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Guro Sæther

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NTNU
Norwegian University of
Science and Technology
Faculty of Information Technology and Electrical
Engineering
Department of Electric Power Engineering

NTNU
Norwegian University of
Science and Technology

Guro Sæther

Peer-to-Peer Energy Trading in Combination with Local Flexibility Resources in a Norwegian Industrial Site

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Guro Sæther

Master of Energy and Environmental Engineering	
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Supervisor:	Olav Bjarte Fosso (IE)
Co-supervisor:	Salman Zaferanlouei (IE) Pedro Crespo del Granado (IØT) Andreas Hammer (NTE Nett AS)

Norwegian University of Science and Technology
Department of Electric Power Engineering

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Trondheim, 02.05.2019

Guro Sæther

Guro Sæther

Abstract

With the increasing deployment of decentralized renewable energy sources (DERs) and energy demanding devices, the power system is facing new challenges, such as the need of flexibility options at local level. Meaning that the power system conventional top-down structure might change as consumers are becoming more active entities. Such a restructuring requires new ideas for market designs that considers local energy features. Thus, energy storage systems and peer-to-peer (P2P) energy trading have emerged as new ways to decrease the stress of the grid and foster the deployment of DERs. Another promising solution to incentive consumers to reduce their power demand and forward efficient network utilization, is to implement a peak power charge in the grid utility tariff. Industrial customers are already subject to such a peak power charge, and are billed for the highest peak drawn from the grid each month.

As some local market designs have been proposed for residential communities and smart grids, this study proposes two market designs for an industrial site centered on the role of P2P energy trading. With higher energy demand and a peak power charge, industrial consumers are subject to a considerably cost of electricity. In this study, the value of P2P energy trading in combination with various local generation and flexibility resources are assessed for a Norwegian industrial site. The objective is to minimize the total cost of electricity, while ensuring a fair market design for all participants in the industrial site. In this regard, the system operation of P2P trading subject to the peak power charge is an additional contribution to the existing literature. An optimization model, based on multi-period linear programming, is built and simulated with a time horizon of one year in GAMS. Several analyses are carried out using time series (representing a proxy industrial site) provided by the grid owner, NTE Nett AS, located in central Norway.

The main findings note that P2P energy trading is able to bring economic benefits to the industrial site, as well as to the individual buildings, with yearly net savings of the total cost of electricity of 6.8 % and 11.0 % in the two local markets. Further, using P2P energy trading for peak shaving purposes are highly beneficial. The total cost of peak power is reduced 15.0 % and 25.6 % in the two case studies, with the substantial peak power charge as key driver, making peak shaving the largest contributor to the net cost savings. Moreover, the industrial site consumes more distributed generation locally, with no power curtailment and reduced grid feed-in. The thesis provides novel results on the benefits of P2P energy trading, especially with regards to industrial customers and the peak power charge.

Sammendrag

Med den økende utrullingen av desentraliserte fornybare energikilder og energikrevende enheter møter dagens kraftsystem nye utfordringer. Som et behov for fleksible alternativer på lokalt nivå. Det betyr at kraftsystemets konvensjonelle struktur kan endres, når kunder går primært fra å være pris takere til å være aktive kunder med produksjon. En slik restrukturering krever nye ideer for markedsdesign som hensyn tar lokale aktører. Fremtredende løsninger for å redusere belastningen på overføringsnettet og fremme distribusjon av fornybare energikilder, er energilager og peer-to-peer (nabo) energihandel på lokalt nivå. En annen lovende løsning kan være å innføre et effektledd i nettleien for gi sluttbrukere et insentiv til å redusere effekttopper. Industri- og næringskunder er allerede tariffert med et kostbart effektledd, og faktureres for den høyeste effekttoppen hver måned.

Etter som flere design for lokale marked har blitt foreslått for bolignabolag og smarte nett, presenterer denne hovedoppgaven to markedsdesign for et industriområde med fokus på rollen til peer-to-peer energihandel. Industribygg har et høyt energi- og effektbehov, og dermed en betydelig kostnad relatert til strømforbruk. I denne studien vurderes verdien av peer-to-peer energihandel i kombinasjon med lokale fornybare energi- og fleksibilitetskilder for et industriområde lokalisert i Midt-Norge. Målet er å minimere de totale strømkostnadene for industriområdet, samtidig som det sikres et rettferdig lokalt marked. En optimaliseringsmodell, basert på multi-steg lineær programmering, er utviklet og simulert over ett år i GAMS. Flere case-studier har blitt utført med last- og produksjonsdata levert av den lokale netteieren, NTE Nett AS.

Resultatene viser at peer-to-peer energihandel gir økonomiske fordeler til industriområdet, samt hvert enkelt industribygg, med årlige totale strømkostnadsbesparelser på 6.8 % og 11.0 % for de to markedsdesignene. Peer-to-peer energihandel er også svært gunstig for å redusere effekttopper, med totale besparelser i effekttoppkostnader på 15.0 % og 25.5 %. Med effektleddet i nettleien som driver, bidrar dette til de største kostnadsreduksjonene for industriområdet. Videre brukes mer av den fornybare produksjonen lokalt, hvor på ingen produksjon er tapt og mindre er solgt til distribusjonsnettet.

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Acronyms

AMS Advanced Metering System

BC Base Case

BESS Battery Energy Storage System

B# Building #

CCU Central Coordination Unit

CHP Combined Heat and Power

C1 Case 1

C2 Case 2

DER Distributed Energy Resource

DG Distributed Generation

DR Demand Response

DSO Distribution System Operator

ESS Energy Storage System

EV Electric Vehicle

FiT Feed-in Tariff

FiUT Feed-in Utility Tariff

GAMS General Algebraic Modeling System

ICT Information and Communication Technology

IEA International Energy Agency

Li-ion Lithium-ion

LS Load Shift

NTE Nett AS	Nord-Trøndelag Power Company AS
NVE	The Norwegian Water Resources and Energy Directorate
PS	Power Subscription (NO: Abonnert effekt)
PV	Photovoltaic
P2P	Peer-to-Peer
RES	Renewable Energy Source
SOC	State of Charge
TOU	Time-of-Use
TØI	Institute of Transport Economics
V2B	Vehicle-to-building
V2G	Vehicle-to-grid

Chapter 1

Introduction

1.1 Background and Motivation

The need for integration of renewable energy sources (RESs) in the electricity generation portfolio have attracted attention from the world, due to the increasing shortage of fossil fuels, rapidly increase in energy demand and pollution problems [2–5]. As a result, the conventional electrical power systems are changing, with a vast deployment of volatile and decentralized renewable energy sources. While distribution systems were originally designed assuming power flow from bulk power generation to end-use load points at the edges of the distribution system, incorporation of distributed energy resources (DERs) increasingly violates this assumption [6, 7]. This introduces new challenges for the distribution system operators (DSOs), such as bidirectional energy flows, voltage instability, and reduction in power quality. [8, 9]. With this, the power systems are drifting away from the conventional top-down structure, with consumers becoming more active. To facilitate this transition and foster the deployment of DERs, distributed flexibility options and microgrid alternatives are emerging [6, 7, 9].

