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Reducing Neighborhood Peak Load with a Peer-to-Peer Approach under Subscribed Capacity Tariffs

Master's thesis in Energibruk og energiplanlegging
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Abstract

Due to the increasing amount of power consumption, the electricity grid is facing a capacity problem and expensive upgrades. A possible solution to this problem is to utilize capacity based grid tariffs and peer-to-peer (P2P) technology to distribute power consumption and thereby create a more stable and resilient power grid. P2P technology in the energy market is still actively being researched and the consequences of new grid tariff structures are still unknown.

This master thesis aims to test the P2P technology and capacity based tariff structures, suggested by the Norwegian water resources and energy directorate (NVE), in terms of ability to reduce power consumption during scarcity hours and promote more grid friendly use. This was done by creating an optimization model of a neighborhood capable of P2P energy trading and applying energy and capacity tariffs both at consumer and neighborhood level. All consumers in the neighborhood have a unique consumption pattern and varying amounts of flexibility.

Four case studies were proposed and tested to see how the neighborhood utilizes the available flexibility and P2P energy trading possibilities under different conditions. The results showed that when operating at neighborhood level under a subscription based grid tariff, the neighborhood was able to reduce the peak power import during scarcity hours by 7% while maintaining a stable power import over a longer period compared to the current energy based tariff. When optimizing under the subscription based tariff for each individual consumer, disabling P2P, the peak power import was reduced by 11%, but the average power import was at a higher level.

The results also enlighten how the subscription based tariff avoids creating new power peaks during scarcity hours, unlike the current energy based tariff. However, the subscription based tariff sometimes gives the consumers sub-optimal price signals, indicating that it is still under development and needs more tuning. A suggestion on how to possibly improve the subscription based tariff is provided in the future work chapter.

The main conclusion from the research done in this thesis is that a subscription based grid tariff applied to the neighborhood as a common node, enabling P2P, is most capable (out of tariff structures and tariff levels tested in this thesis) of reducing peak power import during scarcity hours while maintaining a lower and more stable grid import.

Sammendrag

På grunn av et økende effektforbruk står elektrisitetsnettet overfor et kapasitetsproblem og dyre oppgraderinger. En mulig løsning på dette problemet er å benytte effektbaserte nettariffer og peer-to-peer-teknologi (P2P) for å jevne ut strømforbruket og skape et mer stabilt og robust strømnett. P2P-teknologi i energimarkedet er fortsatt et aktivt felt innen forskning og kosekvensene av nye nettariffstrukturer er fortsatt ukjent.

Denne masteroppgaven har som hensikt å teste P2P-teknologien samt effektbaserte tariffstrukturer, foreslått av Norges vassdrags- og energidirektorat (NVE), med tanke på deres evne til å redusere strømforbruk i høylasttimer og å fremme mer nettvennlig bruk. Dette er gjort ved å utvikle en optimaliseringsmodell av et nabolag som er i stand til å utføre P2P energihandel, samt å anvende ulike nettariffer på forskjellige nivåer. Alle forbrukere i nabolaget har unike forbruksmønstre og varierende mengde fleksibilitet.

Fire casestudier er foreslått og testet for å se hvordan nabolaget benytter fleksibilitets- og P2P-muligheter under ulike forutsetninger. Resultatene viser at når nabolaget opererer under en felles abonnementsbasert nettariff, med P2P, reduseres den høyeste effekttoppen i høylasttimene med 7% og det oppretholdes en stabil import over en lengre periode, sammenlignet med dagens energibaserte tariff. Når det optimaliseres under en abonnementsbasert tariff for hver enkelt forbruker, uten P2P, blir effekttoppen redusert med 11 %, men den gjennomsnittlige importen ligger på et høyere nivå.

Resultatene viser også hvordan den abonnementsbaserte tariffen unngår å skape nye effekttopper ved høylasttimer i motsetning til dagens energibaserte tariff. Derimot, gir noen ganger den abonnementsbaserte tariffen forbrukerne feilaktige prissignaler, noe som tyder på at den fortsatt er under utvikling og trenger videre justering.

Hovedkonklusjonen fra denne masteroppgaven er at den abonnementsbaserte nettariffen, påført nabolaget som en felles node, i størst grad (av de traiffstrukturene og tariffnivåene testet i denne oppgaven) reduserer effekttoppene ved høylasttimer, samtidig som den gir et lavere og mer stabilt forbruk.

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Abbreviations and Nomenclature

Abbreviations

AI	Artificial Intelligence
AMS	Advanced Metering System
DP	Dynamic Programming
DSO	Distribution System Operator
EV	Electric Vehicle
ICT	Information and Communication Technology
IoT	Internet of Things
LMT	LandbruksMetereologisk Tjeneste
LP	Linear Programming
ML	Machine Learning
NOK	Norsk Krone
NVE	Norwegian water resources and energy directive
P2P	Peer-to-Peer
PV	Photovoltaics
R&D	Research and Development
SOC	State Of Charge
SWOT	Strength, Weaknesses, Opportunities and Threats

V2G	Vehicle to Grid
VAT	Value Added Tax
WH	Water Heater

Sets

p	Prosumer index, $p\epsilon[1,30]$
t	Time index [hour], $t\epsilon[1,8760]$

Parameters

$\eta^{bat,ch}$	Battery charging efficiency [%]
$\eta^{bat,dis}$	Battery discharging efficiency [%]
$\eta^{EV,ch}$	EV charging efficiency [%]
η^{P2P}	Efficiency when importing using P2P[%]
B^{cap}	Total battery capacity [kWh]
$B^{ch,max}$	Battery maximum charging power [kW]
$B^{dis,max}$	Battery maximum discharging power [kW]
$B^{SOC,Initial}$	Initial battery SOC [kWh]
$B^{SOC,min}$	Minimum battery SOC [kWh]
C^{energy}	Fixed yearly price, energy tariff [NOK/year]
$C^{fixedsub}$	Fixed yearly price, subscription tariff [NOK/year]
C^{high}	Price, energy imported above sub-limit (Overconsumption cost)[NOK/kWh]
C^{low}	Price, energy imported below sub-limit (Energy cost)[NOK/kWh]
C^{sub}	Subscription price [NOK/kW]
C^{tariff}	Energy cost, energy tariff [NOK/kWh]
C_t^{spot}	Spot price in time step t [NOK/kWh]
E^{over}	Total energy imported above subscription limit [kWh]
E^{tot}	Total yearly energy import [kWh]
EV^{cap}	EV battery capacity [kWh]
$EV^{ch,max}$	Maximum EV charging power [kW]

$EV^{SOC,init}$	Initial EV SOC [kWh]
$EV^{SOC,min}$	Minimum EV SOC [kWh]
EV_t^{avail}	EV availability factor for time step t, $EV_t^{avail} \epsilon [0,1]$
EV_t^{cons}	EV consumption in time step t [kWh/h]
K^{sub}	Subscribed limit [kW]
N	Number of consumers included in the tariff
P^{tariff}	Total yearly tariff price [NOK/year]
P_t^{load}	End user load in time step t [kWh/h]
PV_t^{prod}	Production from PV-cells in time step t [kWh/h]
T^{max}	Maximum temp inside water heater [°C]
T^{min}	Minimum temp inside water heater [°C]
$T^{temp,initial}$	Initial temperature inside water heater [°C]
W^{max}	Maximum power supplied to the water heater [kW]
W^{SHC}	Specific heat of water [J/kg °C]
W^{size}	Size of water heater [L]
W_t^{demand}	Water heater demand in time step t [kWh/h]

Variables

b^{tot}	Total electricity bill [NOK]
b_t^{ch}	Battery charging power in time step t [kWh/h]
b_t^{dis}	Battery discharging power in time step t [kWh/h]
b_t^{SOC}	Battery SOC in time step t [kWh]
e_t^{exp}	Grid export in time step t [kWh/h]
$e_t^{imp,h}$	Grid import above sub-limit in time step t [kWh/h]
$e_t^{imp,l}$	Grid import below sub-limit in time step t [kWh/h]
e_t^{imp}	Grid import in time step t [kWh/h]
ev_t^{ch}	EV charging power in time step t [kWh/h
ev_t^{SOC}	EV SOC in time step t [kWh]

n_t^{exp}	Total neighborhood export in time step t [kWh/h]
$n_t^{imp,h}$	Total neighborhood import above sub-limit in time step t [kWh/h]
$n_t^{imp,l}$	Total neighborhood import below sub-limit in time step t [kWh/h]
n_t^{imp}	Total neighborhood import in time step t [kWh/h]
$p_{p,t}^{exp,g}$	Prosumer grid export in time step t for prosumer p [kWh/h]
$p_{p,t}^{exp,p}$	Prosumer peer export in time step t for prosumer p [kWh/h]
$p_{p,t}^{exp}$	Total prosumer grid export in time step t for prosumer p [kWh/h]
$p_{p,t}^{imp,g}$	Prosumer grid import in time step t for prosumer p [kWh/h]
$p_{p,t}^{imp,h}$	Prosumer grid import above sub-limit in time step t for prosumer p [kWh/h]
$p_{p,t}^{imp,l}$	Prosumer grid import below sub-limit in time step t for prosumer p [kWh/h]
$p_{p,t}^{imp,p}$	Prosumer peer import in time step t for prosumer p [kWh/h]
$p_{p,t}^{imp}$	Total prosumer grid import in time step t for prosumer p [kWh/h]
t_t^{w}	Temperature inside water heater in time step t [°C]
w_t^{power}	Power supplied to the water heater in time step t [kWh/h]

Chapter 1

Introduction

The introduction explains the motivation behind the work done in this thesis as well as the scope of the work. It also covers the problem definition and research questions this thesis aims to answer.

1.1 Motivation

Due to the increasing amount of high power demanding appliances and products, the electricity grid is facing a capacity problem. A large part of this problem is the increasing amount of electric vehicles (EV) and the need for faster charging. Even for a single consumer, the power demand can get increased significantly. A neighborhood with high power consuming habits could force the distribution system operators to expand and upgrade the grid. A possible solution to this problem is to utilize flexible loads and distribute power consumption to avoid power peaks. Decreasing costs for flexible resources such as batteries and EVs, energy production from photovoltaic (PV) panels and the introduction of information and communication technology (ICT) enables end users to have a larger role in the power grid, promoting a more decentralized energy market where energy trades between end users are possible.

In the project leading up to this thesis[1], different grid tariff structures, proposed by the Norwegian water resources and energy directorate (NVE) [2], was tested for a flexible end user showing that a subscription based tariff was the most effective at reducing power peaks. The tariffs were tested by creating a prosumer (energy producing consumer) model in Python with flexible resources and optimizing the control of the flexibility, such that the electricity bill was minimized.

The modelling work done in the specialization project is used as a basis for constructing the neighborhood model in this thesis which consists of 30 different consumers that can trade energy directly with one another (P2P). One of the main concerns raised when NVE proposed new grid tariffs was that the effects a power based tariff has on the distribution grid is unknown [3, 4, 5, 6, 7, 8]. This model makes it possible to test the subscription based tariff on a larger level and will hopefully contribute to a better understanding of how power based tariffs affect the energy market.

1.2 Scope

This thesis includes a literature review of the most important areas of research relevant to this project, especially the P2P and blockchain concepts. Furthermore, background information on grid tariffs, programming method for the simulations, different P2P energy markets and the blockchain technology is given.

An optimization model of a neighborhood is created in Python using the Pyomo software package. Four different case studies are developed to test the subscription and energy based tariff structures to see how well they are able to incentivize consumers in the neighborhood to use their flexibility effectively. The case studies also illuminate the difference in operation when P2P energy trading is enabled compared to when the consumers are operating on their own.

The results will focus on how well the neighborhood is able to reduce power peaks during scarcity hours for the different case studies, the effects of P2P energy trading and a sensitivity study to see which of the flexible resources are more significant when it comes to power peak reduction.

This thesis builds on the work done in the specialization project leading up to the master thesis and will include parts of the background theory and literature review [1].

The work done in this thesis served as a basis for an academic paper submitted to the SEST 2019 conference in Porto. The full paper can be seen in appendix A.

1.3 Problem definition

P2P energy trading markets have been proposed as a way of reducing power peaks in the grid and promote local energy consumption. P2P markets can benefit both end users and distribution system operators (DSO) by reducing costs via economic incentives and preventing expensive grid upgrades.

With this in mind, a model of a neighborhood capable of P2P energy trading has been created to investigate how end user flexibility and P2P trading is being utilized to dampen the strain on the power grid under different grid tariff structures.

1.4 Research questions

The research questions this paper will attempt to answer:

- To which extent optimized flexibility dispatch and peer-to-peer trading in neighborhoods results in lower peak loads during scarcity hours under a subscribed capacity tariff?
- Do subscribed capacity tariff structures incentivize more grid friendly power consumption than energy based tariff structures when consumers are aggregated?
- What is the consequence of aggregating consumers under a common neighborhood based grid tariff, compared to single customers?

Chapter 2

Literature Review

The literature review will focus mainly on the Peer-to-Peer and blockchain concepts in the energy markets, and especially on two research papers that are of great interest and very useful, both of which are literature reviews themselves. The first is a review called *"Peer-to-peer and community-based markets: A comprehensive review"* by Tiago Sousa et al. [9]. And the second is a review called *"Blockchain technology in the energy sector: A systematic review of challenges and opportunities"* by M. Andoni et al. [10]. Both of these will be discussed further in this chapter, along with additional research topics also discussed in the specialization project.

2.1 Peer-to-peer and community-based markets

This section covers the contents of the research paper: *Peer-to-peer and community-based markets: A comprehensive review* by Tiago Sousa et al. [9].

In response to the increasing amounts of renewable energy resources and the emergence of prosumers, a new way of operating the energy market has been proposed: Peer-to-peer (P2P) electricity markets. This type of market design allows for consumers to trade locally produced or excess energy directly with each other. The literature converges on three types of P2P market structures: *Full P2P market*, *community -based market* and *hybrid P2P market*. This review paper [9] explains the motivation behind the emergence of these new markets and presents the three different market designs in terms of mathematical formulation, optimization techniques and advantages and challenges.

To analyze the potential of the P2P market Tiago Sousa et al. has conducted a SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis. This analysis is shown in Table 2.1 below. Tiago Sousa et al. lists postponing grid investments as one of the opportunities of P2P markets which is exactly what the power based grid tariffs investigated in this master thesis are aiming to achieve. The SWOT analysis also highlights threats like legal and regulatory obstacles, technology dependency and poor market structure. Many of which can be solved through futher research.

Table 2.1: Summary of potential strengths, weaknesses, opportunities and threats. SWOT analysis obtained from [9]

Strengths	**Weaknesses**	**Opportunities**	**Threats**
1) Empowerment of consumers, focusing in trust, transparency and openness	1) Sub-optimal energy price of all energy system	1) Democratization of energy	1) Legal and regulatory obstacles, which influence the transition to these markets
2) Consumers have better choice of supply and possibility to produce and sell their own energy	2) Potentially overwhelming transition to this consumer-centric market	2) Increase consumers awareness and cooperation towards environmental energy consumption	2) Energy poverty for some group of consumers
3) Increase resilience and reliability of the system	3) Heaviness of negotiation and clearing mechanisms	3) Create new business models	3) Prosumer engagement and its human dimension
4) Remove potential market power from some players in the wholesale market	4) Life-cycle assessment of hardware infrastructure	4) Boost retailer market, since lacks competition	4) Potential grid congestions
		5) Postpone grid investments from system operators	5) Technology dependency (e.g. blockchain)
			6) Security and privacy with data
			7) Potential failure of these markets if poorly structured

The review paper also includes a test case where the three market designs are tested on the IEEE 14-bus network system. The results showed that the full P2P market was able to reach the highest social welfare and could almost operate isolated from the main grid. The test case has several aspects that are not being considered and is mainly meant as a basis for future research. The data used for the simulations and mathematical formulations can be found in detail in [9].

In summary, this review paper elaborates on the three different P2P market designs the R&D community has converged on being the best, ultimately leading to the choice of market design used in this thesis. The designs are tested using a test case that is openly available for others to continue doing research on. The paper highlights several different R&D pilot projects and conclude that most of them has been focuses on the ICT infrastructure needed to make the P2P concept a reality. The research, however, has limited investigation concerning new market designs that are consumer-centric. Tiago Sousa et al. also addresses regulation and grid operation as the two main challenges that needs to be addressed, new grid tariffs being one of the possible solutions.

2.2 Peer-to-peer in the energy sector

The peer-to-peer concept for the energy sector has been extensively researched and a lot of pilot projects has been developed and set into action as a cause of this. One of the most prominent microgrid pilot projects is the Brooklyn Microgrid. Ester Mengelkamp et al. suggests in [11], a blockchain based microgrid energy market, where consumers can trade self-produced energy in a P2P fashion, and evaluated the Brooklyn Microgrid project in terms of seven key microgrid energy market components. Their conclusion is that the Brooklyn Microgrid satisfies or partially satisfies six of the seven components needed to bulid an efficient microgrid energy market, proving the possibility of P2P energy trading. The seventh component is not satisfied because current regulation does not allow for P2P energy markets in most countries.

A big question when it comes to the design of a decentralized P2P energy market is the pricing and product differentiation. By incorporating blockchain technology, electricity can be traced, opening up for different pricing of local and green energy. In [12] Etienne Sorin et al. proposes a P2P market structure allowing for product differentiation based on consumer preference. They show that a market that includes product differentiation has a positive impact, favoring local and clean energy consumption.

Product differentiation is also researched in [13], where T. Baroche et al. proposes a test case with several ways of allocation cost reflecting different uses of the grid. They illustrate this using the IEEE 39-bus system as a platform. Their conclusion is that by using product differentiation as incentives to account for grid operation cost, the market participants respect the limits of the power grid rather than enforcing them.

As for the general concept of decentralized energy markets and a more consumer-centric focus, Pierre Pinson et al.[14] provides a high-level introduction to these types of markets and elaborates on the impact they may have on the current energy market as well as challenges needed to be solved for these markets to exist.

There are many challenges when it comes to decentralized P2P energy markets, many of which are discussed in [9], such as regulation, sub-optimal energy price and technology dependency. Another factor that needs to be considered is the physical constraints related to network issues, such as overvoltage and congestion. In [15] Jaysson Guerrero et al. presents a case study illustrating the importance of considering network constraints when constructing P2P trading models.

2.3 Blockchain technology in the energy sector:

This section covers the contents of the research paper: *Blockchain technology in the energy sector: A systematic review of challenges and opportunities* by M. Andoni et al. [10].

Decentralized energy markets and a more consumer-oriented focus is at the core of the P2P concept. To achieve the potential of P2P markets, blockchain is pointed to as a possible solution. The blockchain technology, and how it has the potential of removing the third party necessary to make trustworthy and secure energy transfers is, thoroughly discussed in this research paper [10]. M Andoni et al. starts of by explaining the conceptual background behind the blockchain technology and introducing cryptocurrencies such as the well-known Bitcoin. The paper also introduces the blockchain based application Etherum, which is a platform that allows for users to develop applications running on blockchain architecture. Ethereum enables user-created smart contracts and decentralized applications and is utilized by over 1000 projects, according to a recent report [16].

One of the key components of the blockchain technology is the consensus algorithm. Every time a new block is to be added to the blockchain, consensus must be reached. This is done by solving a consensus algorithm, of which there are many. M Andoni et al. goes into detail explaining the different basis of algorithms such as lottery-based and voting-based. The algorithms are judged by Scalability, Speed and Finality and are summarized in Table 2.2.

Table 2.2: Summarized distributed consensus strategies and main characteristics based on [17] [10]. Obtained from [10]

Technical features	Permissioned lottery-based	Permissioned voting-based	Permissionless PoW
Scalability	Good	Moderate	Good
Speed	Good	Good	Poor
Finality	Moderate	Good	Poor

The following consensus algorithms are further elaborated in this review: *Proof of Work* (PoW), *Proof of Stake* (PoS), *Practical Byzantine Fault Tolerance* (PBFT), *Delegated Proof of Stake* (DPoS), *Federated Byzantine Agreement* (FBA), *Proof of Authority* (PoAu), *Proof of Elapsed Time* (PoET), *Proof of Activity* (PoAc), *Proof of Burn* (PoB), *Proof of Capacity* (PoC).

In the next section, the role of the blockchain technology in the energy sector is discussed. M. Andoni et al. lists potential applications and aspects of business models that can be affected by the technology. The following paragraphs are directly transcribed from the review [10].

