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Connecting Prosumer Households in a Local Energy Community for Improved Energy Balancing - An Agent-Based Simulation Model

Master's thesis in Sustainable Manufacturing
Supervisor: Carla Assuad
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EIDA ENERGY

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Abstract

Local energy communities (LEC) have emerged as an innovative concept for local energy balancing and are a promising way to facilitate the integration of distributed renewable energy resources. An LEC consists of several energy producers, consumers and/or prosumers. Within an LEC electricity can be exchanged between participants. This allows for a more efficient use of existing resources (such as PV systems and battery energy storage systems (BESS)). Participants can thus achieve economic benefits by reducing their energy costs and by gaining additional opportunities for revenue. Furthermore, LECs create positive externalities beyond their system boundaries as the local energy balancing can reduce the stress on the distribution grid.

This work investigates a Local Energy Community consisting of 30 residential prosumer households in Norway. Each household is equipped with a PV system and a BESS. The energy exchange between the household is managed by a central energy management trading system (EMTS). The EMTS aims at reducing overall energy costs for the participants of the LEC. Three subgoals are addressed to achieve energy cost reduction: (1) peak shaving, (2) load shifting and (3) increase of self-consumption rate. Peak shaving reduces the monthly demand peaks of the participants and thereby reduces the peak demand charge (also known as "effekt-tariff"). Assuming hourly varying prices, load shifting avoids the energy procurement in periods with high energy prices. Finally, by increasing the rate of self-consumption the energy generated by the PV systems is used more efficiently as self-consumption is economically favourable to selling energy to the grid. The participant's BESS provide the flexibility needed to achieve those goals.

An agent-based simulation was conducted to assess the LEC's capability to achieve the above mentioned goals. Two regional settings impacting the PV-yield and the energy prices were tested. The LEC was set in Oslo (characterized by a rather good PV-yield and high energy prices) and Narvik (characterized by worse PV-yield and very low energy prices). Within each regional setting different BESS sizes were tested out. The simulation was run over a time period of one year.

The results showed that the LEC -in Oslo- could achieve yearly energy cost reductions of 40 604€ compared to a baseline setting without PV systems and BESS, and 3 376€ of cost reduction compared to a scenario with PV systems and BESS but without the possibility of energy exchange between the households. The cost reductions in Narvik were significantly smaller (12 040€ and 1 462€). The energy price was identified as the most influential factor on the LECs performance.

Furthermore, households with small BESS (7.2 kWh) that are connected in an LEC achieved the same cost reduction than households with significantly bigger BESS (14.3 kWh) that are not connected to an LEC. This leads to the conclusion, that connecting prosumer households in an LEC offers the option to reduce the BESS size and therefore the initial investment costs.

Overall, this work shows that connecting prosumer households in a Local Energy Community brings economic advantages to the prosumers as it enables a more efficient usage of the resources. However, in regions with very low energy prices and poor PV-yield it is still challenging to operate an LEC in an economically viable way.

Sammendrag

Lokale energisamfunn (Local energy communities - LEC) har dukket opp som et innovativt konsept for lokal energibalansering og er en lovende måte å integreringen av distribuerte fornybare energiressurser. En LEC består av flere energiprodusenter, forbrukere og/eller *prosumers*. Innenfor en LEC kan strøm utveksles mellom deltakerne. Dette gir mulighet for en mer effektiv bruk av eksisterende ressurser (som PV-systemer og batterienergilagringssystemer (battery energy storage systems -BESS)). Deltakerne kan dermed oppnå økonomiske fordeler ved å redusere sine energikostnader og ved å få ytterligere muligheter for inntekter. Videre skaper LEC-er positive eksternaliteter utover systemgrensene sine ettersom den lokale energibalanseringen kan redusere belastningen på distribusjonsnettet.

Dette arbeidet undersøker et lokalt energisamfunn bestående av 30 boligprosumerhusholdninger i Norge. Hver husstand er utstyrt med et PV-system og en BESS. Energiutvekslingen mellom husholdningen styres av et sentralt handelssystem for energistyring (energy management trading system - EMTS). EMTS reduserer de totale energikostnadene for deltakerne i LEC. Tre delmål er adressert for å oppnå energikostnadsreduksjon: (1) peak-barbering, (2) lastforskyvning og (3) økning av egenforbruksraten. Peak-barbering reduserer de månedlige etterspørselstoppene til deltakerne og reduserer derved peak demand-avgiften (også kjent som "effekt-tariff"). Om det forutsettes timevarierende priser, kan systemet unngår lastforskyvning energianskaffelsen i perioder med høye energipriser. Til slutt, ved å øke selvforbruket, blir energien som genereres av PV-systemene brukt mer effektivt ettersom eget forbruk er økonomisk gunstig for å selge energi til nettet. Deltakerens BESS gir fleksibiliteten som trengs for å nå disse målene.

En agentbasert simulering ble utført for å vurdere LECs evne til å nå målene som ble ønsket. To regionale innstillinger som påvirker PV-utbyttet og energiprisene ble testet. LEC ble satt i Oslo (preget av et ganske godt PV-utbytte og høye energipriser) og Narvik (preget av dårligere PV-utbytte og svært lave energipriser). Innenfor hver regional innstilling ble forskjellige BESS-størrelser testet ut. Simuleringen ble kjørt over en tidsperiode på ett år.

Resultatene viste at LEC -i Oslo- kunne oppnå årlige energikostnadsreduksjoner på 40 604€ sammenlignet med en basisinnstilling uten PV-systemer og BESS, og 3 376€ i kostnadsreduksjon sammenlignet med et scenario med PV-systemer og BESS men uten mulighet for energiutveksling mellom husholdningene. Kostnadsreduksjonene i Narvik var betydelig mindre (12 040€ og 1 462€). Energiprisen ble identifisert som den mest innflytelsesrike faktoren på LECs ytelse.

Videre viste simuleringen analyse at å koble husholdninger med liten BESS (7,2 kWh) i en LEC kunne oppnå sammenlignbare kostnadsreduksjoner med isolerte husholdninger med større BESS (14,3 kWh). Dette fører til konklusjonen at kobling av prosumerhusholdninger i en LEC gjør det mulig å redusere BESS-størrelsen og dermed de initiale investeringskostnadene.

Samlet sett viser dette arbeidet at å koble sammen prosumerhusholdninger i et lokalt energisamfunn gir økonomiske fordeler for prosumerne ettersom en mer effektiv bruk av ressursene er muliggjort. I regioner med svært lave energipriser og dårlig PV-utbytte er det imidlertid fortsatt utfordrende å drive en LEC økonomisk levedyktig.

Preface

I would like to express my gratitude to my supervisor Prof. Carla Assuad for her guidance and support throughout this work.

Furthermore, I'd like to thank Anders Eidberg from Eida Energy AS for the provision of detailed Data, as well as the interesting discussions which helped direct this work towards a promising path.

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Lastly, I'd like to express my gratitude to my fellow students, providing me with council and kind words in stressful times. Special thanks go to Paulina Steffen, who created the more good-looking illustrations in this work.

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List of Abbreviations

ABMS	Agent Based Modelling and Simulation
(B)ESS	(Battery) Energy Storage System
CHP	Combined Heat and Power
DR	Demand Response
DSM	Demand Side Management
DSO	Distribution System Operator
EMTS	Energy Management Trading System
EV	Electric Vehicle
DER	Distributed Energy Resource
LEC	Local Energy Community
LEM	Local Energy Market
LES	Local Energy System
P2P	Peer-to-Peer
PRV	Peak Reference Value
PV	Photovoltaic
RD	Residual Demand
TSO	Transmission System Operator
WTPP	Willingness to Pay a Premium

1 Introduction

1.1 Motivation

The number of distributed (renewable) energy resources (DER) -especially rooftop photovoltaic systems (PV)- and auxiliary energy systems such as small scale battery energy storage systems (BESS) in the energy market is rapidly growing (Sæther et al. 2021). This development is accelerated by technological advances and sinking investment costs for DER and BESS, and improvements in smart grid technologies (Ali et al. 2017). In addition, more prosumer[1] centric legislation has been introduced in recent years (Banet 2018). However, certain challenges in connection with DERs arise and need to be overcome. An optimal utilization of the DERs is not trivial. For example, self-consumption is more profitable and desirable than selling energy to the grid. But as energy generation and demand do not necessarily coincide, a high self-consumption rate is not easily achieved. Storage systems (such as BESS) provide flexibility to overcome this challenge but inflict high additional investment costs. Previously, many European countries used subsidies as a tool to support DERs and incentivize the investment in such systems. These subsidies are now declining or altogether stopped. Furthermore, DERs and BESS may inflict additional stress (in form of voltage fluctuations and increased peak demand) on distribution grids (Dynge et al. 2021). Hence, new approaches to overcome these challenges and optimally exploit the opportunities of DERs are needed. One such approach is the formation of local energy communities (LEC).

In a Local Energy Community these challenges and opportunities are addressed by managing the energy flow within a geographically restricted community and sharing the resources (e.g., PV systems and BESS) of its participants. LECs enable energy trading between the participants. The energy flow within the LEC is managed according to availability of (surplus) energy generation and availability of flexibility (provided by BESSs). The objective is to decrease overall energy costs. Thus, local energy communities utilize DERs more effectively, contribute to local energy balancing, improve economic sustainability for its participants and reduce stress on the distribution grid (Sæther et al. 2021). The LEC’s performance is heavily influenced by external factors, in particular by the energy market in which the LEC is embedded. This also influences the appropriate strategy for energy cost reduction. Generally, increasing the self-consumption rate leads to higher revenue as the price for selling energy is lower than the price for buying energy. This holds especially true in light of subsiding subsidies. Variable energy prices create an incentive for load shifting to avoid procuring energy in periods of high energy prices. Additionally in some markets peak shaving is incentivized. In Norway, part of the grid fees is calculated according to a peak demand charge, where consumers are billed according to the highest peak drawn from the grid in each month. This peak demand charge is also known as “effekt-tariff”. By sharing resources within an LEC, neighbouring prosumer households can increase self-consumption, exploit variable prices more effectively and improve peak

[1] A prosumer is an entity that both consumes and produces energy. For residential household this is most often accomplished through rooftop photovoltaic systems.

shaving. This increases revenues for prosumers and creates an incentive for more investment in DERs.

This work investigates the opportunities of local energy communities for residential households with PV systems and BESS in Norway. The objective is to study the benefits of connecting households in an LEC compared to settings where each household acts isolated and exclusively makes use of its own PV system and BESS. The influence of different energy market settings is investigated. In particular, the LEC is set in two different regions and thereby two different energy market areas in Norway (NO4 in northern Norway and NO1 in southern Norway).[2] The influence of energy tariffs and peak demand charges will be considered. Additionally, several sizes of BESS are tested. This work consequently addresses the following research questions:

1. What economic benefit can prosumer households gain by forming a Local Energy Community for peer-to-peer energy exchange? What other benefits can be created (e.g., increased independence)?
2. To what extend do external factors (such as the energy price) influence the performance of a Local Energy Community?

To answer these questions an agent-based simulation model of an LEC is conducted. An LEC consisting of 30 residential prosumer households (equipped with a PV system and a BESS), an Energy Management Trading System (EMTS) and connection to the superimposed grid is modelled. The model is implemented in an agent-based simulation which will be used to evaluate the performance of the LEC subject to different settings (e.g., varying pricing schemes, PV-yield and BESS size). The simulation model determines the energy costs of the households while being connected in an LEC and in an isolated setting where no energy exchange between the households is possible. The simulation period is set to one year to include the influence of different seasons.

1.2 Background

This following chapter gives a general overview over the field of local energy communities, microgrids and Local Energy Markets. The concepts are briefly explained, describing the opportunities and benefits they offer and the main challenges they face. Additionally, the terms are defined, and a selection of real-life projects pointed out.

While the terms *microgrid*, *Local Energy Market* (LEM) and *Local Energy Community* (LEC) have been used for over a decade now, no universal definitions exist yet. However, a common understanding of the main characteristics exists within the academic community. A *microgrid* consists of several local energy generators and energy consumers, which have a single point of connection with the grid and thus act as a single controllable entity with respect to the grid (Ali et al. 2017). *Local Energy Markets* consist of geographically close energy generators and consumers as well. These energy generators and consumers act as individual agents, however, and can engage in energy trading among each other. In contrast to a Microgrid, more than a single point of connection to the grid may exist (Mengelkamp 2019). The characteristics of a *Local Energy Community* include those of a LEM. In addition, an *LEC* is characterized by collaboratively striving for gaining benefits for all participants by optimally using and sharing the resources (Rana et al. 2022). The model proposed in this work includes a centralized energy management trading system managing

[2] For more information on market areas of the Nordpool Market, see. https://www.nordpoolgroup.com/en/maps/#/nordic (last accessed: 02.06.2022)

the energy flow between the participants striving for overall cost minimisation. As more than one connection point with the superimposed grid exists, the proposed model best fits under the term *LEC.* All three concepts have big similarities and generally address common challenges and opportunities. Therefore, insights from all three fields are regarded in this work. For better readability, the term Local Energy System (LES) will be used in the remainder of this section as an umbrella term comprising microgrids, LEMs, and LECs.

Local Energy Systems strive for local balancing of energy generation and consumption by enabling energy exchange between the participating agents of the LES. In addition to (renewable) energy generators and energy consumers many LES typically include energy storage system. Trading or other forms of energy management within the LES help to balance the energy locally and reduce energy exchange with the superimposed grid. Complete autarchy is most usually not aspired as it would require tremendous excess energy generation capacities at high costs. In addition to energy storage systems some LES use demand side management (DSM), demand response (DR) or electric vehicles (EV) as additional means to provide flexibility (Mengelkamp 2019).

Local energy balancing leads to economic, ecological and social benefits for the LES' participants and additional stakeholders such as grid operators and platform providers. Reducing the energy procurement from the grid reduces energy costs (and grid fees) for the participants. Providing flexibility to distribution system operators (DSO) or transmission system operators (TSOs) (e.g., on the control reserve market) offer an additional income for the LES and provides the DSO or TSO with options for balancing and/or congestion management. Furthermore, the local consumption of energy reduces transmission losses and helps to prevent or delay the need for grid expansion as less transmission capacity is needed. The strengthening of distributed renewable energies increases independency from conventional power plants and thereby reduces overall CO_2-emissions in the energy sector. Social benefits are created, as small prosumers and consumers are enabled to become active players on the energy market. In addition, the created revenues stay within the local community. Thus, LES offer economic, ecological and social incentives for further expanding distributed renewable energy generation.

For these reasons, a growing number of real-world LES projects is and has been sprouting throughout Europe and the world in the last years. The *Brooklyn Microgrid* is a microgrid marketplace in New York City which allows its participants to trade excess solar energy.[3] Quartierstrom is the first LEM in Switzerland, connecting 37 households in a neighbourhood and allowing for energy exchange of generated solar energy.[4] The LAMP project connects residential households with PV systems and a combined heat and power plant (CHP) in a LEM in central Germany.[5] The CityxChange project tests a Local Energy Market for the exchange of solar energy in Trondheim, Norway.[6] For more detailed information on other Microgrid projects, see e.g.: (Weinhardt et al. 2019), (Bjarghov et al. 2021).

[3] For more information on the Brooklyn Microgrid, see: https://www.brooklyn.energy/ (last accessed: 08.06.2022)
[4] For more information on the Quartierstrom-project, see: https://quartier-strom.ch/index.php/en/homepage/ (last accessed: 08.06.2022)
[5] For more information on the LAMP-project, see: (Mengelkamp et al. 2018b).
[6] For more information on the CityxChange project in Trondheim, see: https://www.trondheim.kommune.no/aktuelt/om-kommunen/bk/barekraft/cxc/det-nye-energisamfunnet/ (last accessed: 08.06.2022)

These projects (with the exception of the Brooklyn Microgrid) have in common that their purpose is research and development. Under current conditions, those projects cannot be conducted in an economically viable way without external funding. Apart from significant investment costs for decentralized renewable energies and energy storage systems main obstacles are posed by current regulations. Current regulations in the EU and in Norway were developed to fit the centralized infrastructure of the former energy system and do not acknowledge necessary changes to fit an energy system with share of distributed renewable energies. Energy trading between neighbours is not possible under current regulation. Taxation and fees within LES are unclear as well (Ali et al. 2017), (Mengelkamp et al. 2018a).

However, as these obstacles are likely to be overcome and (future) opportunities outweigh challenges, further research within this area is highly advisable. The EU directive (EU) 2019/944[7] strengthens prosumer rights. It is still unclear, however, how the member states implement the EU directive on the national level. Investment costs for renewable energy systems and energy storage systems are expected to further decline (Fraunhofer Institute 2021).

Agent-based modelling and simulation (ABMS) is a commonly used tool to study electrical systems in general and LES in particular. ABMS allows for the modelling of emergent behaviour of heterogeneous agents. It therefore allows for a bottom-up approach which suits decentralised LES (Ringler et al. 2016). ABMS can procure valid insights on LES much faster and cheaper than real-life projects and serves as an important tool within this research area.

Therefore, this works investigates a Local Energy Community model using agent-based simulation.

1.3 Approach

This work sets out to investigate the potential for energy cost reduction in a Local Energy Community consisting of residential households. An LEC with 30 participating residential prosumer households is investigated. Each household is equipped with a PV system and a BESS. Energy exchange between the participants of the LEC is enabled. Energy exchange with the superimposed grid is possible as well. The LEC's costs are compared to a baseline setting where the households are not equipped with PV systems or BESS, to a PV-only setting (where households have a PV system but no BESS) and to an isolated setting where households are equipped with PV systems and BESS but are not able to exchange energy within the neighbourhood (for an overview of the settings, see Figure 1). The isolated setting is comparable with the status quo of prosumer households. By comparing the different settings, the LEC's capability to reduce energy costs can be assessed and differentiated from the energy cost reduction resulting from the implementation of PV systems and BESS. The LEC will be set in two different areas, which affects the PV yield and the height and composition of the energy price. One tested area is Narvik, where PV-yield and prices are rather low. The other tested area is Oslo, where PV yield and energy prices are rather high. Additionally, the size of the used BESS is varied to investigate the

[7] For further information, see: https://energy.ec.europa.eu/topics/markets-and-consumers/market-legislation/electricity-market-design_en or https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2019.158.01.0125.01.ENG&toc=OJ:L:2019:158:TOC (last accessed: 08.06.2022)

influence of BESS size on the LEC's performance. Agent-based simulation is chosen as a tool to model the energy flows withing the LEC (and with the superimposed grid) and to calculate the associated energy costs.

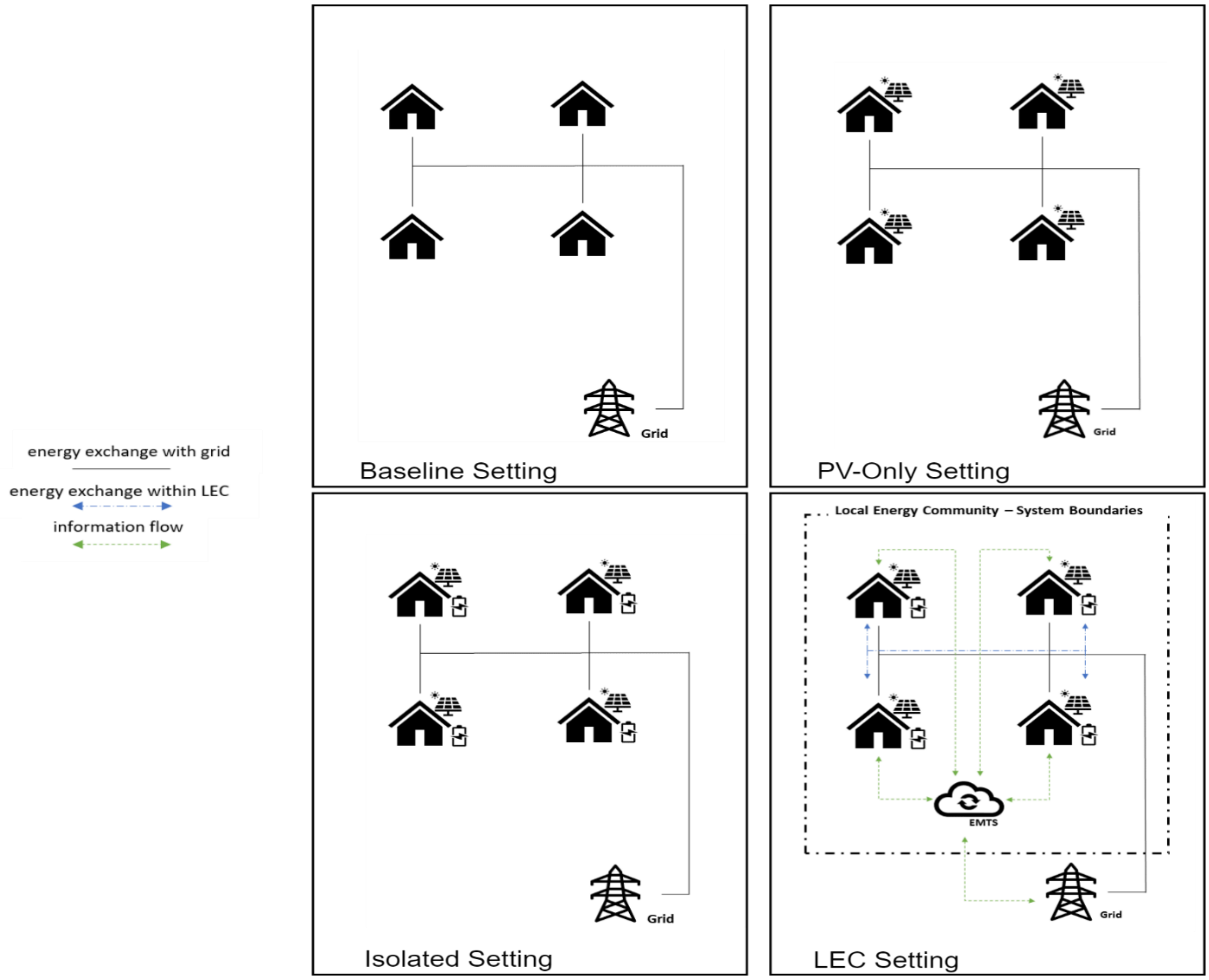

Figure 1: Conceptual representation of different settings of the modeled energy system (own Illustration)

Agent-based modelling is a commonly used tool to investigate LECs, Smart Grids, Micrograids or similar energy systems. Agent-based modelling is capable of effectively modelling and explaining complex systems by creating agents and their environment, determining rules on agent-behaviour and interaction (Wilensky and Rand 2015).

