years when  $r = 0.3$ . This suggests that the electricity price overly affects the refund from the exported power and provides a more economically viable system.

**Table 5.6.** Payback time in accordance with different discount rates in Finland and Germany

Country	$r = 0.2$	$r = 0.3$
Finland	14 years	25 years
Germany	3 years	4 years

Therefore, taking into account the current situation in Finland, this type of building model might become economically beneficial with a reduction in the price of the devices required for such buildings. In addition, as the penetration of renewable energy sources increases, there will be a need to revisit energy prices and utilities regulations to encourage citizens to adopt smart buildings that provide most of their energy through renewable energy systems, as already occurs in Germany.

## 5.2 Microgrid model expanding to a community area

This section expands the microgrid model to include eight houses. The microgrid model is examined in terms of the energy exchanged with the grid between the houses and a larger common storage. For this purpose, individual houses are modelled. Each house has a specific gross floor area, PV panel size and separate energy generation and consumption. The houses are selected from the database in [44], which used measured data for determining the energy generation and consumption of the houses. Section 5.2.1 compares the results of a separate storage house with those using a larger common storage for the model. Section 5.2.2 analyses the economic viability of the different solutions.

### 5.2.1 Community area model and analysis

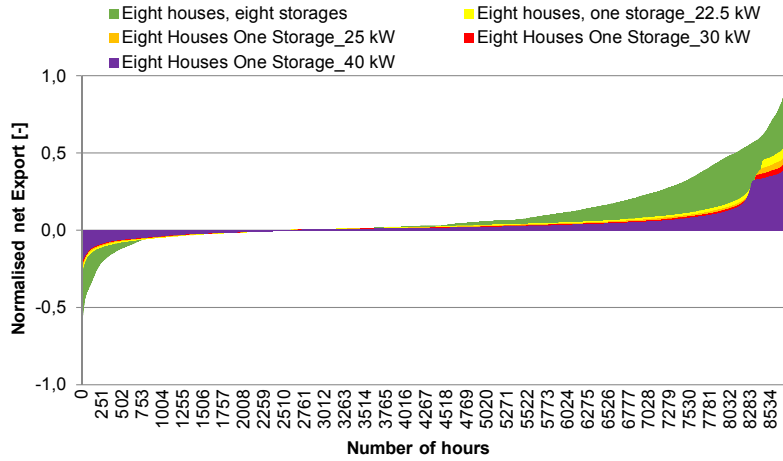
In this section, the optimisation model is (5.4), where each house has its own separate storage. This section applies thermal storage instead of electrical storage. The calculations are implemented for eight houses, each with different energy consumption patterns and PV panel sizes. This model separately studies the energy exchange of each house.

$$F = \min \sum_{t=1}^T w_{IMP}(t) \cdot P_{IMP}(t) + w_{EXP}(t) \cdot P_{EXP}(t) \quad (5.4)$$

In the community area consisting of eight houses, the number of the storage units was reduced to one. This condition made the size of the storage very significant. The size should be selected based on the average consumption of the houses in the community and the power provided from the panels. Therefore, four storage sizes are selected as the larger common storage for the community model. The optimisation model in (5.5) represents the objective function in the community area study. In this equation,  $n$  represents the number of houses and  $i$  is the index of the number of the house.

$$F = \min \sum_{i=1}^n \sum_{t=1}^T w_{IMP}(t)P_{IMP}(t,i) + w_{EXP}(t)P_{EXP}(t,i) \quad (5.5)$$