- *Billing*: Blockchains, smart contracts and smart metering can realize automated billing for consumers and distributed generators [18]. Utility companies might benefit from the potential for energy micro-payments, pay-as-you-go solutions or payment platforms for pre-paid meters [19].
- *Sales and marketing*: Sales practices may change according to consumers' energy profile, individual preferences and environmental concerns [20]. Blockchains, in combination with artificial intelligence (AI) techniques such as machine learning (ML), can identify consumer energy patterns and therefore enable tailored and value added energy products provision.
- *Trading and markets*: Blockchain-enabled distributed trading platforms might disrupt market operations such as wholesale market management [20, 21, 18], commodity trading transactions [19] and risk management. Blockchains systems are currently being developed also for green certificates trading [19].
- *Automation*: Blockchains could improve control of decentralized energy systems and microgrids [20]. Adoption of local energy marketplaces enabled by localized P2P energy trading or distributed platforms can significantly increase energy self-production and self-consumption, also known as behind the meter activities [18], which can potentially affect revenues and tariffs.
- *Smart grid applications and data transfer*: Blockchains can potentially be used for communication of smart devices, data transmission or storage [20]. Intelligent devices in the smart grid include smart meters, advanced sensors,

network monitoring equipment, control and energy management systems, but also smart home energy controllers and building monitoring systems. In addition to providing secure data transfer, smart grid applications can further benefit from data standardization enabled by blockchain technology.

- *Grid management*: Blockchains could assist in network management of decentralized networks, flexibility services or asset management. Blockchains could achieve integrated flexibility trading platforms and optimize flexible resources, which might otherwise lead to expensive network upgrades. As a result, blockchains might also affect revenues and tariffs for network use [18].

- *Security and identity management*: Protection of transactions and security can benefit from cryptographic techniques. Blockchain could safeguard privacy, data confidentiality [20] and identity management [[19].

- *Sharing of resources*: Blockchains could offer charging solutions for sharing resources between multiple users, such as sharing EV charging infrastructure [19], data or common centralized community storage.

- *Competition*: Smart contracts could potentially simplify and speed up switching of energy suppliers [20, 22]. Enhanced mobility in the market could increase competition and potentially reduce energy tariffs.

- *Transparency*: Immutable records and transparent processes can significantly improve auditing and regulatory compliance [19].

As shown by the information above, the blockchain technology can disrupt the current structure of the energy market. With blockchain technology the top down structure, heavily reliant on an authority to manage energy transactions and billing, could be removed and a decentralized structure can come into fruition. The ability to safely and securely track all energy transactions opens up opportunities to increase the share of green or local energy self consumption by product differentiation.

In the review paper, M. Andoni et al. presents and discuss several use cases found in the literature reviewed, including the Brooklyn Microgrid. The Brooklyn Microgrid project completed a successful trial run of P2P energy trading using smart-contracts based on the Ethereum structure. M Andoni et al. elaborates further in their paper, and in [11], an even more detailed analysis can be found.

The final part of the research paper provides a systematic review of R&D projects in the energy business, utilizing Blockchain technology. The research has recognized over 140 blockchain innovation projects and research initiatives related to the energy sector. The research is sorted into eight different fields of study:

1. Metering, billing and security
2. Cryptocurrencies, tokens and investment
3. Decentralized energy trading
4. Green certificates and carbon trading
5. Grid management
6. IoT, smart services, automation and asset management
7. Electric e-mobility
8. General purpose initiatives and consortia

Table 2.3 shows the distribution of the different fields. A detailed description of the eight fields and the R&D projects can be found in the review paper [10].

Table 2.3: Distribution of blockchain R&D projects related to the energy sector

Field of study	**% of 140 R&D projects**
Metering, billing and security	9%
Cryptocurrencies, tokens and investment	19%
Decentralized energy trading	33%
Green certificates and carbon trading	7%
Grid management	8%
IoT, smart services, automation and asset management	11%
Electric e-mobility	7%
General purpose initiatives and consortia	6%

To summarize, this review paper provides insight into how the technology behind blockchain works and highlights its strengths and weaknesses. Further it addresses how the blockchain technology can potentially disrupt and change the end user energy market by providing cost-efficient energy trades between consumers. The paper highlights some of the obstacles this technology faces in order to be adapted in the mainstream, such as the energy needed to solve the consensus algorithm and regulatory challenges. Even though the blockchain technology is not directly used in the model for this thesis, it is still an important subject to discuss when it comes to smart contracts and the P2P energy market. By utilizing blockchains, costs related to billing and energy transactions can be decreased, making low-value transactions cost-efficient. The technology opens up for better resource sharing by distributing the information to the entire network. In this way, a central node, such as the neighborhood in this thesis, will have access to data for all of the consumers and be able to manage import, export and flexibility optimally.

2.4 Change in grid tariff structures

One of the main sources of discussion around the topic of power based grid structures, and the basis for writing this master thesis, is the hearing posted by NVE in 2017 [2]. In this hearing, NVE proposes, and tests, three relevant grid tariff structures for end users in the distribution grid to see whether or not they are able to provide the consumer with price signals to reduce power consumption during peak hours. The three gird tariffs tested are **Subscribed Power**, **Time-of-Use** and **Measured Power**.

NVE concludes that the Subscription based tariff structure is the most capable of giving the consumer correct price signals. NVE has met a lot of critique from the industry on this hearing [4, 5, 8, 3, 6, 7], and many disagree with NVE's conclusion that Subscribed power is the most suitable model, saying that it will be too difficult for consumers to understand. The responders on this hearing also raises concern around the effects of a capacity based tariff in the distribution grid, saying that the consequences are unknown, and that more research needs to be conducted before making any final decisions.

The new Time-of-Use and Subscription based structures NVE proposed have also been tested for a consumer with a battery, EV and PV production in reference [23]. The conclusion being that the new tariffs are able to solve some of the problems in the grid, related to power consumption. The Time-of-Use structure provides great economical potential for the customer while the Subscription based structure manages to reduce power consumption.

Based on the specialization project leading up to this thesis, it was concluded that the subscription based tariff structure indeed provided the best price signals for reducing power import during peak hours. Therefore, the subscription based tariff is being further tested in this thesis, with the main focus being the benefits DSOs can get from peak shaving and utilizing flexible resources.

The number of consumers that both produce and consume energy from the grid, so called prosumers, is increasing. Appliances such as EVs, house batteries, PV-cells and advanced metering systems (AMS), makes the prosumer flexible and a great contributor, when it comes to developing the power system. Reference [14] describes the power market as going from a top-down hierarchy to a more decentralized and consumer-centric structure, with the possibilities for peer-to-peer (P2P) energy trading between prosumers, and in turn a more efficient and green energy system. This is also something that is begin discussed in the review paper [9], where several P2P market designs are proposed. Such a transition is going to take time, and needs to be done step by step. Regulation is a major part of this transition.

2.5 Flexible load modelling

INVADE is a large project, with several partners worldwide that has set out to create a flexibility management system that can aid the grid by controlling flexible loads, such as batteries. The project has initiated five pilot projects to try and implement the INVADE platform in existing grid architecture [24].

INVADE's many deliverables are relevant to this specialization project by providing detailed mathematical formulations for the flexible load models such as the house battery, EV and water heater (WH) used in this project. The mathematical models are described in reference [25]. This thesis uses a simplified mathematical model which does not include parameters such as taxes and VAT when modelling the grid tariffs and a simplified version of the curtailable load (WH).

2.6 The electric vehicle as a distributed energy resource

An important part of this thesis is the implementation of the electric vehicle as an energy contributor. A lot of pilot projects has been performed to explore the possibilities in this area. The technology needed to perform bi-directional charging is available to the public and has been demonstrated in several pilot projects [26, 27, 28].

In reference [29], control algorithms for optimal scheduling of Vehicle-to-Grid (V2G) activity has been developed. One of the algorithms was able to reduce energy costs by 18.08 % proving that there is a lot of potential in this field. In reference [30] a study of the EV's potential to compete in a power supplying market without compromising its ability of transportation, was conducted. Concluding that when it comes to the ancillary service market, and the payments it offers, the EV is able to compete.

Still, a big concern when using V2G, is the degradation of the battery. Since the primary function of a car is transportation, it would be unfit to use it for V2G services if it compromises the battery. EV battery degradation has been researched in [31, 32, 33], The conclusion of the effects of V2G to the EV battery, however, is not clear. Reference [31] reports that V2G activities actually can prolong the battery lifetime, while reference [32] reports the contrary. Since this is a major uncertainty, bi-directional charging for the EV will not be included in this project simulations.

Chapter 3

Decentralized power markets

In this chapter the current regulation of grid tariffs will be explained, including the new subscription based tariff structure that has been proposed and the reactions it has caused. Further, the peer-to-peer technology in the power grid is discussed and lastly, the concept of blockchain, and the role it can play in decentralized power markets, is elaborated on.

3.1 Grid tariffs

This chapter presents the current grid tariff applied for end users in the power grid, and the proposed new tariff structure. It also addresses some of the responses to these new tariffs.

3.1.1 Current tariff structure

The current electricity bill for households in Norway is built up by two payments. The consumer pays for the energy they use, as well as the cost of delivery. The cost of delivery is payed through the grid tariff. The grid tariff is supposed to give the distribution system operator (DSO) revenue to cover the costs of transportation, utilization and network development [34].

To ensure that the electricity grid is operated, utilized and developed in a societal rational and efficient manner, the Norwegian Water Resources and Energy Directorate (NVE) is in charge of economic regulation of the DSOs. NVE controls the revenue of the DSOs in the Norwegian energy market by setting an upper limit for how much they can charge for transmission of electrical energy[35, 36, 37].

The DSO's income framework is calculated based on their previous two years of expenses. For a DSO more efficient than the average DSO, the income framework will allow for a higher revenue. This gives DSOs incentive to improve their efficiency. When the DSOs earns more from the consumers than they are allowed to, this excess income has to be returned to the consumers in form of reduced grid tariff in the following years. The same goes for income shortfall, where the DSOs are allowed to charge a higher grid tariff to compensate. NVE requires the DSO to control the excess income and shortfall towards zero. [37, 34].

As previously mentioned, the electricity bill consists of two payments; price for energy and price for energy delivery. In addition to these, the consumer also has to pay taxes and fees, including VAT, Enova fee[1] and consumption fee. The distribution of the payments and taxes can be seen in Figure 3.1. As shown by the figure, taxes and fees represent almost one third of the total price per kWh for the consumer.

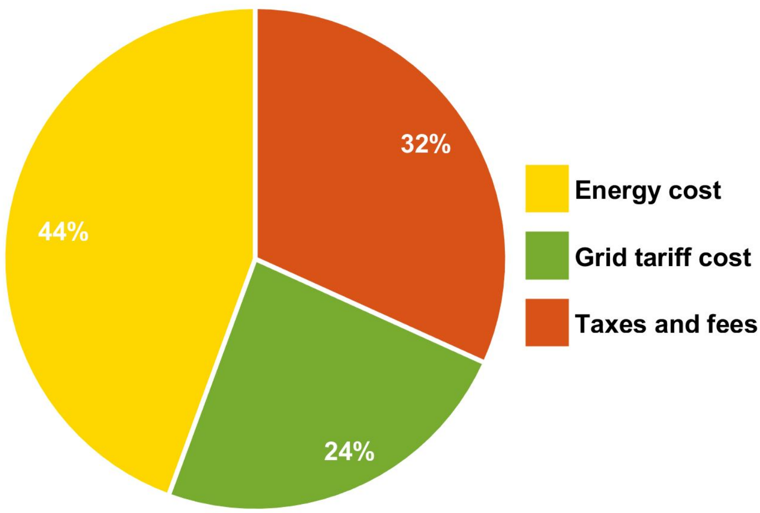

Figure 3.1: Percentage buildup of the price per kWh for a household consumer in 2018 [39]

Table 3.1 below shows the average prices for energy, grid tariff and taxes for a household consumer in the fourth quarter of 2018. The table also includes the yearly energy bill for an example household using these prices.

[1] Fee of 0.01NOK/kWh (private customers) to support energy efficiency measures via the energy fund[38]

Table 3.1: Average energy prices in the end user market as of 2018, fourth quarter [39]

Price elements	NOK/kWh
Total price (energy, grid tariff, taxes and fees)	1.234
Energy price	0.548
Grid tariff	0.294
Taxes and fees	0.392
Total yearly price, household 26 000 kWh	32 084
Total yearly price, household 26 000 kWh no taxes and fees	21 892

3.1.2 Proposed new tariff structures

In a hearing posted in 2017, NVE proposed new grid tariff structures based on power consumption as opposed to the current energy based structure. NVE point to the rise of electrical appliances that are more power demanding, and especially the extreme increase of electrical vehicles in Norway, as the reason for an increasing power demand. They highlight how a consumer can have a low yearly energy consumption, but a high power consumption. An example of such a consumer could be a low energy house owner with an EV that is being charged using a fast charger with a power output of 22 kW [40, 2].

The current tariff structure does not reflect the strain the high power import has on the grid. To clarify the example, this low energy house owner is shown in Figure 3.2. Even though this example is oversimplified and not very realistic, it clearly demonstrates the point NVE is trying to make. The consumer has a constant power import of 0.5 kW to his house for heating and other appliances. The power peaks come from charging the electric vehicle.

The EV is being charged in the morning and after work, typically when there is high power consumption in the grid. Compared to a "normal" consumer, seen in Figure 3.3, who has a lower average power consumption and more evenly distributed consumption pattern, the example customer has larger power peaks that contribute to straining the grid. The total energy consumption of the two examples are identical, at 55 kWh. It is clear that the example customer is most troublesome for the DSOs with regards to needing development and expansion of the grid. Using the current energy based tariff structure, this customer will be neither punished for high power consumption or incentivized to lower the power import. Therefore, NVE has suggested power based tariff structures in order to encourage lower power import.

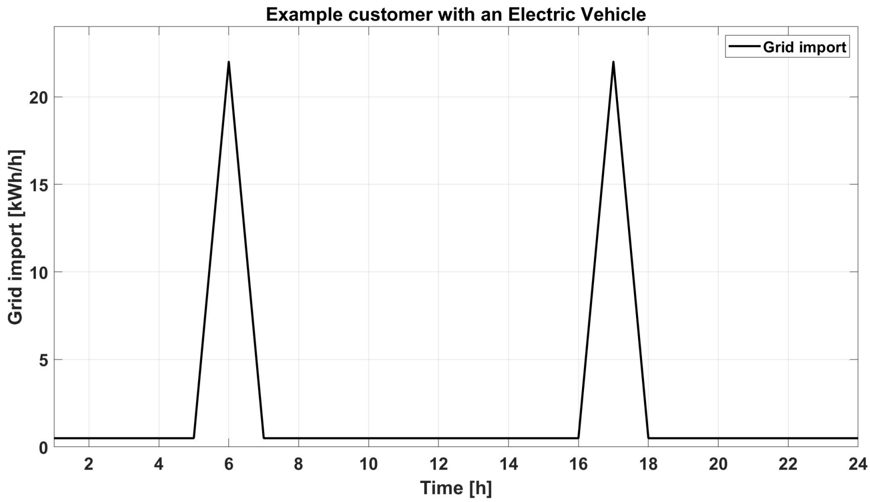

Figure 3.2: Load curve for an example customer with a low energy house and a fast charging EV

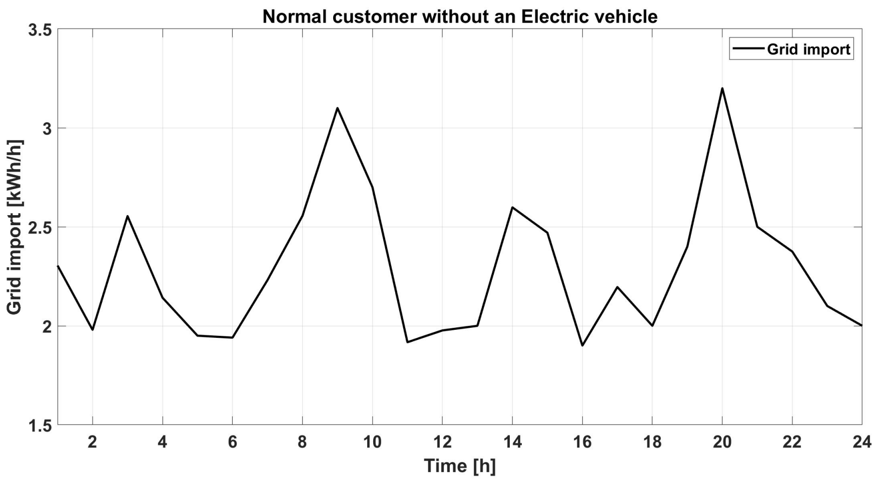

Figure 3.3: Load curve for a household with "normal" consumption pattern

The new grid tariff structures suggested by NVE as the most relevant are as follows; **Subscribed Power**, **Time-of-Use** and **Measured Power**. Results obtained in the specialization project [1] showed that the Subscribed Power structure was the most effective at giving price signals to reduce power peaks. Based on the findings in the specialization project, this thesis will only focus on the Subscribed power structure.

3.1.3 Subscription based tariff structure

The Subscription based tariff structure is billed on the basis of three costs; fixed price, cost of energy and cost of overconsumption. The fixed price consists of a set yearly fee, which is constant regardless of subscription chosen, and a subscription fee. The subscription fee is dependent on the subscription limit chosen. The cost of energy is low and constant and is included to cover the marginal cost of the grid. The overconsumption price has the purpose of incentivizing the consumer to lower power consumption when the power imported exceeds the subscribed limit.

This price structure is supposed to give the consumer short term price signals to lower power consumption to stay below the subscribed limit. For the long term, the consumer will be economically motivated to change habits or invest in flexible resources, such as a battery, to be able to choose a lower subscription limit. In turn, this could reduce the cost or need for expansion of the grid for the DSO [2].

NVE suggests that the DSO sets the price ranges in such a way that the consumer has a certain amount of overconsumption throughout the year. This way, overconsumption will happen during wintertime, when most consumers naturally have a higher consumption. This will lead to more price signals in the wintertime than in the summertime, which also reflects the market needs correctly.

The price ranges NVE proposes are shown in Table 3.2. In the hearing they calculate results using the different tariffs for several households[2]. The Subscription based structure is modeled such that the average overconsumption per household is 670 hours. This fact will be used later in chapter 5.5.3 to calculate the price ranges for the different households used in this paper[2].

Table 3.2: Price ranges for the Subscription based tariff structure as suggested by NVE[2]

Fixed yearly price [NOK/year]	**Subscription fee [NOK/kWh/h]**	**Energy cost [NOK/kWh]**	**Overconsumption price [NOK/kWh/h]**
1060	689	0.05	1.00

3.1.4 Feedback from the community

When NVE distributed their hearing for the proposed new grid tariffs, they wanted to receive feedback from the DSOs, energy companies and other organizations. They got input and comments from over 80 different actors.

Most of the responders agreed that the energy grid is facing changes in the near future with higher power demands, and that going from energy based tariffs to a power based tariff is a positive step. There was mixed response to the statement that a Subscription based structure is a good way of implementing this. Several companies fear increased administrative costs related to explaining the tariff to customers.

There is also concern that the Subscription based structure will give incorrect price signals because of the subscription limit. One example being that when a customer is importing above their subscribed limit in the summertime, the rest of the grid is not heavily loaded. Regardless, the customer will receive price signals to lower the consumption.

Concerns are also that the effects this type of tariff structure will have on smaller customers is yet unknown and needs further research. For bigger customers, the already understood and implemented Measured Power model is seen as good enough. Responders that are somewhat positive to the Subscription based model still cautions NVE not to make any final decisions before the consequences of AMS metering and capacity based tariffs are known.

Several responses see the Time-of-Use tariff structure as the superior choice for smaller customers as the Time-of-Use tariff is more understandable to customers, pose less administrative challenges, gives more accurate price signals reflecting the grid and make better use of the AMS meter [3, 4, 5, 6, 7, 8].

3.2 Peer-to-peer in the power grid

This chapter introduces the P2P concept and different market structures discussed in recent literature. The market structure used for the model in this thesis is presented and the main advantages and challenges related to all the different P2P market structures are displayed.

3.2.1 P2P concept and markets

The Peer-to-peer concept for the power market was suggested as early as 2007 by Hakem Beitollahi et al. [41], defining P2P by three principles related to the use of this technology in the power grid: 1) **The principle of resource sharing**, 2) **The principle of decentralization** and 3) **The principle of self-organization**.

In any P2P network the **principle of sharing resources** is important. This applies to physical resources as well as resources in the form of information. By sharing resources, the P2P network opens up for solutions that are not possible for a single node. In the power grid, the possibility to share energy and information within a community or microgrid, can help streamline the operation and lower power consumption from the grid.