Furthermore, advances in electricity generation, storage and Information and Communication Technology (ICT) technologies coupled with diminishing costs, the planned roll out of smart meters and favorable regulations, traditional energy consumers are becoming prosumers [10–12]. Prosumers can both consume and generate energy. As a result, local energy systems, such as rooftop solar photovoltaic (PV) systems, locally owned energy storages, small-scale wind farms and combined heat and power (CHP), are rapidly entering the power market [5]. Such a restructuring requires a new market design, and the future power markets are expected to go from producer-centric to more consumer-centric. As of today, the existing power market limits the consumers to only select their electricity supplier, and prosumers to individually use their own DERs [12, 13]. An emerging approach is to divide the network into smaller entities, such as communities, CELLs and Microgrids [6].

When prosumers have surplus electricity, they can curtail it, store it with energy storage devices, export it back to the power grid or sell it to other energy consumers [11]. Today, using DERs on-site at a local level are more attractive than feeding into the grid, due to the difference between electricity selling and buying prices and the stress of the distribution grid [14]. To address some of these power system and market challenges, a new alternative is to encourage the use of excess energy within a neighborhood or community, which can be achieved by peer-to-peer (P2P) energy trading [1, 12, 14]. P2P energy trading is the direct and flexible energy trading between consumers and prosumers, without intermediation by conventional energy suppliers. With this, promote effective utilization of DERs, local energy balance, improve self-consumption, decrease the grid stress and strengthen the market position of prosumers [5, 14, 15]. The P2P approach promotes energy trading at internal prices and demand response to available resources in local areas, which could increase the efficiency, flexibility and responsiveness of local resources [6, 15]. However, with the novelty of P2P energy trading, the design of the market features and local trading prices are at an early stage.

With today's accelerating increase in energy demand and the deployment of the smart meters, the Norwegian grid utility tariff scheme is currently up for discussion. To incentive consumers to reduce their power demand and forward an efficient network utilization, a promising solution is to implement a peak demand charge [16]. Commercial and industrial customers are already subject to such a peak power charge, and are billed for the highest peak drawn from the grid each month. These customers make up the largest part of the power demand in the distribution grid, due to energy intensive production processes, heating and cooling systems, etc. [17, 18]. As the peak demand cost may be substantial, there is an incentive for the facilities to reduce their power demand. Some increasingly employed solutions are the installation of distributed generation (DG) to promote self-supply, load shifting and the implementation of on-site flexibility, where the last two solutions take advantage of low electricity price periods [17–19]. An alternative solution may be for the industrial buildings to engage in P2P energy trade to shave their peaks and reduce the electricity bill. Industrial buildings of diverse areas of production and businesses are often located at an industrial site. For this reason, a local P2P collaboration market design could be highly relevant and viable for an industrial site.

However, the P2P energy trade concepts are still at an early stage, as there is no consensus on what market design and local pricing schemes will help to develop local electricity markets. Thus, P2P energy sharing involves novel technologies and business models at the demand-side of power systems. With this in mind, mechanisms should be developed to define the business models, while ensuring a fair market design. The digitization of power systems and proliferation of smart energy technologies at customer sites will enable P2P energy trade and facilitate the establishment of local consumer-centric electricity markets, which eventually can be linked to the existing wholesale power market. As different market designs recently have emerged for residential communities and smart grids, this study proposes several market designs for an industrial community centered on the role of P2P energy trading. The industry is often the first to employ new technology, with the high cost motivating to consume and produce electricity in smarter ways. The focus of this study is the value and role of on-site flexibility under different industrial site configurations and defined market governing rules. Namely, the value of decentralized and shared on-site flexibility in combination with P2P energy trading for an industry site.

1.1.1 Problem Description

In light of the novelty of the field and motivations presented, this thesis aims at evaluating the value of P2P energy trading in combination with various local generation and flexibility resources in a Norwegian industrial site, in the view of the following research questions:

- What is the value of P2P trade at a prosumer industrial site?
- Do P2P collaboration provide a competitive advantage to trading in wholesale markets?
- What local market design alternatives will be suitable for an industrial site?
- How will an industrial site subject to peak power demand charge employ on-site flexibility and P2P trade?

To address these questions, the main objective of this thesis is to model local market designs for an industrial site centered on the role of P2P energy trading. With the basis of industrial buildings located in central Norway, the scope is to analyze whether the implementation of P2P collaboration in combination with local DERs could provide benefits to an industrial site, in terms of reducing the total cost of electricity. The objectives are as follows:

- Give a brief introduction and literature review to the theoretical concepts, centered on the P2P energy concept, local energy markets and the Norwegian power market.
- Model the system configuration and market designs with the objective of minimizing the total cost of electricity for the whole industry site, while ensuring a fair market design.
- Simulating the models and analyzing the results in the view of the presented research questions. Examine the model in terms of sensitivity and discuss findings according to literature.

1.2 Approach

The system models developed in this thesis are based on multi-period linear programming, and the optimization models are implemented in the optimization environment General Algebraic Modeling System (GAMS) and solved using the CBC solver. The objectives of the models are to minimize the total cost of electricity, including all costs and revenues for the related entities. The demand, production and price data is historical data provided by NTE Nett AS and Nord Pool, and are read from Excel. All optimal system results are loaded back to Excel and MATLAB.