In the model proposed in this work, each household is represented by a software agent. The household sends offers and bids for exchanging energy. These offers or bids are formed according to the household's current energy generation, energy demand and the current state-of-charge (SOC) of the household's BESS. The offers and bids are sent to a central energy management trading system (EMTS) which determines the allocation of energy between the households and the energy grid and calculates the associated costs.

The energy management trading system is represented by a software agent as well. The EMTS incorporates the superimposed grid, as the grids functionality is quite simple and does not need to be represented by an additional agent. The grid provides the opportunity to buy or sell unlimited amounts of energy at a varying price. The EMTS manages the energy flow according to the received bids and offers and the current price for buying and selling energy from or to the grid. The EMTS' goal is to reduce energy costs for the LEC's participants.

The goal of energy cost reduction is achieved using several strategies. First, the self-consumption rate is increased. Second, through load shifting and energy arbitrage variable energy prices are exploited. Lastly, peak shaving is conducted to reduce the peak demand charge. These cost reductions strategies are enabled by flexibility provided by the participant's BESS.

Findings from previous work are included: The EMTS-heuristic is based on the microgrid management system proposed in (Morsali et al. 2017). The prices for energy exchange within the LEC follow the *LEP-n%*-arrangement suggested in (Lovati et al. 2020). The risk of possible negative impacts on the grid (e.g., additional demand peaks, voltage fluctuations) described in (Dynge et al. 2021) is avoided by limiting the BESSs' activities for energy arbitrage.

The remainder of the work will be as follows: Chapter 2 summarizes previous work in the area of LECs and highlights the motivational research gaps for this work. Chapter 3 conceptualizes the Local Energy Community modelled in this work. Subsequent, in chapter 4 the implementation of the LEC model in an agent-based simulation is described, including specifications on data and assumptions. The results of the simulation are described in chapter 5. Chapter 6 than presents the results of the sensitivity analysis. Chapter 7 discusses both the results of the chapter 5 and 6. Finally, chapter 8 concludes this work by summarizing the findings and suggesting areas for future research.

2 Literature Review

With the spread of small-scale renewable energies and energy storage systems at a low voltage level, novel challenges and opportunities arise. The local balancing of energy generation and energy demand with the help of energy storage systems in Local Energy Systems potentially brings large benefits to various stakeholders. By exchanging electricity within a neighbourhood, both prosumer and consumer households can benefit economically. Additionally, grid operators benefit from local energy balancing as the need for transmission is reduced.

As pointed out in chapter 1.2 the concepts of microgrids, local energy communities and Local Energy Markets address similar challenges and opportunities using a comparable approach. Therefore, all three terms are considered in this literature review.

In the past decade, simulation models – and in particular agent-based simulation models - gained popularity to investigate Microgrids, LEMs and LECs. Thus, a variety of models have been proposed. Differences can be identified in the set-up of the investigated energy system and the goal of the investigation.

Works that focus on the **impact of Microgrids and LECs on the superimposed distribution grid** include (Dynge et al. 2021), (Rana et al. 2022), (Lezama et al. 2019), (Faia et al. 2019) and (Delamare et al. 2015).

(Delamare et al. 2015) develop a general simulation model of a smart microgrid, using both elements from discrete-event simulation and agent-based modelling. The smart grid consists of interconnected houses which are equipped with PV systems and BESSs. The simulation aims at creating a model which allows for a close investigation of the bi-directional energy flow between the smart grid and the superimposed distribution grid. The modular set-up allows for scalability of the model. In a first example, a simulation of a smart grid consisting of 14 houses over a period of 1 week is conducted.

After identifying a lack of recognition of the distribution network in existing LEC simulation research, (Rana et al. 2022) propose a holistic model approach. The model includes not only the LEC itself, but also its surrounding environment. It consists of three layers: market, controller and grid. The model is purposefully built to enable the inclusion of different market clearing methods (distributed or centralized). A case study is used to illustrate the model.

(Lezama et al. 2019) and (Faia et al. 2019) both focus on economic implications of microgrid interactions with the superimposed grid. (Lezama et al. 2019) focus on the potential of Microgrids to locally balance energy generation and demand and thereby reducing the need for grid capacity. They model the energy management within the investigated Microgrid under uncertainties and its interaction with the wholesale energy market. The conducted case study considers varying prices and shows large potentials for cost reduction. (Faia et al. 2019) on the other hand focus on the potential for DSOs to use LEMs for congestion management. By acquiring flexibility from the LEM, the DSO can avoid network congestions. In their model, the participants of the LEM are remunerated for providing flexibility, while the DSO can avoid costly grid expansions. The study focuses on the DSO perspective. The behaviour of the participants of the LEM is, however, modelled in a very simplified way.

(Dynge et al. 2021) investigate voltage fluctuations and power losses in the distribution network caused by peer-to-peer (p2p) trading in LEMs. A two-step approach was chosen. In the first step, an optimization of the peer-to-peer market for each day is conducted. In the second step a power flow analysis is conducted to investigate the impacts on the distribution grid. This two-step approach also allowed for a separate evaluation of both economic and technical result indicators. The results were compared to a baseline scenario without the possibility for peer-to-peer trading. The influence of the different assets in the LEM (PV, BESS, EV) was assessed. A case study of an existing distribution grid with 52 connected end users was conducted. The results showed interesting insights. The integration of PV could lower total system losses and the peak demand of the LEM, regardless of whether P2P trading was allowed or not. But the integration of the batteries led to higher demand peaks and more voltage fluctuations, as it allowed for more trading with the grid due to the possibility for energy arbitrage. The sensitivity analysis showed a high sensitivity for different market models. Taking into account battery degradation (which was not done in the study) might impact the results, as it disincentivizes the use of batteries for energy arbitrage. Concluding, from a DSO perspective, LEMs with P2P trading might impose further challenges on the grid.

The investigation of **economic opportunities for the participants** and other direct stakeholders of Local Energy Systems is the predominant topic within current research. (Lovati et al. 2020), (Alabdullatif et al. 2020), (Zade et al. 2022), (Paudel et al. 2019), (Sæther et al. 2021) and (Firoozi et al. 2020) investigate business models and their economic opportunities for LESs.

(Lovati et al. 2020) investigate three different business models for peer-to-peer trading within a Local Energy Market using agent-based-modelling. The LEM is based in Sweden and consists of 48 different prosumer households with PV systems. By comparing the different business models, a business model that is most suited to incentivize further investment in PV systems is identified. The main difference between the tested business models lay in the ownership of the PV systems. Both private and common ownership have been investigated. The study is highly sophisticated regarding agent behaviour and reveals insights into business opportunities of different stakeholders. However, some crucial expansions of the simulation such as energy storages are still missing.

(Alabdullatif et al. 2020) suggest a very sophisticated two-stage energy market design for local energy communities. The market includes a double-auction hour-ahead market and a real-time minute-by-minute balancing market recognizing deviations from the predicted energy demand and supply. The work investigates the electricity cost changes for individual participants of the LEC. It thereby recognizes the fact, that for an LEC it is very important that not only the overall LEC can achieve improvements, but also each participant can reduce their costs to incentivize the participation in such projects. As the participation of prosumers (especially with BESS) is important, the suggested market model incentivizes the investment in PV and BESS-systems. The market design is tested in an agent-based simulation model. Overall, the market model proved to be successful in achieving energy cost reductions and creating incentives to invest in BESS and PV.

(Zade et al. 2022) investigates a number of clearing mechanisms for a Local Energy Market. The clearing mechanisms within a Local Energy Market is of utmost importance, as it defines the possibility for participants to gain economic advantages by participating.

The authors investigate a number of existing clearing mechanisms and suggest further mechanisms. Additional to common economic indicators, the possibility to include the WTPP (willingness to pay a premium) is included. This allows participants to express their willingness to pay more for an energy mix coming from local, renewable energy sources. The novel clearing mechanism is verified with the help of a Monte-Carlo Simulation.

(Paudel et al. 2019) model the behaviour of energy buyers and sellers in a small peer-to-peer trading community. Both within the group of buyers and the group of sellers non-cooperative behaviour was modelled. A simulation with a network of 5 prosumers (with PV systems and possibly BESS) has been modelled. The simulation showed clear cost-reduction potentials for the participants by reducing the need for energy exchange with the superimposed grid.

(Sæther et al. 2021) investigate a Local Energy Market for a complex of industrial buildings in Norway. PV systems and a combined heat and power plant (CHP) are included as energy sources. Electric vehicles and a large, shared energy storage system, as well as demand side management provide flexibility. The work investigates the LEM's capability of minimising energy costs, focusing mainly on reducing the peak demand charge. The authors develop a linear optimization model and test it with the help of a simulation over a one-year time-period. The authors chose a centralized approach; therefore, the objective function minimised the overall energy costs of all participants combined. The model achieves energy cost reductions of up to 11%, proving the potential for energy cost reduction through shared usage of flexibility within a LEM.

(Firoozi et al. 2020) propose a Local Energy Community as a reserve unit with the purpose to maximize the LECs profits by providing flexibility to the TSO. Opposed to previous work, the authors implement a realistic two-stage market model in accordance with regulation in the Nordic energy market. Flexibility is provided by BESS and EVs present in the LEC. A case study consisting of a hypothetical LEC in Finland with 50 households, a shared PV system, BESS and a number of EVs is used to illustrate the model. The case study showed that participation in the flexibility market can be highly profitable for LECs. However, different BESS utilization schemes lead to very different levels of profits. Therefore, a careful estimation of the BESS utilization is vital.

(Battery) energy storage systems are widely acknowledged as a vital component of LESs. A BESS can provide flexibility, which is very valuable in light of uncertain, hard-to-predict energy generation, energy demand and (in some cases) energy prices. With declining investment costs, the importance of BESS will grow in the future. Therefore – to no surprise - a large number of studies concerning themselves with **the management of BESSs in Microgrids or LECs** exist.

The role of BESS management in Microgrids is investigated in detail in (Morsali et al. 2017). Cooperative agent behaviour is modelled in a grid-connected microgrid with renewable energies and diesel generators, energy loads and BESSs. As a focus lays on the battery management, three different BESS management strategies are compared. The first strategy simply stores excess PV-generation in the BESS when possible and uses the BESS when PV-generation does not suffice to cover energy demand. The second strategy aims at stabilizing the overall net demand of the Microgrid from the grid and tries to keep it as close as possible to the average demand at all times. The third strategy takes the energy price as the major decision variable and aims at holding the energy price stable over the course of one day. While the first strategy slightly increased overall costs of the Microgrid compared to a setting without BESS, strategies two and three could achieve significant cost reductions. This shows the importance of implementing an appropriate strategy for BESS management.

(Morstyn et al. 2018) suggest a novel control strategy for state of charge balancing of BESS in a low voltage microgrid. The agent-based control method focuses on efficiency increasement and reduction of lifetime degradation. The performance of the control strategy was verified in a simulation model.

A multi-agent control method with a focus on the state of charge balancing of BESSs in Microgrids is developed in (Kang et al. 2019). The approach includes distributed loads and generation as well as BESS. The authors follow a two-layer approach, where agents are situated on a top communication network, while the bottom layer is composed of the actual distributed generators, loads and BESS. The agents communicate with their neighbours and aim for SOC-balancing of the BESS. The proposed method aims at achieving stable voltage levels within the Microgrids and the superimposed distribution grid in light of uncertainties, communication delays, and link failures. The method was verified with the help of a simulation. The focus lays on network security problems while economic parameters are not investigated in detail.

(Lee et al. 2021) use a multi-agent-based optimization model to explore the optimal size of a BESS and the optimal amount of demand response within a Microgrid. The Microgrid consisted of multiple renewable energy sources (PV and Wind), residential loads and a centralized BESS. The behaviour of the agent representing the energy loads, which have the possibility to engage in demand response or use the BESS have been modelled using game-theory strategies. With optimal BESS size and demand response, an operation cost reduction of 8,5% compared to a base scenario could be achieved. While variable energy prices have been considered, the possibility to sell excess energy to the grid was not included.

(Merabet et al. 2022) propose an energy management system for a Microgrid, focusing on the utilization of the battery storage. Energy cost reduction is achieved by shifting energy procurement to periods with low prices while using the energy storage in periods of high energy prices. Additionally, battery degradation is minimized, prolonging the battery's lifespan. For these purposes, the authors introduce a *contribution factor* for the battery, which determines the optimal energy drawn from the battery in each timestep. Additional flexibility is introduced with controllable loads. The proposed EMTS was tested in a simulation. Significant energy cost reductions could be achieved compared to a conventional control mechanism.

(Lüth et al. 2018) investigate the case of a peer-to-peer-trading microgrid, consisting of consumers and prosumers. The focus lays on energy storage systems that help to increase flexibility and thereby self-consumption, which decreases energy costs. Two different scenarios were investigated: One with a centralized BESS and one with private decentralized BESSs. An optimization with realistic data from the UK was conducted. The authors found big cost reduction potential, with slight advantages for the decentralized approach. The authors do not include uncertainty in their model, which leaves doubts whether a real-life peer-to-peer microgrid could reach results as good as the results shown in this work.

As mentioned before, uncertainties and poor predictability of energy demand and generation impose challenges on Microgrid concepts. Among others, (Tayab et al. 2021) and (Marín et al. 2019) take these factors into consideration in detail.

(Tayab et al. 2021) suggest an improved forecasting method for microgrid energy management systems. With the usage of grey wolf optimization improved day ahead forecasting of PV-generation and energy demand is achieved. With these improved forecasts energy scheduling within the energy management system is done. The methodology is verified in a small experimental set-up, consisting of one PV system, one BESS and one load. The experiment showed reduced operational costs through improved forecasting. However, a verification of the results on a larger scale is needed.

(Marín et al. 2019) use a two-level hierarchical energy management system based on robust model predictive control strategy to manage energy flows in a Microgrid and reduce energy costs. Often, predictions in Microgrid models either lack accuracy or sufficient accuracy comes with prohibitive computational time. By introducing uncertainties in their model, (Marín et al. 2019) could yield improved results without the need for accurate predictions. Energy cost reductions were achieved by minimizing the cost of energy drawn from the grid and increasing the self-consumption rate. The investigated microgrid includes non-controllable loads, renewable energy generators and an energy storage system. As the energy storage system is the only controllable unit, the energy management system focused on the control of that. The energy management system was verified and tested in a simulation of a Microgrid situated in the UK, consisting of 30 households. A three-level time-of-use tariff for buying electricity from the grid was considered. The simulation showed not only overall reduced energy costs for the Microgrid, but also a flattened the energy demand curve, which brings advantages to the DSO.

The research field of LEMs, LECs and Microgrids is still an emerging field, though it has gained more and more attention in the last decade. The potential of Local Energy Systems to create economic value for their participants has been investigated, using different business models and different methods for energy exchange and remuneration within the LES. Furthermore, the usage of LES for energy balancing and congestion management has been regarded, showing the potential of LES to contribute to a more stable and efficient grid. Many works identify energy storage systems as a key element of LES. Therefore, different control strategies for (B)ESS have been proposed.

However, there is still no predominant framework for such concepts for a number of reasons. First, important influencing circumstances (e.g., energy prices, regulation, taxation etc.) differ greatly in different countries or different regions. Second, the future development of these circumstances remains vastly uncertain. Third, ongoing technical advances reveal new opportunities and open up more possible research directions. Therefore, there is a need for more research to investigate models under different energy market structures, policies and legal obligations.

Existing research in the field already covers a variety of energy exchange mechanisms in LECs or Microgrids including PV systems and BESS under different circumstances. Yet, most simulation models only cover short time periods of a few weeks. This limits the validity of the results as seasonal effects, which effect the results greatly, are not included. Additionally, while the influence of energy prices within the LEC or Microgrid is often subject of investigation, the influence of energy prices and energy price structures of the superimposed grid is investigated less often. Finally -to the authors knowledge- no work has yet investigated the potential cost reduction through peak shaving for residential households, as energy demand charges are still uncommon on low voltage levels throughout Europe. The novelty of this work therefore lies in the inclusion of peak shaving in a residential context and the close examination of the energy price influence on the LEC.

Furthermore, the simulation period will be set to one year to account for seasonal influences on the PV-generation.

3 Local Energy Community Model

The goal of the Local Energy Community (LEC) is to achieve energy cost reductions for its participants. Three subgoals are addressed, to aim for maximum energy cost reductions:

(1) Peak shaving
(2) Load shifting
(3) Increase of self-consumption rate

Peak Shaving: Norwegian grid fees vary depending on the responsible distribution system operator (DSO). However, generally speaking, the grid fee for low voltage customers consists of an energy-based charge and a peak demand charge. The energy-based charge depends on the amount of energy withdrawn from the grid. The peak demand charge depends on the maximum demand within one hour in a month. By reducing the (monthly) peak demand (*peak shaving*, see Figure 2), consumers can therefore reduce their electricity bills. A further shift towards a higher focus on peak-demand tariffs is expected in the near-term future (NordReg 2021), (RME 2020). Therefore, peak shaving may gain even more importance in the future.

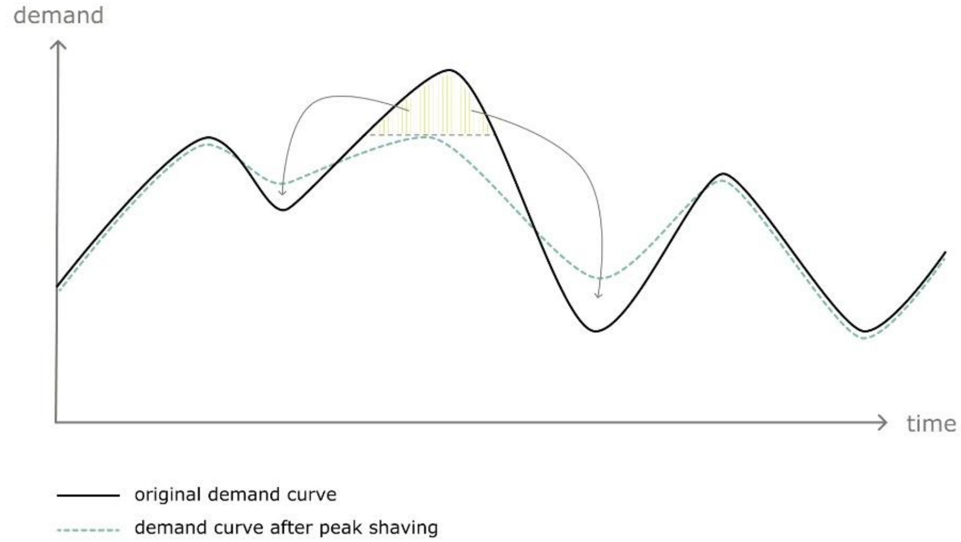

Figure 2: Peak Shaving (Illustration: Paulina Steffen)

Load Shifting: (Hourly) varying energy prices are well-established in Norway. In other countries varying energy prices for (low voltage) end-users are still uncommon. But as various benefits from variable prices for consumers as well as other stakeholders are expected, an increase of time varying energy prices can be expected (Steriotis et al. 2018). Varying prices hold the possibility for saving energy cost by load shifting. This means, that households avoid buying energy in times of high energy prices (e.g., by using energy stored in the BESS), and shift their energy consumption to periods with low prices (see Figure 3).

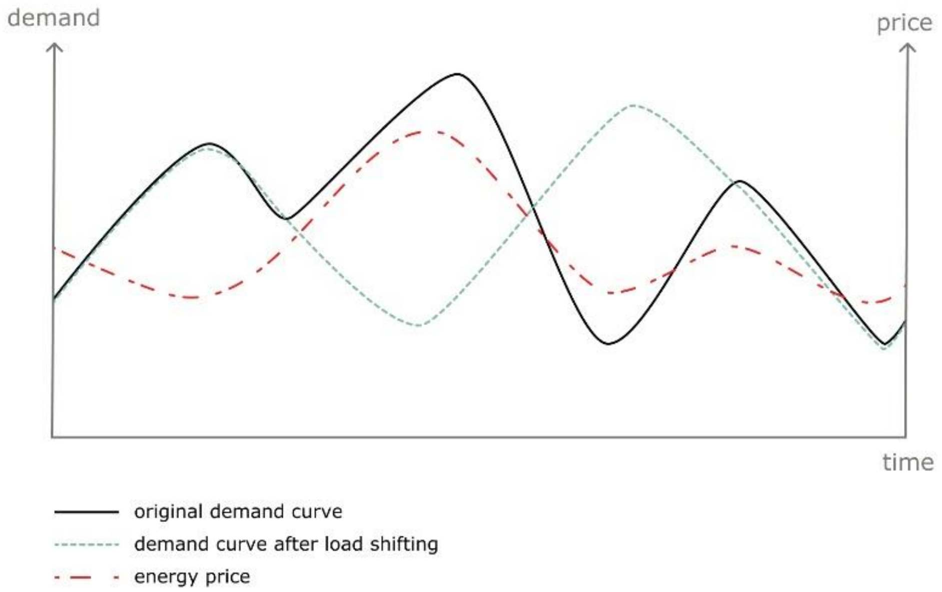

Figure 3: Load Shifting (Illustration: Paulina Steffen)

Increase in self-consumption rate: Generally, remuneration for feeding energy into the grid is lower than the price for buying energy from the grid. Therefore, an increase of the self-consumption rate (at constant overall energy consumption) leads to overall energy cost reduction.

The integration of a BESS in addition to a PV system is being used by private households and other entities (e.g. office buildings, small and medium sized businesses) to provide flexibility and address the three described goals. By intelligently connecting a number of prosumers and sharing the resources (particularly BESS) overall energy costs can be reduced more profoundly and efficiently as compared to a system with no shared resources. This approach is in need of an intelligent energy management within the Local Energy Community. The chosen approach will be described in more detail in the following sections.

3.1 Entities

Two types of entities interact in the proposed model: First, the household, which can buy, sell or store energy, and second, the energy management trading system, which manages the energy flow within the LEC and the energy exchange with the superimposed grid. Each household and the EMTS is represented by a software agent. The software agents have (limited) knowledge of their surroundings and autonomously make decisions on energy trading. The remainder of this chapter will describe both types of entities in more detail.