The increasingly decentralized nature of the power system has caused many to rethink the structure of the energy grid. Consumers are more important than earlier, and the market is decentralizing. Pierre Pinson et al. discusses the emergence of such consumer-centric electricity markets in [14]. **The principle of decentralization** is an important contributor to these markets, and a big part of the P2P concept. P2P energy markets give the consumers more power over their own consumption, by letting the consumer choose where to import energy from.

The decentralized nature of P2P networks means that no central node is in charge of coordinating the activity or storing information. This means that the nodes in the network has to self-organize. **The principle of self-organization** and the fact that not only a single node contains all the information on the network operation, makes for a more resilient network. P2P networks are able to cope with failures by reorganizing the power flow and can also operate without the need for a central grid.

3.2.2 Market structures

Tiago Sousa et al. [9] conducted a comprehensive literature review of 90 publications relevant to P2P and community-based markets, which was discussed earlier in this thesis in Chapter 2. Throughout this review they conclude that there are three main P2P structures: **Full P2P market**, **community-based market** and **hybrid P2P market**, as seen in Figure 3.4. Figure 3.4a shows the full P2P market with single consumers and prosumers interacting and trading directly with other consumers and prosumers without any centralized supervision. Figure 3.4b shows the community-based market where a pool of consumers trade together with other communities via a community manager or a third party regulator. The hybrid market is a combination of a and b and will end up with different layers consisting of communities and single entities that can interact with each other.

Since the model in this thesis is based around a neighborhood where grid tariffs are applied to either each consumer, or to the neighborhood as a whole, through a community manager, the community-based market is the most relevant structure. The community-based market will be explained further in this chapter.

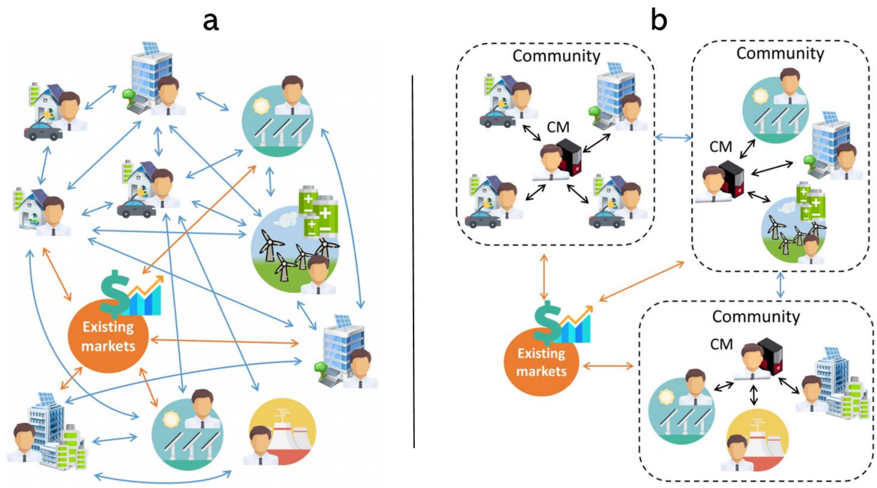

Figure 3.4: Different P2P market structures. Figure 3.4a: Full P2P market, Figure 3.4b: Community-based market [9]

3.2.3 Community-based market

As previously mentioned, the community-based market is more structured than the full P2P market because there is a community manager who manages the trading inside the community and deals with other communities or entities. A P2P community can be created for neighboring prosumers with access to electrical vehicles, photovoltaic cells or battery capacity, or just for a set of consumers with close geographical proximity. The most important aspect of a P2P community market design is that all members have a common goal or interest such as green or local energy use and are willing to share their energy with each other. Tineke van der Schoor et al. [42] highlights the importance of a common vision in a community, when developing a local energy network.

In this thesis, a P2P community is created in the form of a small neighborhood consisting of 30 households of different size, demand and flexible capabilities. The neighborhood will be used to illuminate the difference between having a community-manager controlling the appliances in the neighborhood and all consumers working towards a common goal, versus all of the households acting on their own. The neighborhood model is explained in detail in Chapter 5.

3.2.4 Advantages and challenges

Even though the P2P concept has a lot of potential, it is still being cautioned against optimism [43]. The three different market designs all come with their challenges and complexities that require more investigation and investment to fully understand the potential of P2P. This section puts forth the main advantages and challenges for the different P2P markets.

Full P2P market

The main advantage of the Full P2P market structure, is that the all agents are given the freedom to choose where to buy and sell energy from. In this way, the consumers preferences are being considered and the consumer is given control. A consumer interested in buying green energy can do this directly from one of the other members in the community without having to go through a third party or a community manager.

This democratization of energy use also comes with its challenges, mainly in the form of scalability issues related to computational difficulties and predictability of system behavior. Negotiating with several participants simultaneously can become an immense computational burden, and scalability is still a challenge to be solved. In this regard, the community- or hybrid market design will decrease the computational burden and negotiation process by gathering several participants through a community manager. When all consumers are in control of their own energy trades, they are not necessarily working towards a common goal, which may lead to difficulties predicting the system behavior for the DSO.

Community-based market

When the community is more structured through a community manager, the involvement and cooperation of the community members are being strengthened through a common goal. When working towards a common goal, the community manager is able to provide services to the DSOs as an aggregator. This could be through flexibility management or peak shaving. Providing a service to the DSO will create revenue for the community. The community-based market does not face the same scalability challenge as the full P2P market, since the community manager takes responsibility for the energy trades for all its members.

As opposed to the full P2P market design, the community-based market cannot always take all agents preferences into consideration. One of the members might have a goal that differs from the common goal of the community. The community also encounters a challenge in finding a fair and unbiased way of distributing the potential revenue from grid services, since each member can contribute varying amounts of flexibility and power production.

Hybrid P2P market

The hybrid P2P market structure can combine the two previous designs and avoid the scalability problems of the full P2P market, while still empowering the users to some extent. This market is seen as most likely to develop in the future, since it can be implemented according to the resources available, geographical location and consumers' willingness to participate.

3.3 Blockchain technology

As touched upon in the literature review, the blockchain technology allows for a decentralized network where secure transactions can be recorded and stored. It works by adding blocks to a linked chain, making it permanent and unalterable. It all starts when someone requests a transaction and creates a block. A block can contain transactions, records and other information. This request is distributed to all the nodes in the network, which could be millions, and the nodes then approve and validate the block by solving a consensus algorithm. There are several different consensus algorithms, some of which are briefly discussed in Chapter 2.3.

When the algorithm is solved, the new block is added to the existing chain of blocks creating the blockchain. The chain is stored by all of the nodes in the network, and all of the blocks are cryptographically linked together, making it virtually unalterable and secure. There is a small statistical chance that a block can get altered, but the longer the chain, the more secure it gets. Since there is no central authority in such a network, there is no transaction cost. This is one of the key elements of the blockchain technology and why it has such huge potential. By removing the transaction fee, minuscule transactions can be made profitable [44, 10].

For the energy market, the blockchain technology allows for a decentralized market where peers can trade energy with each other. This does not only benefit the end users by removing taxes and providing cheaper energy, but it can also benefit the DSOs. By enabling P2P energy trading in a neighborhood, power peaks can be reduced, and grid upgrades delayed. Since the blockchain allows for information to get stored, tracking of green energy is also possible. By letting the consumer choose which type of energy they want to buy, local and green energy consumption can be increased [12].

The process of creating and adding a new block to the existing blockchain is visualized in Figure 3.5 below.

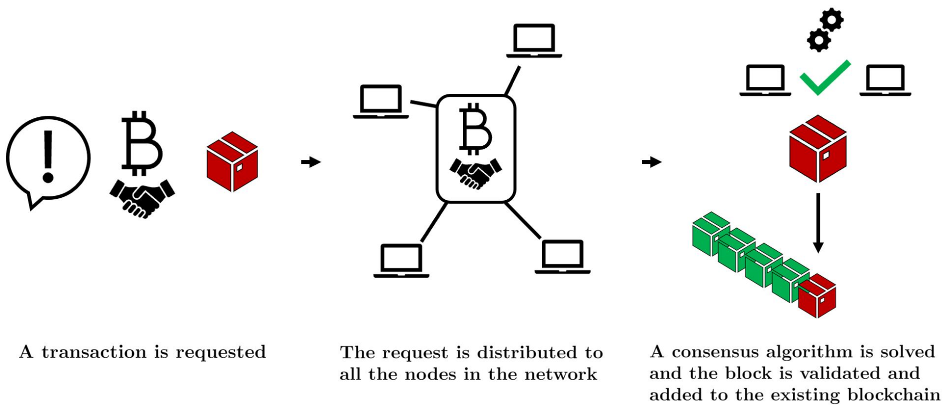

Figure 3.5: The process of creating, validating and adding a new block to the existing blockchain

Chapter 4

Optimization and programming methods

This chapter discuss the optimization method chosen for the problem put forth by this thesis. It also explains the differences between linear programming (LP) and dynamic programming (DP) and deterministic and stochastic models.

4.1 Optimization method

All of the data used for the model in this thesis is known before the simulations start (no random elements) and the problem can be described by linear functions and constraints. This type of problem is most easily solved using LP where all decisions are made up front, instead of stopping at each time-step to make a choice (DP). Therefore, this project uses LP to solve the optimization problem.

The optimization program used for simulations in this project is Gurobi Optimizer. Gurobi is a commercial product that offers a solver for, among others, LP problems. To be able to use Gurobi a license is required. For the use in this project a student license was applied[45]. The code, objective functions and constraints needed to define and solve the linear problem was written in Python using the Pyomo software package.

4.2 Linear programming

In linear programming an optimizing problem is solved by minimizing or maximizing a linear function such that a set of linear constraints are true. A simple example of a problem solved by linear programming can be found in reference [46], and is shown below.

The cost function $P = -2x + 5y$ is to be maximized such that the following constraints are true:

$Constraints$:
$100 \leq x \leq 200$
$80 \leq y \leq 170$
$y \geq -x + 200$

This problem consists of a linear function and a set of linear constraints and can be solved graphically. All of the linear constraints can be draw into the same diagram and the feasible solutions can be seen. This is shown in Figure 4.1. The constraints build walls for the objective function. The feasible region for the x and y coordinated of the objective function can be seen in grey in Figure 4.1. This region has five different intersections that are possible solutions. These are marked with yellow circles.

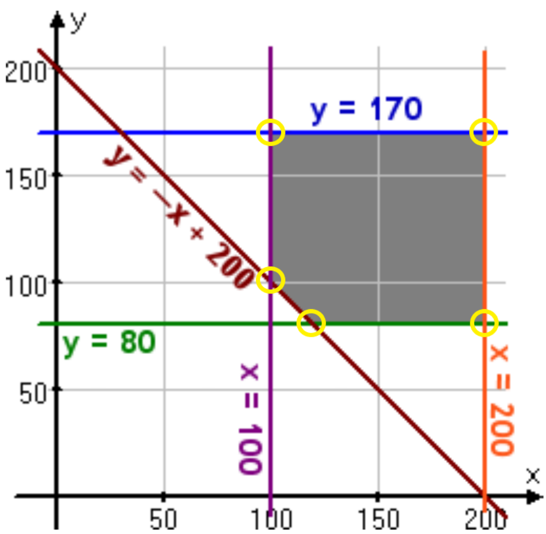

Figure 4.1: All of the linear constraints defining the edges of the problem. Obtained from [46]

The (x,y) coordinates for the intersections are: (100,170), (200,170), (200,80), (120,80) and (100,100). To find the optimal solutions these five are tested in the objective function:

$P = -2 \cdot \mathbf{100} + 5 \cdot \mathbf{170} = \mathbf{650}$
$P = -2 \cdot 200 + 5 \cdot 170 = 450$
$P = -2 \cdot 200 + 5 \cdot 80 = 160$
$P = -2 \cdot 120 + 5 \cdot 80 = 160$
$P = -2 \cdot 100 + 5 \cdot 100 = 300$

Thus, the optimal solution to the linear problem is 100 of x and 170 of y.

4.3 Dynamic programming

In dynamic programming a function is maximized or minimized by making a series of decisions at each stage such that a set of constraints are true. The set of decision available depends on decisions made previously in the solution. A complex problem can be broken down into smaller, easier problems that are possible to solve. An example from reference [47] will be used to explain the process of dynamic problem solving.

In the Figure 4.2 below, a map of intersections between the home of a commuter to the downtown parking lots is shown. Each intersection is associated with a delay in minutes. The objective is to get from left to right (home to parking) as quick as possible. i.e. the objective is to find the route that takes the least amount of time. There are several ways of attacking this problem. In this example, the method of forward induction will be used. Forward induction starts on the left and ends up on the right.

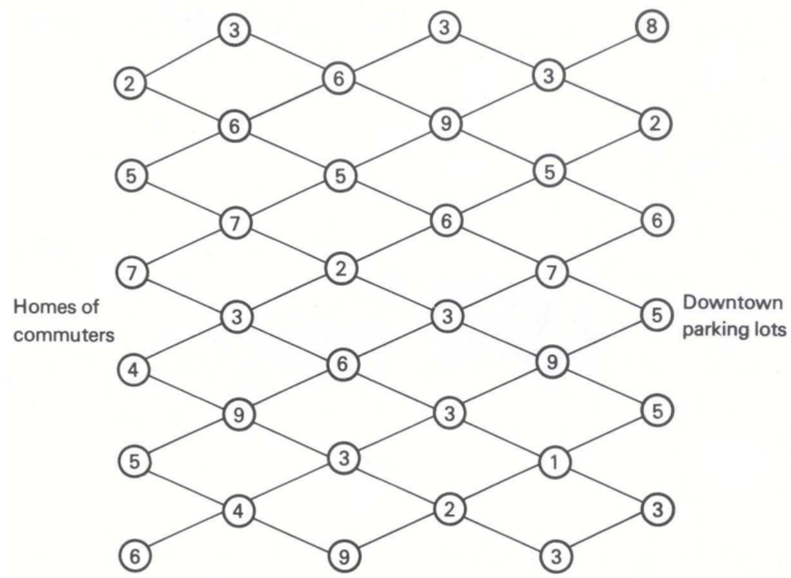

Figure 4.2: Street map with intersection delays. Obtained from [47].

The commuter starts from the left and ends up on the right side. The commuter has to follow the lines and can only move to one of the adjacent intersections. At each intersection a new decision has to be made on which intersection to go to next. The options the commuter can choose depends on which choices they have made previously and the solution to this problem is not obvious. The problem can be simplified to making a single choice based on the options available at each stage.

Figure 4.3 (b) shows how the commuter starts in the leftmost column and is given two choices at each intersection. For the topmost column (intersection with a 2 minute delay) the two choices are; 10 and 8 minutes. The optimal choice is the intersection with 8 minutes delay. In the next step the route through the 10 minute is discarded and the way through the 8 minute intersection continues to develop. This is shown in Figure 4.3 (c). When the decisions have been made for all starting points and all stages, the optimal solution can be found. The optimal solution is highlighted in Figure 4.3 (f).

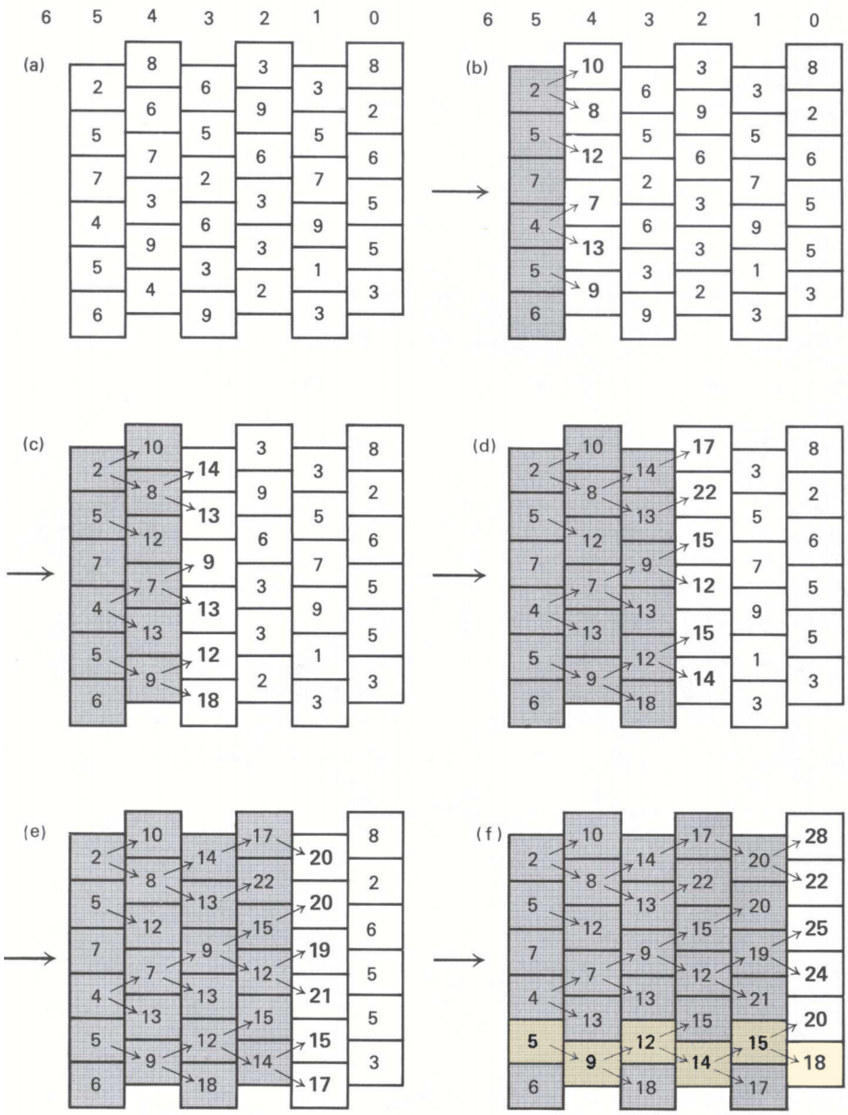

Figure 4.3: How the optimal solution is found using dynamic methods and forward injection. Taken from [47]

4.4 Deterministic vs Stochastic models

A model can be either deterministic or stochastic. The difference between a deterministic model and a stochastic model is the element of something random. A deterministic model can be compared to an equation where, if you have a certain input, you will always receive the same output because all variables are known from the start. In a stochastic model the output will not be the same every time. The output of the stochastic model will depend on the random element, or elements, and are often given as probability distributions[48]. The random, or probabilistic, element in a stochastic model is given by a distribution, such as Gaussian or Poisson distribution. The model created in this thesis includes no random elements and is therefore a deterministic model.

Chapter 5

Modelling

In this chapter the equations and structure for the neighborhood model will be presented. Section 5.1 defines the problem and gives an overview of the model structure. Section 5.2 describes the framework of the neighborhood and the prosumer, while sections 5.3 and 5.4 explain the different flexible appliances and data sets used in the model, including parameters and equations where relevant. Lastly, section 5.5 gexplains the structure of the different grid tariffs and the corresponding objective functions used in the simulations.

5.1 Problem definition

As previously mentioned, a model of a neighborhood, consisting of 30 different prosumer, has been created through the work done in this thesis. It has been coded in Python using the Pyomo software package. The model is built by creating blocks for the different components and arranging them in a top-down structure. The blocks/components are arranged in the following way.

- Neighborhood
  - Prosumer
    - Battery
    - Electric Vehicle
    - Water Heater
    - PV

In summary, there is one neighborhood with 30 prosumers, each able to include three different flexible appliances and PV-production. The optimizing program finds the optimum way to control the appliances of the prosumer to minimize the objective function, using linear programming. In this thesis the objective function will equal the total electricity bill for either a single prosumer or the neighborhood. The total electricity bill is defined in two different ways depending on the grid tariff the consumers are operating under. The objectives of the optimization program is summarized in Table 5.1 and the different objective functions are given in detail in Chapter 5.5.

Table 5.1: Summary of the objectives for the optimization program

Objective	**Sense**
Electricity bill under energy tariff	Minimize
Electricity bill under power based tariff	Minimize

The tools the optimization program can use to solve the problem are the battery, EV and WH (flexible appliances). The appliances have restrictions defined by certain constraints, which are presented in chapters 5.3.1, 5.3.2 and 5.3.3.

5.2 Modelling of neighborhood and prosumer

As previously stated, the model is created by constructing several different blocks and arranging them in as shown in Chapter 5.1. This section will address the neighborhood and prosumer blocks.