1.3 Structure of the Thesis

Due to the novelty of the topic, it became clear that the study would be a relevant contribution to the field. As such, the thesis is conducted paper-based, in terms of an individual journal paper and additional material. The thesis is structured as follows:

Chapter 1, *Introduction*, introduces the reader to the background and motivation for the thesis. It presents a short overview of the objectives of the work conducted and seeks to put the thesis in context.

Chapter 2, *Theory*, presents briefly some important concepts related to P2P energy trading and the Norwegian power market. As the paper in Chapter 3 is to be published and read independently, the concept and technology theory related to the system are presented throughout the paper.

Chapter 3, *Paper: Peer-to-peer electricity trading in an Industrial site*, presents the individual journal paper to be published. The paper is organized as follows:

- Section 1, *Introduction*, introduces the motivation and objectives of the study.
- Section 2, *Related Literature*, gives an overview of related studies conducted in the literature, in terms of local energy markets and P2P energy trading.
- Section 3, *Model formulations of the industrial site*, describes the different market rules and designs of the industrial site and the related mathematical model formulations.
- Section 4, *A Norwegian industrial site: model implementation and data*, describes the industrial site in terms of characteristics and input parameters, thus the model data.
- Section 5, *Results*, presents the simulation results of each case study and related evaluation.
- Section 6, *Conclusions*, concludes the main aspects of the study.

Chapter 4, *Further Elaboration of the Industrial Site Data and Solution Method*, provides some further understanding and details regarding the presented solution method and data, as the paper is limited in terms of length.

Chapter 5, *The Material Behind the Results and Further Analyses*, provides the complete material behind the results presented in the paper. For further interest and evaluation, sensitivity analyses and a future scenario are conducted and presented.

Chapter 6, *Discussion*, gives a discussion of the main findings from the results.

Chapter 7, *Conclusion and Recommendations for Further work*, summarizes and concludes the main aspects of the study, results and findings, before giving some suggestions for further work.

Chapter 2

Theory

As the journal paper in Chapter 3 is to be published and read independently, without the additional chapters in the thesis, theory regarding the related concepts and technologies are presented throughout the paper. For this reason, the theory in this chapter is kept short and is included to establish some important concepts related to the Norwegian power market and the P2P energy sharing mechanisms.

2.1 The Power Market of Today

The restructuring of the electricity supply industry brought market economy into the power sector, with the scope of achieving social benefits by introducing free competition. The roles of participants of the electricity market changed accordingly. The concept of the deregulation process in different countries involved separating generation and retail of electricity from the natural monopoly of transmission and distribution, and establishing wholesale and retail electricity markets [20]. With the deregulation of the power market, followed a more efficient market with exchange of power between countries and increased security of supply. In addition, the power market ensures reasonable prices of electricity and optimal use of production resources and capacities [21]. As power transmission and generation capacity have been extended over the years, transmission of power between countries has become more common. This has led to a dynamic market where power can be purchased and sold across areas and countries more easily. As a result, the generation mix consists of power from many different sources, which ensures a secure power supply [21].[1]

Nord Pool is a joint Nordic electric power exchange market, where electric power is purchased and sold at equilibrium electricity price, as in other markets [22]. The Nordic Power Market is divided into different price-areas, where the power capacities of the transmission grid between these areas are fixed. The area electricity prices gives signals about surplus and shortage in the market, hence forwards the correct price signals to the producers and consumers in the power market. Short-term, this is important for efficient usage of the production resources. Long-term, it provides investment signals and gives the opportunity to plan ahead, as the prices indicate where there may be power supply shortage, as the price of power raises [23, 24].[1]

As presented in Section 1.1, the power market is again facing a possible transition and restructuring. Electricity markets are expected to go from producer-centric to consumer-centric, hence drifting away from the top-down structure. To address some of the challenges, local energy markets and P2P energy trade have emerged as new alternatives to foster the deployment of DERs. P2P trading promotes local energy trading and demand response to available resources in local areas, which increases the efficiency, flexibility and responsiveness of distributed resources and reveals the grid of stress [6]. Figure 2.1 illustrates various structural designs of local markets [10].

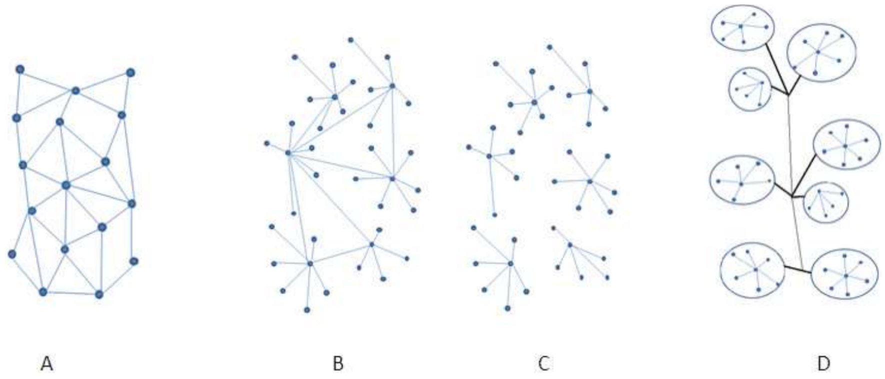

Figure 2.1: Structural attributes of prosumer markets, extracted from [10].

2.2 The Cost of Electricity

This thesis aims at developing a local market design for a community of industrial buildings, which minimizes the total cost of electricity by optimal usage of P2P trading, local energy storage and community

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[1] This section is based on theory from the unpublished Specialization Project handed in spring 2018.

DERs. Hence, it is important to understand how households and industrial- and commercial- buildings interact with the power market today. As this thesis presents a Norwegian industrial site case study, using data from central Norway, the Nordic power market will be used as foundation for this thesis.

Each user of the power grid, or consumer, is charged for the delivered energy and the usage of the grid. The electricity bill normally consists of two parts; the cost of delivered energy and the grid rent. The cost of delivered energy is the cost of the total amount of energy bought from the power supplier in each billing period, where the prices are based on the market *spot price*. The grid rent, given by the *utility tariff*, covers all cost related to transferring energy and government taxes, and is charged by the local network company. Typically, the electricity bill for residential buildings in Norway is approximately distributed; 45 % energy usage and 55 % grid rent [20, 25].