Each household has a varying and individual energy demand, a PV system for energy generation and a BESS for storing energy. The energy demand needs to be fulfilled in each time step. The energy generated from the PV system needs to be fully used up in each time step. This can be done either by fulfilling the energy demand, by selling the energy to other households or to the grid or by storing the energy in the BESS. Each household has knowledge about their current and past energy demand, their current and past energy generation and the state-of-charge (SoC) of their battery. The households have no knowledge of the status of their peers, which is a realistic assumption considering data privacy concerns. The households have no information on their future energy demand or generation. According to their knowledge each household submits bids for buying energy and offers for selling energy. Evidently, energy bids are created to fulfil surplus energy demand, while energy offers are created to offer surplus energy generation from the PV system. The BESS can either be charged or discharged (limited by its current SoC and technical restrictions) and can therefore be used to create both energy offers and bids.

The EMTS in turn manages the energy exchange between the different households and the energy grid. It receives all bids and offers from all households within the LEC. Additionally, the EMTS receives information on the price for buying and selling energy to the superimposed grid. It is assumed that the grid can buy and sell unlimited quantities of energy at all times. The EMTS then matches bids and offers and informs the households about the accepted bids or offers and their resulting energy costs or revenues. A detailed description of the matching heuristic of the EMTS is done in chapter 3.2.

Figure 4displays and sums up the general structure of the model. The EMTS receives and bundles all the information from the households and the grid. It determines the energy flow within the LEC and the energy exchange with the grid.

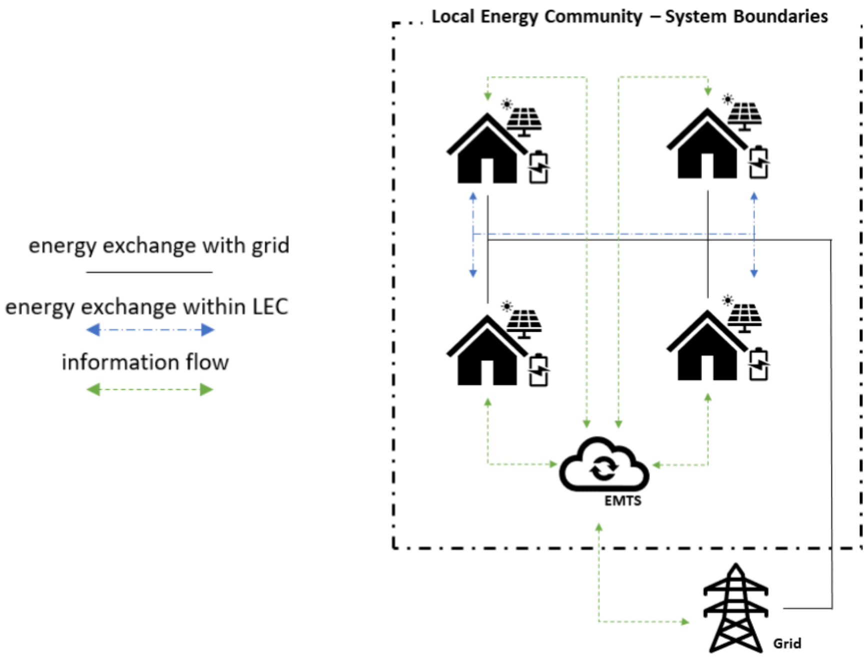

Figure 4: Conceptualization of the Local Energy Community (own Illustration)

3.2 Energy Management Trading System

The energy management trading system manages the energy flow between the participants of the LEC and the superimposed grid. The EMTS must fulfil all constraints (all energy demand needs to be fulfilled, all energy generation needs to be used) and aim at fulfilling the three goals for energy cost reduction (peak shaving, load shifting, increase of self-consumption rate). The heuristic of the EMTS will be explained in the following.

The EMTS receives bids and offers from all participating households. A bid or offer contains information on the amount of energy offered or demanded and about which household is sending the bid or offer. Additionally, it contains information about the type of bid, which is needed for the EMTS to match the bids and offers according to the goals described in the beginning of chapter 3.

There are five different types of bids or offers:

- *PV-generation-offer*: Offer of surplus energy generated by a PV system.
- *Discharge-offer:* Offer of energy currently stored in a BESS.
- *Charge-bid:* Request for energy for the purpose of storing it in a BESS.
- *Demand-bid*: Request for energy to fulfil a household's energy demand.
- *Peak-demand-bid*: Request for energy to fulfil a household's energy demand. In contrast to the *demand-bid,* the *peak-demand-bid* indicates that this bid needs to be prioritized over demand bid as the household has an especially high demand at this timestep which might cause additional costs due to the peak-demand charge.

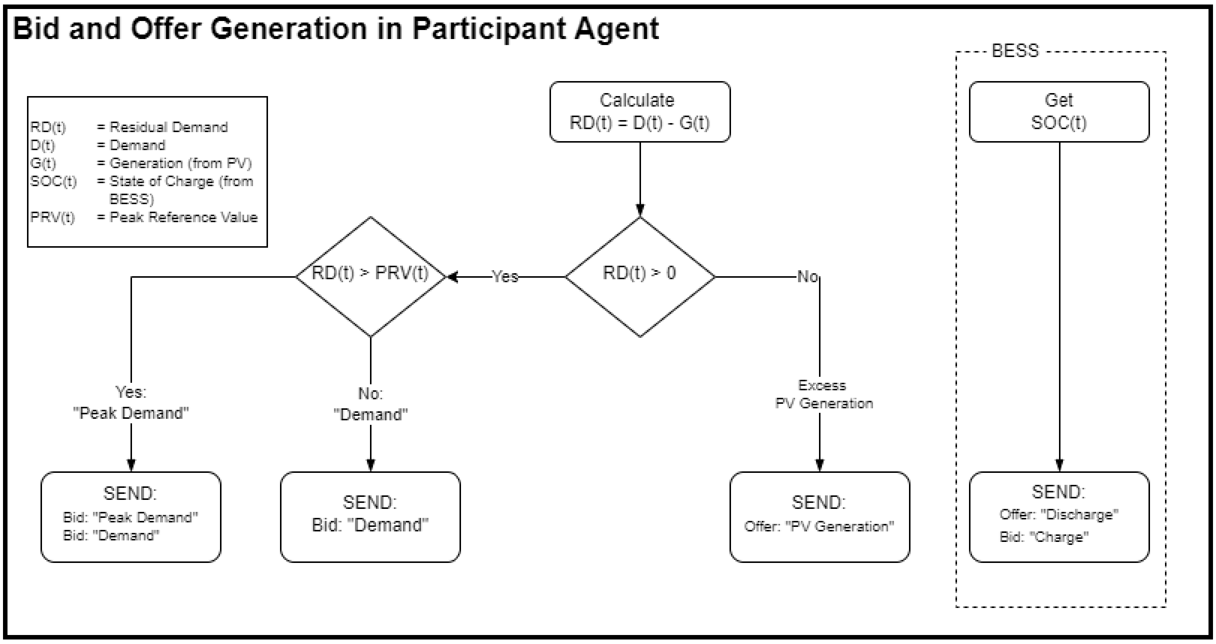

Figure 5: Flowchart: Bid and offer generation in participant-agent (own illustration)

Before sending bids and offers, in each timestep the participant assesses the current SoC of the BESS. Usually, the BESS will neither be fully charged, nor fully discharged. Therefore, usually the possibility for charging or discharging exist simultaneously and the participant will send both an offer of the type «discharge» and a bid of the type «charge» to the EMTS. The maximum charging/discharging rate of the BESS are taken into account as constraints.

By subtracting the energy generation (PV system) from the energy demand, the participant-agent assesses the residual demand (RD). If the RD is negative, more energy than needed is generated with the PV system. In that case, an offer (of type «PV-generation») over the excess energy is sent to the EMTS. If the residual demand is positive a further differentiation is needed to provide the EMTS with the necessary information to achieve goal *(1) (Peak Shaving)*. To achieve this goal, it is necessary to decide whether the current residual demand is considered to be a "peak demand". To do that, the current residual demand is compared to a *peak reference value* (PRV). This value is calculated using the last *n* timesteps. All demand values above this *peak reference value* are considered to be *peak demand*, and therefore their fulfilment needs to be prioritized. In case the residual demand lays above the PRV, two bids are sent to the EMTS. The first bid is of the type «peak demand» and comprises the amount of energy that goes above the PRV. It is calculated as: RD(t) – PRV. The second bid comprises the rest of the current residual energy demand (and therefore is of type «demand»). The bid-and-offer generation is shown in Figure 5.

The heuristic with which the various bids and offers are matched and the energy flow within the microgrid is managed combines aspects of the management strategy II and III proposed in (Morsali et al. 2017) (see chapter 2 for more details). Figure 6 shows a flowchart of the EMTS heuristic.

The matching system aims at addressing the three subgoals described above. The first goal (peak shaving) is prioritized over the second and third goal.

First, the "peak demand" bids are fulfilled with the offers from the PV generation and the BESS. In a second step, a differentiation is made according to the current price of electricity. For a price that is above the average price of the past *n* time steps (left path in Figure 6), the remaining offers from the PV generation are used to first fulfil the remaining demand bids, and then to charge the BESS. If the PV-Generation is not sufficient to fulfil the demand, energy from BESS-offers is used. Lastly, remaining energy demand is covered by energy procurement from the grid.

Should the price be below the average price (right path in Figure 6), the order is reversed, and the charging of the BESS is prioritized. After that, energy demand is fulfilled by the grid.

This approach helps to decrease the amount of energy bought from the grid in times of high energy prices.

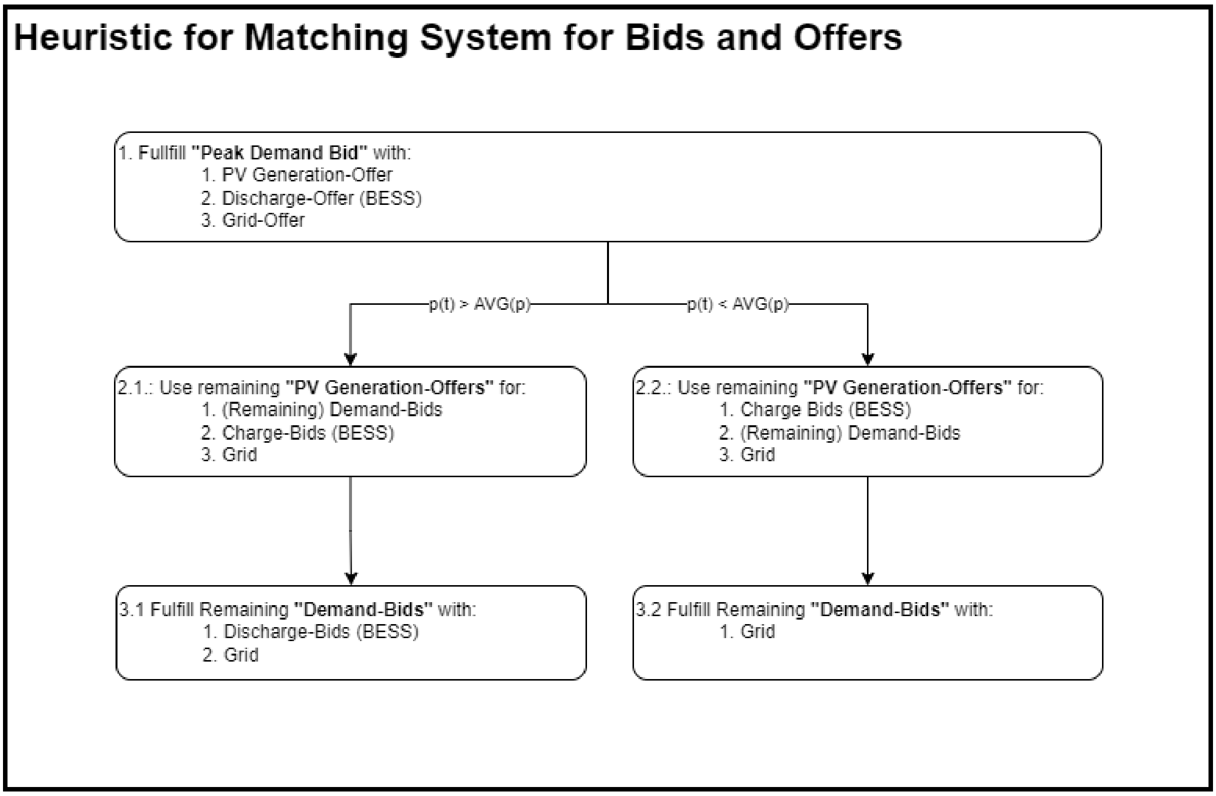

Figure 6: Flowchart: Energy Management Trading System – Heuristic (own illustration)

Independent of the current price of energy, selling PV-generated energy to the grid is always the least favoured option. This is in line with goal (3) and increases the self-consumption rate.

After completing the matching between bids and offers, the EMTS sends information to each participant about its accepted bids or offers. The accepted information included in these bids comprises the amount of energy bought or sold and the price at which this is done. The price formation is explained in the following chapter 3.3.

3.3 Accounting

To account for the energy exchange between the households (and the superimposed grid) prices need to be set on all successful exchanges of bids and offers. All energy bought from the grid is bought at a price P_{Buy}. All energy sold to the grid is sold at a price P_{Sell}. The price for selling energy is lower than the price for buying energy ($P_{Sell} < P_{Buy}$) in each timestep. Both the price for selling and buying energy to/from the grid are external values, that cannot be influenced within this model. Detailed information about the prices can be found in chapter 4.1.

This leaves the question on how to account for energy exchanged between households from the LEC. A number of different suggestions have been made in literature and LES-projects (see e.g., (Perez-DeLaMora et al. 2021) for an overview). In this model, the price for energy exchange between participants within the LEC (P_{LEC}) will be set to halfway between the price for selling and buying energy. Therefore, the price is calculated according to the following formula (1):

$$P_{LEC} = \frac{P_{Sell}+P_{Buy}}{2} \tag{1}$$

Setting P_{LEC} as suggested distributes the benefits evenly between the buying and the selling households. While the buyer profits from a lower price than P_{Buy}, the seller profits from a price higher than P_{Sell}. This approach largely follows the *LEP-n%*-arrangement suggested in (Lovati et al. 2020). The LEP-n%-arrangement assumes, that a central instance sets the price for energy exchange within the LEC (in our case this central instance is the EMTS). Setting the prices higher than P_{Buy} or lower than P_{Sell} does not make sense, as energy exchange with the grid would be preferred to energy exchange within the LEC. By setting the price to halfway between P_{Buy} and P_{Sell} both energy buyers and energy sellers benefit equally from the energy exchange. A price closer to P_{Buy} would favour the energy buyer. This might make sense in some cases to incentivize the investment in (larger) PV systems.

3.4 Envy-Free Allocation

The allocation heuristic described in chapter 3.2 manages the allocation of energy and the energy flow between different agents. However, in each step the aggregated demand of energy of one type can be bigger than the aggregated supply or vice versa. In that case, an allocation method needs to be found to determine which individual participants receives or sends which amount of energy.

To make the point clear, let us consider the following example with 5 households (assuming there are no BESSs for simplicity). Let us say participant A has an energy demand of 5 and participant B has an energy demand of 10. That leads to an aggregated energy demand of 15. Participant C has an offer of PV-generated energy of 10, participant D has an offer of 5, and participant E has an offer of 4, which leads to an aggregated offer of 19. So, in this case the aggregated offer exceeds the aggregated demand. If we use the energy offers from participants C and D to fulfil our demand, participant E would need to sell its energy to the grid and receive a lower price than participants C and D. This would be unjust. Therefore, instead of iterating through the bids/offers until the respective demand is fulfilled, an envy-free allocation method as described in (Brams and Taylor 1995) and -in the context of community energy markets- in (Alabdullatif et al. 2020) is used. To allocate the energy "envy-free" in the given example, the energy demand (15) is divided by the number of participants willing to fulfil this demand (3). Each fulfilling participant than gets the right to fulfil one proportional share of the demand (if capable). So, in the example each participant gets to fulfil a demand of 5 Units. As participants E only has a capacity to fulfil 4 Units, we get the primary allocation of 5, 5, 4 (for the participants C, D, E). This leaves us 1 Unit, which is again separated by the remaining participants. Only two participants remain now, which leads to an overall allocation of 5.5, 5.5, 4.

By using the envy-free allocation approach a systematic discrimination of certain households is avoided. Instead, the benefits of trading energy locally are shared in an envy-free way between the households.

3.5 Enhanced Energy Storage Usage

The above explained heuristic for matching bids and offers within the LEC and with the superimposed grid does not use the full potential of the BESS and leads to inadequate BESS utilization. The heuristic focuses on the utilization of PV-Energy as a mean to charge the BESS. However, the heuristic does not allow the BESS to be charged directly from the grid. This limits the possibility for energy arbitrage significantly.

An enhanced BESS usage scheme -that allows charging from the grid- can exploit the BESSs potential better and lead to further cost savings. By allowing for a usage of the

BESS for the purpose of energy arbitrage, energy costs can be directly reduced. By allowing charging the BESSs from the grid, (on average) the overall SoC within the LEC is higher. This implies, that situations where peak shaving is not possible due to insufficient available stored energy occur less often. Accordingly peak shaving can be conducted more successfully.

However, enhanced BESS usage bears the risk of unintentional negative impacts on both the households and the superimposed grid. The uncontrolled usage of BESS for energy arbitrage leads to increased trading activity and to increased demand peaks and voltage fluctuations (Dynge et al. 2021). The reason for the increased demand peaks is, that in times of low prices households are incentivized to charge their battery as much as possible. These increases in demand peaks pose a challenge on the grid operators and stand in contrast to the overall interest for the LEC to be beneficial both to the participants and the superimposed grid. Furthermore, there is a trade-off between the usage of BESS for energy arbitrage or peak shaving. As one of the two goals needs to be prioritized over the other, a strong focus on energy arbitrage diminishes the potential for peak shaving and vice versa.

Therefore, the proposed enhanced BESS usage scheme aims at allowing for energy arbitrage usage of the BESS under the condition, that no new demand peaks are created. After having received the results of the energy trading between the households and the grid by the EMTS, within each household a decision is made whether or not the BESS is to be charged during this time period. The BESS will be charge if the following conditions are fulfilled:

1. No energy is discharged from the BESS in this timestep (simultaneous charging and discharging is impossible).
2. The battery is not fully charged.
3. The maximum charging rate has not been exhausted by the energy flows determined by the EMTS.
4. The current energy price is lower than the benchmark price. The benchmark is calculated by multiplying the average price of the last two weeks with the battery efficiency. The benchmark price serves as a substitute for a price prediction.

If these conditions are fulfilled, the battery is charged. However, the battery is only charged to a degree, that the overall energy demand does not exceed the peak reference value in order to prevent the creation of a new demand peak.

The enhanced energy storage usage scheme allows for a more efficient usage of the BESS while avoiding the risk of creating new energy demand peaks and thereby increasing energy costs.

4 Simulation

Agent-based simulation is used to assess the proposed EMTS and evaluate the potential energy cost reductions for prosumer households by connecting in an LEC. The simulation period is set to one year. This way, the influence of all four seasons is considered. The changing solar radiation over the year heavily influences energy generation of the PV systems. Uncertainty of future energy prices, energy demand and energy generation is assumed. Absolute certainty of future states of these is highly unrealistic and would contort the results. This approach neglects the possibility for predictions and will therefore lead to more conservative results. An integration of realistic predictions lays beyond the scope of this work. The remainder of this chapter is structured as follows. In chapter 4.1 the data used for this simulation is presented. Chapter 4.2 discusses the chosen assumptions and the parameters that were varied in different simulation runs. Finally, chapter 4.4 presents the indicators used for assessing the simulation results.

4.1 Data

Data on energy demand of residential households, energy generation of small-scale PV systems, energy prices and technical characteristics of battery energy storage systems is needed for the simulation model. All data sources have been chosen to allow for a realistic setting.

Energy Demand

Eida Energy AS provided hourly energy demand profiles from two 4-person households in Norway over the time span of one year.[8] To be able to model a system with a multitude of different households, the *Load Profile Generator* as described in (Pflugradt and Muntwyler 2017) and in (Pflugradt 2016) was used to create additional load profiles. The *Load Profile Generator* is a sophisticated simulation tool, that generates realistic energy demand profiles for a wide variety of households. This study made sure to include different types of households (e.g., families, couples, singles) with different states of occupation (working, jobless, retired, students, etc.). 36% of the households were equipped with electric vehicles. Thus, energy demand data of a realistic heterogenous neighbourhood was created.

Energy Generation

The PV-generation data was created using the method by (Pfenninger and Staffell 2016).[9] A PV system with a capacity of 8 KWp, a tilt of 35°, and an azimuth angle of 180° was chosen. Data from two different locations (Oslo and Narvik) were used. A load profile for the duration of one year was created using weather data from the year 2019.

[8] Due to data privacy concerns no further information on the households can be provided. For more information on Eida Energy AS, see: https://www.eidaenergy.no/home-en (last accessed: 07.04.2022)

[9] The data is kindly made available for research purposes by the authors on https://www.renewables.ninja/ (last accessed: 07.04.2022).

Energy Prices

When investigating energy costs for household customers both the energy price and the grid fees need to be considered. Additionally, taxes need to be included as well.

For the energy price historical data from the period of May 2021 – April 2022 from the regions NO1 (including Oslo and South-East Norway) and NO4 (including Narvik and Northern Norway) from the Nord Pool Market for buying energy were taken (Nord Pool AS 2022). This means, that the energy price is changing hourly. Historical data was chosen, as accurate energy price predictions for the future years are very difficult and lay beyond the scope of this work.

It is noticeable that the energy price between the two investigated areas differs greatly. In the investigated period the Nordpool market price in the NO4 area (northern Norway) on average was ~70% lower than the price in the NO1 area (southern Norway). Furthermore, the energy price in the NO1 area was far more volatile. The standard deviation of the price in the NO1 area was about two times higher than in the NO4 area. This shows that energy prices in southern Norway are significantly higher than energy prices in northern Norway. Still, compared to the energy price in central Europe even energy prices in southern Norway are still comparatively low. The average energy price in Germany in this period was about 25% higher than in the NO1 area.

Grid fees change according to the responsible DSO. There are approximately 130 DSOs in Norway (NVE 2018). While the exact prices and the pricing scheme varies from DSO to DSO, the fee is usually made up of two different components. One part of the fee depends on the amount of energy withdrawn from the grid. The other part depends on the peak demand within one month. For each hour the demand is measured. According to the hour with the highest demand within a month a fixed charge is added to the grid cost. For this study, tariffs of the two Norwegian DSOs Halogaland Kraft Nett and Elvia AS were used (Halogaland Kraft Nett 2022), (Elvia AS 2022).