5.2.1 Neighborhood

The neighborhood, n, is designed as an entity connected to a transformer and consists of an energy balance. The energy balance contains the energy imported and exported through the transformer, i.e. the energy exchange between the neighborhood and the power grid. The import and export through the transformer are dependant on the consumption and production for all of the consumers and prosumers in the neighborhood. The energy flow in the neighborhood is visualized in Figure 5.1, and the mathematical formulation is given by equation 5.1.

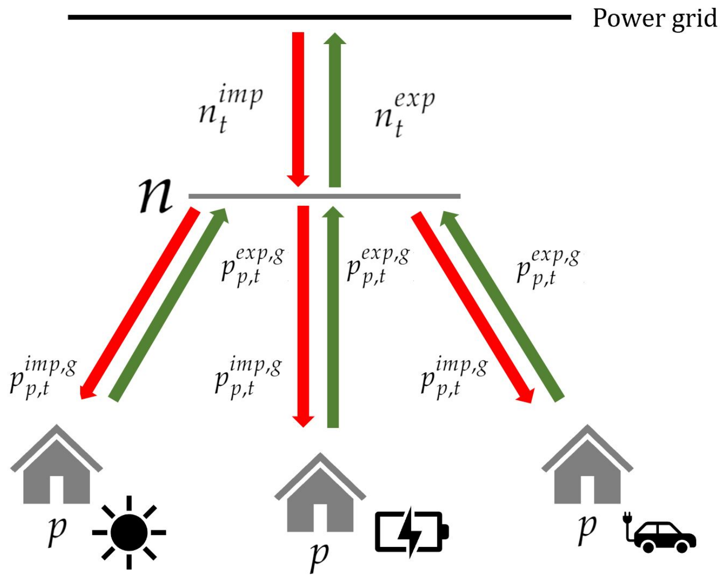

Figure 5.1: Visualization of energy flow in the neighborhood from grid to end-user

$$n_t^{imp} - n_t^{exp} = \sum_p (p_{p,t}^{imp,g} - p_{p,t}^{exp,g}) \tag{5.1}$$

, where

n_t^{imp}	= Total neighborhood import in time step t [kWh/h]
n_t^{exp}	= Total neighborhood export in time step t [kWh/h]
$p_{p,t}^{imp,g}$	= Prosumer grid import in time step t for prosumer p [kWh/h]
$p_{p,t}^{exp,g}$	= Prosumer grid export in time step t for prosumer p [kWh/h]
$n_t^{imp,h}$	= Total neighborhood import above sub-limit in time step t [kWh/h]
$n_t^{imp,l}$	= Total neighborhood import below sub-limit in time step t [kWh/h]

When the subscription based tariff is applied, the neighborohood import, n_t^{imp}, is split into low and high, $n_t^{imp,l}$ and $n_t^{imp,h}$, to be able to allocate the overconsumption price explained in Chapter 5.5.

5.2.2 Prosumer

The prosumer is structured in the same way as the neighborhood in sense that it is designed as an energy balance. The difference between the neighborhood and the prosumer is that the prosumer includes all of the different appliances and loads, whereas the neighborhood only included the prosumers import and export. The mathematical formulation for the prosumer is given by Equation 5.2. The prosumer, p, is visualized in Figure 5.2. As is going to be explained in Chapter 6, there are several different types of consumers, with different amounts of flexibility. The consumer in Equation 5.2 and Figure 5.2 includes all of the flexible appliances available and PV-production. For consumers with less appliances or without PV-production, these will be equal to zero.

$$\begin{aligned} p_{p,t}^{imp,p} \cdot \eta^{P2P} + p_{p,t}^{imp,g} - p_{p,t}^{exp,p} - p_{p,t}^{exp,g} = P_t^{load} \\ +b_t^{ch} - b_t^{dis} + ev_t^{ch} + w_t^{power} - PV_t^{prod} \end{aligned} \tag{5.2}$$

, where

η^{P2P}	= Efficiency when importing using P2P [%]
P_t^{load}	= End user load in time step t [kWh/h]
PV_t^{prod}	= Production from PV-cells in time step t [kW]
b_t^{ch}	= Battery charging power in time step t [kWh/h]
b_t^{dis}	= Battery discharging power in time step t [kWh/h]
ev_t^{ch}	= EV charging power in time step t [kWh/h]
w_t^{power}	= Power supplied to the water heater in time step t [kWh/h]
$p_{p,t}^{exp,g}$	= Prosumer grid export in time step t for prosumer p [kWh/h]
$p_{p,t}^{exp,p}$	= Prosumer peer export in time step t for prosumer p [kWh/h]
$p_{p,t}^{imp,g}$	= Prosumer grid import in time step t for prosumer p [kWh/h]
$p_{p,t}^{imp,h}$	= Prosumer grid import above sub-limit in time step t for prosumer p [kWh/h]
$p_{p,t}^{imp,l}$	= Prosumer grid import below sub-limit in time step t for prosumer p [kWh/h]
$p_{p,t}^{imp,p}$	= Prosumer peer import in time step t for prosumer p [kWh/h]

Similarly to the neighborhood energy balance, the prosumer grid import, $p_{p,t}^{imp,g}$, will also be split into low and high, $p_{p,t}^{imp,l}$ and $p_{p,t}^{imp,h}$, when the subscription based tariff is applied.

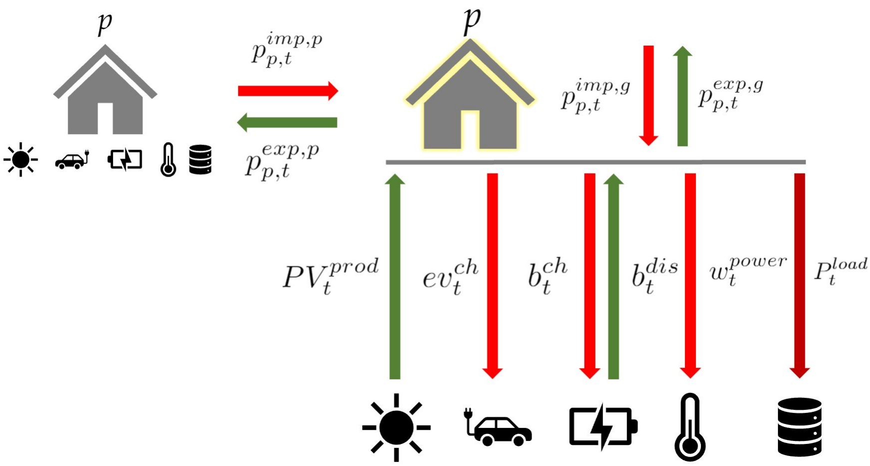

Figure 5.2: Visualization of energy flow for a prosumer with all felxible appliances and PV-production

5.3 Modelling of appliances

This next section will address the blocks for the different flexible appliances connected to the prosumer, shown in Equation 5.2 and Figure 5.2. The flexible appliances include the battery, electric vehicle and water heater. Since the PV is not modeled directly, but input as a data set, it is not going to be included in this section.

5.3.1 Battery

For the battery, the Tesla Powerwall 2 was chosen. There are a lot of different options available on the market, and even more to come. Many companies are delving into the home battery business, but few are as well known to the public as Tesla. Tesla's product is on the high end when it comes to capacity, and is available in North America, Europe, Asia and the Middle-East [49].

The usable capacity of the battery is 13.5 kWh, with a depth of discharge (DOD) at 100%. and can deliver a peak power of 7 kW. For this project it means that the battery is able to use all of the 13.5 kWh, at a maximum of 7 kWh/h, each time step. The round-trip efficiency of the battery is 90%, meaning the efficiency when charging and discharging the battery, is approximately 95%.

The key battery parameters used for simulation in the model is the battery capacity, maximum power input/output and efficiency and is presented in Table 5.2. The neighborhood will include a total of five a batteries.

Table 5.2: Key battery parameters used in simulations

Parameter		Value
Capacity	B^{cap}	13.5 [kWh]
Max charge/discharge power	$B^{ch,max}$ / $B^{dis,max}$	7 [kW]
Charge/discharge efficiency	$\eta^{bat,ch}$ / $\eta^{bat,dis}$	95 [%]
Minimum SOC	$B^{SOC,min}$	0 [kWh]
Initial SOC	$B^{SOC,Initial}$	0 [kWh]

The battery is modeled by a set of equations telling the optimization program how the battery behaves, and what limitations it has. Battery SOC evolution, minimum and maximum charging and discharging power and minimum and maximum SOC limits are given by equations 5.3 and 5.4.

$$b_t^{SOC} = b_{t-1}^{SOC} + b_t^{ch} \cdot \eta^{bat,ch} - \frac{b_t^{dis}}{\eta^{bat,dis}} \tag{5.3}$$

$$\text{For } t = 0,\ b_t^{SOC} = B^{SOC,Initial}$$

$$b_t^{ch} < B^{ch,max} \tag{5.4a}$$

$$b_t^{dis} < B^{dis,max} \tag{5.4b}$$

$$B^{SOC,min} < b_t^{SOC} < B^{cap} \tag{5.4c}$$

, where

$\eta^{bat,ch}$	= Battery charging efficiency [%]
$\eta^{bat,dis}$	= Battery discharging efficiency [%]
B^{cap}	= Total battery capacity [kWh]
$B^{ch,max}$	= Battery maximum charging power [kW]
$B^{dis,max}$	= Battery maximum discharging power [kW]
$B^{SOC,Initial}$	= Initial battery SOC [kWh]
$B^{SOC,min}$	= Minimum battery SOC [kWh]
b_t^{ch}	= Battery charging power in time step t [kWh/h]
b_t^{dis}	= Battery discharging power in time step t [kWh/h]
b_t^{SOC}	= Battery SOC in time step t [kWh]

5.3.2 Electric vehicle

The EV chosen for the model in this thesis has a maximum capacity of 80 kWh and a charge/discharge efficiency of 90%. Since research on the impact bi-directional charging has on the battery life of an EV is inconclusive, this model assumes the EV to be a curtailable load. Meaning the prosumer only has the option of choosing when to charge the EV. In order for the EV to always be charged when the consumer needs it, a lower limit for SOC is set at 60 kWh. This ensures that the consumer always has available capacity and does not allow for the EV to be totally discharged.

When charging the vehicle at home, a Type 2 (Mennekes – IEC 62196) charger is typically used. This can provide a maximum power output at 16.5 kW, but this needs a 3-phase grid connection, which is unusual for the majority of households. For a 1-phase connection, the maximum power output is 7.4 kW, which will be used in this project [50]. The key EV parameters used for the simulations in the model are presented in Table 5.3.

Table 5.3: Key EV parameters used in simulations

Parameter		Value
Capacity	EV^{cap}	80 [kWh]
Max charging power	$EV^{ch,max}$	7.4 [kW]
Charging efficiency	$\eta^{EV,ch}$	90 [%]
Initial SOC	$EV^{SOC,Initial}$	70 [kWh]
Minimum SOC	$EV^{SOC,min}$	60 [kWh]

The consumption for the EV is modeled based on the average yearly Norwegian mileage for personal vehicles from Statistics Norway (SSB) [51]. EV consumption is ranging from 155–304 Wh/km, and the average distance driven by personal vehicles in Norway in 2017, was 12 228 km [50, 51]. This gives an average consumption of 2806 kWh/year for an electric vehicle. Assuming the vehicle is used roughly the same amount every day, this gives a daily usage of 7.7 kWh. Based on this information four different usage patterns were created to reflect different types of consumers.

Consumption pattern 1 reflects someone who drives to and from work every day and uses the EV every other weekend. Pattern 2 reflects someone who drives to and from work, but also uses the car in the evening. Consumption pattern 3 reflects someone who drives to and from work, but works during the nighttime. And finally, pattern 4 reflects someone with an irregular consumption, who also uses their EV when on vacation. Along with the consumption pattern, the availability pattern is simultaneously defined. The EV is available when there is no consumption. The neighborhood will in total include 15 electrical vehicles. An overview of the four different availability patterns as well as how many prosumers have the different patterns is shown in Table 5.4.

Table 5.4: Overview of EV availability patterns

Availability pattern	Number of prosumers	Available
Pattern 1	5	17:00-08:00 and every other weekend
Pattern 2	4	21:00-08:00 and 17:00-18:00 on weekdays, 18:00-11:00 on Saturdays and on Sundays
Pattern 3	4	04:00-12:00 and 15:00-19:00 and Friday thru Saturday
Pattern 4	3	Irregular availability, is unavailable during vacations

The EV is modeled by a set of equations telling the optimization program how the EV behaves, and what limitations it has. Equation 5.5 describes the SOC evolution and Equation 5.6 defines the EV's constraints in terms of minimum and maximum charging power and minimum and maximum SOC limits.

$$ev_t^{SOC} = ev_{t-1}^{SOC} + ev_t^{ch} \cdot \eta^{EV,ch} - EV_t^{cons} \tag{5.5}$$
$$\text{For } t = 0,\ ev_t^{SOC} = EV^{SOC,Initial}$$

$$ev_t^{ch} < EV^{ch,max} \cdot EV_t^{avail} \tag{5.6a}$$
$$EV^{SOC,min} < ev_t^{SOC} < EV^{cap} \tag{5.6b}$$

, where

$\eta^{EV,ch}$	= EV charging efficiency [%]
EV^{cap}	= EV-battery capacity [kWh]
$EV^{ch,max}$	= Maximum EV charging power [kW]
$EV^{SOC,Initial}$	= Initial EV SOC [kWh]
$EV^{SOC,min}$	= Minimum EV SOC [kWh]
EV_t^{avail}	= EV availability factor in time step t, $EV_t^{avail} \epsilon [0,1]$
EV_t^{cons}	= EV consumption in time step t [kWh/h]
ev_t^{ch}	= EV charging power in time step t [kWh/h]
ev_t^{SOC}	= EV SOC in time step t [kWh]

5.3.3 Water heater

The water heater (WH) is modeled as a typically sized commodity, at 200 liters with a demand equal to that of a small household. To model the demand of such a WH, the standard found in [52] is used, where WH demand for different sized households are given with an hourly resolution. The minimum and maximum temperatures are set to $55°C$ and $90°C$, respectively with an initial temperature of $70°C$. The water heater has a maximum power input of 2 kW, and will act as a curtailable load in the same way as the EV. All of the prosumers in the neighborhood have this water heater. The key parameters used in simulations are presented in Table 5.5.

Table 5.5: Key water heater parameters used in simulations

Parameter		Value
Maximum temperature	T^{max}	90 [°C]
Minimum temperature	T^{min}	55 [°C]
Initial temperature	$T^{temp,Initial}$	70 [°C]
Maximum power input	W^{max}	2 [kW]
Specific heat of water	W^{SHC}	4186 [J/kg C]
Size of water heater	W^{size}	200 [L]

The water heater temperature evolution is given by Equation 5.7, limitations on minimum and maximum temperatures and maximum power input is given by Equation 5.8

$$t_t^w = t_{t-1}^w - \frac{W_t^{demand}}{W^{size} \cdot W^{SHC}} + \frac{w_t^{power}}{W^{size} \cdot W^{SHC}} \tag{5.7}$$

$$\text{For } t = 0,\ t_t^w = T^{temp,Initial}$$

$$w_t^{power} < W^{max} \tag{5.8a}$$

$$T^{min} < t_t^w < T^{max} \tag{5.8b}$$

, where

T^{max}	= Maximum temperature inside water heater $[^{\circ}C]$
T^{min}	= Minimum temperature inside water heater $[^{\circ}C]$
$T^{temp,Initial}$	= Initial temperature inside water heater $[^{\circ}C]$
W_t^{demand}	= Water heater demand in time step t [kWh/h]
W^{max}	= Maximum power supplied to the water heater [kW]
W^{SHC}	= Specific heat of water [J/kg $^{\circ}$C]
W^{size}	= Size of water heater [L]
t_t^{w}	= Temperature inside water heater in time step t $[^{\circ}C]$
w_t^{power}	= Power supplied to water heater in time step t [kWh/h]

5.4 Data sets

In this chapter, the data used in this project is presented. This includes production from the PV-cells, load data for the consumers and spot price data. The load and price data used in this project is relevant for the Trondheim area in 2012, while the PV data is collected from 2016.

5.4.1 Photovoltaic cell production

To model the PV-cells, the method explained in reference [23] is used. The PV panels produce $0.19kW/m^2$ and cover an area equal to $37.84m^2$ giving a maximum theoretical power output of 7.2 kW. For this model, irradiation and temperature data from 2016 is collected from LandbruksMeteorologisk Tjeneste's (LMT) weather station at Skjetlein. Skjetlein is the weather station closest to Trondheim, where the load data is collected.

The rest of the parameters needed to calculate the power output from the solar cells can be found in reference [23]. The power output data has an hourly resolution and the total energy output for 2016 is calculated to be 5858.8 kWh. A total of 10 prosumers in the neighborhood will have PV production. The key parameter of the PV-cell is the hourly output, PV_t^{prod}, given in [kWh/h].

5.4.2 Load data

The load data used in the simulations are gathered from a substation in Trondheim, with a total of 95 different nodes. From this selection, 30 different sets of yearly measurements, with an hourly resolution, were collected. The load profiles include mostly small apartments with an energy consumption between 0.64-3.5kW, but also a grocery store and a pre-school with consumption ranging from 10-31 kW. The measured values are gathered from 01.01.2012 to 30.12.2012 and adds up to a total energy consumption of 789 MWh.

In this thesis, the load data will be used in the simulations, but also to develop the price ranges for the grid structures. The data set does not include information about what appliances are being used, therefore, it is assumed that the load data does not include use of water heaters, electrical vehicles or PV-production. The demand for the EV and WH will be added manually, based on how many appliances exist in the neighborhood, to create a reference case for calculating the grid tariff price ranges. In total, the demand for 30 water heaters and 15 electric vehicles will be added to create the reference case

5.4.3 Price data

The price data is collected from NordPool's historical marked data library for elspot prices [53]. NordPool offers data in different currencies and for several different areas including Trondheim, which was used in this project. Price data from 01.01.2012 to 30.12.2012, given in an hourly solution and NOK/kWh is used for the simulations.

5.5 Objective functions depending on different grid tariffs

In this thesis there are two different grid tariffs being tested, energy based and subscription based. Therefore, there are two different objective functions for the optimization program to minimize. This section explains the structure of the two grid tariffs and presents the objective function for each of them separately. This section also explains the tariff levels the neighborhood can operate under.

The results found in the specialization project leading up to the master thesis found that of the three different power based grid tariffs that NVE proposed, the subscription based tariffs was most effective at incentivizing consumers to reduce power consumption during peak hours. The subscription based tariff reduced power peaks by up to 87.1%, while the time-of-use tariff only was able to reduce peaks by 37.8% (Measured Power was not tested). Therefore, only the subscription based tariff will be further tested in this master thesis. To be able to develop the price ranges for the subscription based tariff, and to have something to compare the results to, the current energy based tariff structure is also tested.

5.5.1 Tariff levels

Both tariff structures are tested on two different levels; Neighborhood level and Consumer level. This is visualized in Figure 5.3. The main difference between the two tariff levels, is who pays the electricity bill. For the neighborhood level, Figure 5.3a, the neighborhood will act as a common node for all the consumers, and only one electricity bill will be generated. For the consumer level, Figure 5.3b, all of the consumers are responsible for their own electricity bill. The differences between the two levels will be explained in further detail in Chapter 6, where the case studies are introduced.

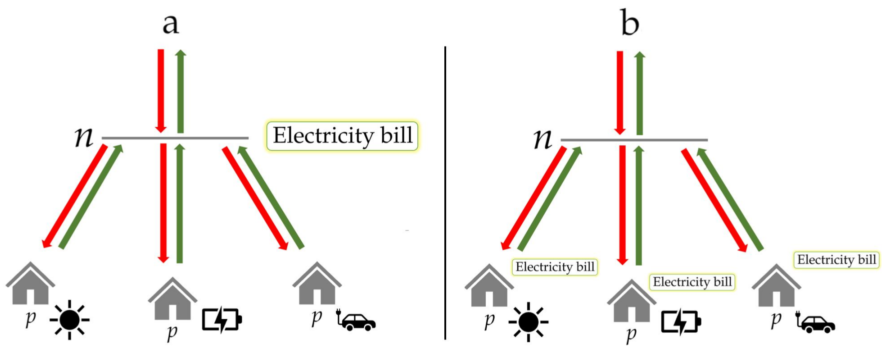

Figure 5.3: (a): Tariff applied on the neighborhood level (b): Tariff applied on consumer level

In the following parts of this chapter, how the grid tariffs are created and how they are implemented in the model is explained. All grid tariffs are modelled without VAT and taxes. This is done so as not to unnecessarily complicate the model. Without taxes and VAT, it is still possible to see the DSO's earning potential as well as the consumers savings potential.