2.2.1 Spot Price[2]

In power markets, the price of power is determined by the balance between supply and demand [21]. Nord Pool operates the Northern European electric power exchange market, owned by the Nordic and Baltic transmission system operators. Nord Pool offers day-ahead and intraday markets, and takes care of the bidding process within these markets [26]. The power market is divided into different price-areas, reflecting the limits in the grid. As such, the wholesale prices varies in the areas. [23].

The day-ahead market is the main arena for power trading. Here, the hourly spot prices are set at 12:00 CET the day ahead, when all buyers and sellers have submitted their bids to Nord Pool. The bids reflect the market participants hourly willingness to pay for or sell a volume of power [21]. The day-ahead spot prices are set at the market equilibrium by the market operator, based on these bids and the availability of the transmission capacity [24]. The intraday market supplements the day-ahead market and helps secure the balance between demand and supply [21].

2.2.2 Utility Tariff

In addition to price of the delivered energy, all consumers are subject to a grid rent from the local utility company. This fee is determined by the utility tariff, which covers the operation, maintenance and development of the grid and government taxes. In Norway, The Norwegian Water Resources and Energy

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[2] This section is based on theory from the unpublished Specialization Project handed in spring 2018.

Directorate (NVE) determines a yearly revenue limit for each individual utility company, which in turn governs the company's utility tariff [25]. The utility tariff can either be a flat rate or a time-based rate. With the flat rate tariff, all consumed kWh during a period of time is charged the same rate, where this constant price may or may not be seasonal dependent. For time-based tariffs on the other hand, the cost per kWh is dependent on the time of use [20, 27].

In restructured power systems, like the Nordic, flat rate tariffs are traditionally used [20]. Today, this tariff scheme is the most widespread in Norway, called energy based utility tariff. This way consumers are subject to the same price per kWh, regardless of when it was delivered or at how high a power. The energy based tariff consists of a fixed term and a energy term, as described in Equation 2.1. The fixed term is a yearly cost [NOK/year] which is independent of the energy delivered, e.g. investments and government taxes. The energy term is reflecting the cost of grid usage, e.g. losses, given in [NOK/kWh] [16, 28].

$$\text{Consumer utility tariff} = \text{Fixed term} + \text{Energy term} \tag{2.1}$$

By 2019, all consumers in Norway will have a smart meter, known as an Advanced Metering System (AMS). The AMSs measure hourly electricity consumption in real time, and transmits this information to the utility company. In addition, this communication is bidirectional, thus consumers may receive advanced information about their electricity consumption, a more accurate meter reading and better opportunities to engage in demand response[3]. Moreover, the widespread installation of AMS allows for new and innovative utility tariff structures, which might lead to a more effective usage of the grid [29]. Hence, time-based tariffs will become increasingly deployed. NVE is planing to introduce a time-based utility tariff structure including consideration of power demand by 2021, where the power consideration will be included to limit the power at any given time and day. As of today, the two most discussed structures are [16, 20]:

- *Time-of-use pricing (TOU)*: The cost of energy is dependent on time in a predetermined way. The energy tariff is divided into periods of time, where the prices are constant. To relive the grid of high stress, the prices are higher during peak periods to encourage customers to reduce their demand.
- *Power Subscription*[4] *pricing (PS)*: The cost of energy is dependent on the hour of usage and the hourly power drawn. Each consumer subscribes to a fixed limit for maximum power usage, based on the

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[3] Demand response provides an opportunity for consumers to play a role in the operation of the electric grid by reducing or shifting their electricity usage during peak periods in response to time-based rates or other forms of financial incentives.

consumer's historical usage, and is subject to an extra cost if this limit is overdrawn.

Industrial- and commercial consumers are already subject to a peak power demand charge, in addition to being charged for both the energy consumed and the grid rent. The utility tariff for these consumers also include a power term based of the peak power drawn from the grid in each billing period, as described in Equation 2.2. The power term is often set high to reflect that the consumption peaks cause stress on the grid, and for some consumers the peak demand charge might be as high as the cost of consumed energy. This gives incentives for flattening of the peak demand to reduce the total electricity bill [28, 30]. This can be done by for example implementing a energy storage system or by trading with local DER, where stored or produced excess energy are used during peak hours to shave the peaks.

$$\text{Large consumer utility tariff} = \text{Fixed term} + \text{Energy term} + \text{Power term} \tag{2.2}$$

NVE [16] states that the introduction of the new utility tariff structure will give more incentives for effective usage and smarter development of the grid. A power demand consideration can give price signals to consumers making them more aware of the possibilities within smart technologies, as batteries, demand response and smart charging of electrical vehicles (EVs). NVE highlights how power-based structures might accelerate the adoption of batteries due to load leveling[5] and peak shaving[6] operations. In addition, the economic value of energy storage systems is further increased under a time-based tariff structure, as the potential for price arbitrage operations[7] increases. This is especially beneficial for areas where the price difference between peak and off-peak hours are high, which may become the reality in Norway. The spot prices in Norway will most likely consist of higher price peaks and more volatile prices with the increasing penetration of fluctuating RES. In addition, the Norwegian power market is becoming more and more linked to Europe, where the price of electricity is higher and more volatile [31]. When the time-based utility tariff is introduced, ESS can utilize these price fluctuations and provide additional savings. Furthermore, these tariff and price prospects may increase the benefits and willingness for communities to engage in P2P energy trading.

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[4] In Norwegian: Abonnert effekt

[5] Load leveling is a method where large fluctuations in the electricity demand is flattened.

[6] Peak shaving is a method where energy is stored in non-peak periods to be discharged during peak demand periods.

[7] In price arbitrage operations the battery is charge when the price of electricity is low, and discharged to supply the load when the price is high.

2.2.3 The Feed-in Utility Tariff

The Feed-in Utility Tariff (FiUT) determines what a producer pay to feed in energy at a certain point in the grid. The structure of the FiUT depends on the grid level of where the producer is connected, for instance the tariff structure is different for the distribution and regional power grid. The general structure of the tariff composite of the same terms as the described consumer utility tariff, given in Equation 2.1. The fixed term is given in [NOK/kWh], based on the producer's average yearly production the last 10 years and a fixed amount given from NVE. The energy term is calculated individually for each producer and is given as [NOK/kWh], to represent the marginal cost of losses at the point of connection based on the total system load. In addition, producers are charged for any consumption of active and reactive power [32, 33].