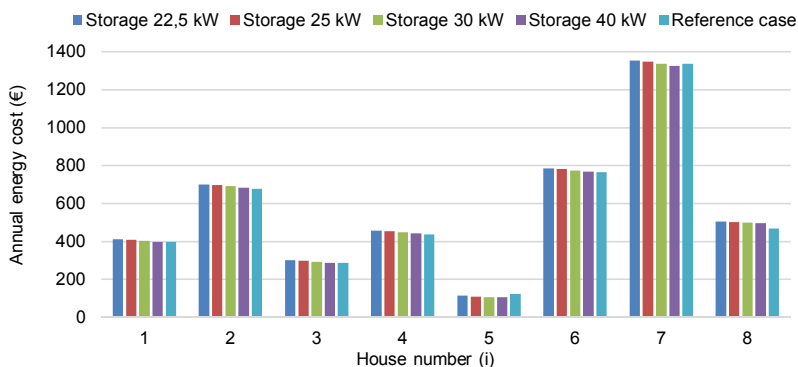
Duration curves are applied to compare the effect of the common storage on the case of each separate-storage house. Figure 5.4 compares the normalised net export for each separate-storage house (reference case) and the utilised common storage in four different sizes.



**Figure 5.4.** Normalised net export comparing the reference case with the common storage of 22.5 kW, 25 kW, 30 kW and 40 kW sizes

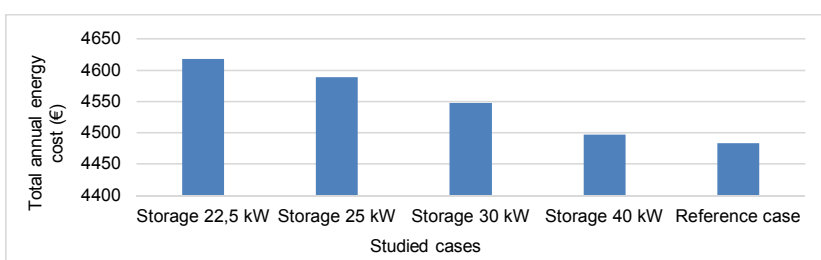
The results in Figure 5.4 illustrate that applying a common storage reduces the amount of imported and exported power. As each house has a different consumption pattern and PV generation model, creating the community allows an energy exchange between the houses. Therefore, the amount of import power and export power is less in most of the hours compared to the reference case, although there is always a power transfer with the grid.

Figure 5.5 summarises the annual energy costs paid by each house in the case of the community model compared with the reference case. Thus, the energy consumption of each house is calculated separately in the case of the common storage and is compared with the reference case, where each house has a separate 10 kWh storage.



**Figure 5.5.** Annual energy costs comparison for each house

Comparing the annual energy cost of different cases for each house shows that there is no significant change between the annual energy costs when a common storage is applied compared to the reference case. Thus, the individual costs of each house might even decrease by tens of euros in the case of a common storage. Even though the decrease is not significant, the investment costs for each resident would decline as they pay for the storage price as a group and each house's share would be much lower than the case of installing individual storage units. Thus, Figure 5.6 represents the accumulated energy cost of different cases. Each column bar in this figure shows the total sum for the annual energy costs of the eight houses. The results reveal that the amount of money that the whole community should spend for one year depends on the storage size. Figure 5.6 illustrates that even for the smallest storage size considered for the community, the difference in total costs is about 150 euros, which becomes smaller with increasing size of the storage unit. A storage size of 40 kW, which is half of the sum of the storage sizes of the reference case, differs insignificantly from the reference case. Thus, the residents could save a substantial amount on their initial investments.



**Figure 5.6.** Accumulated annual energy cost of the community in respect to different studied cases

Considering the initial investment of the thermal storage based on market prices, using a common storage size could reduce the initial investment costs by about two-thirds. Thus, in the next subsection, the payback time is calculated for the reference case and the community model in order to determine the time that would be required for the residents to gain some benefit from their investment.

### 5.2.2 Economic assessment

Equation 5.3 is applied to evaluate the revenue from the community and study the payback time of different cases. Table 5.7 shows the payback time for the different cases with respect to the case that no storage is installed in the community system, whether it be an individual or a common storage facility.

**Table 5.7.** Payback time for different cases of the storage size in the community in accordance to the case without any storage

Cases	$r = 0.2$	$r = 0.3$
Reference case	2,5 years	3,6 years
Storage size_22.5 kW	1,8 years	1,6 years
Storage size_25.0 kW	1,74 years	1,54 years
Storage size_30.0 kW	1,7 years	1,5 years
Storage size_40.0 kW	1,6 years	1,4 years

Table 5.7 compares two discount rates of 0.2 and 0.3. The discount rate reflects the opportunity cost of the mobilised capital, which increases with the estimated riskiness of the innovation opportunity. Indeed, riskier projects are expected to provide higher returns, thereby making such an approach risk-adjusted. As a result, applying a common storage to a community would seem to be very efficient, since the residents could receive revenues from such a system in less than two years compared to the reference case. In addition to revenue and the payback time, the duration curves show better results in a community compared to the reference case.