Additional energy costs such as taxes, fees and levies were set according to current Norwegian legislation (Statistisk Sentralbyra 2022), (Norwegian Ministry of Petroleum and Energy 2021).

For selling energy to the grid the Nordpool spot market price is assumed. This is in accordance with current practice for prosumers with less than 100kW feed-in power in Norway (Sæther et al. 2021).

Battery Energy Storage System

The characteristics for the BESS are set according to data from (SmartEnergySystems 2022) and are in line with current academic research (Noyanbayev et al. 2018): BESS sizes between 3.6kWh and 14.3kWh are chosen. The maximum (charging and discharging) rate is set to 5 kWh/h. The round-trip efficiency is set to 92.15%. Both the maximum charging rate and the efficiency in reality depend on different parameters such as state of charge and temperature. As a simplification, this model assumes constant values. Battery degradation is neglected in the simulation.

4.2 Assumptions and Parameters

The simulation is run over a period of one year in one-hour time steps. A total number of n=30 households participate in the LEC. Each household has an 8 kWp photovoltaic system and a unique energy demand profile. 11 out of the 30 participants own an electric vehicle which contribute to the energy demand. Each household owns a BESS.

This simulation model includes no prediction of future energy demand, energy generation or energy prices. Participants have knowledge of past states of these variables. However, each participant only has knowledge of its own energy demand and generation and does not have information on other participants.

While in the conducted simulation all households own the exact same PV system and BESS, the model is built in a way that easily allows for an adaption and a set-up with different types and sizes of PV systems or BESS. Future work might therefore easily investigate different set-ups, e.g., the inclusion of households without PV systems and/or BESS.

Participants of the LEC exchange energy and pay each other accordingly. It is assumed, that no taxes or other fees need to be paid for energy exchange within the LEC. It is unclear how future regulation will treat energy exchange within a restricted geographical area (e.g., a neighbourhood). Once this is clarified later work should include these taxes or fees.

As part of the sensitivity analysis the influence of variations of energy demand, energy generation, energy prices and the battery efficiency on the results is tested.

4.3 Scenarios

Within the simulation different scenarios are tested. The proposed LEC-model is set in two different regions which influences the input data concerning energy prices and energy generation from the PV systems. As a first location Oslo is tested (scenarios A-D, Table 1). Oslo is located in southern Norway and part of the NO1 market area of the Nordpool market. Prices in that area are relatively high. Solar radiation is relatively high as well, which means that the PV-yield is good. The second location is Narvik (scenarios E-H, Table 1). Narvik is located in northern Norway and part of the NO4 market area of the Nordpool market. Prices in that area are very low. Solar radiation is less high than in southern Norway. Therefore, the PV-yield is less good.

In addition, different BESS sizes are tested out to investigate the influence of the energy storage capacity on the LECs performance. Within each of the two region, 4 different BESS sizes are tested out: 3.6 kWh, 7.3 kWh, 10.7 kWh and 14.3 kWh. It is assumed that all participating households are equipped with the same BESS.

Scenario	A	B	C	D	E	F	G	H
Location	Oslo				Narvik			
BESS Size (kWh)	14.3	10.7	7.2	3.6	14.3	10.7	7.2	3.6

Table 1: Overview Scenarios

4.4 Result Indicators

To evaluate the results of the simulation both economic and ecological indicators are used.

As economic indicator the yearly energy costs are assessed. This includes all variable grid fees, costs for energy purchase and taxes that -directly or indirectly- depend either on the energy consumption or on the monthly peak demand. Costs that cannot be influenced (such as the fixed part of the grid fee) are not taken into account. Looking at the absolute yearly energy costs is not sufficient to meaningfully compare different scenarios. For example, a scenario with higher energy prices will certainly result in higher energy cost.

To meaningfully compare different scenarios a different perspective on the energy costs is needed. Therefore, the focus lays on the achieved cost reductions. Within each scenario, the energy costs are compared to a baseline-case where the households own neither PV systems nor BESS. Furthermore, the energy cost is also compared to a PV-only setting where the households own PV systems but no BESS and to an isolated household setting where the households are equipped with PV systems and BESS, but no energy exchange within the LEC is allowed (see: Figure 1). This allows for a comparison between different settings and scenarios.

Further economic impacts of an implementation of an LEC are expected. By reducing the energy exchange with the grid -or more importantly, the maximum peak demand from the grid- a reduction of needed grid capacity may be possible. This may result in economic advantages for the DSO. However, the assessment of those economic impacts lay beyond the scope of this work.

Assessing the ecological impact of the proposed LEC is difficult and less straightforward than the assessment of the economic impacts. In most cases outside of Norway it is interesting and most useful to look into the (avoided) CO_2-emissions by using more energy from local sources than from the grid. However, in the case of Norway this indicator proves to be less important. 98% of Norwegian energy generation comes from renewable sources, mainly from hydropower (Ministry of Petroleum and Energy 2016). Therefore, only insignificant changes in the caused CO_2-emissions are expected. As hydropower plants do have severe negative ecological impact on the local nature it is still in the best ecological interest to reduce the need for hydropower plants (Kuriqi et al. 2021), (Auestad et al. 2018). Furthermore, southern Norway imports significant quantities of energy from Germany, where CO_2-intense technologies such as lignite and coal are still in use.[10] The self-sufficiency rate of the LEC serves as an indirect indicator to measure the independency from energy from the grid and therefore independence from hydropower plants and a (possibly) more CO_2-intensive energy mix. A higher self-sufficiency rate in addition means that less grid capacity is needed which is an improvement as well.

The self-consumption rate is assessed as well. A higher self-consumption rate indicates fewer transmission losses, as the energy is used locally. Additionally, the local consumption of energy is beneficial for the DSO as it means that the amount of energy fed back into the grid is reduced. This means a reduced need for grid capacity and reduces the complexity of grid operation.

Table 2 shows an overview of the used result indicators.

Indicator	Category	Notes
Yearly Energy Costs	Economic	The yearly energy costs of different settings are compared. This allows for an assessment of yearly cost savings.
Self-Consumption Rate	Ecological	-
Self-Sufficiency Rate	Ecological	-

Table 2: Overview Result Indicators

Social impacts are unfortunately and shamefully (as in most related works) neglected. It is however noted that user engagement and social factors are important for the success

[10] See: https://www.ssb.no/en/energi-og-industri/energi/statistikk/elektrisitet (last accessed: 01.06.2022)

of LEC, Microgrid or Smart Grid projects. For a more user centric view on Microgrid projects see, e.g.: (Gangale et al. 2013).

5 Results

This chapter presents the results of the simulation. The simulation used the data as presented in chapter 4.1 and the assumptions as presented in chapter 4.2. Different scenarios are tested within the simulation (chapter 4.3). The indicators explained in chapter 4.4 are used to illustrate the results.

The conducted sensitivity analysis is described in detail in chapter 6. It investigates the influence of changing energy demand, energy generation, BESS efficiency and energy prices on the result indicators.

5.1 Regional Setting NO1 (Oslo)

In this scenario, the input data is set according to a set-up of the LEC within the Oslo-Area. As Oslo is located in the south of Norway the PV yield is rather good. The overall PV yield of the chosen 8 kWp PV system over the course of one year is 8017 kWh. The electricity prices and taxation are set according to the prices in the market region NO1 (which includes Oslo, Viken and Innlandet) of the NordPool Market[11]. As described in detail in chapter 4.1, the energy prices in the NO1 region are very high compared to northern Norway, but still rather low compared to other European countries. The height of the grid fees as well as the pricing scheme for the grid fees is set according to the pricing policy of the DSO Elvia AS who is the responsible DSO for the regions Oslo, Viken and Innlandet[12]. The BESS capacity is set to 14.3 kWh.

The yearly energy costs of the LEC compared to the *baseline setting* are assessed. In the *baseline setting* households do not own PV systems or BESSs and procure all energy needed from the grid. To allow for a more in-depth-analysis additionally a differentiation between different settings towards a fully connected LEC is made. The first setting includes the integration of PV systems but does not include BESS or energy exchange between households (*PV-only setting*). In the second setting, a BESS for each household is integrated in addition to the PV systems. Energy exchange between the households is still not allowed (*isolated households setting*). In the last and most advanced setting, households are equipped with BESSs, PV systems and exchange energy between themselves according to the EMTS-heuristic explained in chapter 3.2 (*LEC-setting*).

In the *baseline* setting yearly energy costs of the neighbourhood amount to 140 285€. Through the integration of PV systems those costs can be reduced to 107 346€ in the *PV-only* setting. The inclusion of BESSs in an *isolated* setting further reduces the costs by 4 289€, and finally the connection of the households in an LEC reduces the costs by another 3 376€ to 99 682€. Overall, the LEC achieved energy cost reductions of 40 604€ (Figure 7). This corresponds to a cost reduction of 29%. The integration of PV systems is responsible for 81 % of those cost reductions. Integration of BESS without the possibility

[11] For more information on Norwegian and European Price Areas, see: https://www.nordpoolgroup.com/en/Market-data1/#/nordic/map (last accessed: 26.05.2022)
[12] For more information on Elvia AS, see: https://www.elvia.no/nettleie/alt-om-nettleie/ (last accessed: 26.05.2022).

for energy exchange achieved 11 % of the cost reduction; and the connection of the households in an LEC another 8 % (Figure 8).

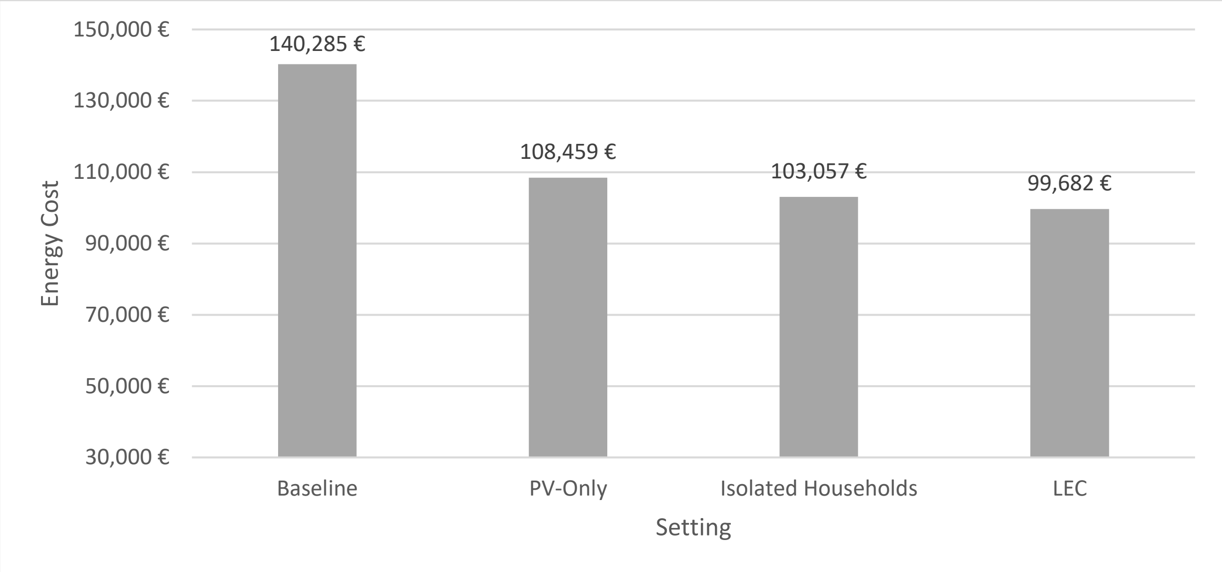

Figure 7: Oslo: Energy Costs over the simulation period of one year. Cumulated energy costs of all households of the neighbourhood.

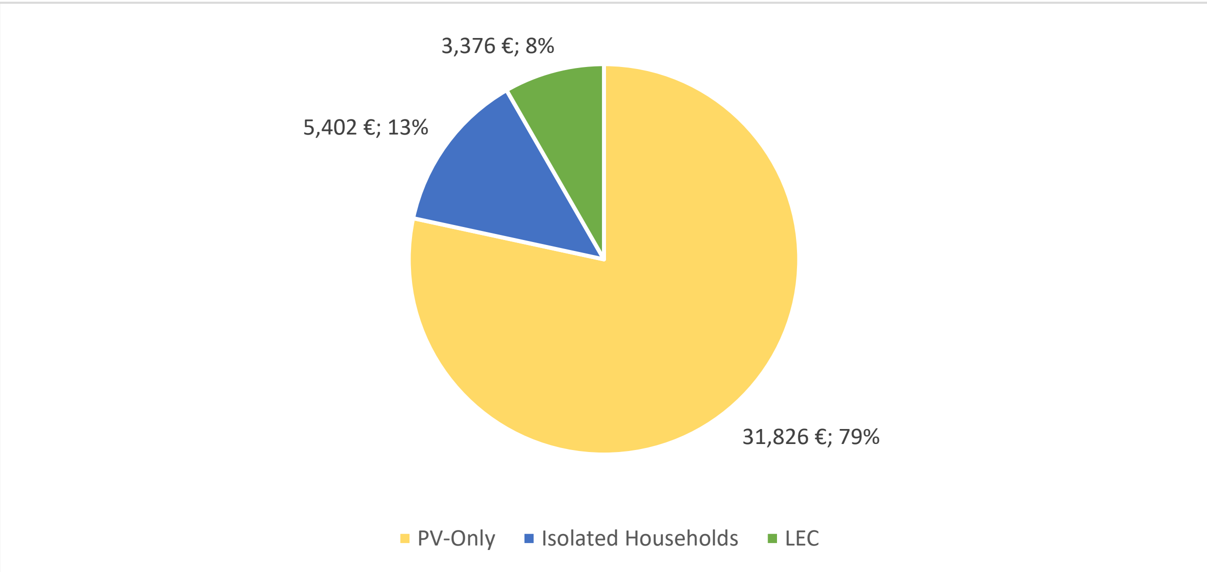

Figure 8: Oslo: Relative Energy Cost Reduction by setting

The LEC's strategy to reduce energy costs for the households achieves energy cost reductions using different approaches. Self-consumption is increased, and load shifting is done to avoid buying energy in periods with high prices. In addition, peak shaving is practised to reduce the monthly peak demand and thereby reduce the energy costs afflicted by the peak demand charge (or "effekt-tariff").

It is worthwhile to determine the share each of the different approaches contributes to the overall energy cost reduction. Increase of self-consumption and load shifting will be combined, as they both work on reducing the energy charge, while peak shaving reduces the peak demand charge. As identified above, through the integration of BESSs and the connection of the households in an LEC 7 665 € in savings could be achieved in addition to the savings generated by the PV systems alone. Out of those 7 665 €, 2 141 € (or 28%) were achieved through increased self-consumption and load shifting while 5 524 € (or 72 %) were achieved through peak shaving and reduction of costs afflicted by the peak demand charge (Figure 9).

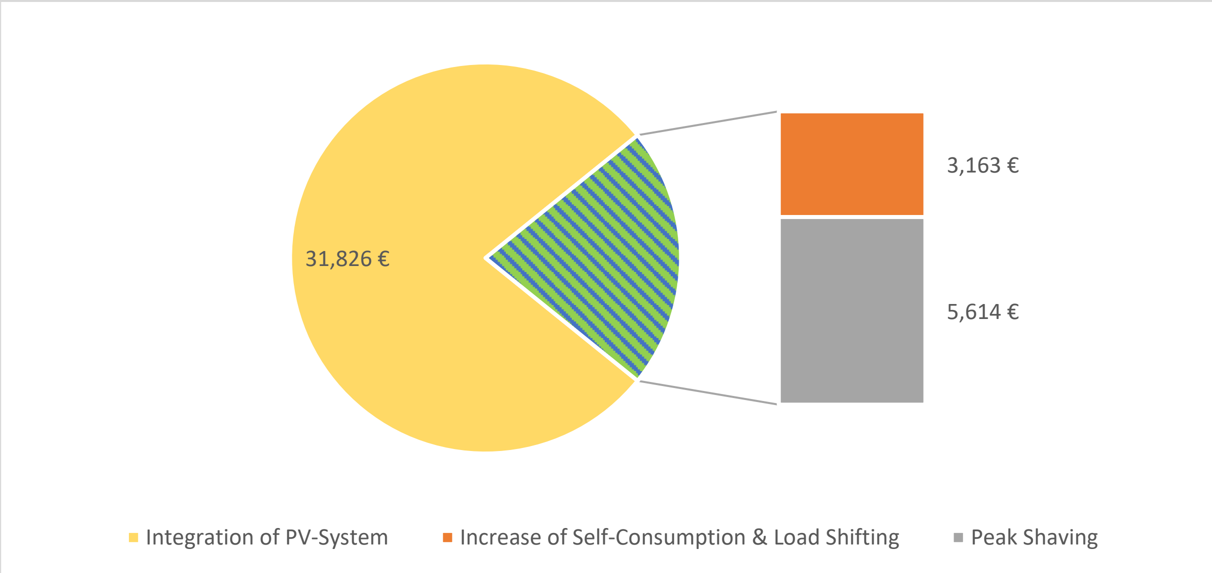

Figure 9: Oslo: Cost Reduction by Electricity Tariff Part

On average, the overall yearly cost reductions amount to 1 353 € per household (this corresponds to an average cost reduction of 29%). It is however worthwhile to investigate the actual allocation of the cost reduction per household. As can be seen in Figure 10 the cost reduction is distributed unequally between the households. Especially the additional savings generated by the fully connected LEC are distributed unequally. The households with the largest additional savings from a connection to the LEC (household no. 24 with 391 €) saves almost 10 times more than the household with the smallest additional savings (household no. 29 with 44 €). A closer look reveals that households that bought relatively high amounts of energy from their neighbours could achieve larger cost reductions. However, it can also be clearly seen that all households profit from being connected to the LEC.

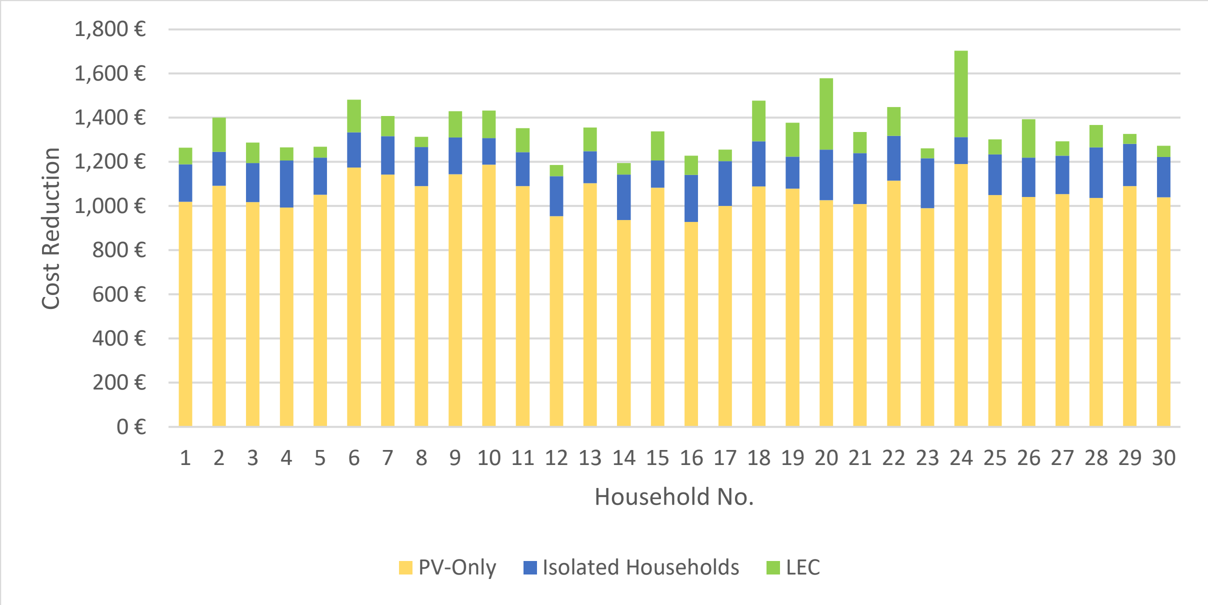

Figure 10: Oslo: Cost Reduction per Household

The self-consumption-rate and the self-sufficiency-rate cannot be meaningfully assessed for the baseline-scenario. Therefore, only a comparison of these values for the *PV-only setting*, for the *isolated setting* and for a fully connected *LEC* can be done. The values are shown below in Figure 11. As could be expected, the values increase significantly with inclusion of BESS and further improve in the fully connected LEC setting.

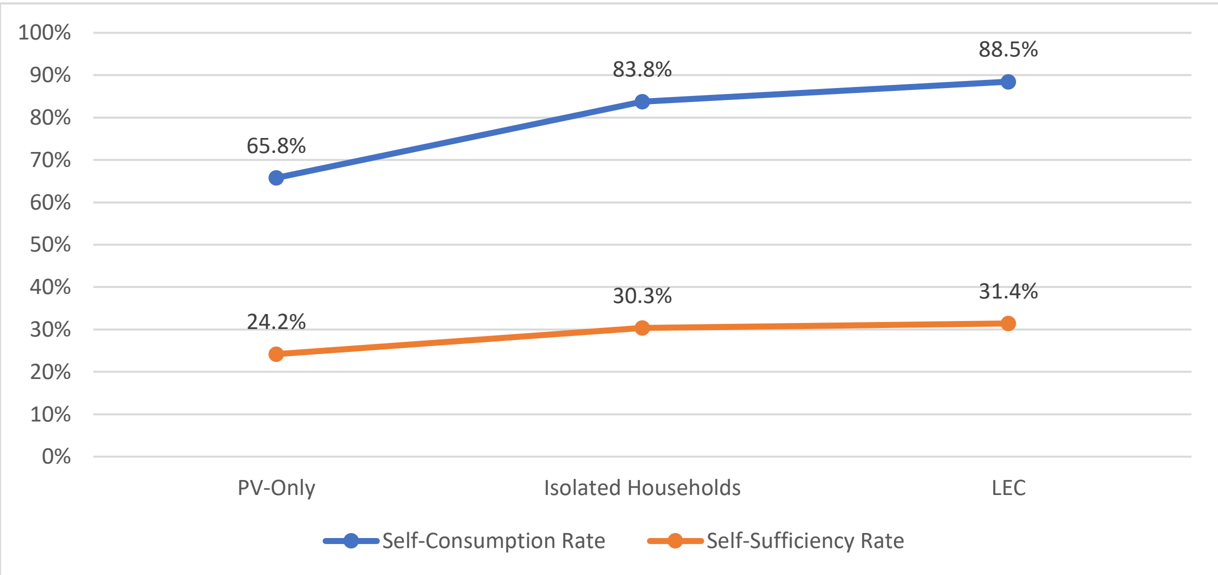

Figure 11: Oslo: Self-Consumption and Self-Sufficiency Rate - Oslo

5.2 Adjusted BESS-Capacity

This chapter describes the results of the simulation with adjusted BESS capacities. Input data concerning energy demand, PV-generation and energy prices is set according to the setting in the Oslo-area described in chapter 4.1. In addition to the BESS-capacity of 14.3 kWh, scenarios with BESS-capacities of 10.7 kWh, 7.2 kWh and 3.6 kWh are simulated. This corresponds to BESSs currently offered by the company SmartEnergySystems (SmartEnergySystems 2022).