2.2.4 The Prosumer Agreement

A consumer with local electricity production that sometimes exceeds its demand is called a prosumer. In January 2017 NVE accepted a new prosumer agreement, which redefines the definition of prosumers. The new definition states that a prosumer is a consumer with consumption and production behind the grid connection point, where the feed in power never exceeds 100 kW. This production installation cannot be subject to a concession. With this new prosumer agreement, prosumers are allowed to sell their surplus energy to the market without being subject to the same tariffs as larger producers. Hence, the prosumers are not subject to the fixed term of the utility tariff for delivered energy to the grid, and they are usually paid the spot price for the feed-in energy [34].

In principle, the agreement imply that prosumers cannot sell their excess energy directly to other consumers or participate in the power market, hence have to sell to an energy supplier [34]. However, the energy sector is currently subject to many changes and the power markets are expected to go from producer-centric to more consumer-centric. The characteristics of both DER and battery storage induce the possibility of redefining the role of market participants, hence include P2P- and community-based components in the market [13].

2.3 Peer-to-Peer Trading

In this section, local energy markets and P2P energy trading are briefly presented, in terms of potential strengths and opportunities and market designs. The journal paper in Chapter 3 provides both a literature review and further information, thus this section is kept short.

Table 2.1: Summary of potential strengths, weaknesses, opportunities and threats of P2P trading in local markets, from a SWOT analysis performed by Sousa et al. [12] in a comprehensive review.

Strengths	**Weaknesses**	**Opportunities**	**Threats**
• Empowerment of consumers, focusing in trust, transparency and openness. • Consumers have better choice of supply and possibility to produce and sell their own energy. • Increase resilience and reliability of the system. • Remove potential market power from some players in the wholesale market.	• Sub-optimal energy price of all energy systems. • Potentially overwhelming transition to this consumer-centric market. • Heaviness of negotiation and clearing mechanisms.	• Democratization of energy. • Increase consumers awareness and cooperation towards environmental energy consumption. • Create new business models. • Boost retailer market, since lacks competition. • Postpone grid investments from system operators.	• Legal and regulatory obstacles, which influence the transition to these markets. • Energy poverty for some groups of consumers. • Potential grid congestions. • Technology dependency (blockchain). • Co-existence with existing electricity markets. • Security and privacy with data. • Potential failure of these markets if poorly structured.

The existing power market limits the consumers to selecting their electricity supplier, and prosumers to individually use their own DERs or feed-in to the distribution grid. As such, prosumers mainly aim at high levels of self-sufficiency[8] and self-consumption[9] for their own household, however procuring from the wholesale market is generally needed. As such, their market participation opens the possibility of a new market in a community of prosumers, and the potential of prosumers and their installed DERs could be fully exploited. With P2P collaboration in a local market, the prosumers and consumers first share their generation and consumption in a local market at internal prices, and then trade with a retailer to

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[8] Self-sufficiency describes the share of load that is supplied by the DG production [5].

[9] Self-consumption is defined as the ration between DG production consumed by the household, and the overall DG power generated [15].

cover the remaining electricity deficit or surplus. The local pricing scheme is usually set between the feed-in grid price and price of grid electricity, thus all local participants may benefit from the P2P energy trading sharing [15]. Sousa et al. [12] has performed a comprehensive review of P2P and community-based markets, including a analysis of opportunities and challenges. Table 2.1 presents a summary of the potential strengths, weaknesses, opportunities and threats of the topic, from a SWOT analysis presented in the review.

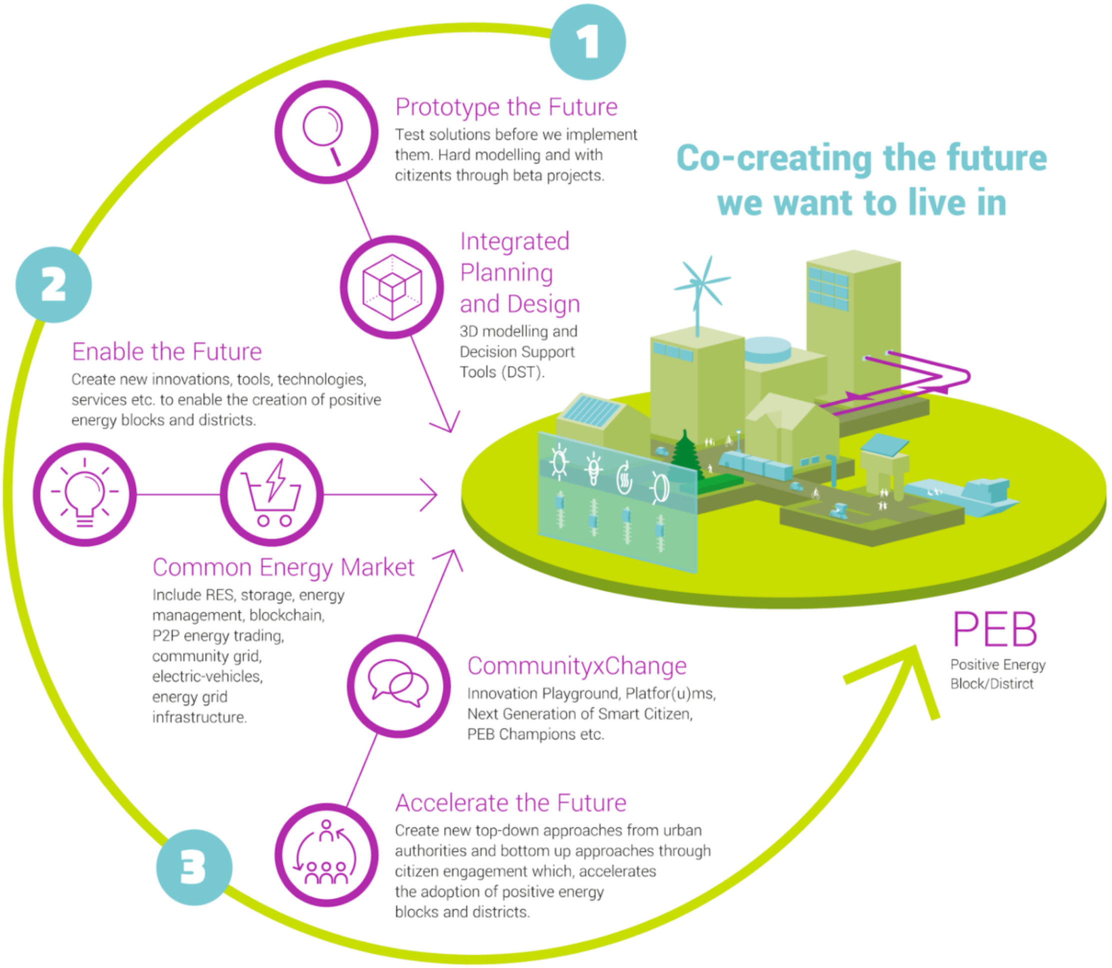

Figure 2.2: Evolution process for local energy markets with P2P trading, extracted from [35].