## 5.3 Conclusion

This chapter started with temporal escalation of the microgrid model to one year. In addition, the model introduced the possibility of integrating a vehicle into the home and its effect on net-zero energy buildings. The economic viability of the model was explained and the results were compared in two heating scenarios using either district heating or a ground-source heat pump.

The second part of this chapter included an introduction to spatial escalation of the microgrid model. A community consisting of eight houses was introduced, while a common storage was used in the model instead of eight individual storage units. The results were compared in terms of energy transfer with the grid and the savings that could be achieved via different sizes of common storage with respect to the case when no storage is installed in the microgrid model.

## 6. Conclusions

The need for microgrid studies and their undeniable effect on improving the quality and efficiency of energy systems is currently obvious to energy system producers, transmitters and distributors. Increasing penetration of renewable energy systems into the power generation chain has raised the importance of microgrids. A microgrid enables independent onsite power generation and consumption, either in islanded or grid-connected mode. Thus, the main goal of this dissertation has been to find solutions for energy transfer in such systems as well as their sizing and functionality.

The dissertation began with the design of the microgrid model, comprised of a single-family home. For this task, Chapter 2 introduced the microgrid model, and explained the simulated appliances and devices. As most of the appliances currently work with DC, a DC distribution design was considered for the model. The efficiency was also compared in AC and DC electricity distribution designs.

Chapter 3 analysed the microgrid energy and electricity systems. The analysis was implemented by studying two cases. Electrical storage sizing was implemented in one case. Energy exchange with grid utilities and the storage charging/discharging pattern were investigated to examine the efficacy of the proposed model. In one case, demand response control was examined for thermal storage using the greedy variable neighbourhood algorithm.

Any model in its early design stages requires validation before testing in real physical plants. Therefore, Chapter 4 provided validation for the proposed models. Hardware-in-the-loop tests were implemented in order to evaluate the control models. When performing HIL, the actual physical plant was replaced by a simulated model with the control system being tested on this model instead of the real plant. This method decreased the risks of directly applying the control system to physical equipment. The demand response model was validated in the two cases. The first case applied PV panels and electrical storage, and the second case thermal storage and solar thermal collectors.

Finally, Chapter 5 extended the microgrid model temporally and spatially to observe the results of the proposed models over longer periods of time and larger scales of space. The model was extended to one year while integrating an electric vehicle into the model. The extended model was examined through energy matching indices to evaluate the success of this model in approaching the requirements for a net-zero energy building. A community consisting of eight houses was considered for spatially expanding the model. These houses were compared by contrasting the use of individual storage units for each house

against a single common storage unit of different sizes shared by the entire community. In terms of energy and costs, the possible benefits for residents of adopting a community model with a common storage unit were considered, as well as the possible total revenue for the community.

Overall, with the increasing penetration of renewable energy systems, it can be expected that the importance of microgrids will grow rapidly. Microgrids of any size, from single-family homes to large communities, will remain demanding due to the flexibility they provide along with some uncertainties for the grid utilities. Nevertheless, since their necessity is significant for the power grids in near future, further research should pave the way to approach an ideal system.

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Increasing environmental concerns about the use of fossil fuels have generated great interest in emerging technologies to produce clean energy. Current research aims to mitigate this concern by proposing solutions for applying clean energies in residential buildings for the development of a microgrid model that would be sustainable, energy-efficient, economically viable and easily implemented.

This research presents a sequence of approaches to optimally utilise distributed energy resources, such as PV systems, battery energy storage, thermal storage and electric vehicles, with the aim of minimising imports from utility electricity grids, as well as helping houses, buildings, and communities to reduce energy bills.



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