To analyse the effectiveness of different BESS sizes, the energy costs in scenarios with the different BESS are compared. Both the results in an *isolated setting* and in a fully connected *LEC setting* are assessed. As can be seen in Figure 12 lower BESS capacities led to higher yearly energy costs. In the *LEC setting* a scenario with BESS capacities of 3.6 kWh led to energy costs of 103 182 € compared to energy costs of 99 682 € in a scenario with BESS capacities of 14.3 kWh. It is also noticeable, that both the *LEC setting* with a capacity of 10.7 kWh and with 7.2 kWh achieve lower energy costs (100 313 € and 101 383 €) than the *isolated setting* with the biggest tested capacity which resulted in energy costs of 103 057 € (Figure 12).

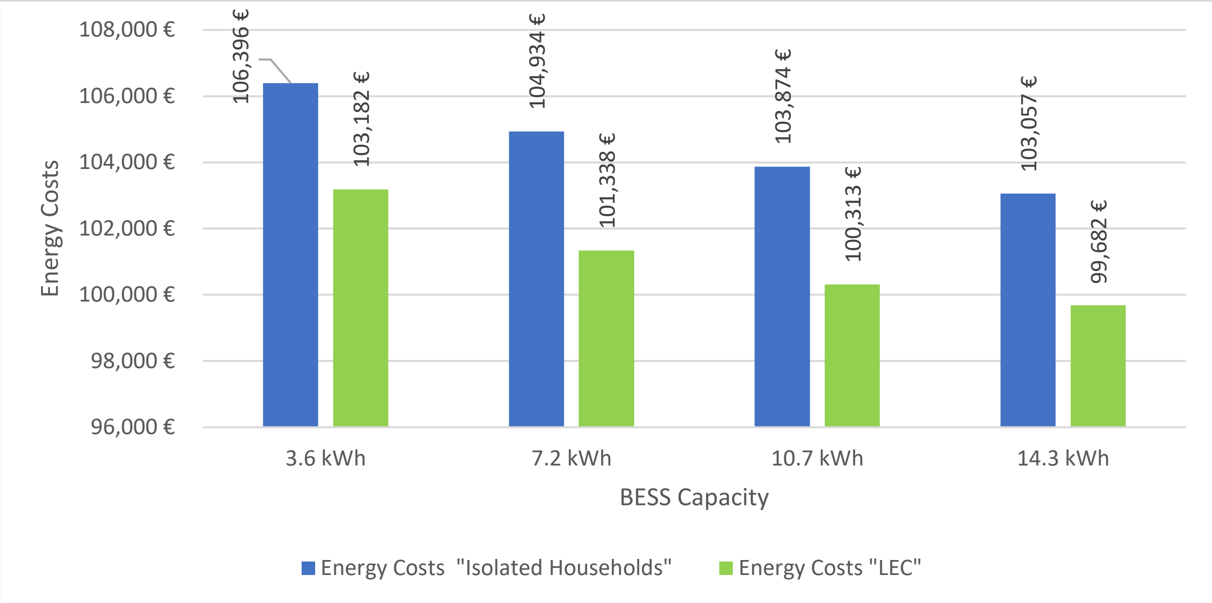

Figure 12: Energy Costs in scenarios with different BESS sizes

Both the self-consumption and the self-sufficiency rate increase with increasing BESS capacities. The self-consumption rate increased from 77% with a BESS Capacity of 3.6 kWh to 88 % with a BESS Capacity of 14.3 kWh in the *LEC setting*. The self-sufficiency rate increased from 28% with a BESS Capacity of 3.6 kWh to 31 % with a BESS Capacity of 14.3 kWh in the *LEC setting*. For the *isolated* setting the pattern remains the same, though the values are overall lower (Figure 13).

This chapter only described the results of the variations of BESS size in the LEC with the locational setting in Oslo. Variations of the BESS size in the Narvik-setting led to very similar results. These results can be found in the appendix.

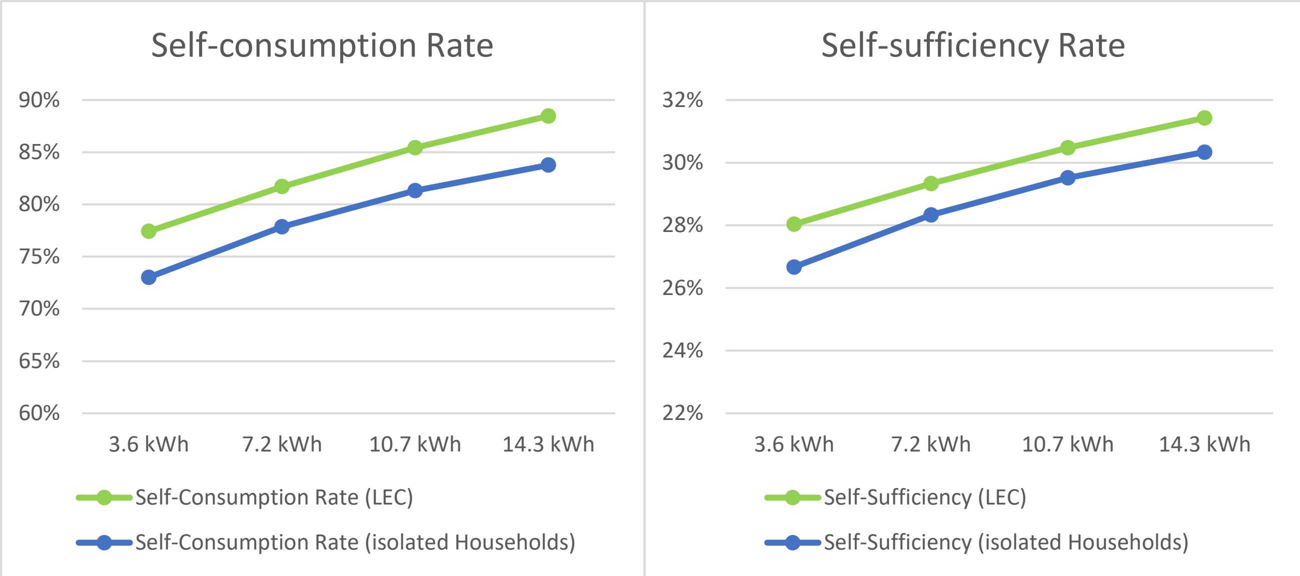

Figure 13: Self-consumption and Self-sufficiency rate in scenarios with different BESS Capacities

5.3 Regional Setting NO4 (Narvik)

This chapter describes the results of the simulation with input data set according to a set-up of the LEC in the Narvik-Area. As Narvik is situated in the north of Norway the PV-yield is worse than in the setting in Oslo. The same PV system is used, however, the overall PV-yield amounted to 6 854 kWh, which is 15% less than in the Oslo setting. The electricity prices and taxation are set according to the prices in the market region NO4 (North and North-West Norway, including Narvik) of the NordPool Market. The prices in the NO4 region are significantly lower than in the NO1 region (see chapter 4.1). The height of the grid fees as well as the pricing scheme for the grid fees is set according to the pricing policy of the DSO Halogaland Kraft Nett who is the responsible DSO for the regions Narvik and the surrounding area.[13] The BESS capacity is set to 14.3 kWh.

Similar to chapter 5.1 the yearly energy costs of the LEC compared to the baseline scenario are assessed. Again, a differentiation between different settings towards a fully connected LEC is made. Energy costs of a *baseline* setting (without PV or BESS systems), a *PV-only setting* (with PV systems but without BESS), an *isolated setting* (including PV and BESS, excluding energy exchange) and an LEC *setting* (including PV, BESS and energy exchange within the neighbourhood) are compared.

In the *baseline setting* yearly energy costs amount to 53 834€ for all 30 households of the neighbourhood. Through the integration of PV systems those costs can be reduced to 44 753€ in the *PV-only setting*. The integration of BESS in an *isolated setting* further reduces the costs by 1 497€, and finally the connection of the households in an LEC reduces the costs by another 1 462€ to 41 795€. Overall, the LEC achieved energy cost reductions of 12 040€ (Figure 14). This corresponds to a cost reduction of 23%. The integration of PV systems is responsible for 64 % of overall cost reduction. Integration of BESS without the possibility for energy exchange achieved 18 % of the cost reduction; and the connection of the households in an LEC another 18 % (Figure 15).

[13] For more information on Halogaland Kraft Nett, see: https://hlk.no/om-halogaland-kraft-nett/ (last accessed: 26.05.2022).

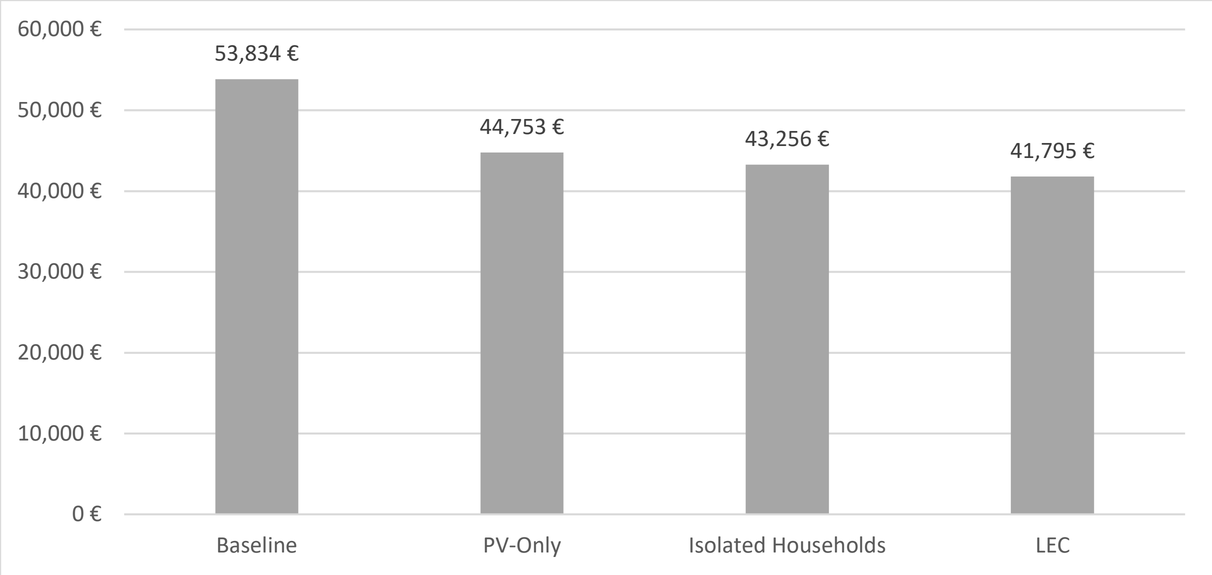

Figure 14: Narvik: Energy Costs with different Settings

Overall yearly cost reductions of 12 040 € could be achieved. The integration of PV systems was responsible for the biggest share of cost reductions (9 082 €). The inclusion of (isolated) BESSs led to additional cost reductions of 1 497 €. The full connection of the households in an LEC further reduced costs by 1 462 €.

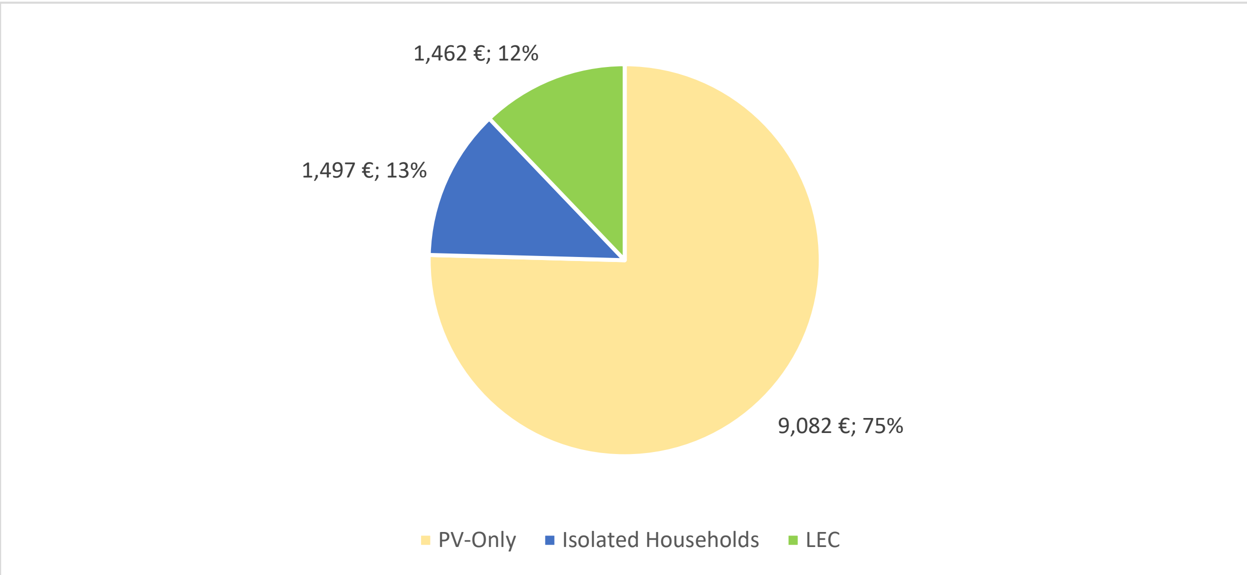

Figure 15: Narvik: Cost Reduction by setting

Comparing these results to the findings of the Oslo-setting presented in chapter 5.1 shows that the achieved cost reductions were much smaller in Narvik. Especially when looking at the absolute cost reduction a big discrepancy (40 604 € in Oslo compared to 12 040 € in Narvik) is found. In relative terms, the results lay closer. In the Oslo-setting a cost reduction of 29% was achieved, while the Narvik-setting achieved a cost reduction of 22%.

Just as in the Oslo-setting, the LEC's strategy to reduce energy costs can be divided into increasing self-consumption, load shifting and peak shaving. Again, the cost reduction achieved by the different approaches is split up and looked upon independently. Increasing self-consumption and load shifting is be combined as they both work on reducing the energy charge, while peak shaving reduces the peak demand charge. As identified above, through the integration of BESSs and the connection of the households in an LEC 2 958 € cost reductions could be achieved in addition to the reduction generated by the PV systems alone. Out of those 2 958 €, 437 € (or 15%) were achieved through increasing self-consumption and load shifting 2 521 € (or 85 %) were achieved through peak shaving (Figure 16).

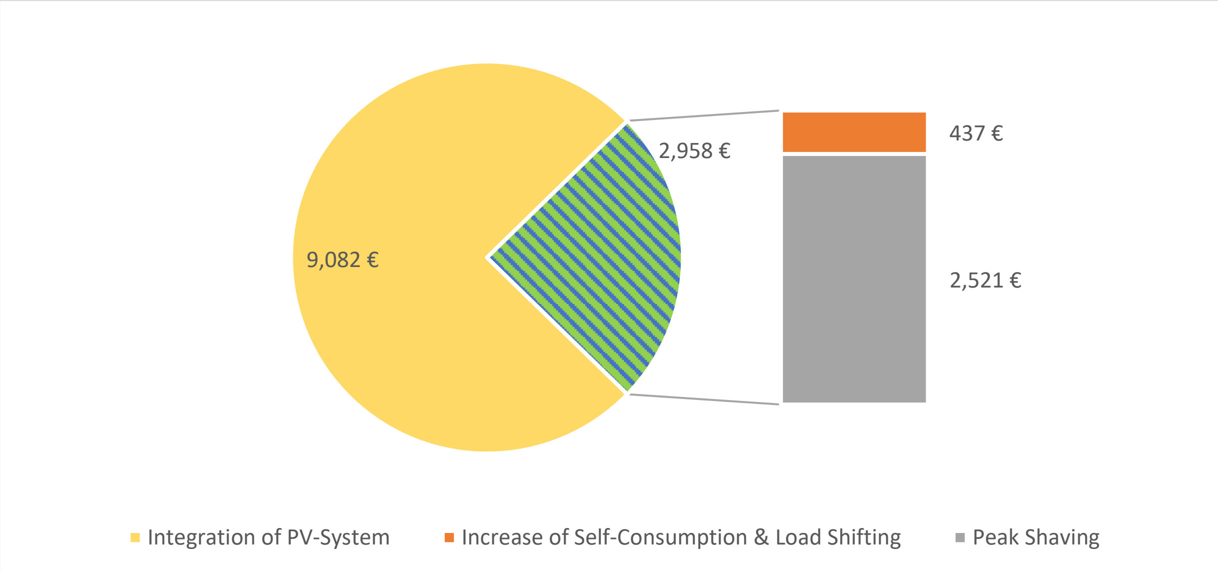

Figure 16: Narvik: Cost Reduction by Electricity Tariff Part

The results of the self-consumption-rate and the self-sufficiency-rate in the Narvik-setting are shown below in Figure 17. Similar to the results in the Oslo-setting, both values increase with the integration of BESS and the possibility for the households to exchange energy within the LEC.

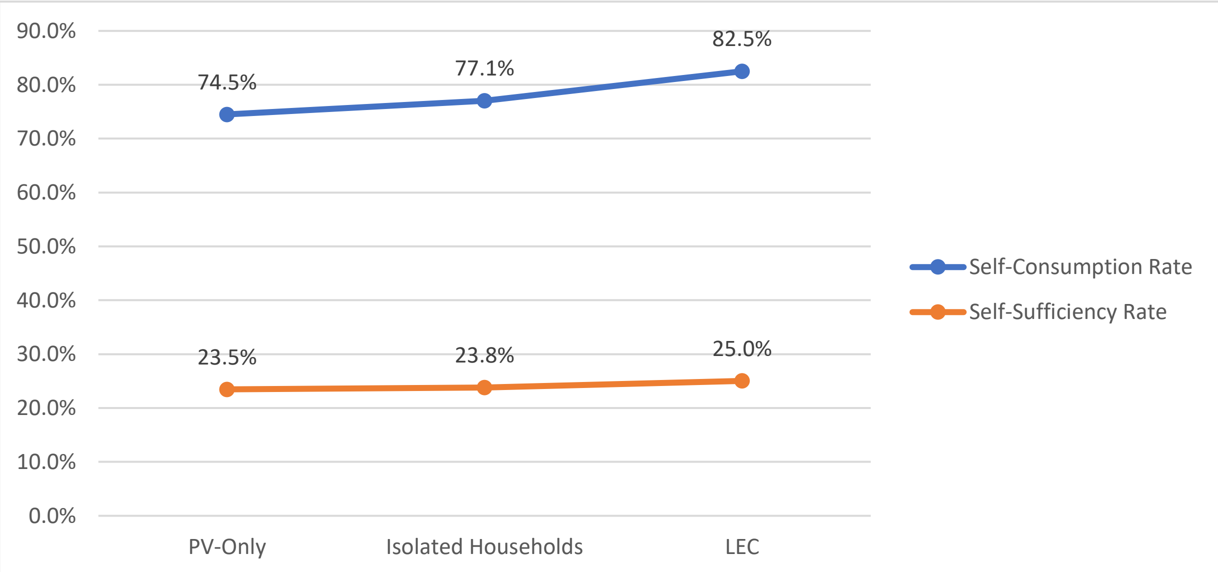

Figure 17: Narvik: Self-Consumption and Self-Sufficiency Rate

6 Sensitivity Analysis

In the sensitivity analysis the influence of variations of input-variables on the output indicators was tested. The energy demand, energy generation by PV, energy price, and battery efficiency was varied. The effect on the yearly energy costs, the self-consumption rate and self-sufficiency rate was assessed.

The variations of the results will be compared in a setting in the Oslo-region with a BESS capacity of 14.3 kWh.

6.1 Energy Demand

For the sensitivity analysis the energy demand was varied ranging from 50% of the original values to 200% of the original energy demand. The form of the consumption curves of the household (due to the time of use of electric appliances etc.) has been left unchanged.

A reduced energy demand leads to lower cost reduction achieved in the *LEC setting*. Reducing the energy demand to 50% of the original value reduced the cost reductions by 13% to 35 110 €, while increasing the energy demand to 200% left the cost reduction almost unchanged. Increasing the energy demand has a very slight influence on cost reduction potential (Figure 18).

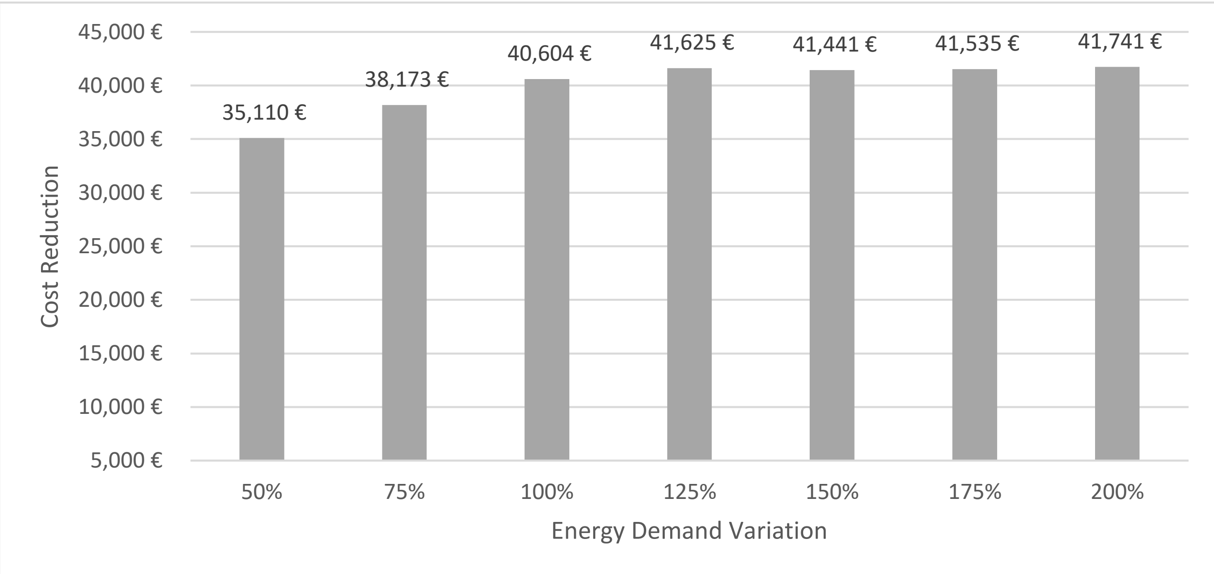

Figure 18: Sensitivity Analysis – Energy Demand: Energy Cost Reductions achieved in *LEC setting* compared to *Baseline setting*

Looking more closely at the cost savings achieved in the *LEC* setting compared to the *PV-only* setting reveals a different pattern. Both smaller and bigger demand diminish additional savings. The original demand data led to cost reductions of 8 778 € compared to a *PV-only* setting. If the demand is reduced to 50% only cost reduction of 6 672 € are achieved. An increase of demand to 200% leads to reduced cost reduction of 7 044 € compared to the *PV-only* setting (Figure 19).