Figure 2.2 illustrates an evaluation process of local energy markets with P2P trading. The process is the vision of +CityxChange [35], a project related to smart cities and sustainable urban ecosystems, based on the following framework: 1) Prototype the future – Integrated planning and design; 2) Enable the future – Creation of a common energy market; 3) Accelerate the future. This framework incorporates several demonstration projects to create solutions for local energy markets. The process highlights the evolution process of P2P energy trading and local markets, as there are still key enablers remaining and barriers before the concepts can become widespread.

2.3.1 Local Market Designs

For the operation and coordination of interconnected communities and microgrids, different coordination strategies are possible. This section presents the three primary market designs proposed in the research for local energy markets with P2P energy trading: full P2P market, community based market and hybrid P2P market. It should be noted that due to the novelty of the field, there is a lack of extensive research directed toward possible P2P trading market designs.

Full P2P Market

In order to sell and buy electricity, this market design is based on market participants directly trading and negotiating with each other. As such, the market design is a decentralized strategy without third-party supervision. Mengelkamp et al. [36] developed an energy market framework for a microgrid, which enables small agents to trade energy without a central entity. This market design is gaining momentum in the industrial research field. In an optimization problem, the full P2P market is often solved in a centralized matter, minimizing the total cost of electricity [12]. Further, with a decentralized solution strategy each agent can optimize its own problem, in a coordinated matter. Instead of one large optimization problem, there are many small individual optimization problems defined for each agent. Furthermore, as each agent just uses its own information, their privacy is guaranteed. The main disadvantage is that the obtained solution is sub-optimal for the community [4]. To forward this strategy, decentralized optimization techniques are proposed [4, 37]. Each agent share the price and power it is willing to trade, without revealing DER characteristics, demand patterns and preferences [12].

Community Based Market

In the community based P2P market, a community manager coordinated the trading activities within the community. The market design is based on a distributed negotiation between the members and the community manager. Further, the manager serves as an interface between the community and the rest of the power system. In general, a community is based on members sharing common interests and goals [12]. The members can be co-located or spread to different locations, as in the SonnenCommunity in Germany [38]. In SonnenCommunity the household batteries are linked to a virtual community energy pool, where surplus energy are fed into this virtual energy pool, serving other members in times when they cannot produce sufficient energy. In such a centralized solution strategy, one single central entity optimizes the complete model of the system with information about the state of each agent. As such, decides the operation schedule for each entity. This strategy achieves the optimal solution, however at a burdensome computational effort due to the amount of information [4]. Finally, the approach allows the system manager to provide services to the grid owner, which could be shared among the community members [12].

Hybrid P2P Market

The hybrid P2P market is a combination of the two previous designs, also called hierarchical-distributed control strategy. In this design a central coordination unit (CCU) gathers information from all agents, however it do not solve a large optimization problem as for the central strategy. Instead, the central unit performs computations based on the state of the system and forwards price signals to the agents, where each agent solves their optimal problem based on this signal. As such, the information exchange is moderate and the obtained solution is better than with the decentralized strategy [4]. Correspondingly, the approach is the most suitable for P2P applications in a exchange context and a power system [12].

Chapter 3

Peer-to-Peer Electricity Trading in an Industrial Site:

Value of Peak Load Reduction and Shared Flexibility Assets

Manuscript will be submitted to Elsevier in May 2019

Peer-to-Peer electricity trading in an Industrial site: Value of peak load reduction and shared flexibility assets

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Abstract

In order to make a business case for flexibility options (e.g. demand response, storage, and others) needed to balance renewables, new local based market designs have been recently proposed. For example, price flexibility options and distributed energy resources (DERs) at the site of consumption (micro grids, communities, services for the DSO, etc). Alternatively, integrate DERs as part of wholesale markets and open the opportunity to provide grid services. In this paper, we propose a market design that consider the potentials of local markets by considering its interaction with wholesale markets. We focus on peer-to-peer (P2P) energy trading as a new way to share local flexibility and foster the deployment of distributed generation technologies. We propose a market design to study the benefits of shared energy storage and other flexibility assets (e.g. demand response and electrical vehicles) in combination with P2P energy trading. The objective is to investigate the value of P2P energy trading in combination with on-site flexibility resources for a Norwegian industry site. As the industrial consumers are subject to the substantial peak power charge for grid usage, the study analyses how the market designs affect the peak power demand management. Results show a yearly net savings of the total cost of electricity of 6.8 % to 11.0 % based on P2P trading features. The total cost of peak power is reduced up to 25 %, making peak shaving the largest contributor to the net cost savings. Moreover, the industrial site consumes more distributed generation locally, with no power curtailment and reduced grid feed-in.

Keywords: Peer-to-peer trade, Battery storage, Market design, Community, Local electricity market, Utility tariff, Industry consumer, Peak shaving

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1. Introduction

Local energy systems, such as rooftop solar photovoltaic (PV) systems, locally owned energy storages, small-scale wind farms and combined heat and power (CHP), are rapidly entering the power market [1]. This is being further accelerated by technology development of batteries, smart grid technologies, deregulation, and the shift from traditional energy consumers to prosumers [2, 3, 4]. This adoption of decentralized renewable energy sources (DERs) will

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require new market designs as future power markets are moving from producer-centric to more consumer-centric. As of today, power markets limits the consumers to only select their electricity supplier [4, 5]. An emerging approach is to create smaller entities and gather them as communities, CELLs and Microgrids [6]. There, using DERs at a local level is more attractive than feeding into the grid, due to the difference between electricity selling and buying prices, losses and the stress of the distribution grid [7].