5.5.2 Energy based tariff structure

The energy based tariff structure is constructed as explained in Chapter 3.1.1 with two price parameters. According to NVE, the total cost of the grid tariff should provide the consumer with the same yearly electricity bill regardless of whether it is based on energy or power[2]. Consequently, to design the subscription based tariff structure, the total cost when using the energy based tariff needs to be calculated. NVE's statistics for households, is used to calculate the total tariff price for the neighborhood in 2012 [54]. The price ranges for the energy based tariff from 2012 are presented in Table 5.6.

Table 5.6: Energy tariff price ranges in the Trondheim region from 2012 [54]

Price parameter		**Cost**
Energy price [NOK/kW]	C^{tariff}	0.197
Fixed yearly price [NOK/year]	C^{energy}	1900

First, the total tariff cost for the neighborhood is calculated based on the total energy consumption for the all 30 consumers combined, after adding EV and WH demand. Then, the total tariff cost for a single consumer is calculated based on the average yearly consumption for all the smaller households (including EV and WH demand) Lastly, the total cost for the grocery store and pre-school is calculated. A total of four different tariff costs are calculated. The total yearly tariff price for the energy based structure is calculated as shown in Equation 5.9.

$$P^{tariff} = E^{tot} \cdot C^{tariff} + C^{energy} \cdot N \tag{5.9}$$

, where

P^{tariff}	= Total yearly tariff price [NOK/year]
E^{tot}	= Total yearly energy import [kWh/year]
C^{tariff}	= Energy cost [NOK/kWh]
C^{energy}	= Fixed yearly price [NOK/year]
N	= Number of consumers included in the tariff

The different tariff costs are shown in Table 5.7. These will be used when calculating the price ranges for the subscription based grid tariff in 5.5.3. Note that the grocery store and pre-school includes WH demand, but no EV demand. In the model, the total electricity bill will consist of both the grid tariff and the energy price at each time step (spot price).

Table 5.7: Energy consumption and total tariff cost for the different consumers and neighborhood

Consumer	Yearly energy consumption [kWh/year]	Total tariff cost [NOK/year]
Neighborhood	899577	234217
Small household	20109	5862
Grocery store	273541	55788
Pre-school	93649	20349

Objective function, energy based tariff

The objective function when the energy based tariff is applied, is equal to the electricity bill b^{tot} for either the consumer or the entire neighborhood and is given by Equation 5.10, with import/export and price elements.

$$min \sum_t (e_t^{imp} \cdot (C_t^{spot} + C^{tariff})) - \sum_t (e_t^{exp} \cdot C_t^{spot}) + C^{energy} \tag{5.10}$$

, where

C^{energy}	= Fixed yearly price [NOK/year]
C_t^{spot}	= Spot price in time step t [NOK/kWh]
C_t^{tariff}	= Energy cost in time step t [NOK/kWh]
e_t^{imp}	= Grid import in time step t [kWh/h]
e_t^{exp}	= Grid export in time step t [kWh/h]

For the neighborhood level, e_t^{imp} and e_t^{exp} is equal to n_t^{imp} and n_t^{exp} respectively, and for the consumer level, e_t^{imp} and e_t^{exp} is equal to $p_{p,t}^{imp}$ and $p_{p,t}^{exp}$ respectively.

5.5.3 Subscription based tariff structure

The Subscription based tariff structure is built up in the same way as NVE proposes in their hearing [2]. This includes a fixed price for grid service, a subscription fee depending on the subscription chosen, a price for the total energy used and a price for overconsumption. An overview of the elements in the Subscription based tariff is given in Table 5.8 below.

Table 5.8: Price ranges for the subscription based tariff structure

Price parameter		**Cost**
Energy price [NOK/kWh]	C^{low}	0.05
Overconsumption price [NOK/kWh]	C^{high}	1.00
Fixed yearly price [NOK/year]	$C^{fixedsub}$	1900
Subscription price [NOK/kW]	C^{sub}	
Neighborhood		1057.83
Grocery store		962.24
Residential		866.69
Pre-school		513.82

This tariff structure is more complicated than the current tariff and requires the consumer to make a choice based on previous power use. The consumer chooses a subscription of a certain amount of kW, and every time the consumer surpasses this limit, they will pay an overconsumption price in addition to the energy price. This is the difficult part for the consumer to understand, and will likely be a source of frustration. The choice is supposed to be made based on previous power consumption, for example, last year's load curve. In the simulations, however, the subscription limit is set by the optimization program to the ideal value. The total yearly tariff price is calculated as shown in Equation 5.11 below:

$$P_{tariff} = E^{tot} \cdot C^{low} + E^{over} \cdot C^{high} + C^{fixedsub} + C^{sub} \cdot K^{sub} \tag{5.11}$$

, where

$C^{fixedsub}$	= Fixed yearly price for the subscription based tariff [NOK/year]
P^{tariff}	= Total yearly tariff price [NOK/year]
C^{high}	= Price for overconsumption [NOK/kWh]
C^{low}	= Price for energy [NOK/kWh]
C^{sub}	= Subscription price [NOK/kW]
E^{over}	= Total energy imported above subscription limit [kWh]
E^{tot}	= Total energy import [kWh]
K^{sub}	= Subscribed limit [kW]

Values for fixed price, energy consumption price and overconsumption price are the same as NVE suggests in their hearing. Since the consumers tested in this thesis are different from the one NVE tested, the Subscription fee has been recalculated. NVE suggest designing the tariff such that the consumer ends up with 670 hours of overconsumption [2]. The subscription fee, C^{sub}, for the different consumers is calculated by solving equation 5.11 for C^{sub} when E^{over} is 670 kW, and P^{tariff} is equal to the corresponding total tariff cost given in Table 5.7. The calculated subscription prices are presented in Table 5.8.

In this tariff structure the fixed yearly price, energy consumption price and overconsumption price are all constant. This is to ensure a minimum revenue for the DSO. In the model, the total energy bill will consist of both the grid tariff and the energy price at each time step (elspot price).

Objective function, subscription based tariff

The objective function when the subscription based tariff is applied, is equal to the electricity bill b^{tot} for either the consumer or the entire neighborhood and is given by Equation 5.12, with import/export and price elements.

$$\begin{aligned} min \sum_t ((e_t^{imp} - e_t^{exp}) \cdot C_t^{spot}) + \sum_t (e_t^{imp,l} \cdot C^{low} + e_t^{imp,h} \cdot C^{high}) \\ + C^{sub} \cdot K^{sub} + C^{fixedsub} \end{aligned} \tag{5.12}$$

, where

$C^{fixedsub}$	= Fixed yearly price for the subscription based tariff [NOK/year]
C^{high}	= Price for overconsumption [NOK/kWh]
C^{low}	= Price for energy [NOK/kWh]
C^{spot}	= Spot price in time step t [NOK/kWh]
C^{sub}	= Subscription price [NOK/kW]
K^{sub}	= Subscribed limit [kW]
e_t^{exp}	= Grid export in time step t [kWh/h]
e_t^{imp}	= Grid import in time step t [kWh/h]
$e_t^{imp,h}$	= Grid import above subscription limit in time step t [kWh/h]
$e_t^{imp,l}$	= Grid import below subscription limit in time step t [kWh/h]

For the neighborhood level, e_t^{imp} and e_t^{exp} equals n_t^{imp} and n_t^{exp} , and p_t^{imp} and p_t^{exp} for the consumer level. Similarly, $e_t^{imp,l}$ and $e_t^{imp,h}$ will be equal to $n_t^{imp,l}$ and $n_t^{imp,h}$ or $p_t^{imp,l}$ and $p_t^{imp,h}$ determined by the level of the grid tariff.

Chapter 6

Case studies

The four case studies, aimed to test the capabilities of the grid tariffs and the P2P technology, are introduced in this chapter. All of the case studies are based on the same load data for 30 different households in Steinkjaer, Norway. The load profiles include mostly small apartments, but also a pre-school and a grocery store. The neighborhood is visualized in Figure 6.1.

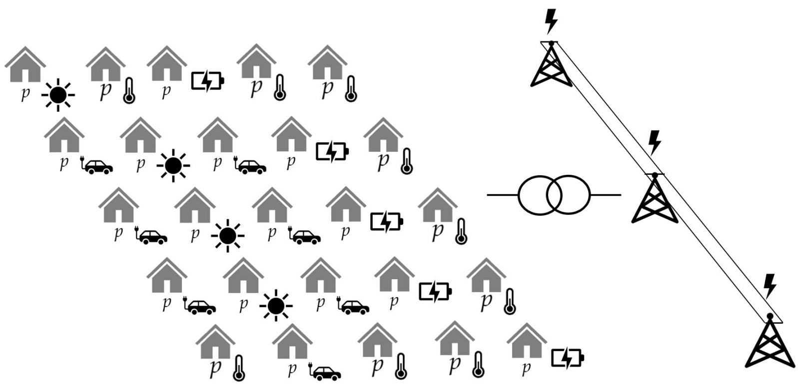

Figure 6.1: Overview of the neighborhood created from the load curves from Steinkjaer

As explained in Chapter 5, the available flexible appliances are the battery, EV and WH. The flexible resources and PV-cells, are distributed throughout the neighborhood, resulting in some consumers having more flexibility than others, but all consumers will have some level of flexibility through the WH. The role of the prosumers have been reserved for the small apartments as it is seen as more likely that private customers have invested in PV, EV and batteries.

The two grid tariff structures will be applied on two levels: Neighborhood level and Consumer level. On the neighborhood level all of the consumers will contribute to a common electricity bill, and therefore also work together to minimize it. For the consumer level, all consumers are working individually and is unaffected by the operation of the other households. A visualization of the different tariff levels is provided in Figure 5.3. P2P trading will only be available for the consumers when the tariffs are applied at the neighborhood level. A summary of the four different case studies can be seen in Table 6.1, with a more detail description following.

Table 6.1: Summary of the four different case studies

Case	Tariff level	Tariff	P2P
Case 1	Consumer	Energy	No
Case 2	Neighborhood	Energy	Yes
Case 3	Consumer	Subscription	No
Case 4	Neighborhood	Subscription	Yes

The reference case mentioned in 5.4.2, will be used as a comparison for the optimized results of the two grid tariffs. The reference case includes the original load curves, consumption for the EVs and WHs, and does not have any form of optimization. The reference case does not include batteries or PV. In the four case studies, the neighborhood has introduced flexible resources in the form of five batteries as well as ten PV-cells and the optimization program can distribute the EV and WH demand freely. An overview of the components in the neighborhood is given in Table 6.2, and will be the same for all of the four case studies. The structure of the grid tariffs is explained in Chapter 5.5.

Table 6.2: Appliances in the neighborhood

Appliance	Number
Water heater	30
Electric vehicle	15
Battery	5
PV-cell	10

6.1 Case 1: Energy based tariff on consumer level

Case study 1 emulates the current state of the distribution market with an energy based grid tariff that only charges for the total energy consumed, and does not take into account the power consumption. The grid tariff is applied to every single consumer individually, and therefore does not allow for peer-to-peer trading between the households. A prosumer in this case study will therefore only have the opportunity to sell its excess energy back to the grid. The components in the neighborhood and grid tariff price ranges are presented in Table 6.2 and Table 5.6 respectively. The objective function is given by Equation 5.10.

6.2 Case 2: Energy based tariff applied on neighborhood level

The second case study moves the grid tariff from the consumer level, up to the neighborhood level. By doing this, all of the households will be able to cooperate to reduce the total cost for the neighborhood. This can be done by trading energy internally (P2P). The components of the neighborhood are identical to those of case study 1, and the grid tariff has the same price ranges. The objective function is given by Equation 5.10.

6.3 Case 3: Subscription based tariff on consumer level

For the third case study the grid tariff is changed to the subscription based structure. The components are the same as in case study 1 and 2 and the grid tariff is applied to each consumer individually, meaning there is no possibility for P2P energy trading. The price ranges for the subscription based structure can be seen in Table 5.8 and the objective function is given by Equation 5.12. In this case study, the individual subscription prices for the grocery store, residential and pre-school are applied.

6.4 Case 4: Subscription based tariff applied on neighborhood level

The final case study applies the subscription based grid tariff to the neighborhood level, enabling P2P energy trading. The components of the neighborhood is unaltered from the previous case studies and are presented in Table 6.2. The price ranges for the tariff structure are identical to the one displayed in Table 5.8 for case study 3, and the objective function is given by Equation 5.12. This case study only applies the neighborhood subscription price.

Chapter 7

Results and Discussion

In this chapter, the results from the different case studies will be presented and compared. First, the case studies were compared in terms of ability to reduce power peaks during scarcity hours in the national grid. Next, they were compared in terms of P2P energy trading and flexibility operation. Further, a sensitivity analysis was conducted to see to which extent the flexible appliances are assisting the consumers, and the subscription based tariff was investigated in terms of the price signals given to the consumer. Lastly, blockchain technology is discussed along with the sources of error.

7.1 Power peak reduction during scarcity hours

To be able to compare the results obtained from the different case studies, the national load in Norway from 2012 was used [55]. The 438 hours (5%) with the highest consumption, was chosen to represent peak load and scarcity hours. These hours were then used to collect the corresponding hours of the optimized results, to see how the consumers operate during critical hours. These results are presented in figures 7.1 and 7.2, for consumer level and neighborhood level respectively, where the total import is sorted from largest to lowest, with respect to the energy tariff. Figure 7.3 shows the duration curves for all the different case studies and tariff structures during the scarcity hours.

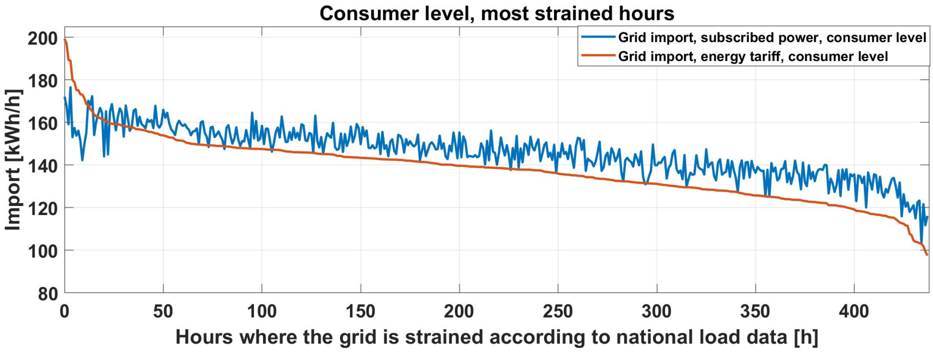

Figure 7.1: Total import for the neighborhood during scarcity hours with grid tariffs applied at consumer level

Figure 7.1 shows the neighborhood import for the two grid tariffs during the peak load hours of the national load, with tariffs applied at consumer level. It is clear that the energy based grid tariff manages to maintain a lower level of import for most of the hours. The average import of the energy based tariff is lower than the subscription based tariff at 138 kW compared to 146 kW, but for the 25 hours with the highest import, the averages are 171 kW and 167 kW, for the energy and subscription based tariffs respectively. The energy based tariff has the highest peak import of the two at 199 kW whereas the subscription tariff only reaches 177 kW, corresponding to an 11 % decrease in peak power import.

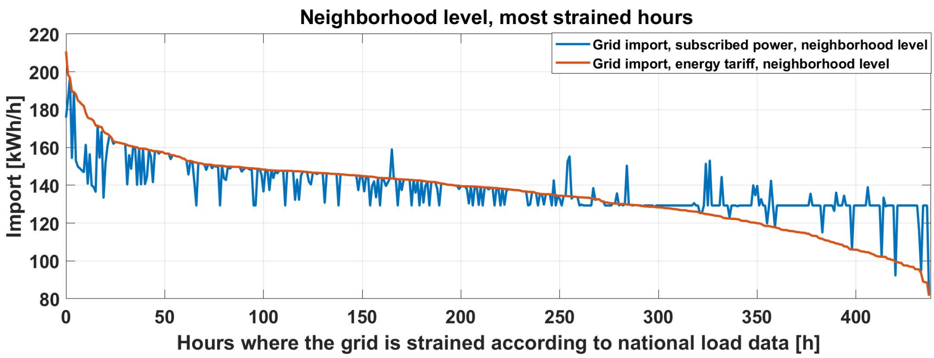

Figure 7.2: Total import for the neighborhood during scarcity hours with grid tariffs applied at neighborhood level

Figure 7.2 displays the neighborhood import when the grid tariffs applied at neighborhood level during national peak hours. When optimizing under the subscription based grid tariff, the neighborhood import is generally lower, until it reaches the subscription limit at 129 kW, clearly outperforming the energy based tariff, with respect to reducing peak load during scarcity hours. Similarly to the case at consumer level, the energy based tariff has the highest import value during the peak hours at 211 kW compared to 196 kW for the subscription based structure, a drop of 7 %. The average import during the 25 most strained hours is 179 kW for the energy tariff and 166 kW for the subscription tariff. The subscription tariff has a lower average import until the energy based tariff imports below the subscribed limit of 129 kW, at 143 kW compared to 147 kW for the energy based tariff.

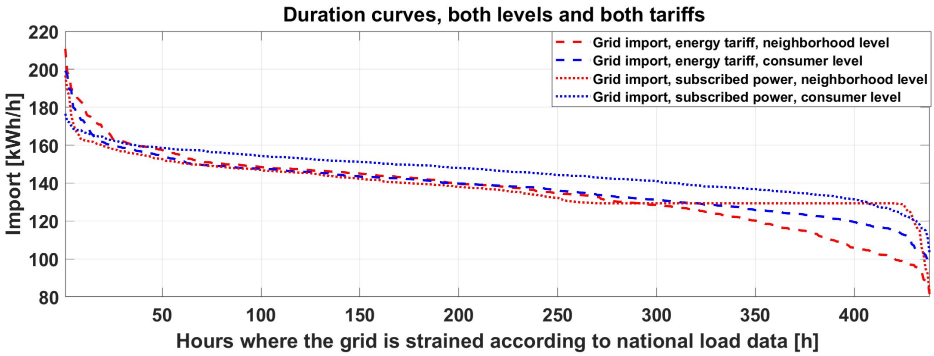

Figure 7.3: Duration curves based on neighborhood import during scarcity hours for all four cases studies

The duration curves for the four case studies displayed in Figure 7.3, shows how the subscription based structure provides a more stable import for the neighborhood. This is particularly clear for the subscribed power at neighborhood level (red dotted line), where the import is constant at the subscribed limit for over 150 hours. The figure also shows that for the neighborhood level, the average neighborhood import is reduced compared to the consumer level. This is true for both tariff structures at 1.4% reduction and 5.2% reduction for the energy based and subscription based tariff, respectively.

To further investigate the impacts of the different grid tariffs, a day with several consecutive scarcity hours was chosen to exemplify flexibility operation. The 13th of December contained 15 hours from the selection of 438 peak load hours. This is presented in figures 7.4 and 7.5 for a single prosumer and the neighborhood respectively.

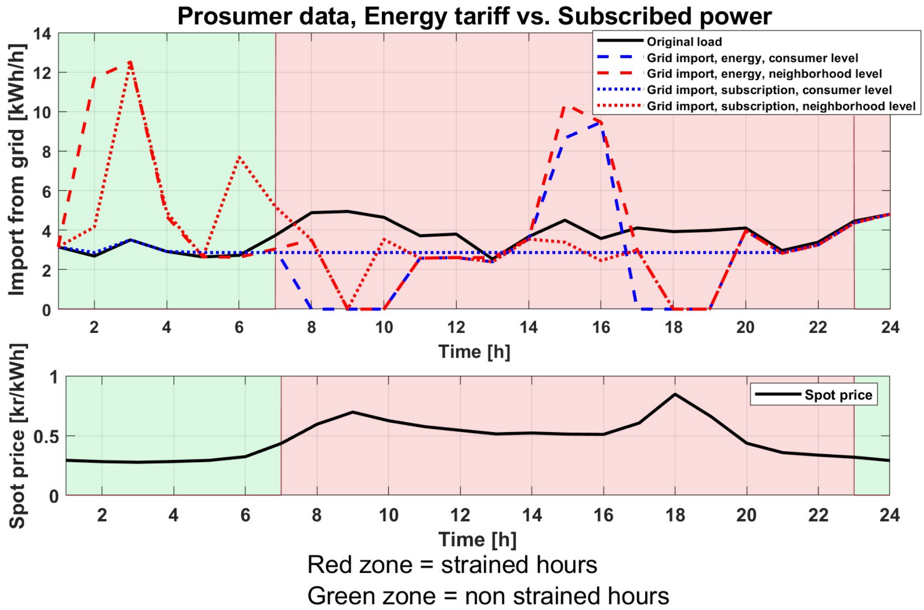

Figure 7.4: Prosumer import for all four cases studies compared to the reference case load curve on December 13

Figure 7.4 shows how on the neighborhood level (red), both of the tariff structures import during low load hours (01:00-07:00), to reduce import during higher priced hours, occurring at 09:00 and 18:00. Both tariffs manage to reduce the power import at price spikes, but the energy based tariff creates a new power peak at 15:00-16:00. This is disadvantageous as this is during the national peak hours.