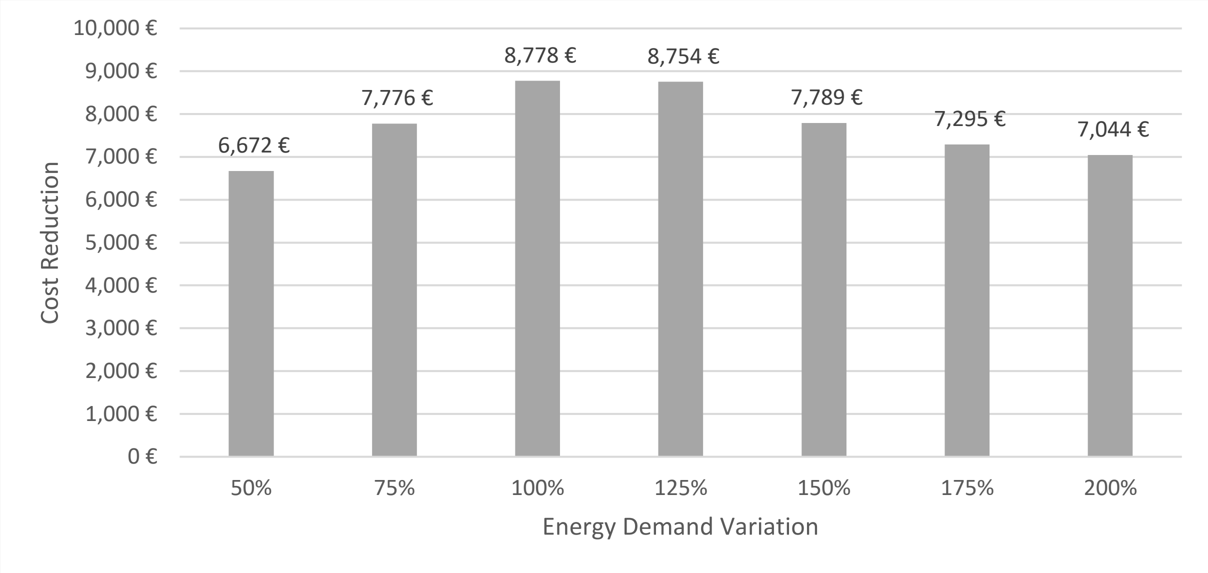

Figure 19: Sensitivity Analysis - Energy Demand: Energy Cost Reduction achieved in *LEC* setting compared to *PV-only* setting

Both the self-consumption-rate and the self-sufficiency-rate behave as expected. Self-consumption increases to 100 % with an increased demand, while self-sufficiency decreases down to 18% (Figure 20).

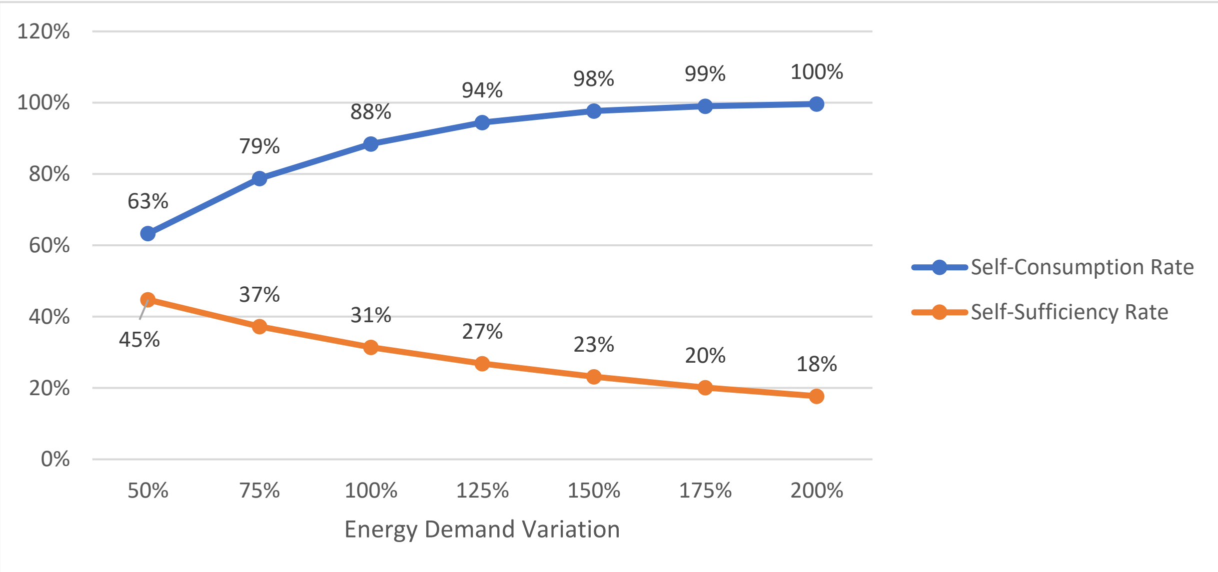

Figure 20: Sensitivity Analysis - Energy Demand: Self-Consumption and Self-Sufficiency Rate

The sensitivity analysis shows that both an increase and a reduction of the energy demand diminishes the cost savings generated by the LEC. However, in both cases the LEC is still able to reduce energy costs.

6.2 Energy Generation

For the sensitivity analysis the energy generation of the PV system was varied ranging from 50% of the original energy generation to 200% of the original energy generation. The form of the generation curves (influenced by the solar radiation over time) has been left unchanged.

A positive correlation between the energy generation and the energy cost reduction in this simulation model is obvious and almost not worth mentioning. Apart from storage or trading within the neighbourhood the households have the possibility to sell excess PV generation to the grid for a strictly positive price. Therefore, more energy generation necessarily leads to more income and therefore reduced energy costs (Figure 21).

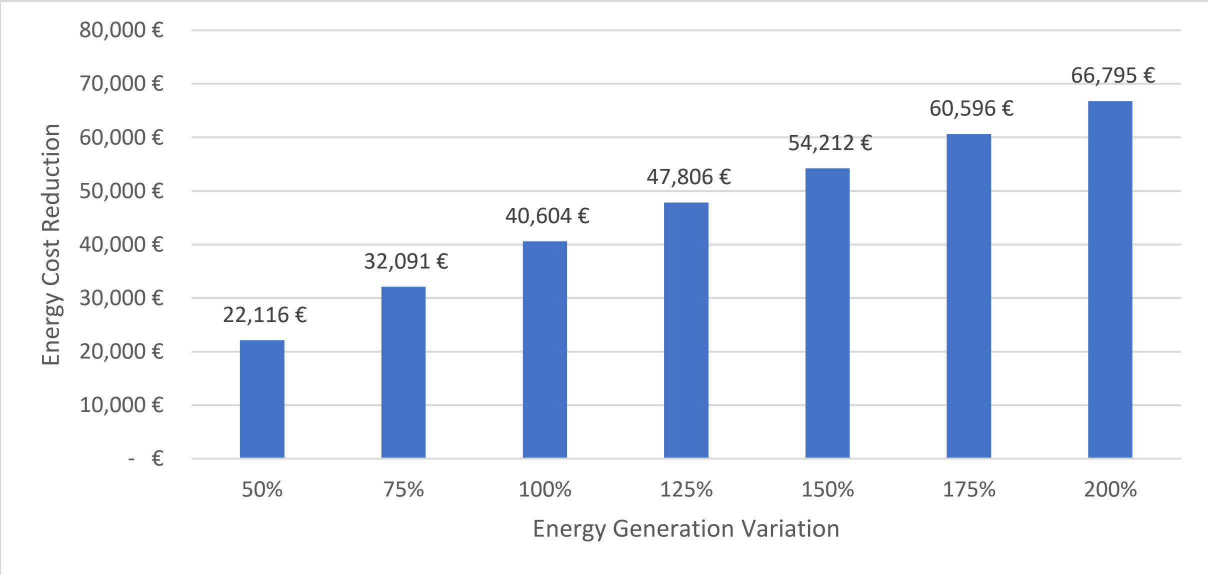

Figure 21: Sensitivity Analysis - Energy Generation: Energy Cost Reduction achieved in *LEC setting* compared to *Baseline* setting

It is, however, more interesting to look at how a change in PV-generation affects the cost reduction through the implementation of BESS and the connection of the households in an LEC *setting*. There is a positive correlation between the energy generation and additional cost reduction in the *LEC setting* compared to a *PV-only setting*. A steep increase of the additional cost reduction between the steps of 50 % of energy generation and 100 % can be noted. When the energy generation is further increased, the curve of the additional cost reductions flattens (Figure 22).

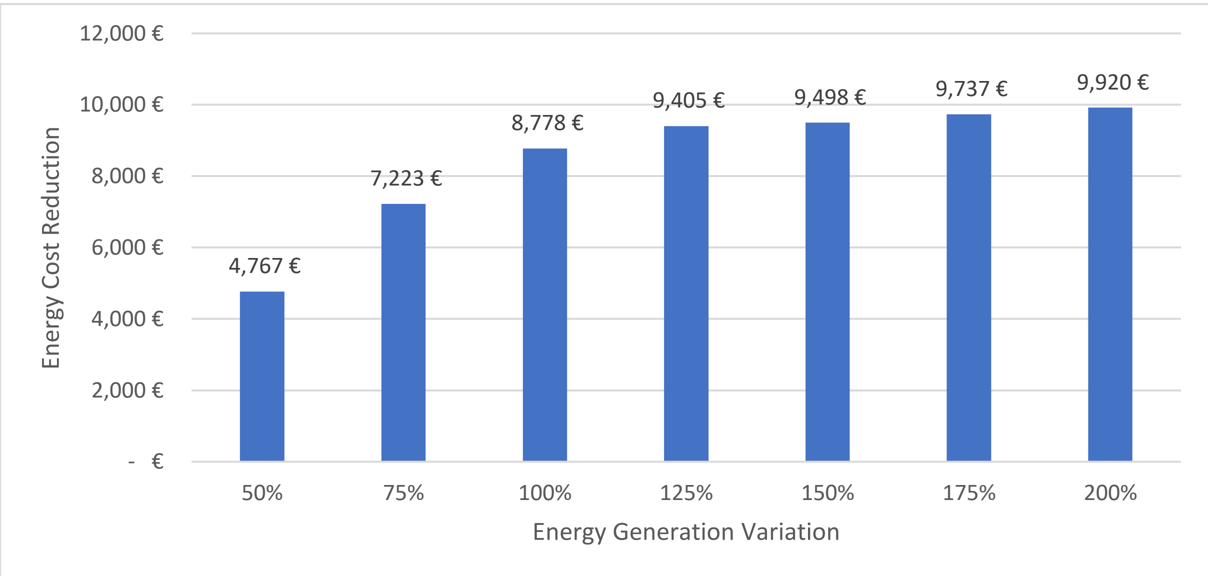

Figure 22: Sensitivity Analysis - Energy Generation: Energy Cost Reduction achieved in *LEC setting* compared to *PV-only setting*

Both the self-consumption-rate and the self-sufficiency-rate behave as expected. Self-consumption decreases from 100% in a case with low PV-generation to 56% in the case of high PV-generation in the *LEC setting*. Self-sufficiency on the other hand increases from 17% in the case of low PV-generation to 40% in the case of high PV generation (Figure 23). The *PV-only* setting followed a similar pattern, though poorer results were achieved.

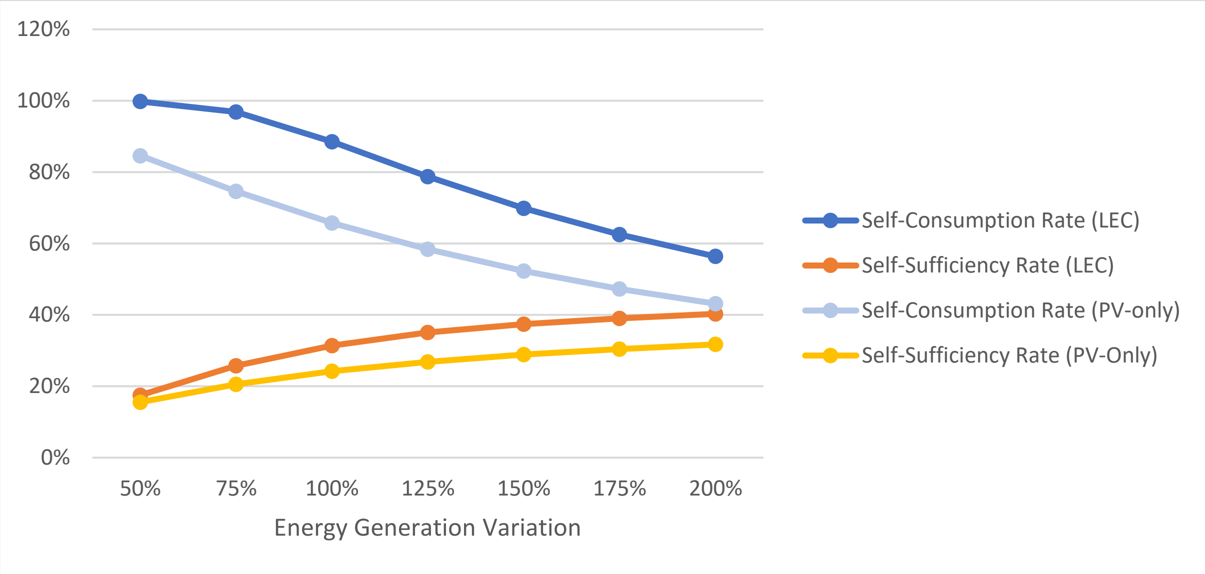

Figure 23: Sensitivity Analysis - Energy Generation: Self-consumption and Self-sufficiency rate

The sensitivity analysis shows that a reduction of PV-generation diminishes the cost savings generated by an LEC. Increasing the PV-generation on the other hand, leads to (almost) no changes in the achieved additional cost reductions.

6.3 Energy Price

The energy price can be separated into two different parts. The first part is the energy tariff which charges the households according to the amount of energy withdrawn from the grid. As the price changes hourly, the time of withdrawal influences overall costs as well. The second part is the peak demand charge (or "effekt-tariff") which depends on the monthly peak demand.

Within the sensitivity analysis these two parts are treated separately. Both prices are examined in a range of 50% - 200% of the original data.

To no surprise there is a positive correlation between the energy prices and the possible energy cost reductions. Already comparing results from the Oslo-region (with rather high prices) and the Narvik region (with very low prices) hinted at that correlation, as in the Oslo-region far higher cost reductions could be achieved. However, as more factors varied between the Oslo setting and the Narvik setting the sensitivity analysis is needed to confirm this suspicion.

Varying the price of the energy tariff has a much bigger influence on overall cost saving than varying the peak demand charge (Figure 24). An increase of the energy tariff to 200% of the original price led to an increase in cost reductions to 178%. For the peak demand charge, only an increase to 116% is noted.

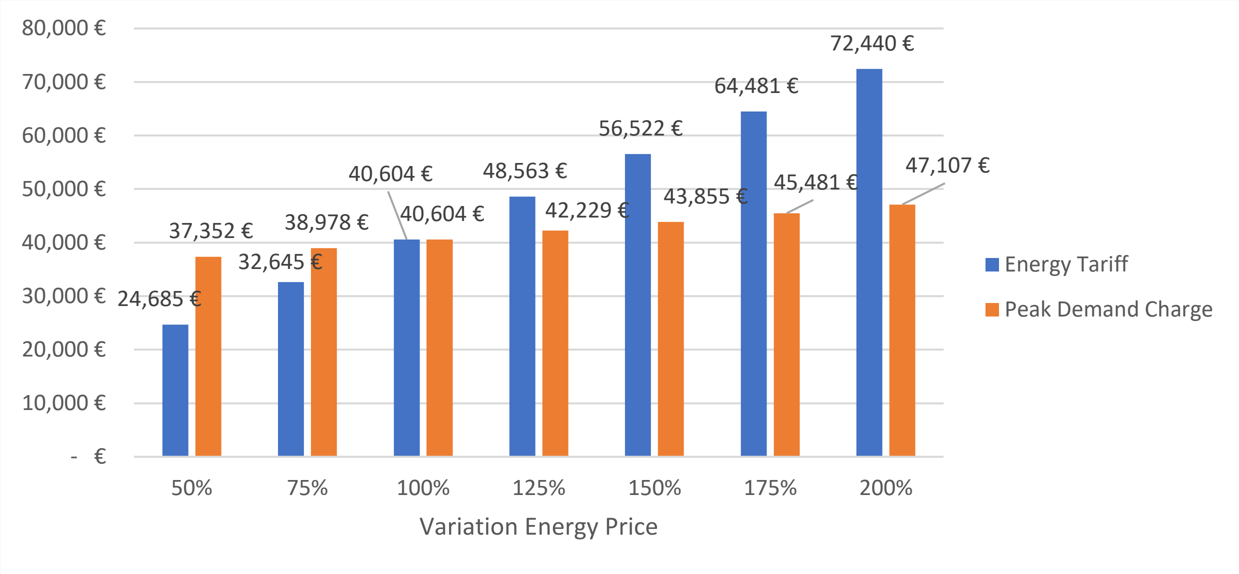

Figure 24: Sensitivity Analysis – Energy Price: Cost Reduction achieved by *LEC setting* compared to *Baseline setting*

However, looking at the cost reduction generated in the LEC-setting compared to a setting with isolated BESS the variation of the peak demand charge has a bigger influence than the energy tariff (Figure 25). That suggests that an increasing peak demand charge leads to a rising importance of LEC-concepts.

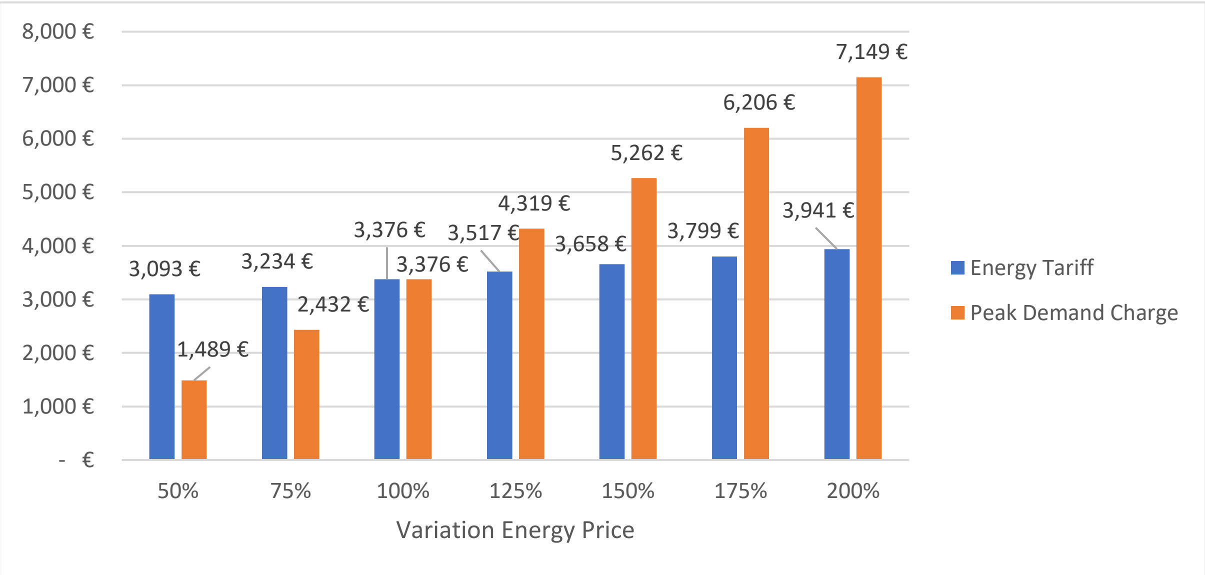

Figure 25: Sensitivity Analysis – Energy Price: Cost Reduction achieved by *LEC setting* compared to *isolated setting*

6.4 Battery Efficiency

For the sensitivity analysis the BESS efficiency was set to 96% and 100% in addition to the efficiency of 92.15 % tested in the regular setting.

As expected, an increase in the total cost reduction with an increased efficiency is noted. Both in the isolated setting and in the fully connected LEC-setting cost reductions increase. Additional cost reductions achieved in an LEC-*setting* compared to a *PV-only setting* increased to 10 818 € with 96 % efficiency and to 11 421 € with 100 % efficiency (Figure 26).