To address some of these local power system and market challenges, a new alternative is to encourage the use of excess energy and manage peak demands within a neighborhood or community, e.g. based on peer-to-peer (P2P) energy trading [4, 7, 8]. P2P entails a direct energy trading between consumers and prosumers. The objective is to promote effective utilization of DERs, local energy balance, improve self-consumption, decrease the grid stress and strengthen the market position of prosumers [1, 7, 9]. The P2P concept promotes energy trading based on local prices and flexibility energy sources (e.g. demand response or storage) availability [6, 9]. In this regard, an important market based feature influencing P2P trading is the grid utility tariff scheme. In Norway, for example, to incentive consumers to reduce their power demand for an efficient network utilization, a promising solution is to implement a peak demand charge [10]. Commercial and industrial customers are already subject to such a peak demand charge, and are billed for the highest peak drawn from the grid each month. These large customers make up the largest part of the power demand in the distribution grid, due to energy intensive production processes, heating and cooling systems, etc. [11, 12]. As the peak demand cost may be substantial, there is an incentive for the costumer to reduce their power demand. Some increasingly employed solutions are the installation of distributed generation, load shifting and the implementation of on-site flexibility [11, 12, 13]. In this setting, an interesting option for industrial buildings would be to engage in P2P energy trade to shave their peaks and reduce the electricity bill. Industrial buildings of diverse areas of production and businesses are often located at an industrial site. There, a local P2P collaboration market design could be highly relevant.

Based on different local market designs recently proposed for residential communities, this study proposes market designs for an industrial site centered on the role of P2P energy trading. The industry is often the first to employ new technology, with the high cost motivating to consume and produce electricity in smarter ways. The focus of this study is the value and role of on-site flexibility under different industry site configurations and define market governing rules. Namely, the value of decentralized and shared on-site flexibility in combination with P2P energy trading for an industry site. The paper contributes to related literature by addressing the following questions:

- What is the value of P2P trade at a prosumer industrial site? Do P2P collaboration provide a competitive advantage to trading in wholesale markets?
- What local market design alternatives will be suitable for an industrial site?
- How will an industrial site subject to peak power charge employ on-site flexibility and P2P trade?

To address these questions, a P2P trading model is developed to evaluate

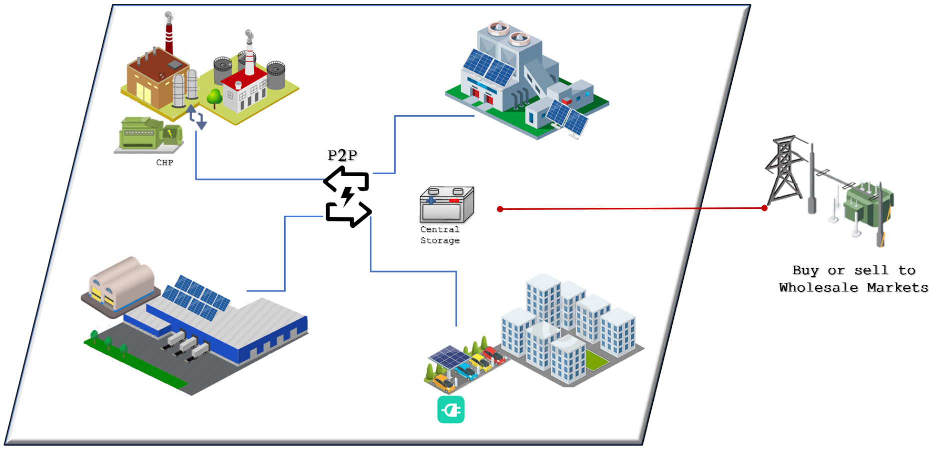

Figure 1: P2P electricity trading in an industrial site.

the large consumer benefits of several distributed power system configurations and market designs centered on the role of on-site flexibility. The model is based on multi-period linear program. The objective is to investigate the value of P2P energy trading in combination with various on-site generation and flexibility resources for an industrial site. The on-site DERs consist of decentralized building energy features, such as load shifting, electric vehicle (EV) parking lot, PV systems and CHP, and a shared community energy storage (see Figure 1). The model minimizes the total cost of electricity for the whole industry site, subject to a local supply-demand balance which determines the optimal procurement from the grid, grid feed-in, DER operation, shared storage usage and P2P trade. Historical demand, generation and grid price (utility tariff and wholesale prices) data are used to represent an industrial site located in central Norway, supplied by the local grid owner; NTE Nett AS. The paper provides novel results on the benefits of P2P energy trading, which are highly relevant due to the novelty of the subject.

The remaining part of this paper is structured as follows. A number of studies have been conducted in the literature on designing proper market mechanisms for P2P energy trading, and there is a rapidly growing number of commercial or pilot projects being realized. Hence, these will be presented in a literature review in the Section 2. Section 3 describes the different market rules and designs of the industry site and the related mathematical model formulations. Further, Section 4 presents the Norwegian industrial site model data. The case study results and analysis are given in Section 5. Finally, conclusions and perspectives for future work are gathered in Section 6.

2. Related Literature

Local based P2P electricity trade concepts is at an early stage and there is no consensus on what market designs and pricing schemes will support developing local electricity markets. Recent research in the field has focused on 1) the role of aggregators in coordinating local flexibility sources for balancing (see [14] and [15]), 2) designing price and bidding mechanisms for local trade ([16] and [17]), 3) digitalization and internet of things applications or methods ([18]), and 4) coordination algorithms and computational properties needed for P2P frameworks [19], and others. For a comprehensive review on overall work in the field refer to [20] .

Some of this existing research was partially inspired by real-life demonstration projects such as the Brooklyn Microgrid [21], Enerchain [22] and others (Piclo in the UK, Vandebron in Netherlands, and sonnenCommunity in Germany, see [3]). For example, in the novel paper by [8], the authors investigate the benefits of residential electricity storage in the presence of P2P trade in local electricity markets. The role of battery flexibility is assessed under different market designs based on the accessibility of storage. This is further expanded in [23] to examine possible frameworks and market designs for a community of prosumers and consumers to participate in the wholesale electricity market based on P2P balancing. In these and other papers, a recurrent view is that the proliferation of smart grid technologies will enable P2P energy trade and facilitate the establishment of local consumer-centric electricity markets that can eventually be linked to the existing wholesale power market. In this regard, a possible enabler of local markets is the use of blockchain technologies as they will facilitate the creation of secured, affordable and automatized trading platforms [24].