When looking at the consumer level (blue), a similar scenario takes place. Both tariffs avoid the price spikes at 09:00 and 18:00, but the energy based tariff creates a new power peak at 15:00-16:00. The subscription based tariff structure manages to import at a stable rate by working towards, but preferably not over, the subscribed limit and thus distributes the load effectively. Figure 7.4 shows how subscribed capacity incentivizes stable net import during peak load hours, shifting large imports to low load hours, typically during the night.

An important aspect of the import curves in Figure 7.4 is the points where they are zero. In these time periods the prosumer is exporting electricity, but only for the neighborhood level will the prosumer be exporting this electricity to another consumer, and thus help the neighborhood as a community (P2P). This effect is visible in Figure 7.5 and will be discussed later.

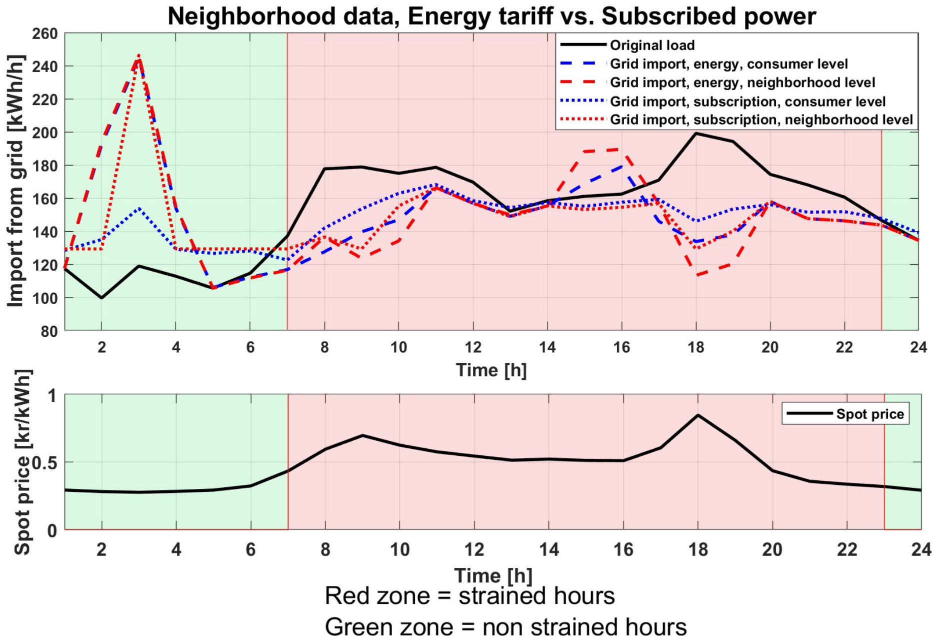

Figure 7.5: Neighborhood import for all four cases studies compared to the reference case load curve on December 13

When looking at the import for the neighborhood in Figure 7.5, it is clear that the subscription based tariff is able to reduce the original load during peak hours, while the energy based tariff creates a new power peak (Which is not necessarily less favorable than the two for the original load, but still worse than for subscribed power). This is the case for both neighborhood level (red), and consumer level (blue). The figure clearly shows the positive effects of P2P trading for the neighborhood. In the time period 18:00-19:00, where the prosumer is exporting energy (Figure 7.4), the neighborhood is importing less energy from the grid, for both tariffs when P2P trading is available (red), compared to when every consumer is working individually (blue).

7.2 Peer-to-peer energy trading and flexibility operation

For case study 2 and 4, P2P energy trading is enabled, meaning prosumers with excess energy are able to help other consumers, eliminating the need for grid import. Figure 7.6 visualize how the energy is being shared between the different consumers in an hour with particularly much P2P activity. As shown by the figure, prosumers with excess PV-production (1-10), are exporting energy to the consumers with no energy production (11-30). Except for consumer 19 and 22 which are not participating in P2P activities at this particular hour, because there is no locally produced energy to spare. Since the model in this thesis is unable to track energy transactions, it is assumed that the energy goes through a peer-pool where all consumers have access.

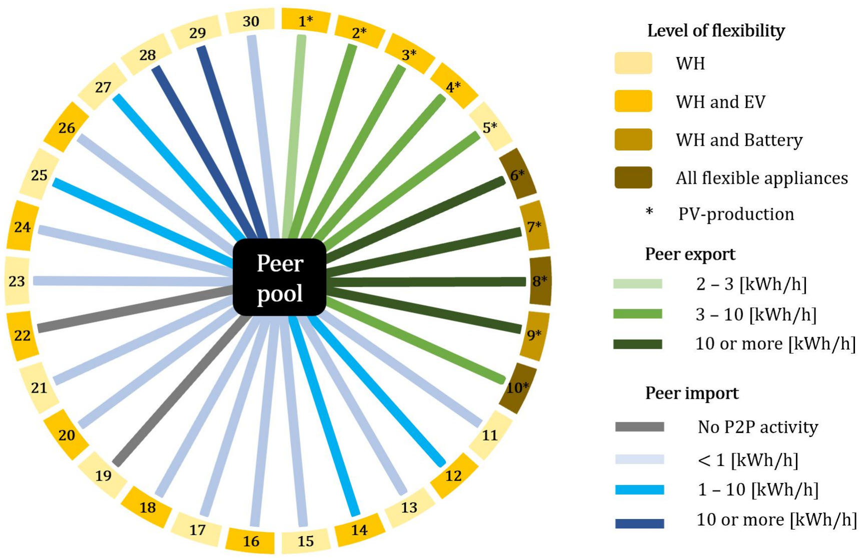

Figure 7.6: Peer-to-peer activity between the consumers in the neighborhood for an hour with high occurrence of P2P energy trading

Table 7.1 shows the peer import and export activity during the year, for the entire neighborhood. When optimizing under the energy based tariff, the P2P activity is increased by 10.3% compared to the subscription based tariff. Still, the total grid import for the subscription based tariff is the lower by 506 kWh (0.6% decrease). This suggests that under the energy based tariff, the prosumers are more willing to share their energy, but that they use it more wisely under the subscription based tariff. When trading via peers there is a 3% energy loss, which is avoided by charging the EV or WH instead (self-consumption). This is probably what causes the difference of 506 kWh throughout the year.

Table 7.1: Totel peer-to-peer energy trading activity in the neighborhood for the two tariff structures in case study 2 and 4

Yearly import/export	**Grid import [kWh/year]**	**Grid export [kWh/year]**	**Peer import [kWh/year]**	**Peer export [kWh/year]**
Energy tariff	852702	0	27526	28377
Subscription tariff	852196	0	24957	25729

The total peer import and export activities for a single prosumer with all flexible resources, are presented in Table 7.2. Both tariffs have very similar import and export activities for the entire year, and there is no clear distinction. If however, the import and export activities during the national scarcity hours is considered, it is clear that the energy based tariff utilizes P2P more than the subscription based tariff. This is most likely due to the spot price being the strongest incentive for the energy tariff. Still, Figure 7.2 and Figure 7.5, as discussed earlier, show that the subscription based tariff is more effective at reducing peak power import.

Table 7.2: Import and export for a single prosumer when P2P energy trading is enabled (Case study 2 and 4)

Yearly import/export	**Grid import [kWh/year]**	**Grid export [kWh/year]**	**Peer import [kWh/year]**	**Peer export [kWh/year]**
Energy tariff	17206	0	20.3	3474.8
Subscription tariff	17215	0	17.8	3493.2
Scarcity hours	**Grid import [kWh]**	**Grid export [kWh]**	**Peer import [kWh]**	**Peer export [kWh]**
Energy tariff	1039	0	0	325
Subscription tariff	946	0	0	73

As expected, the flexible prosumer is exporting more energy through peers than it is importing. This is the case for the entire year as well as during scarcity hours for both tariffs. This is a clear indicator that the strong prosumers with a lot of flexibility, are incentivized to help the other consumers with less flexibility, as shown in Figure 7.6.

To visualize how different prosumers use their available flexibility and P2P trading, a prosumer with only the WH as flexibility is compared to a prosumer with PV production, battery, and WH. The plots are shown in Figures 7.7-7.10 and gathers data from the same day displayed in Figures 7.4 and 7.5, including import and export activities, PV-production, battery SOC and WH input. The plots show how the different consumers shift the demand of the water heater and when they import or export energy via peers.

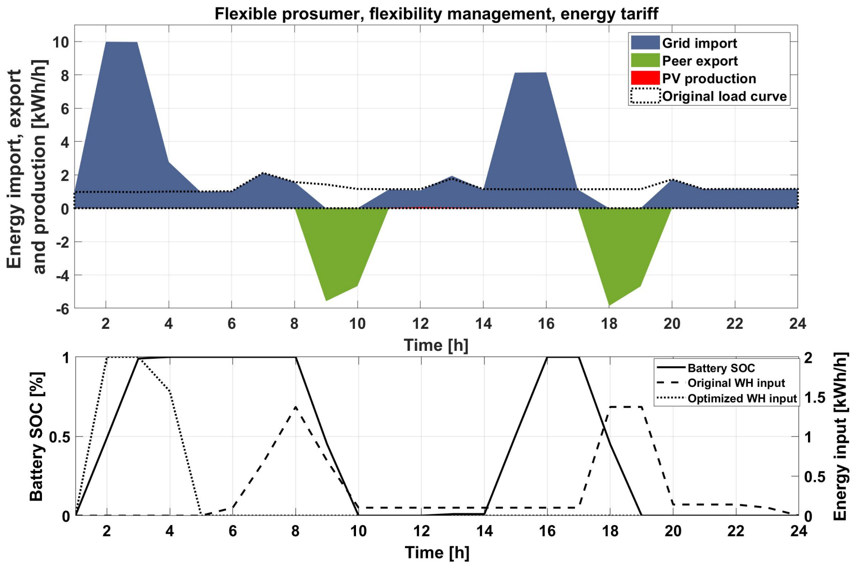

Figure 7.7: Import/export activities and flexibility management for a prosumer with WH and battery operating under the energy based tariff

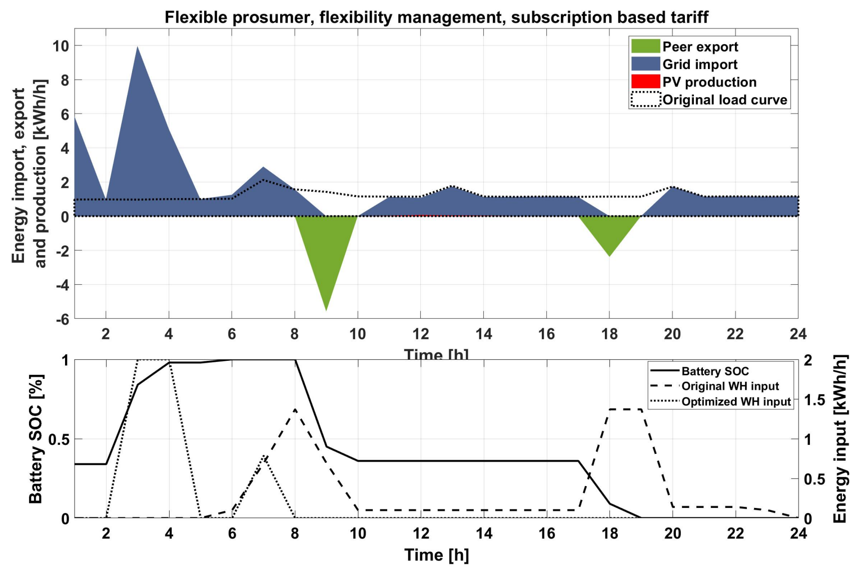

Figure 7.8: Import/export activities and flexibility management for a prosumer with WH and battery operating under the subscription based tariff

Figures 7.7 and 7.8 shows a prosumer, with a WH and battery as flexible resources and PV production, operating under the two different tariff structures. Since this is in the middle of December, naturally, the PV production is low and almost not noticeable. For both tariff structures, the optimization program chooses to charge the battery and heat the water in the middle of the night or during the early morning. By doing this, the demand for the water heater is moved from peak hours in the morning and evening, to low load hours. The battery capacity gained here is being used to export energy to other peers later in the day for both tariffs.

The main difference between the two tariff structures is the new power peak created by the energy tariff from 15:00-16:00, also observed in Chapter 7.1. Since the energy based tariff does not take into consideration how much power is imported, the prosumer will be incentivized to buy energy when the spot price is low, creating these new peaks. The power based tariff, on the other hand, is actively trying to stay below the import limit that has been set by the neighborhood and manages to avoid new power peaks during typical peak hours. The figures also show how the battery is being used to help other less flexible consumers by exporting energy when prices are high.

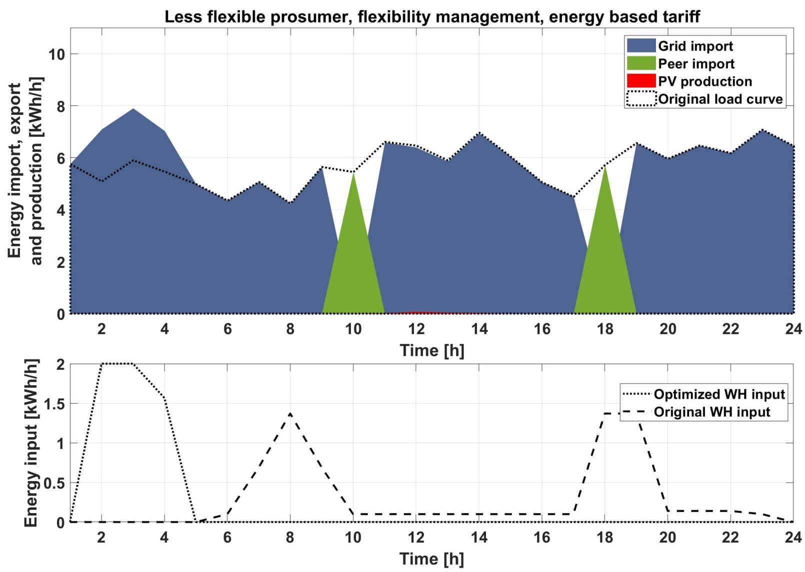

Figure 7.9: Import/export activities and flexibility management for a prosumer with only a WH operating under the energy based tariff

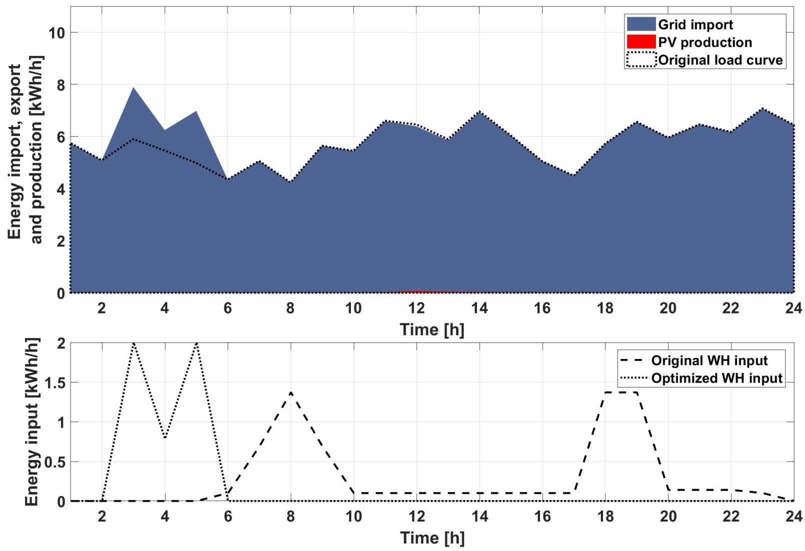

Figure 7.10: Import/export activities and flexibility management for a prosumer with only a WH operating under the subscription based tariff

In Figures 7.9 and 7.10 a less flexible prosumer operating under both tariff structures is presented. This prosumer only has the WH as a flexible resource and PV production. Both tariff structures manage to shift water heating to low load hours, but only the energy based tariff structure takes advantage of local energy. The energy based tariff structure import energy from peers when the price is high, and by doing so, does not contribute to the total energy grid import. The subscription based tariff, however, does not import any energy from its peers, the reason most likely being that another consumer in the neighborhood got prioritized by the optimization program, and thus no more local energy was available for the prosumer investigated in this case.

The two sets of figures (7.7-7.8 and 7.9-7.10) show how the more flexible prosumers contribute to lowering the total grid import by sharing excess energy with the other less flexible consumers in the neighborhood. They also show how energy demand is moved from the typical peak load hours by charging batteries and heating water during the nighttime.

7.3 Sensitivity analysis

The neighborhood has consumers with different amounts of flexibility. As previously stated, all of the consumers have some flexibility in the form of the water heater, which they are able to postpone or expedite power to. This type of prosumer is most common in the neighborhood with 13 out of 30 residents. The rest of the consumers will have some sort of flexible appliance, either in the form of an EV or a battery, some even both. An overview of the flexibility distribution in the neighborhood is shown in Table 7.3.

Table 7.3: Overview of the flexibility distribution in the neighborhood

Level of flexibility	WH	WH & EV	WH & Battery	WH, EV & Battery
Amount of consumers	13	12	2	3

In this chapter, one consumer/prosumer from each level of flexibility is compared in terms of peak power reduction during scarcity hours and total electricity bill for all case studies. This is shown in Tables 7.4 and 7.6. Scarcity hours are defined in the same way as in Chapter 7.1.

Table 7.4: Difference in average consumption during scarcity hours compared to reference case load curve for the different consumer levels in all the case studies

	Difference in average consumption during scarcity hours compared to reference case load curve[NOK/year]			
Level of flexibility	**WH**	**WH & EV**	**WH & Battery**	**WH, EV & Battery**
Energy tariff Consumer level	-2.4%	-2.8%	-47.8%	-30.9%
Energy tariff Neighborhood level	-2.6%	-2.8%	-10.5%	-16.5%
Subscription tariff Consumer level	-1.6%	2.5%	4.2%	-2.3%
Subscription tariff Neighborhood level	-2.1%	-2.2%	-32.9%	-24.0%

From the results shown in Table 7.4, it is clear that the battery has the biggest impact on power peak reduction. When a consumer has a battery and a water heater, it can reduce power peaks during scarcity hours by 47.8%. The EV and WH by themselves, are only able to reduce power peaks by 2.8%, for certain cases.

The battery is the most versatile flexibility resource since it can be both charged and discharged. In Table 7.5, battery activity for a prosumer with all flexible appliances is shown. Case study 2 utilizes the battery the most, at 3096 kWh of charge per year, while case study 3 deploys the battery the least at 1808 kWh of charge per year.

Table 7.5: Battery use for the different case studies for a prosumer with all flexible appliances

Case study	Battery charge [kWh/year]
Case 1	2745
Case 2	3096
Case 3	1807
Case 4	2973

Table 7.4 also shows how when the subscription based tariff is applied at the consumer level, it is difficult for the neighborhood to lower its total import. For all levels of consumer flexibility, case study 3 achieved the least power peak reduction. This is due to the consumer working towards its own subscribed limit, and by doing so, the consumer will often increase the import compared to the reference load. This was also observed in Chapter 7.1, Figure 7.1 where the average power import for the subscribed capacity stays above the energy based tariff for almost all scarcity hours.

Table 7.6: Total yearly electricity bill for prosumers with different levels of flexibility in all case studies

<table>
<tr><th></th><th colspan="4">Total yearly electricity bill [NOK/year]</th></tr>
<tr><th>Level of flexibility</th><th>WH</th><th>WH & EV</th><th>WH & Battery</th><th>WH, EV & Battery</th></tr>
<tr><td>Energy tariff
Consumer level</td><td>9770</td><td>9501</td><td>3803</td><td>7908</td></tr>
<tr><td>Energy tariff
Neighborhood level</td><td colspan="4">434269</td></tr>
<tr><td>Subscription tariff
Consumer level</td><td>10405</td><td>9592</td><td>3599</td><td>7967</td></tr>
<tr><td>Subscription tariff
Neighborhood level</td><td colspan="4">430101</td></tr>
</table>

Table 7.6 shows the total yearly electricity bill for the four different flexibility levels, as well as the total electricity bill for the neighborhood when the two different tariffs are applied. For the consumer with WH and EV, the electricity bill is approximately the same with at 9501 and 9592 NOK/year. This is also the case for the most flexible consumer at 7908 and 7967 NOK/year.