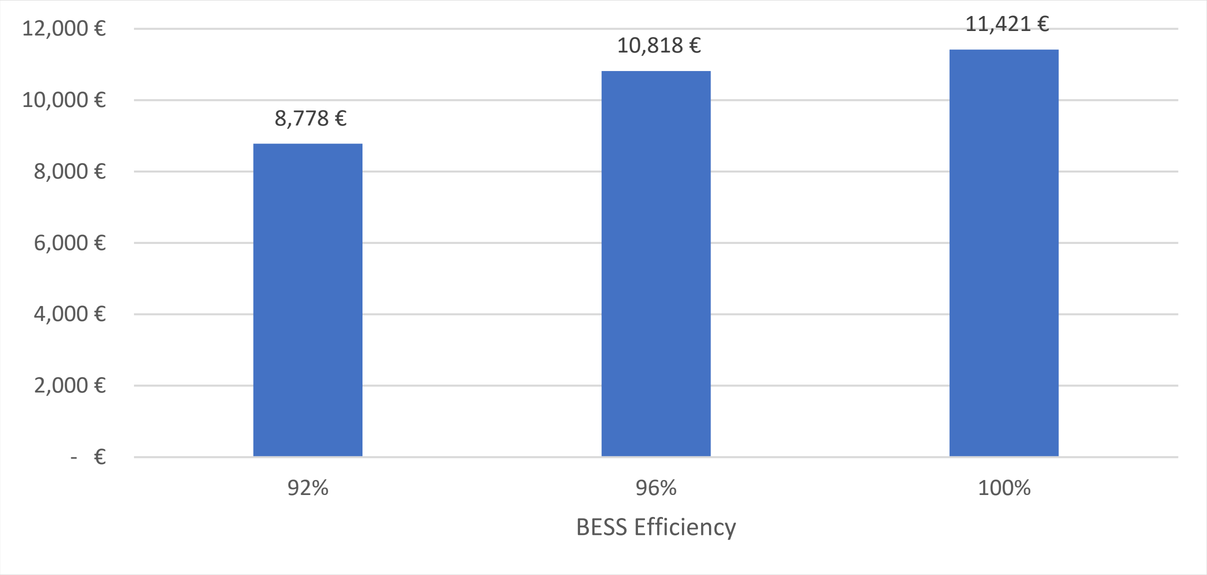

Figure 26: Sensitivity Analysis – BESS Efficiency: Cost Reduction of *LEC* setting compared to *PV-only* setting

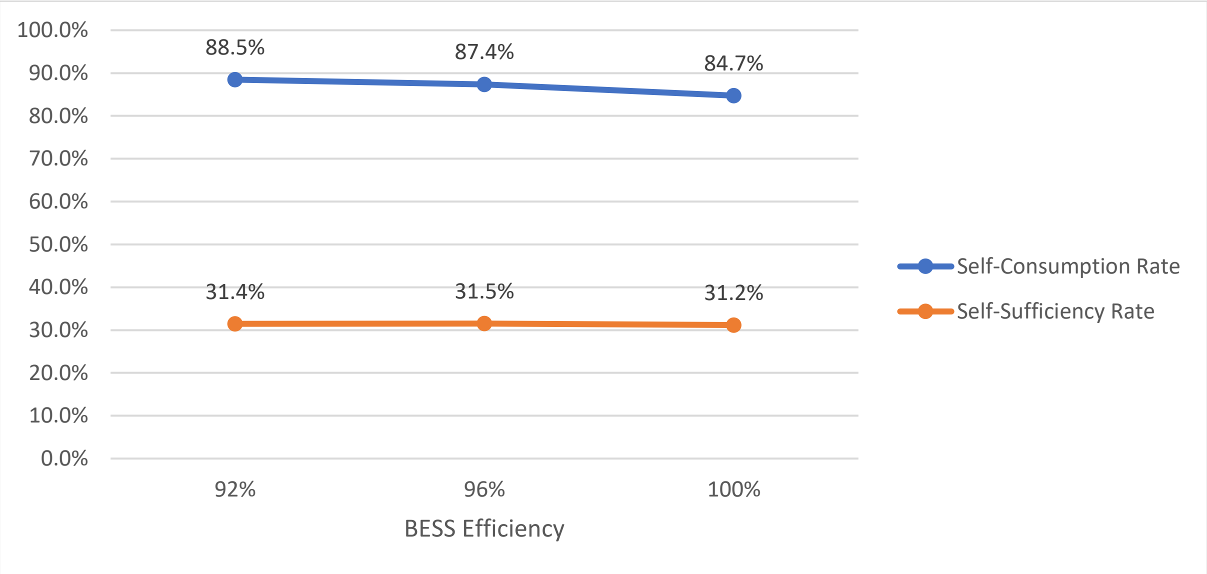

Figure 27: Sensitivity Analysis - BESS Efficiency: Self-consumption and Self-sufficiency Rate

The increase in battery efficiency counterintuitively led to a slightly lower self-consumption and self-sufficiency rate (Figure 27).

The reason for the decreased self-consumption rate lays in the way the lost energy is accounted for. PV-generated energy that is lost due to poor BESS efficiency is accounted for as "self-consumed" energy. Therefore, a higher efficiency leads to a lower self-consumption rate.

The reason for the decreased self-sufficiency rate lays in the heuristic of the enhanced BESS usage scheme. A higher BESS efficiency increases the profitability to charge the

BESS from the grid for energy arbitrage or peak shaving. This increases the total amount of energy purchased from the grid and therefore reduces the self-sufficiency rate. On the other hand, a higher BESS efficiency also leads to a more efficient usage of the PV-generated energy as a more efficient storage is possible. This reduces the need for energy procurement from the grid and increases the self-sufficiency rate. Both effects almost cancel each other out. Therefore, only a minor variation can be noted.

7 Discussion

The results obtained and explained in the previous chapter are discussed in the following sections. The emphasis of the discussion is set on four different points. First, in section 7.1 the economic benefits for participating households in local energy communities are examined. Section 7.2 investigates the influence of different input parameters on the simulation's result, focusing on the most important influencing parameter: the energy price. Afterwards, section 7.3 illuminates external benefits of LECs that go beyond system boundaries. Section 7.4 takes the investment costs into consideration and calculates the net present value of the LEC in different settings. Section 7.5 in the end briefly sums up the findings of the discussion and critically assesses simplifications and assumptions of the model to indicate possible future research areas.

7.1 Local Energy Communities Offer the Possibility to Increase Profitability for Prosumer Households within a Neighbourhood

The results shown in chapter 5 confirm previous research and show that the inclusion of BESS in addition to residential PV systems can optimize the energy usage of the generated energy and help reduce overall energy costs for prosumer households. Settings with bigger BESS capacities led to bigger cost reductions. The BESS achieves energy cost reductions through several ways. First, the BESS stores energy generated by the PV system in times where it cannot be consumed directly. The stored energy can be used later in times where no or not sufficient energy is generated by the PV system to cover energy demand (increase of self-consumption rate). This aspect is especially important in the combination of PV systems and residential households. PV systems produce most energy around midday where the energy consumptions in most households is low as the residents are (usually) at work. The effectiveness of this approach is shown by the increasing self-consumption rate. Second, BESS can be used for load shifting. By shifting the consumption to periods with rather low energy prices further cost reductions can be achieved. BESS can also be used to actively practice energy arbitrage by charging the BESS with energy from the grid in times of low energy prices. The third approach to use BESS for energy cost reduction lays in its ability for peak shaving. Using stored energy in peak demand periods reduces the costs inflicted by the peak demand charge (or "effekt-tariff") of the DSOs. There is a trade-off between using the BESS for energy arbitrage or using it for peak-shaving. Using BESS for energy arbitrage can even lead to additional demand peaks (Dynge et al. 2021). The simulation model conducted in this study successfully limits the use of the BESS for energy arbitrage purposes so that no additional demand peaks are created. Thereby, the different approaches to achieve cost reductions are combined and the risk to create additional demand peaks is averted.

Connecting several households in a Local Energy Community and allowing for energy exchange between them further reduces yearly energy costs for the community. For the investigated LEC (in a setting in the Oslo-area) with 30 participating households additional yearly cost reduction of 3 376€ compared to an *isolated setting* where energy exchange between households is not possible are achieved. A comparison of settings with different BESS sizes revealed, that an LEC with BESSs with a 7.2 kWh capacity outperforms an isolated setting with BESSs with a 14.3 kWh capacity. By connecting the households in an

LEC, BESS capacities can be used more efficiently. Even though the storage capacity is cut in half, still the same level of flexibility can be provided. This leads to a major finding: Connecting households to an LEC can not only increase cost reduction of prosumer households but also allows for a decreasing BESS capacity while still having sufficient flexibility. A decreased BESS capacity significantly lowers initial investment costs. These lower investment costs lead to much higher economic value of the LEC (for details, see chapter 7.4). In response to the research question, it can be stated that: Connecting prosumer households to an LEC can either increase yearly energy cost reduction or decrease initial investment costs by investing in smaller BESS while still providing sufficient flexibility and achieving comparable energy cost reductions.

The reason why the LEC is able to generate additional cost reduction compared to isolated households with BESS lays in the shared use of their resources. To illustrate how the sharing of resources benefits the LECs participants, let us consider the case of a household being on vacation for two weeks. During those two weeks the household will have a very low energy demand. Its PV system will naturally still generate energy according to the solar radiation during this time. If the household is not connected to the LEC (and therefore no energy exchange with its neighbours is possible), the household's BESS will (likely) be fully charged during their absence but all energy that cannot be stored will be sold to the grid for a relatively low price. If the household is connected to an LEC, the energy generated can still be used to charge the household's own BESS. But in addition, the energy can also be directly used by the neighbours or be used to load the neighbour's BESS. This way, a bigger part of the locally generated energy (and therefore locally generated revenue) stays within the LEC. The household on vacation benefits from selling the energy for a higher price to the neighbours, while the buying neighbours benefit from still paying a lower price than the grid price. These advantages outweigh the disadvantage for the travelling household that it may come back home to a BESS that is not fully charged. The example of a two-week holiday is rather an extreme case. On a smaller scale the sharing of resources happens on a daily basis due to different energy demand patterns that might be caused by different working times or just generally different energy usage habits. It is therefore likely that an LEC is able to generate more cost reductions if its participants display more varying energy demand patterns.

The result data showed furthermore that *all* participating households benefit from the connection to the LEC and can reduce their overall energy cost. Though this may seem trivial at first, it is not. Providing energy from your BESS to your neighbour at a certain point in time means risking that you don't have enough energy stored left to react to changes of external parameters in later points in time (e.g., extreme price peaks, demand peaks). The fact that all participants benefit from the connection to the LEC is an important incentive for prosumers to join the LEC as there is no risk of losing money. However, the results also show that some households achieve almost ten times higher cost reductions than others. A closer look reveals that households that bought relatively high amounts of energy from their neighbours could achieve large cost reductions through the inclusion in the LEC. Adjusting the accounting method for energy exchange within the LEC, so that households selling energy are favoured, might achieve more balanced results (see chapter 3.3).

Additionally, generated revenue stays within the community, which can be seen as valuable on its own. First, the LECs participants might invest the saved money within their community. Second, participants in other Microgrid or LEC projects expressed their preference of green and locally produced energy (Mengelkamp et al. 2018c). Therefore, the general utility of the LEC is further improved by increasing the share of local, green energy within the overall energy consumption.

The largest share of energy cost reductions achieved by the LEC is achieved through peak shaving. In the Oslo-setting 72% of the LEC's additional cost reduction are achieved by peak shaving. In Narvik, this value is even higher (85%). This indicates that the Norwegian approach of a peak demand charge can serve as an effective incentive to lower demand peaks and allow for cost reductions for consumers. It may lead to a win-win situation, where DSOs achieve reduced need for transmission capacity while consumers can lower their energy bill. The higher impact on peak shaving on the LEC's results is due to its prioritization over load shifting in the proposed model. Setting the LEC in regions with lower or no peak demand charge leads to the need for an adapted heuristic for the energy exchange within the LEC.

In addition to monetary benefits the LEC increases independence from the grid. Increasing independence from the grid ensures a low, stable and plannable energy price in the future as changes on the energy market do not affect the LEC's participant as strongly. The self-sufficiency rate serves as an indicator for independence. The self-sufficiency rate increased from 27.1% in a PV-only setting to 31.4% in a fully connected LEC setting (area: NO1-Oslo). Admittedly, this is only a modest increase in self-sufficiency. The proposed LEC-model, however, did not focus on improving the self-sufficiency rate. Especially loading the BESS from the grid for the purpose of energy arbitrage counteracts that. This leads to an increase of energy procured from the grid which naturally decreases self-sufficiency. Under these conditions, even a small increase in self-sufficiency can be seen as a success. LEC-heuristics with a stronger focus on independence might yield better results in this field. This risks, however, negatively impacting economic indicators as energy arbitrage is restricted.

Generally speaking, the LEC setting in Oslo exhibited better results than the LEC setting in Narvik. Compared to a scenario with isolated households, the LEC in Oslo achieves yearly additional cost reductions of 3 376€, while the LEC in Narvik only achieved yearly additional cost reductions of 1 462€. Compared to a scenario without PV systems or BESS, the LEC achieves cost reductions of 40 604€ in Oslo and 12 040€ in Narvik. Both the self-sufficiency rate and the self-consumption rate achieved poorer results in Narvik as well. Two main reasons for the differences in the performance depending on the location are the PV-yield and the energy price. As Narvik is situated further north than Oslo the PV-yield is significantly lower, which reduces the possibility for intelligently usage, storage and trading of self-generated energy within the LEC. The more important factor, however, is the energy price. In Narvik both the energy price and its volatility are much lower than the energy price and volatility in Oslo. This influences the simulations outcomes greatly (for more details, see chapter 7.2).

7.2 Prices Influence Potential of Local Energy Communities Heavily

The price of energy is the most important factor influencing the potential of LECs to reduce energy costs for their participants. Other investigated factors (energy demand, energy generation and BESS capacity) influence the results in the simulation as well. An improved BESS efficiency -obviously- improves the performance of the LEC as losses can be reduced or avoided. Improved BESS-efficiency is therefore desirable, but as modern BESS can already reach round trip efficiencies above 90% there is only small room for improvement

(Noyanbayev et al. 2018). Bigger PV systems (which yield more energy generation) generate more income. However, with very high PV-generation the LEC could not achieve (significantly) higher cost reduction. The reason for that might be, that a sufficiently high energy supply reduces the need for intelligent storing mechanisms. If surplus energy is no longer a scarce good, the BESS can easily be charged (nearly) fully in most times. This way, the few times energy is needed the BESS can provide it. Thus, a connection of neighbours in an LEC is no longer necessary, as an increase or improvement of flexibility simply is not necessary. The same holds true for a diminished energy demand. With diminished energy demand the current PV-generation suffices to cover demand more often. When looking at an opposed case with diminished PV-generation and/or increased energy demand the use-case for an LEC is reduced even more. As both these variations reduce the times where an energy surplus is generated, the need for storage is reduced as all or most energy can be used directly. As chapters 5 and 6 showed, the LEC achieved the highest cost reductions in settings with typical energy demand and generation. Even with big variations in energy generation or demand the LEC was still able to achieve cost reductions. On top of that, neither energy generation nor energy demand can easily be influenced and need to be considered as fixed values in most cases. The capacity of PV systems (in residential areas) is mostly determined and limited by available rooftop area. Other factors influencing the energy yield such as solar radiation cannot be influenced. Residential energy consumption has remained relatively stable throughout the last decade in Norway[14]. Concluding, even though battery efficiency, energy demand and generation influence the performance of the LEC, no significant variations of these factors is likely in the foreseeable future. The energy price however is likely to change more due to the ongoing changes in the European energy market. Therefore, the energy price remains the most important and interesting factor influencing the performance of LECs.

Two different components of the energy price need to be addressed. On the one hand, the energy tariff which sets the cost according to the amount of energy withdrawn from the grid and -as the model in this work is assuming time varying prices- according to the time of withdrawal. On the other hand, the peak demand charge (or "effekt-tariff"), which sets the energy costs according to the monthly peak demand within one hour.

For both components a clear correlation between the height of the price and the possible cost reductions can be seen. This is not surprising, as e.g., an increase in self-consumption and therefor avoidance of buying energy from the grid will lead to more cost reduction with higher prices. Evidently, the same principle holds true for peak shaving and energy arbitrage. Results of the sensitivity analysis (see chapter 6.3) show that a variation in the height of the peak demand charge influences the results more than variations of the energy tariff. In this model, the EMTS -that is the heuristic with which energy is exchanged between participants of the LEC- prioritises peak demand reduction over energy arbitrage. A different EMTS-heuristic might lead to different results. However, the chosen focus on the peak demand reduction seems more reasonable as it evidently allows for large cost reductions in the LEC. Additionally, from a broader perspective a reduction of the peak demand is beneficial beyond the boundaries of the LEC as DSOs benefit from reduced peak demand as it reduces the need for the expansion of grid capacities.

Apart from the height of the price, its volatility influences results greatly as well. The two investigated pricing areas (NO4 including Narvik, and NO1 including Oslo) differ a lot in

[14] See: https://www.statista.com/statistics/1025221/net-electricity-consumption-per-capita-in-households-in-norway/ (last accessed: 07.04.2022)

the characteristics of the price curve. The energy price in the NO1 area is very stable over longer periods of time. The energy price in the NO4-area shows much more volatile behaviour and large oscillations of the energy prices over periods of a few hours are not unusual. Energy prices in other European market areas fluctuate even more due to the higher share of volatile renewable energies. The LEC achieves better results in the market area with more volatile prices. This is not altogether surprising, as more fluctuations in the energy price allow for more effective energy arbitrage. The pricing scheme of the DSOs peak demand charge (or "effekt-tariff") differs from DSO to DSO as well. About 130 different DSOs operate in Norway. Each DSO is responsible for the pricing scheme in their area. In the simulation in this work, pricing schemes of two different DSOs (Elvia AS, Halogaland Kraft Nett) have been used. While Elvia AS set a strictly linear relation between the households monthly peak demand and the energy costs, Halogaland Kraft Nett has a stepwise cost function that increases costs once certain thresholds in peak demand are surpassed. The results show that with a linear relation between peak demand and energy costs higher cost reductions can be achieved. The reason for that is that even small reductions of peak demand are remunerated. This insight that the structure of the peak demand charge influences the possible cost reduction of the LEC indicates that it may be beneficial to adjust the EMTS of the LEC according to the pricing scheme of the local responsible DSO. Furthermore, an adjustment of the EMTS according to the energy tariff pricing zone can bring benefits as well. In pricing zones with stable prices (NO4, NO3) an even stronger focus on peak shaving might prove sensible. In pricing zones with more volatile prices (NO1, NO2, NO5 or in other European countries) an EMTS that is more balanced between energy arbitrage and peak shaving or focuses more on energy arbitrage seems advisable.

LEC concepts likely benefit from future developments in the energy market. Volatility of prices likely increases in most parts of Europe, as the share of volatile renewable energies rises (Bjarghov et al. 2021). This will affect (southern) Norway directly, as its energy market is linked to the German, Dutch, Swedish and Danish energy market. An increase in transmission capacity between northern and southern Norway is likely, as limited capacities have been identified as a cause for high social economic costs.[15] Additionally, a further shift towards peak-demand charges for the grid fees is expected in the near term future (NordReg 2021), (RME 2020). The further spread of EVs on the one hand increases energy demand and especially increases peak demand. On the other hand, the inclusion of EVs as additional means of energy storage into LECs or Microgrids bears the opportunity to further increase flexibility of such systems. These foreseeable changes in the energy market indicate that LEC concepts will become more useful and more (economically) beneficial in the future.

7.3 System Benefits Going beyond the Borders of the LEC are Possible

The results obtained in the conducted simulation model indicate possible positive system benefits that go beyond the boundaries of the LEC. As argued in chapter 4.4, within this work it is not possible to exactly quantify the externalities beyond system boundaries of the proposed LEC-model. However, the determined result indicators allow for qualitative conclusions on certain externalities.

[15] https://www.energinorge.no/fagomrader/stromnett/nyheter/2020/lave-overforingskapasiteter-gir-samfunnsokonomiske-tap/ (last accessed: 01.06.2022)

The local balancing of energy demand and energy generation within the LEC reduces the need for transmission capacities and might lead to reduced need for grid expansions. The increased self-sufficiency indicates that less energy from the grid is needed. The increased self-consumption on the other hand indicates that less energy is fed back into the grid. Both these indicators show that less energy needs to be transported, which reduces the stress on the grid. Especially bi-directional energy flow in the grid (that is, energy flow also occurs from low to higher voltage levels) poses challenges to DSOs as it is a relatively new phenomenon (Delamare et al. 2015). The achieved reduction of the peak demand is even more important. As the needed transmission capacities depend mainly on the peak demand (and not on the absolute amount of energy transmitted), a reduction of peak demand might allow for a reduced need for grid expansion. This is especially important in Norway, as peak demand has been rising in the last years even though the overall energy demand is slightly decreasing (Inderberg 2020). As (Dynge et al. 2021) pointed out, the usage of BESS in LECs for energy arbitrage also bears the risk to create additional peak demand and destabilize the energy grid. This work showed an approach that limited the usage of BESS for energy arbitrage and could thus prevent such unwanted side effects while still reducing energy costs for the LEC and its participating households.

Another external effect of the LEC is the reduced need for energy generation from large scale energy plants (in the case of Norway: hydropower plants). The aforementioned behaviour of result indicators (increase of self-sufficiency, reduction of peak demand) results in a reduced need for energy from large scale power plants. This in turn helps to reduce environmental damages inflicted by building hydropower plants, such as ecological damages by buildings dams. In settings in central Europe the avoided environmental damages by reducing the reliance on conventional power generation weight even more. CO_2-emissions and the creation of radioactive material can be reduced as coal- and nuclear power plants still provide a relevant portion of energy.

Whilst the extend of the externalities cannot be reliably determined with the results of the conducted simulation model, all obtained results indicate positive externalities. In addition, the possibility for prosumer households to increase profits by connecting with their peers in an LEC create further incentives for households (or other investors such as smart grid operators) to invest in PV systems and BESS. This leads to a further spread of decentralized renewable energies and an effective and efficient use of the otherwise unused rooftops of (residential) buildings. A further spread of decentralized renewable energies helps Europe achieve its goals towards a CO_2-neutral future in a cost-efficient way.

7.4 Net Present Value

The previous chapters 7.1 - 7.3 showed that LECs are capable of reducing energy costs for their participants. An LEC allows to use smaller BESS, while still providing the same level of flexibility and benefits for the LECs' participants. An LEC based in the Oslo-area improves the energy costs to a much bigger extend than an LEC in the Narvik-area. This is mainly due to lower energy prices in northern Norway, but the poorer PV-yield also impacts the results negatively.