The consumer with a WH and battery manages to reduce the total electricity bill by 5.4% when using the subscription based tariff, compared to the energy based tariff, while the least flexible consumer increases the bill by 8.5% in the same scenario. The table also shows that the total electricity bill for the neighborhood only differs by 0.96%. It is difficult to make any definite conclusions based on these results since the subscription based tariff for the consumers is based on the average yearly consumption of all of the 28 smaller households in the neighborhood. This means that the consumer will be either charged more or less depending on how the actual consumption compares to the yearly average.

7.4 Ability to provide reasonable price signals

To investigate if the subscription based tariff structure gives good price signals to the consumers, the total neighborhood import is plotted for case 4, and the total import for a prosumer with all flexible resources is plotted for case 3. These are presented in Figure 7.11.

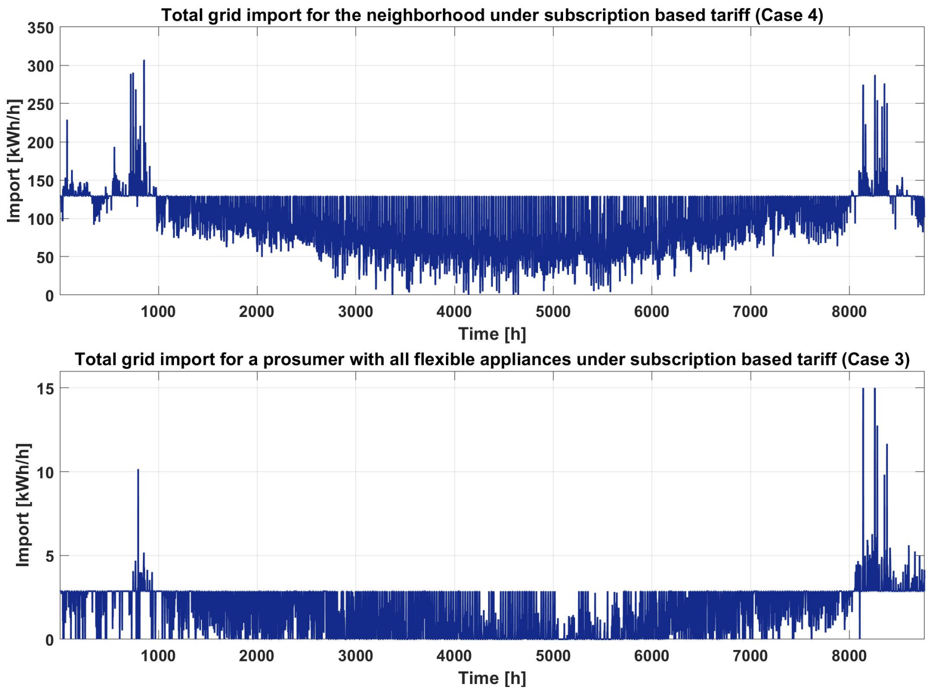

Figure 7.11: Total yearly grid import for the neighborhood in case 4 and total yearly grid import for a flexible prosumer in case 3

For both cases, the import stays below the subscribed limit during the summer months, meaning consumers are given price signals to reduce their consumption when the grid is not typically strained. A solution to this could be to implement a seasonal dynamic subscription limit that can be increased or decreased depending on the strain in the grid.

Also common for both cases it that when the optimization program has decided that it needs to import above the subscription limit, it will do so far above the limit. At the most, the power import is 234% and 523% higher than the subscribed limit for the neighborhood and prosumer respectively. This is due to the design of the subscription based tariff. Currently, it does not punish the consumer differently if they import 1 or 100 kW above the subscribed limit. The high import spikes seen in Figure 7.11 does not necessarily occur during scarcity hours, but could help contribute to new power peaks and a less stable grid. A possible solution to this problem could be to make the cost of overconsumption quadratic. By making the overconsumption cost quadratic, the consumer is incentivized to keep overconsumption as low as possible, this will help distribute the import more evenly. To make the overconsumption cost quadratic, the import above the subscribed limit, $e_t^{imp,h}$, in Equation 5.12 is raised to the power of two. A quadratic overconsumption cost is visualized in Figure 7.12.

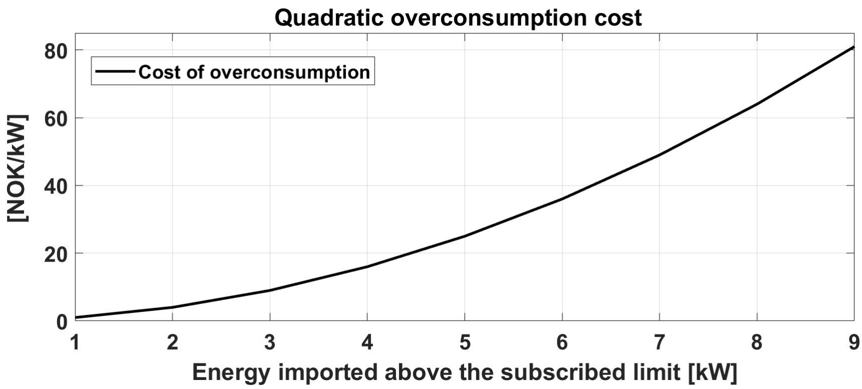

Figure 7.12: Overconsumption cost as a function of how far above the subscription limit energy is imported, when the overconsumption cost is quadratic

A simulation where the electricity bill has a quadratic overconsumption cost was conducted to see the effects this would have on a flexible prosumer. Figure 7.13 shows a prosumer's original unoptimized reference load curve, optimized grid import when operating under the original subscription based tariff and optimized grid import when operating under a subscription based tariff with a quadratic overconsumption cost. It is important to note that for the day presented in Figure 7.13, the prosumer is importing above the subscribed limit at all hours.

For the quadratic cost function, the prosumer increases import during the first 9 hours of the day, in order to avoid higher power import when the demand increases at 12:00-14:00 and 19:00-20:00, keeping the grid import at a stable level. The original cost function does not take into consideration how far above the subscribed limit it is located, and imports enough to cover the original load (including the demand of the water heater in time steps 16:00-20:00). This result shows that the subscription based tariff structure can be significantly improved.

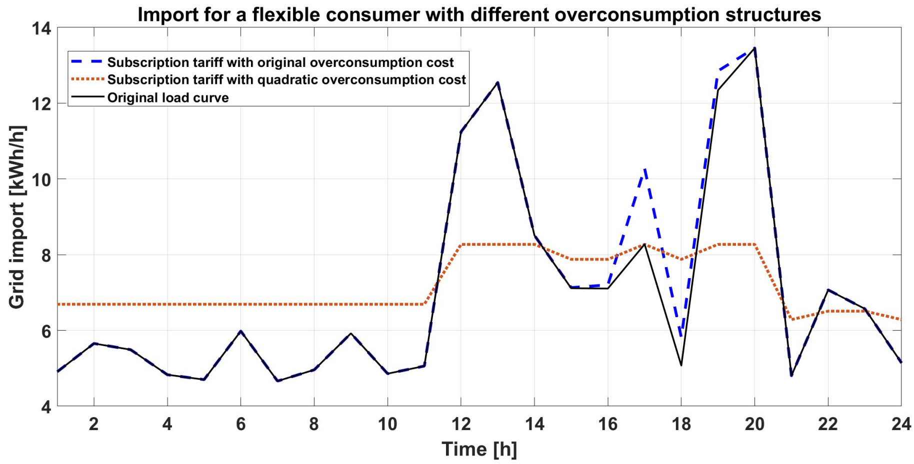

Figure 7.13: Optimized import for a flexible consumer operating under the original overconsumption cost compared to a consumer operating under under a quadratic overconsumption cost

7.5 Blockchain technology

Even though blockchain technology is not directly used in the construction of the neighborhood model, it is a prerequisite for the model to work. The model assumes that a P2P network is in place and that energy transactions between nodes in the network are cost-efficient and work seamlessly. This requires blockchain technology. In addition to making minuscule transactions cost-efficient, the blockchain stores information about the transactions in a secure manner, opening up for better tracking of local or green energy production and automated billing for consumers through smart contracts.

The main challenge for the blockchain technology is scalability. Every time a new block is added to the existing blockchain, a consensus algorithm must be solved. when a network is expanded, and all nodes are initiating their own transactions, this could become a substantial computational burden and revenue from the minuscule energy transactions may get overshadowed by the electricity cost from solving the consensus algorithms. In addition to improving the consensus algorithms, the structure of the network can help with scalability. As discussed in Chapter 3.2, a community based market structure, where several nodes are aggregated through a community manager, working towards a common goal, greatly helps with scalability.

7.6 Sources of error

This section will discuss aspects of the model that could contribute to varying results. Suggestions for improvements is given in Chapter 9.

The EV is modeled such that only 20 kWh of the 80 kWh battery available. This is because the $EV^{SOC,min}$ constraint, set to 60 kWh, tells the optimization program that the EV cannot leave or arrive at the charging point below this limit. By doing this, the consumer cannot drive for longer distances than 20 kWh requires, making the model inaccurate. Realistically, the EV is able to use all of the 80 kWh available and can arrive at the charger with 0% SOC, leading to a higher EV demand than what is currently reflected in the model. On the background of this, the optimization program could make decisions differing from the current results.

The WH model does not include heat loss. Heat loss is dependent on the temperature inside the tank, i.e the heat loss is at highest for T^{max}, and lowest for T^{min}. If this was included in the model, the optimization program would have postponed heating the water as long as possible and would have kept the temperature as close to T^{min} as possible, to keep heat loss to a minimum. The current state of the model does not consider what temperature the water has, just that it stays inside the set temperature limits.

Furthermore, the WH demand used for all consumers in this model, are equal. For this to be more realistic, demand curves representative for each of the different sized consumers, should be applied. Especially for the grocery store and pre-school, since these represent a larger power demand and energy consumption than the one used in this thesis. However, it is difficult to assess how this would have impacted the results since the load data used in this model most likely include water heater consumption.

The irradiation and temperature data used to create the PV power output was obtained from 2016. This was the same data used in the specialization project when the load and price data was also collected from 2016. In this thesis, however, the load and price data are from 2012. This means that the solar energy production is not correctly reflected by the power demand and spot price. If the years 2012 and 2016 are immensely different in terms of solar power production, this would have an impact on the results, but not a bigger impact than if a different setup for the PV-cells were chosen.

Based on the results found in the specialization project, the time-of-use tariff structure was not investigated in this thesis. This is one of the grid tariffs NVE proposed as a possible replacement for the energy based tariff. The model has developed a lot since this conclusion was made, and the effects P2P energy trading and aggregated flexibility management has on peak shaving under this grid tariff is unknown. This will be suggested as further work for this thesis.

Chapter 8

Conclusion

In this chapter, conclusions are drawn from the results in Chapter 7, and the research questions are answered.

The research questions this thesis aims to answer is:

- **To which extent optimized flexibility dispatch and peer-to-peer trading in neighborhoods results in lower peak loads during scarcity hours under a subscribed capacity tariff?**

  When operating under a subscribed capacity tariff, the peak power import during scarcity hours is reduced by 11% for the consumer level (P2P disabled), and 7% for neighborhood level (P2P enabled), compared to the energy based tariff at the same tariff level. However, the average power import during scarcity hours is only reduced compared to the energy based tariff, when the neighborhood is operating under a common tariff.

- **Do subscribed capacity tariff structures incentivize more grid friendly power consumption than energy based tariff structures when consumers are aggregated?**

  The subscription based tariff is able to reduce peak power import and maintain a lower import until the subscription limit is reached, keeping the import at a stable level for over 150 of the 438 scarcity hours, clearly outperforming the energy based tariff. Reduction in peak power import and a more stable consumption proves that the capacity based tariff incentivize more grid friendly power consumption, compared to the energy based tariff.

- **What is the consequence of aggregating consumers under a common neighborhood based grid tariff, compared to single customers?**

  Aggregating the consumers in the neighborhood increases the peak power import, but decreases the average consumption during scarcity hours compared to when consumers are operating individually. This is true for both grid tariffs at 1.4% and 5.2% reduction, for the energy based tariff and subscription based tariff, respectively, but most prominent for the subscription based tariff due to the introduction of the subscription limit.

The subscription based tariff structure has advantages on the energy based tariff, but it also has its downsides. The subscription based tariff provides price signals to reduce consumption when the grid is not strained and does not prevent the optimization program from importing far above the subscribed limit. A quadratic overconsumption cost might be a solution to this problem.

The results also showed that more P2P trading does not necessarily mean more power peak reduction and that it depends on the right tariff structure to get the most effect out of the flexible resources. Of the three different flexible resources (battery, EV, and WH), the battery proved most influential in power peak reduction.

Chapter 9

Further work

For further work, the following aspects of the neighborhood model should be considered.

Changes in the model, as discussed in Chapter 7, can be made to make the simulations more realistic in terms of vehicle use, water heater consumption and PV-production. This should include a lower limit for EV departure, but no lower limit for EV arrival. The water heater model should be modeled to include heat loss and demand profiles accurate to each individual consumer. Ideally, load curves without water heater demand should be used, although this might be difficult to obtain. For future simulations, all data should be gathered from the same time period.

The grid tariffs in the current model are representative of the current energy based grid tariff for household customers, and the subscription based tariff suggested by NVE. As discovered in the specialization project leading up to this thesis, and in this thesis itself, the subscription based tariff has some flaws. Mainly that when the consumer imports electricity above the subscribed limit, it does not matter how far above the limit they import. Simulations using a subscription based tariff, with a quadratic overconsumption cost, to see the effects this would have on the import for the neighborhood should be conducted.

In addition to making the overconsumption cost quadratic, it would also be interesting to add seasonal change in overconsumption price. This could possibly eliminate the sub-optimal price signals during the summertime when there are few scarcity hours.

Future work should also include testing of the Time-of-use tariff structure proposed by NVE. This tariff was not included in this thesis, because it was proven less effective compared to the subscription based tariff in the specialization project. However, this might change when the tariffs are applied to a neighborhood capable of P2P energy trading.

As for more future work and what the model can be used for, it should be looked into creating a P2P or local energy market structure, where consumers are given different incentives to participate. The results in this thesis gave little evidence that a prosumer saves money by owning flexible appliances and using them to help other consumers. This market design should include a price suggestion for selling and buying local energy, and possibly use a blockchain platform to track where the energy is being produced and used. An idea would be to include a higher cost for green and local energy, compared to energy bought from the grid. With such a market, a detailed cost analysis can be conducted to see how long it will take for consumers to earn back the cost of flexible resources and or how much the DSO is willing to pay the consumer for their flexibility.

The model created in this thesis consists of 30 different consumers with three different flexible appliances (EV, WH, and battery), PV production and two different grid tariff structures. The neighborhood can easily be expanded to include more than 30 households and other types of consumers. It would be interesting to see how the flexibility operation of the neighborhood is handled in a much larger neighborhood, with more consumers accompanied by higher power and energy demand.

The neighborhood model should also be expanded in terms of physical and technical limitations, such as the maximum power import/export of the transformer and the fuses of each consumer to investigate the possible benefits or downsides P2P energy trading has on issues such as congestion and overvoltage.

This study aims to give an idea of how different grid tariff structures and a peer-to-peer market design can be used to reduce peak loads, and is thus deterministic, showing benchmark results with perfect foresight of load, PV production, prices, and EV availability. Future studies could be done using stochastic programming in order to illuminate the consequences of not including uncertainty in this study.

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Appendix - Conference paper

The appendix includes the full academic paper submitted to the SEST 2019 conference in Porto.

Reducing Neighborhood Peak Loads with a Peer-to-Peer Approach under Subscribed Capacity Tariffs

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***Abstract*—Increased power demand is a growing problem for distribution system operators (DSO) capable of causing unwanted and expensive grid upgrades. Descending prices for flexible resources and power generation such as house batteries, electric vehicles (EV) and photovoltaic (PV) cells allow for consumers to have a more active role in the energy system and possibly help avoid these expensive upgrades. In this paper we propose a peer-to-peer (P2P) market structure which allows for electricity trading between end-users to investigate how aggregated operation under different tariffs can reduce power consumption during peak hours. We developed a mixed integer linear programming (MILP) optimization model performed on a small neighborhood consisting of 30 consumers with different amounts of flexible resources to test the market structure. We simulate four different case studies, and the results show an 11% decrease in peak power import during scarcity hours and a more stable import when P2P trading is enabled under a subscription based tariff structure. The main conclusion from this study is that there is a clear potential in local electricity markets and capacity based grid tariff structures, especially when metered at neighborhood level.**

***Index Terms*—Neighborhood peak load, Prosumer, Peer-to-peer, Battery, Electrical Vehicle, Flexible loads, Grid tariffs,**

NOMENCLATURE

Sets

p	Prosumer index, $p\epsilon$[1,30]
t	Time index [hour], $t\epsilon$[1,8760]

Parameters

$\eta^{bat,ch}$	Battery charging efficiency [%]
$\eta^{bat,dis}$	Battery discharging efficiency [%]
$\eta^{EV,ch}$	EV battery charging efficiency [%]
η^{loss}	Loss when importing using P2P[%]
B^{cap}	Total battery capacity [kWh]
$B^{ch,max}$	Battery max charging power [kW]
$B^{dis,max}$	Battery max discharging power [kW]
C^{energy}	Fixed yearly price, energy tariff [NOK/year]
$C^{fixedsub}$	Fixed yearly price, subscription tariff [NOK/year]
C^{high}	Price, energy imported above sub-limit [NOK/kWh]
C^{low}	Price, energy imported below sub-limit [NOK/kWh]
C^{sub}	Subscription price [NOK/kW]
C^{tariff}	Grid tariff price, energy tariff [NOK/kWh]
C_t^{spot}	Spot price in time step t [NOK/kWh]
EV^{cap}	EV-battery capacity [kWh]
$EV^{ch,max}$	Max EV charging power [kW]
$EV^{SOC,min}$	Min EV SOC [kWh]
EV_t^{avail}	EV availability factor for time step t, $EV_t^{avail}\epsilon$[0,1]
EV_t^{cons}	EV consumption in time step t [kW]
K^{sub}	Subscribed limit [kW]
P_t^{load}	End user load in time step t [kW]
PV_t^{prod}	Production from PV-cells in time step t [kW]
T^{max}	Max temp inside water heater [°C]
T^{min}	Min temp inside water heater [°C]
W^{max}	Max power supplied to the water heater [kW]
W^{SHC}	Specific heat of water [J/kg °C]
W^{size}	Size of water heater [L]
W_t^{demand}	Water heater demand in time step t [kW]

Variables

b^{tot}	Total electricity bill [NOK]
b_t^{ch}	Battery charging power in time step t [kW]
b_t^{dis}	Battery discharging power in time step t [kW]
b_t^{SOC}	Battery SOC in time step t [kWh]
e_t^{exp}	Energy export in time step t [kWh]
$e_t^{imp,h}$	Energy import above sub-limit in time step t [kWh]
$e_t^{imp,l}$	Energy import below sub-limit in time step t [kWh]
e_t^{imp}	Energy import in time step t [kWh]
ev_t^{ch}	EV charging power in time step t [kW]
ev_t^{SOC}	EV SOC in time step t [kWh]
n_t^{exp}	Total neighborhood export in time step t [kWh]
$n_t^{imp,h}$	Neighborhood import above sub-limit in time step t [kWh]
$n_t^{imp,l}$	Neighborhood import below sub-limit in time step t [kWh]
n_t^{imp}	Total neighborhood import in time step t [kWh]
$p_{p,t}^{exp,g}$	Prosumer grid export in time step t for prosumer p [kWh]
$p_{p,t}^{exp,p}$	Prosumer peer export in time step t for pro-

	sumer p [kWh]
$p_{p,t}^{exp}$	Total prosumer export in time step t for prosumer p [kWh]
$p_{p,t}^{imp,g}$	Prosumer grid import in time step t for prosumer p [kWh]
$p_{p,t}^{imp,h}$	Prosumer grid import above sub-limit in time step t for prosumer p [kWh]
$p_{p,t}^{imp,l}$	Prosumer grid import below sub-limit in time step t for prosumer p [kWh]
$p_{p,t}^{imp,p}$	Prosumer peer import in time step t for prosumer p [kWh]
$p_{p,t}^{imp}$	Total prosumer import in time step t for prosumer p [kWh]
t_t^w	Temp inside water heater in time step t [° C]
w_t^{power}	Power supplied to the water heater in time step t [kW]

I. Introduction

The increasing amount of power demand, especially due to electric vehicles, is a major concern for DSOs. Higher power demand leads to expensive upgrades for the DSOs. A possible solution to these grid expansions is to utilize flexible loads, which has been researched extensively in recent years. In addition to utilization of flexible loads, P2P trading has also been suggested as early as in 2007 in [1]. In [2] Alexandra Lüth et al. research the role of battery flexibility in a P2P market by creating an optimization model, reaching savings of up to 19.6%.

The P2P trading concept is still an area of the energy market that is still actively being investigated and needs a lot more research to be able to go commercial. Pilot projects such as the Brooklyn Microgrid project by Mengelkamp et al. [3], has achieved successful results in implementing the P2P concept in Brooklyn and has shown the technology's potential. In [4] Pierre Pinson et al. introduce consumer-centric electricity markets and highlight challenges they are facing in order to function.

The technology does not come without challenges. In [3] Mengelkamp et al. also discusses seven steps that need to be fulfilled in order for the P2P concept to work, the two biggest being blockchain and regulation. Blockchain technology is needed to make the small energy trades done in a P2P system cost-effective. Blockchain can do this by eliminating the need for a third party to approve the transactions and distributing this task to all of the nodes in the system. This, however, also comes with its challenges, one of which is discussed in [5], where Andoni et. al raises the concern for the energy used to solve the different consensus algorithms.

This paper asks how grid tariffs and P2P trading affect the energy import management of a small neighborhood. This is done by modelling a neighborhood of 30 unique households/entities that are able to trade energy locally (P2P) as well as utilize several different flexible loads. It is assumed that every minuscule energy trade is cost efficient and possible.

II. Model

The model arranges the neighborhood, prosumers and appliances in a hierarchical structure with the neighborhood on top. The Python-based open-source optimization language Pyomo is used to develop the model which is described in the following chapters.

A. Problem definition

The optimization program aims to optimally schedule end-user flexibility in order to minimize total costs, using a MILP formulation. Through investigating the total cost under energy based and subscription based tariffs, we illuminate how the peak load during scarcity hours are reduced. In this paper two grid tariffs are investigated: Energy based and Subscription based (Power). These are explained in detail in Chapter II-H. The optimization program minimizes the cost by utilizing flexible resources, curtailable loads and energy production (PV). The optimization problem is run for a year with an hourly resolution.

B. Neighborhood

The neighborhood consists of 30 unique load data sets with an hourly resolution for the calendar year of 2012. 28 of the data sets are small households, while the two remaining are a grocery store and a pre-school. The neighborhood model includes an energy balance consisting of total grid-import and export for all the different consumers. This does not take into account the energy traded internally between the households (P2P). The energy balance is shown in equation 1.

$$n_t^{imp} - n_t^{exp} = \sum_p (p_{p,t}^{imp,g} - p_{p,t}^{exp,g}) \tag{1}$$

When the subscription based tariff is applied, the import is split into low and high, $n_t^{imp,l}$ and $n_t^{imp,h}$, to be able to allocate the overconsumption price explained in II-H.

C. Consumer/Prosumer

All of the consumers have an associated energy balance, which includes all of the appliances available, shown in equation 2. The flexible appliances will be explained throughout this chapter.

$$\begin{aligned} p_{p,t}^{imp,p} \cdot \eta^{loss} + p_{p,t}^{imp,g} - p_{p,t}^{exp,p} - p_{p,t}^{exp,g} = P_t^{load} \\ + b_t^{ch} - b_t^{dis} + ev_t^{ch} + w_t^{power} - PV_t^{prod} \end{aligned} \tag{2}$$

The consumer level also splits the import into low and high, $p_t^{imp,l}$ and $p_t^{imp,h}$, when the subscription based tariff is applied.

D. Battery

The battery is modeled to emulate the Tesla Powerwall 2 unit [6] with a maximum capacity of 13.5 kWh, maximum power input/output of 7 kW and a charge/discharge efficiency of 95%. It is assumed that the battery starts completely discharged with a state-of-charge (SOC) at zero. Battery SOC evolution, min and max charging power limitations and max SOC limits are shown equation 3.

$$b_t^{SOC} = b_{t-1}^{SOC} + b_t^{ch} \cdot \eta^{bat,ch} - \frac{b_t^{dis}}{\eta^{bat,dis}} \tag{3a}$$
$$b_t^{ch} < B^{ch,max} \tag{3b}$$
$$b_t^{dis} < B^{dis,max} \tag{3c}$$
$$0 < b_t^{SOC} < B^{cap} \tag{3d}$$

E. Electric vehicle

The EV is modeled as a curtailable load, meaning it does not have the option of bi-directional charging. The EV chosen for this paper has a maximum capacity of 80 kWh and an efficiency of 90%. In order for the EV to always be charged when the consumer needs it, a lower limit for the SOC is set at 60 kWh. The consumption for the EV is modeled based on the average yearly Norwegian mileage for personal vehicles from Statistics Norway (SSB). Four different usage patterns were created to reflect different types of consumers. It is assumed that the EV starts with a SOC at 70 kWh. Equation 4 describes the EV SOC evolution, charging limitations under availability conditions, and min and max SOC limits.

$$ev_t^{SOC} = ev_{t-1}^{SOC} + ev_t^{ch} \cdot \eta^{EV,ch} - EV_t^{cons} \tag{4a}$$
$$ev_t^{ch} < EV^{ch,max} \cdot EV_t^{avail} \tag{4b}$$
$$EV^{SOC,min} < ev_t^{SOC} < EV^{cap} \tag{4c}$$

F. Water heater

The water heater (WH) represents a typically sized commodity at 200 liters with the consumption equal to a small household. To model the demand of such a WH the standard found in [7] is used. The min and max temperatures are set to 55$°C$ and 90 $°C$, respectively. The water heater has a maximum power input of 2 kW and will act as a curtailable load described in equation 5 with temperature evolution, max input power and min/max temperature limits.

$$t_t^w = t_{t-1}^w - \frac{W_t^{demand}}{W^{size} \cdot W^{SHC}} + \frac{w_t^{power}}{W^{size} \cdot W^{SHC}} \tag{5a}$$
$$w_t^{power} < W^{max} \tag{5b}$$
$$T^{min} < t_t^w < T^{max} \tag{5c}$$

G. PV cells

Irradiation and temperature data from a weather station close to Trondheim, Norway was used to calculate output from the PV-cells. In total the PV-cells cover 37.84m^2 and produce 0.19 kW/m^2 giving a total of 7.2 kW of maximum theoretical power output. The data time resolution is hourly. The calculations are explained in detail in [8].

H. Grid tariffs

The energy based grid tariff charges the consumer based on energy consumption. This is the current grid tariff applied to the majority of consumers in Norway, with exception of bigger consumers such as industry and corporate customers. It consists of a price per kWh the consumer imports from the grid and a fixed yearly cost. The price ranges for the energy based tariff is collected from NVE for 2012 [9] and are shown in Table I. This study does not include taxes as it would be the same for both tariff structures.

TABLE I
ENERGY TARIFF PRICE RANGES [9]

Price parameter		Cost
Energy price [NOK/kW]	C^{tariff}	0.197
Fixed yearly price [NOK/year]	C^{energy}	1900

To incentivize consumers to lower power consumption and thereby lowering power peaks in the system, a subscription based grid tariff has been proposed [10]. This charges the consumer based on power and not energy imported. The consumer will subscribe to a certain amount of kW and pay a low price per kWh as long as they keep their consumption below this power limit. Once they import above the subscribed limit the grid tariff cost per kWh will increase. The subscription based structure also includes a fixed yearly cost.

The energy price, overconsumption price and fixed yearly price shown in Table II are identical to the ones suggested by NVE in [10]. The subscription price is calculated on the basis of the electricity bill the consumer/neighborhood attains under the energy tariff without any form of flexibility or optimization. The total electricity bill should be equal for both tariff structures when the average consumption is the same to cover the cost of the DSO. The calculated subscription cost for the different types of consumers as well as the neighborhood can be seen in Table II.

TABLE II
PRICE RANGES FOR THE SUBSCRIPTION BASED STRUCTURE [10]

Price parameter		Cost
Energy price [NOK/kWh]	C^{low}	0.05
Overconsumption price [NOK/kWh]	C^{high}	1.00
Fixed yearly price [NOK/year]	$C^{fixedsub}$	1900
Subscription price [NOK/kW]	C^{sub}	
Neighborhood		1057.83
Grocery store		962.24
Residential		866.69
Pre school		513.82

I. Objective function

The objective functions represent the yearly electricity bill b^{tot} for either the consumer or the entire neighborhood. For the energy based grid tariff the objective function is described in equation 6 with import/export and price elements.

$$\begin{aligned} min \sum_t (e_t^{imp} \cdot (C_t^{spot} + C^{tariff})) \\ - \sum_t (e_t^{exp} \cdot C_t^{spot}) + C^{energy} \end{aligned} \tag{6}$$

e_t^{imp} and e_t^{exp} is equal to n_t^{imp} and n_t^{exp} for the neighborhood level and $p_{p,t}^{imp}$ and $p_{p,t}^{exp}$ for the consumer level. For the subscription based grid tariff equation 7 describes the objective function with import/export and price elements.

$$\begin{aligned} min \sum_t ((e_t^{imp} - e_t^{exp}) \cdot C_t^{spot}) \\ + \sum_t (e_t^{imp,l} \cdot C^{low} + e_t^{imp,h} \cdot C^{high}) \\ + C^{sub} \cdot K^{sub} + C^{fixedsub} \end{aligned} \tag{7}$$

e_t^{imp} and e_t^{exp} equals n_t^{imp} and n_t^{exp} for the neighborhood level and p_t^{imp} and p_t^{exp} for the consumer level. $e_{imp,l}$ and $e_t^{imp,h}$ will similarly be equal $n_t^{imp,l}$ and $n_t^{imp,h}$ and $p_t^{imp,l}$ and $p_t^{imp,h}$ determined by the level of the grid tariff.

III. Case Studies

In this paper four different case studies are tested. All of which are based on load data for 30 different households in Steinkjaer, Norway. The load profiles include mostly small apartments with an average power consumption between 0.64-3.5 kW, but also a pre-school and a grocery store with an average between 10-31 kW. As explained in Chapter II, the available flexible appliances are battery, EV and WH. The flexible resources and PV-cells, are distributed throughout the neighborhood resulting in some consumers having more flexibility than others, but all consumers will have some sort of flexibility through the WH. An overview of the appliances can be seen i Table III.

TABLE III
Appliances in the neighborhood

Appliance	Amount
Water heater	30
Electric vehicle	15
Battery	5
PV-cell	10

The two grid tariff structures will be applied on two levels: Neighborhood level and Consumer level. On the neighborhood level all of the consumers will contribute to a common electricity bill and therefore also work together to minimize it. For the consumer level all consumers are working individually and is unaffected by the operation of the other households. P2P trading will only be available for the consumers when the tariffs are applied at the neighborhood level. A summary of the four different case studies can be seen in Table IV.

TABLE IV
Summary of case studies

Case	Tariff level	Tariff	P2P
Case 1	Consumer	Energy	No
Case 2	Neighborhood	Energy	Yes
Case 3	Consumer	Subscription	No
Case 4	Neighborhood	Subscription	Yes

A reference case was used to derive the price ranges of the tariff structures as well as to observe the effects of flexibility and P2P functionalities. The reference case includes the original Steinkjaer load curves, WH consumption and usage patterns for the EVs. The reference case has no form of optimization. It is assumed that the original load curves do not include WHs and that all WHs follow the same usage patterns mentioned in Chapter II. The reference case does not include batteries or PV.

IV. Results

To be able to compare the results obtained from the different case studies the national load in Norway from 2012 is used. The 438 hours (5%) with the highest consumption represents peak load or scarcity hours. These hours are then used to collect the corresponding hours of the optimized results to see how the consumers operate during critical hours. These results are shown in figures 1 and 2, for consumer level and neighborhood level respectively, where the total import is sorted from largest to lowest with respect to the energy tariff. Figure 3 shows the duration curves for all the different case studies, and tariff structures during the peak load hours.

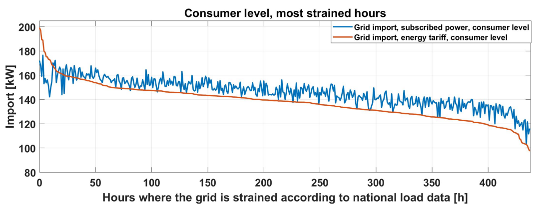

Fig. 1. Total import for the entire neighborhood with grid tariffs applied at consumer level

Figure 1 shows the neighborhood import for the two tariffs during the peak load hours of the national load with tariffs applied at consumer level. It is clear that the energy based grid tariff manages to maintain a lower level of import for most of the hours. The average import of the energy based tariff is lower than the subscription based tariff at 138 kW compared to 146 kW, but for the 25 hours with the highest import the averages are 171 kW and 167 kW, for the energy and subscription based tariffs respectively. The energy based tariff has the highest peak import of the two at 199 kW whereas the subscription tariff only reaches 177 kW, which corresponds to a 11 % decrease in peak load.

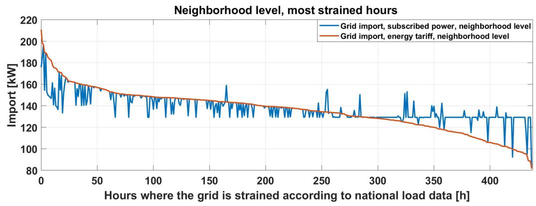

Fig. 2. Total import for the entire neighborhood with grid tariffs applied at neighborhood level

Figure 2 displays the neighborhood import with tariffs applied at neighborhood level during national peak hours. When optimizing under the subscription based grid tariff, the neighborhood import is lower until it reaches the subscription limit at 129 kW, clearly outperforming the energy based tariff with respect to reducing peak load during scarcity hours. Similarly to the case at consumer level, the energy based tariff has the highest import value during the peak hours at 211 kW compared to 196 kW for the subscription based structure, a drop of 7 %. The average import during the 25 worst hours is 179 kW for the energy tariff and 166 kW for the subscription tariff. The subscription tariff has a lower average import until the energy based tariff imports below the subscribed limit of 129 kW at 143 kW compared to 147 kW for the energy based tariff.

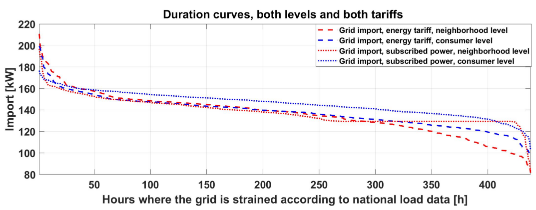

Fig. 3. Import for all four cases studies compared to the original load curve on neighborhood level.

The duration curves for the four different cases displayed in Figure 3 shows how the subscription based structure provides a more stable import for the neighborhood. This is particularly clear for the subscribed power at neighborhood level where the import is constant at the subscribed limit for over 150 hours.

To further investigate the impacts of the different grid tariffs, a day with many consecutive scarcity hours is chosen to exemplify flexibility operation. The 13th of December contains 15 hours from the selection of 438 peak load hours. This is shown in figures 4 and 5 for a prosumer and the neighborhood respectively.

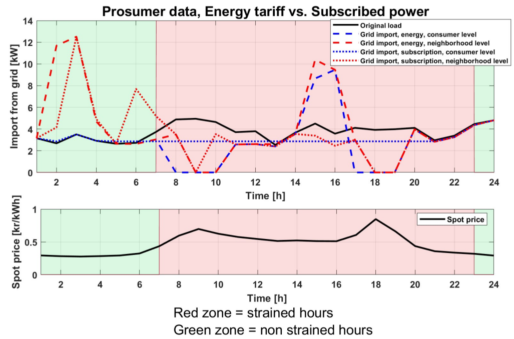

Fig. 4. Import for all four cases studies compared to the original load curve on consumer level.

Figure 4 shows how on the neighborhood level (red), both of the tariff structures import during the low load hours (01:00-07:00) to reduce load during high price hours occurring at 09:00 and 18:00. Both tariffs manage to reduce the power import at price spikes, but the energy based tariff creates a new power peak at 15:00-16:00. This is disadvantageous as this is still during the national peak hours.

When looking at the consumer level (blue) a similar scenario takes place. Both tariffs avoid the price spikes at 09:00 and 18:00, but the energy based tariff creates a new power peak at 15:00-16:00. The subscription based tariff structure manages to import at a stable rate by working towards, but preferably not over, the subscribed limit and thus distributes the load effectively. Figure 4 shows how subscribed capacity incentivizes stable net import during peak load hours, shifting large imports to low load hours, typically during the night.

An important aspect of the import curves in Figure 4 is the points where they are zero. In these time periods the prosumer is exporting electricity, but only for the neighborhood level will the prosumer be exporting this electricity to another consumer, and thus help the neighborhood as a community (P2P). This effect is visible in Figure 5 and will be discussed later.

When looking at the data for the neighborhood in Figure 5 it is also clear that the subscription based tariff is able to reduce the original load during peak hours, while the energy based tariff creates a new power peak. (Which is not necessarily worse than the two for the original load, but still worse than the subscribed power). This is the case for both neighborhood level (red) and consumer level (blue). This figure clearly shows the positive effects of P2P trading for the neighborhood. In time period 18:00-19:00 where the prosumer is exporting, the neighborhood is importing less energy from the grid for both tariffs when P2P trading is available (red) compared to when every consumer is working individually (blue).

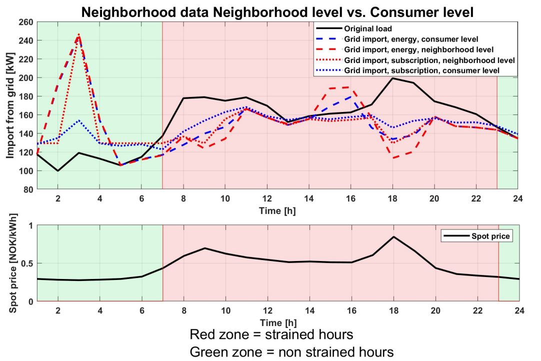

Fig. 5. Import for all four cases studies compared to the original load curve on neighborhood level.

V. Discussion

Figures 1 and 2 show that the subscription based tariff structure outperforms the energy based structure in reducing power peaks during scarcity hours for the national load. A reduction of 11% and 7% was seen for the consumer level and neighborhood level respectively. When looking at the 25 worst hours, the subscription based tariff has a lower average import at both tariff levels.

From the DSOs standpoint a stable grid is important. This makes future investments and expansions more predictable and less expensive. From Figure 3 it is clear that the subscription based tariff structure has the most stable import during scarcity hours. The results also show that aggregation outperforms consumer level metering. Figure 5 shows this effect clearly as the import is lower for both the cases where P2P trading is available. By operating under a common node, the strong prosumers are given incentive to help neighbors with less flexibility to reduce peak loads.

The difference in total cost between the subscription based tariff and the energy tariff in this paper is less than 1% for both consumer and neighborhood level. The results provided by this paper proves that the P2P technology is effective at removing power peaks during peak hours in the grid.

VI. Conclusion

The results show that the subscription based tariff structure was most effective at reducing power peaks in the 25 most critical hours. The subscription based tariff was also able to maintain a more stable import during peak load hours. Further, it was shown that tariffs applied at neighborhood level allowing for P2P trading, were most effective at lowering the total neighborhood import during scarcity hours with an 11 % peak load reduction. In conclusion, the subscription based tariff structure shows great potential for peak shaving, especially when combined with aggregated operation.

A possible improvement to the subscription based structure is to add another layer of overconsumption where if the import surpasses a certain point above the subscribed limit, the overconsumption price increases. This would further help keep power peaks to a minimum. Exploring the willingness to pay for local electricity (P2P) could also be interesting.

The current study aims to give an idea of how different grid tariff structures and a peer-to-peer market design can be used to reduce peak loads, and is thus deterministic and shows benchmark results with perfect foresight of load, PV production, prices and EV availability. Future studies could be done using stochastic programming or a sensitivity analysis in order to illuminate the consequences of not including uncertainty in the study.

This paper focuses on the duration curves and import for the neighborhood. In future research how and when the different flexible resources are being used, should be investigated to determine which are more effective and what impact they have.

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