However, so far, the investment costs have been neglected. Therefore, this chapter sets out to calculate the net present value (NPV) of the system in order to estimate the economic value of the modelled LEC. The NPV is calculated according to equation (2), with [R(t)] being the net cost reductions of the LEC at time [t], [i] being the discount rate and [Inv] the investment costs for the LEC.

$$NPV = \sum_{t=0}^{t} \frac{R(t)}{(1+i)^t} - Inv \quad (2)$$

The estimated investment costs are shown in Table 3. For a scenario with BESS capacities of 14.3 kWh the estimated investment costs are 615 000 €. For a scenario with BESS capacities of 7.2 kWh the estimated investment costs are 480 944 €. The lifetime for both the PV system and the BESS system is set to 20 years. Regarding the PV system, this value is rather conservative. Current research estimates the typical lifespan of small-scale PV systems to be 30 years. For the lifespan of the BESS however, the value is a bit optimistic, as current research sets the typical BESS lifespan at 15 years (Fraunhofer Institute 2021). The interest rate [i] is set to 2 %.

	specific costs	capacity	Investment Costs (BESS 14.3 kWh)	Investment Costs (BESS 7.2 kWh)
PV system	1 437.50 €/kWp[16]	8 kWp * 30 Households	345 000 €	345 000 €
BESS (14.3 kWh)	629.37 €/kWh[17]	14.3 kWh * 30 Households	270 000 €	-
BESS (7.2 kWh)	629.37 €/kWh[8]	7.2 kWh * 30 Households	-	135 944 €
Sum	**-**	**-**	**615 000 €**	**480 944 €**

Table 3: Investment Costs for the LEC

The NPV is calculated both for a setting of the LEC in Oslo (see Table 4), and in Narvik (see Table 5). For both locations, the NPV is calculated for a setting with BESS capacities of 14.3 kWh where no energy exchange between the households is allowed (isolated setting) and for a fully connected LEC setting where energy exchange is allowed for BESS capacities of 7.2 kWh and 14.3 kWh. The yearly energy costs reductions (R(t)) are taken from chapter 5 and are assumed to remain constant over the lifespan.

Oslo	**Isolated setting** BESS Cap.: 14.3 kWh	**LEC setting** BESS Cap.: 14.3 kWh	**LEC setting** BESS Cap.: 7.2 kWh
R(t)	37 228 €	40 604 €	38 947 €
NPV	**- 6 269 €**	**48 934 €**	**155 895 €**

Table 4: NPV of the LEC in different settings in Oslo

[16] The investment costs for the PV system were provided by Eida Energy AS and are in line with (Fraunhofer Institute 2021).
[17] The investment costs for the BESS-system were provided by Eida Energy As and are in line with (IEA 2020).

Narvik	Isolated setting BESS Cap.: 14.3 kWh	LEC setting BESS Cap.: 14.3 kWh	LEC setting BESS Cap.: 7.2 kWh
R(t)	10 578 €	12 040 €	11 692 €
NPV	**- 442 035 €**	**- 418 129 €**	**- 289 763 €**

Table 5: NPV of the LEC in different settings in Narvik

It can be seen that the integration of the households in an LEC significantly improves the NPV of the system. Especially the possibility to reduce BESS capacity (and thereby investment costs) while still achieving high yearly cost savings offers the possibility to greatly improve the NPV. In the case of the setting in Oslo, connecting the households in an LEC turned the overall NPV positive, and reducing the BESS capacity more than tripled the NPV again. However, it can also be seen, that the NPV in the Narvik setting is negative, both in scenarios with LEC connection and without connection of the households. This shows, that the modelled LEC under the given assumptions and input data is not capable of running in an economically viable way. As argued before, the main reasons for that are the low energy prices and the poor PV-yield in northern Norway. Future development towards higher energy prices and lower investment costs may lead to circumstances that allow for an economically viable operation of LECs in all parts of Norway.

7.5 Summary of Discussion and Critical Assessment

This section sets out to sum up the insights from the preceding discussion chapter. In particular, it is pointed out to what extent the research questions can be answered. Additionally, a critical assessment is undertaken to point out possible research areas for future work.

Summing up the insights from the discussion, this model shows that the integration of prosumer households created a significant positive impact. In particular, the energy costs could be reduced further in comparison to a setting where the households are not connected to each other. It is worthwhile to mention, that all participating households obtained additional benefits, though some benefited more than others. The LEC also allowed for reducing the BESS capacity, while still providing enough flexible storage capacity for the community. This in turn reduces investment costs and improves the systems NPV greatly. Furthermore, secondary indicators such as the self-consumption rate and the self-sufficiency rate, as well as the LECs capability to reduce the peak-demand of its participants indicate external benefits beyond the LECs boundary by reducing stress on the local distribution grid.

That answers the first research question posed in chapter 1. Connecting prosumer households in a Local Energy Community allows for further significant reduction of energy costs through improved peak shaving, load shifting and an increased self-consumption rate. By reducing the need for big BESS, initial investment costs can be lowered and the barrier to become a prosumer is reduced.

Attending to the second research question, the energy price was identified as the most important influence on the LECs capability for effective cost reduction. Both the height and the structure (e.g., its volatility) influence the outcome greatly. This is also the main reason why the setting in Oslo performed better than the setting in Narvik. Prices on such a low level as in the NO4 market area (Navik) of the Nordpool market make it difficult to reach economic viability. Future trends such as rising energy prices, sinking investment costs and more prosumer-friendly legislation are likely to improve the use-case of LECs throughout all of Norway.

The model incorporates several assumptions and simplifications that likely influence the outcome and should be investigated further in future work. The model did not incorporate any kind of prediction mechanism for energy prices, energy demand or energy generation. A prediction method can effectively improve the LECs performance, by helping to make the decision whether to store energy for a later point in time. This might improve the results significantly. The simulation executed the energy exchange in one hour time steps. While one hour time intervals are usual on the energy market, in a real system with PV and BESS, changes in states occur within minutes or even seconds. Therefore, narrower timesteps should be included in future works. Narrower time steps likely increase the need for BESS capacity. Another assumption was, that the energy exchange between households of the LEC is not subject to taxations or other kind of fees. As such a form of energy exchange between neighbours is not yet legal, it is hard to predict what fees or taxes might or might not be added. However, current research advocates for low fees for energy exchange within neighbourhoods to incentivize local balancing (Bjarghov et al. 2021). The BESS was greatly simplified. Factors such as the battery rate and the efficiency in reality depend on a number of factors, such as the temperature and the current state of charge. Furthermore, battery degradation was neglected. BESS degradation can also be influenced by the way of charging and discharging the BESS. Additionally, it would be interesting to include EVs as a mean to store and discharge energy. In this model, EVs have only been included as a pure energy sink. However, they could also be used to provide flexibility to the LEC. The model did not include demand side management (DSM) or participation on the FFR-market. Both approaches are seen as promising possibilities for further revenues in the field of LECs and Microgrids. Especially demand side management calls for further investment (e.g., in smart home technique) and for the willingness of the participants to actively react on (price) signals and potentially change their habits in regard to using certain electrical appliances. Participation on the FFR-market might be solemnly done by automatically providing battery capacity to an aggregator or a system operator. However, technical requirements need to be tested and clarified.

8 Conclusion

This work develops a Local Energy Community model set in Norway. The LEC is composed of residential prosumer households equipped with PV systems for energy generation and battery energy storage systems. Energy costs occurring for the households are made of two different parts: Energy costs for energy procured from the grid and a peak demand charge for the monthly peak demand. Excess energy from the PV systems can be sold to the grid. The price for selling energy to the grid, however, is significantly lower than the price for procuring energy from the grid. An energy management trading system manages the energy exchange between the participating households within the grid. Its goal is to reduce energy costs for all participants. Through shared use of the household's resources the flexibility of the BESS is utilized more effectively. Three main approaches are used for energy cost reduction. First, the self-consumption rate of the LEC is increased. Second, through load shifting energy procurement in periods with high prices is avoided. Third, peak shaving is conducted to reduce peak demand charges. Peak shaving is prioritized over the former two approaches. Energy balancing is done using an hour-by-hour approach.

Evaluation of the proposed LEC model is done using agent-based simulation with 30 participating households over the time span of one year. Each household is equipped with a PV system and a BESS of equal size. Energy generation by the PV system is modelled according to historic solar radiation data. Each household has an individual energy demand, depending on its inhabitants, their occupation and energy consumption habits. Energy prices are set according to historical data from the Nordpool Market from the period 05.2021 – 04.2022. Demand peak charges are set according to current pricing schemes from local Norwegian DSOs. No prediction methods for prices, demand or energy generation are included. Yearly energy cost of the LEC is used as the main result indicator. Self-sufficiency rate and self-consumption rate are measured as additional indicators.

To evaluate the LEC's performance the simulation's results are compared to a baseline setting, a PV-only and a setting with isolated households. In the baseline setting, the households are not equipped with PV systems or BESS and no energy exchange between households is possible. Energy can only be procured from the grid. The PV-only setting includes PV systems but no BESSs. The setting with isolated household describes the status quo for prosumers. The households are equipped with PV systems and BESS but energy exchange between the households is not allowed. This allows to calculate energy cost reductions achieved by the LEC.

The LEC is tested in two different regional settings and with varying BESS sizes. The first region is the Oslo region (set in the NO1 market area of the Nordpool market), characterised by rather high energy prices and rather high solar radiation and therefore good PV yield. The second investigated area is the Narvik-are (set in the NO4 market area of the Nordpool market), characterised by very low energy prices and poor PV yield. The BESS size is varied from a capacity of 3.6 kWh to 14.3 kWh. Additionally, a sensitivity analysis assesses the influence that variations of energy demand, energy generation, BESS efficiency and energy price have on the results.

The results of the simulation show that an LEC can help the participating prosumers to decrease their energy costs. Yearly energy cost in the LEC can be reduced by up to 3 376€ compared to a setting with isolated households. Compared to the baseline setting energy cost reductions of up to 40 604€ are achieved. While these numbers comprise all participants of the LEC the results also show that each participant individually benefits from the connection to the LEC. The self-sufficiency rate and the self-consumption rate of the LEC improve compared to the isolated and the baseline setting as well, indicating positive externalities beyond system boundaries. To no surprise, settings with bigger BESS lead to improved results. More interestingly, the results showed that an LEC with 7.2 kWh-BESS generated lower energy costs than an isolated setting with 14.3 kWh-BESS.

The achieved energy cost reductions differed greatly between the two tested regions. In the Oslo region cost reductions of 40 604€ compared to the baseline setting and 3 376€ compared to an isolated setting are noted. In Narvik, the cost reductions are significantly lower at 12 040€ (compared to baseline) and 1 462€ (compared to isolated setting). One reason is the poorer PV yield in Narvik. More significant than that, however, are differing energy prices. Energy prices in the NO4 area (Narvik) in the investigated period are roughly 70% lower on average. Additionally, energy prices in the NO4 are a lot less fluctuating. That limits the potential to reduce energy costs through load shifting and energy arbitrage.

The energy price is the most important influencing factor on LEC's potential to reduce energy costs. Comparing the results from the LEC setting in Narvik and in Oslo already indicates the energy price's strong influence. The sensitivity analysis confirmed this. The height of the energy price is the most influential factor for the LEC's potential to reduce energy costs compared to the baseline setting. The LEC's potential to reduce costs compared to an isolated setting is more strongly influence by the peak demand charge, however. That is in line with the finding that the LEC is capable of reducing the peak demand of its participants significantly.

The influence of variations of energy demand and generation needs to be regarded differently. Strong reductions or increases of energy demand or generation reduce the use case of LECs. The reason for that is that both a high surplus of generated energy reduced the need for flexibility and a big shortage of energy generation leaves little to no excess energy to store in BESS and trade within the neighbourhood. However, typically neither energy generation nor energy demand can be influenced significantly. Generation is limited by available rooftop area for the PV system and energy consumption patterns are hard to influence. Within typical generation and demand patterns the LEC achieves maximal energy cost reductions.

An analysis of the net present value of the LEC in different settings shows interesting results. Connecting the prosumer households in an LEC greatly improves the LEC. In the isolated setting the neighbourhoods LEC is - 6 269€ (in Oslo, with 14.3 kWh-BESS). This value could be increased to 48 934€ by connecting the households in an LEC. More importantly, the LEC allowed for a reduction of the BESS size without suffering losses of flexibility. By thus reducing the investment the NPV could be increased to 155 895€ in a setting with 7.2 kWh-BESS. This illustrates the great potential of LECs to increase profitability. The NPV results for an LEC setting in Narvik on the other hand illustrate the difficulties. All settings display a negative NPV. This shows the difficulty for economically viable prosumer networks or LECs in regions with poor PV yield and low energy prices.

The impact of this work is therefore twofold. On the one hand the results can be seen as a reassurance of the profitability of LEC projects in regions with good PV yield and high energy prices such as southern Norway. On the other hand, this work can serve as an encouragement to further follow the path towards local energy systems even in regions with less optimal circumstances. By including additional measures (such as demand side management or participation on the FFR market) the final step towards economic viability can be achieved.

Concluding, this work shows that connecting residential prosumer households in an LEC reduces energy costs and thereby creates further incentives for investment in decentralized renewable energies. All participants achieved economic benefits. The results furthermore indicated economic and ecological benefits beyond system boundaries. Further research increasing the complexity of the model is advised. Including predictive methods for energy prices, energy demand and energy generation might greatly improve the results. EV-to-grid technologies offer additional flexibility without (or with low) additional investment costs. Further possibility for revenue can be achieved by including the possibility to sell flexibility on the FFR-market. Simulating the energy balance in a minute-by-minute fashion instead of the chosen hour-by-hour approach improves validity.

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Appendices

Appendix 1: Result Data

Location: Oslo BESS-Size: 14.3 kWh	Baseline	PV-Only	Isolated Households	LEC
Yearly Energy Cost (without Peak Demand Charge)	115,401 €	84,464 €	80,903 €	81,301 €
Yearly Cost Peak Demand Charge (Effekt-Tariff, DSO: Elvia AS)	24,884 €	23,995 €	22,154 €	18,381 €
Self-Consumption Rate	-	65.8%	83.8%	88.5%
Self-Sufficiency Rate	-	24.2%	30.3%	31.4%
Total Energy Costs	140,285 €	108,459 €	103,057 €	99,682 €

Appendix 1, table 1: Result Data; Location: Oslo, BESS-size: 14.3 kWh

Location: Oslo BESS-Size: 10.7 kWh	Baseline	PV-Only	Isolated Households	LEC
Yearly Energy Cost (without Peak Demand Charge)	115,401 €	84,464 €	81,518 €	81,773 €
Yearly Cost Peak Demand Charge (Effekt-Tariff, DSO: Elvia AS)	24,884 €	23,995 €	22,356 €	18,540 €
Self-Consumption Rate	-	65.8%	81.3%	85.4%
Self-Sufficiency Rate	-	24.2%	29.5%	30.5%
Total Energy Costs	140,285 €	108,459 €	103,874 €	100,313 €

Appendix 1, table 2: Result Data; Location: Oslo, BESS-size: 10.7 kWh

Location: Oslo BESS-Size: 7.2 kWh	Baseline	PV-Only	Isolated Households	LEC
Yearly Energy Cost (without Peak Demand Charge)	115,401 €	84,464 €	82,304 €	82,343 €
Yearly Cost Peak Demand Charge (Effekt-Tariff, DSO: Elvia AS)	24,884 €	23,995 €	22,630 €	18,995 €
Self-Consumption Rate	-	65.8%	77.9%	81.7%
Self-Sufficiency Rate	-	24.2%	28.3%	29.3%
Total Energy Costs	140,285 €	108,459 €	104,934 €	101,338 €

Appendix 1, table 3: Result Data; Location: Oslo, BESS-size: 7.2 kWh

Location: Oslo BESS-Size: 3.6 kWh	Baseline	PV-Only	Isolated Households	LEC
Yearly Energy Cost (without Peak Demand Charge)	115,401 €	84,464 €	83,301 €	82,983 €
Yearly Cost Peak Demand Charge (Effekt-Tariff, DSO: Elvia AS)	24,884 €	23,995 €	23,095 €	20,199 €
Self-Consumption Rate	-	65.8%	73.0%	77.4%
Self-Sufficiency Rate	-	24.2%	26.7%	28.0%
Total Energy Costs	140,285 €	108,459 €	106,396 €	103,182 €

Appendix 1, table 4: Result Data; Location: Oslo, BESS-size: 3.6 kWh

Location: Narvik BESS-Size: 14.3 kWh	Baseline	PV-Only	Isolated Households	LEC
Yearly Energy Cost (without Peak Demand Charge)	32,893 €	24,576 €	23,698 €	23,795 €
Yearly Cost Peak Demand Charge (Effekt-Tariff, DSO: HLG)	20,941 €	20,581 €	19,558 €	18,000 €
Self-Consumption Rate	-	66.1%	77.1%	82.5%
Self-Sufficiency Rate	-	20.8%	23.8%	25.0%
Total Energy Costs	53,834 €	45,157 €	43,256 €	41,795 €

Appendix 1, table 5: Result Data; Location: Narvik, BESS-size: 14.3 kWh

Location: Narvik BESS-Size: 10.7 kWh	Baseline	PV-Only	Isolated Households	LEC
Yearly Energy Cost (without Peak Demand Charge)	32,893 €	24,576 €	23,851 €	23,875 €
Yearly Cost Peak Demand Charge (Effekt-Tariff, DSO: HLG)	20,941 €	20,581 €	19,666 €	18,068 €
Self-Consumption Rate	-	66.1%	75.7%	81.0%
Self-Sufficiency Rate	-	20.8%	23.5%	24.7%
Total Energy Costs	53,834 €	45,157 €	43,517 €	41,943 €

Appendix 1, table 6: Result Data; Location: Narvik, BESS-size: 10.7 kWh

Location: Narvik BESS-Size: 7.2 kWh	Baseline	PV-Only	Isolated Households	LEC
Yearly Energy Cost (without Peak Demand Charge)	32,893 €	24,576 €	24,041 €	23,990 €
Yearly Cost Peak Demand Charge (Effekt-Tariff, DSO: HLG)	20,941 €	20,581 €	19,834 €	18,152 €
Self-Consumption Rate	-	66.1%	73.9%	79.1%
Self-Sufficiency Rate	-	20.8%	22.9%	24.3%
Total Energy Costs	53,834 €	45,157 €	43,875 €	42,142 €

Appendix 1, table 7: : Result Data; Location: Narvik, BESS-size: 7.2 kWh

Location: Narvik BESS-Size: 3.6 kWh	Baseline	PV-Only	Isolated Households	LEC
Yearly Energy Cost (without Peak Demand Charge)	32,893 €	24,576 €	24,278 €	24,121 €
Yearly Cost Peak Demand Charge (Effekt-Tariff, DSO: HLG)	20,941 €	20,581 €	20,062 €	18,672 €
Self-Consumption Rate	-	66.1%	71.1%	76.8%
Self-Sufficiency Rate	-	20.8%	22.2%	23.7%
Total Energy Costs	53,834 €	45,157 €	44,340 €	42,793 €

Appendix 1, table 8: Result Data; Location: Narvik, BESS-size: 3.6 kWh

Appendix 2: Data Sensitivity Analysis

Sensitivity Analysis: Energy Demand	50% Energy Demand	75% Energy Demand	100% Energy Demand	125% Energy Demand
Yearly Energy Cost Savings (Compared to PV-Only)	6,672 €	7,776 €	8,778 €	8,754 €
Self-Consumption Rate	63.3%	78.8%	88.5%	94.4%
Self-Sufficiency Rate	44.8%	37.2%	31.4%	26.9%

Appendix 2, table 1: Sensitivity Analysis of Parameter: Energy Demand (Pt. 1)

Sensitivity Analysis: Energy Demand	150% Energy Demand	175% Energy Demand	200% Energy Demand
Yearly Energy Cost Savings (Compared to PV-Only)	7,789 €	7,295 €	7,044 €
Self-Consumption Rate	97.7%	99.0%	99.6%
Self-Sufficiency Rate	23.2%	20.1%	17.7%

Appendix 2, table 2: Sensitivity Analysis of Parameter: Energy Demand (Pt.2)

Sensitivity Analysis: Energy Generation	50% Energy Generation	75% Energy Generation	100% Energy Generation	125% Energy Generation
Yearly Energy Cost Savings (Compared to PV-Only)	4,767 €	7,223 €	8,778 €	9,405 €
Self-Consumption Rate	99.8%	96.9%	88.5%	78.7%
Self-Sufficiency Rate	17.5%	25.7%	31.4%	35.0%

Appendix 2, table 3: Sensitivity Analysis of Parameter: Energy Generation (Pt. 1)

Sensitivity Analysis: Energy Generation	150% Energy Generation	175% Energy Generation	200% Energy Generation
Yearly Energy Cost Savings (Compared to PV-Only)	9,498 €	9,737 €	9,920 €
Self-Consumption Rate	69.9%	62.5%	56.4%
Self-Sufficiency Rate	37.4%	39.1%	40.3%

Appendix 2, table 4: Sensitivity Analysis of Parameter: Energy Generation (Pt. 2)

Sensitivity Analysis: Energy Price	50% Energy Price	75% Energy Price	100% Energy Price	125% Energy Price
Yearly Energy Cost Savings (Compared to PV-Only)	4,726 €	6,752 €	8,778 €	10,803 €
Self-Consumption Rate	88.5%	88.5%	88.5%	88.5%
Self-Sufficiency Rate	31.4%	31.4%	31.4%	31.4%

Appendix 2, table 5: Sensitivity Analysis of Parameter: Energy Price (Pt. 1)

Sensitivity Analysis: Energy Price	150% Energy Price	175% Energy Price	200% Energy Price
Yearly Energy Cost Savings (Compared to PV-Only)	12,829 €	14,855 €	16,880 €
Self-Consumption Rate	88.5%	88.5%	88.5%
Self-Sufficiency Rate	31.4%	31.4%	31.4%

Appendix 2, table 6: Sensitivity Analysis of Parameter: Energy Price (Pt. 2)

Sensitivity Analysis: Peak Demand Charge (Effekt Tariff)	50% Peak Demand Charge	75% Peak Demand Charge	100% Peak Demand Charge	125% Peak Demand Charge
Yearly Energy Cost Savings (Compared to PV-Only)	5,970 €	7,374 €	8,778 €	10,181 €
Self-Consumption Rate	88.5%	88.5%	88.5%	88.5%
Self-Sufficiency Rate	31.4%	31.4%	31.4%	31.4%

Appendix 2, table 7: Sensitivity Analysis of Parameter: Peak Demand Charge (Pt. 1)

Sensitivity Analysis: Peak Demand Charge (Effekt Tariff	150% Peak Demand Charge	175% Peak Demand Charge	200% Peak Demand Charge
Yearly Energy Cost Savings (Compared to PV-Only)	11,585 €	12,989 €	14,392 €
Self-Consumption Rate	88.5%	88.5%	88.5%
Self-Sufficiency Rate	31.4%	31.4%	31.4%

Appendix 2, table 8: Sensitivity Analysis of Parameter: Peak Demand Charge (Pt. 2)

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