Another central aspect for the realization of P2P energy sharing is to define new business models. That is, market mechanisms should promote business models that ensure a fair and sustainable source of revenues for consumers and prosumers. For instance, [25] proposes creating "federated power plants" based on synergies of P2P and virtual power plants. Authors propose incentives to improve the efficient allocation of DERs in P2P trading platforms. In [26], the paper explores the viability of locally buying and selling electricity among electric vehicles. It explores demand response incentives to discharging EVs to balance local electricity demand. This case and similar work concludes that to facilitate the development of local electricity markets and foster the deployment of DERs, distributed flexibility options, virtual power plants, and microgrid based options are key catalyst to this endeavour [6, 27, 28]. This is highly relevant for a cluster of industrial buildings with high peak demands. P2P collaboration can provide savings from peak shaving operations and incentivize the value of flexibility assets (e.g. battery or demand response). In this regard, [29] proposes a real-time P2P market to enable surplus renewable electricity trading among different buildings in a Chinese industrial site. The case concludes that P2P incentivizes energy exchange and income for industrial buildings but does not consider the role of flexibility assets.

In short, existing literature has focused on P2P applications for residential buildings. However, limited research has considered P2P market design applications for an industrial case. In other words, analyzing industrial buildings collaboration to jointly achieve peak demand reductions based on P2P is an important contribution of this paper. Specially if this is compared with related literature that does not consider the value of using a diversified portfolio of flexibility assets. For example, a join analysis of P2P interactions with DERs, battery, electrical vehicles and demand response is investigated in this paper. Moreover, although there are various studies about shared storage in communities (e.g. [30] and [1]), this paper presents storage interaction with multiple DERs features to value P2P trading in a rel-life industrial site.

3. Model formulations of the industrial site

A local market entails a community of interconnected buildings in which certain DERs produce surplus (e.g. solar) or provide flexibility (e.g. batteries or demand response (DR)). Hence, to model a local market, we consider a community consisting of B industry prosumers and consumers locally connected through a distribution network. Each industrial building has energy flexibility feature and/or generation technologies, such as load shift (LS), storage unit of EVs, solar PV and CHP. The overall objective of the industry site is to minimize the grid consumption by incentive self-sufficiency and local energy balance, hence prioritizing local trade and consumption.

In this chapter, the different market rules and designs of the industry site and related mathematical model formulations are presented. Fig. 1 visualize the industrial site in terms of market design, entities and power flows.

3.1. Local market designs

A market design defines the rules and practical arrangements governing how the different entities (consumers and suppliers) operate. The main objective is to obtain a fair and efficient market. In such markets all participants usually have equal access to the market and to all relevant information about prices and supply conditions [31]. To evaluate the value of P2P energy trade in combination with on-site flexibility resources in a local market, the market structure and rules must be defined and compared. This includes local trading rules and how the flexibility resources can be managed to provide the most benefit to the community. In this study, different industry site community market designs are compared to a base case with the traditional top-down market structure.

Today, prosumers are allowed to both consume from and feed-in to (up to a certain limit) the main grid [32]. For all system setups with P2P trade, prosumers have the ability to trade both excess electricity from building DERs and extra power supplied from the grid. This provides arbitrage potentials, in terms of shifting grid consumption by trading or utilizing on-site flexibility resources. These market rules are based on the interface of today between a prosumer and grid owner. On the other hand, the interface between a community and grid owner might not allow for this kind of active trading, which is not further explored in this paper.

The various market designs with the different flexibility resources and rules are presented below:

- *Base Case - Flexible buildings*: In this market setup the on-site flexibility resources are the individual energy features and generation at each industrial building. This is considered the reference market design. Assigned market rules determine the grid consumption and employment of the flexibility resources.
- *Collaboration case 1 - P2P trade*: This market design allows for P2P trade within the industry site, in addition to the utilization of the individual building flexibility features. The buildings can trade locally produced and stored power and power bought from the grid.
- *Collaboration case 2 - P2P trade and central storage*: This market setup consists of a shared community energy storage, in addition to the consumer level flexibility and generation. The buildings can trade locally and at the same local P2P prices as for the previous market design. The shared storage is located centrally and is owned by the industry site. Charging and discharging can originate from the same sources as the P2P trade, where charging is compensated in terms of benefits and discharging is priced individually and at slightly higher rate. Further, the storage cannot act as an independent entity or agent and charge directly from the grid, due to interface difficulties of today regarding prices, ownership and market position.

To create a fair marketplace, the market designs require certain rules for prices. The essential market features are summarized in Table 1. To incentive self-consumption for the overall industry site, price mechanisms for the P2P trade are designed to ensure power flows on the local level. In terms of, favorable prices for peer electricity compared to the cost of consuming from the main grid and feed-in revenues. Hence, all internal prices are bounded between the feed-in tariff and grid electricity prices, as in the work of Liu et al. [33].

Table 1: Overview of proposed market designs.

	Base Case	**Case 1**	**Case 2**
Energy sources	Grid Building DERs	Grid Building DERs P2P trade	Grid Building DERs P2P trade Central storage
Prices	grid price ($c_{g,tot}$) feed-in price ($c_{feed-in}$) $c_{feed-in}<c_{g,tot}$	grid price ($c_{g,tot}$) P2P trade price (c_{p2p}) feed-in price ($c_{feed-in}$) $c_{feed-in}<c_{p2p}<c_{g,tot}$	grid price ($c_{g,tot}$) P2P trade price (c_{p2p}) discharge price (c_{dch}) charge compensation (c_{ch}) feed-in price ($c_{feed-in}$) $c_{feed-in}<c_{ch}<c_{p2p}<c_{dch}<c_{g,tot}$

In addition to the market framework for trading rules and prices, assumptions is a part of the market structure. Some assumptions have been made for the system characteristics in order to simplify the problem concerning complexity and computational effort. The following simplifying assumptions have been made:

- Unlimited grid power capability at any time, which typically is limited by the transmission lines.
- Physical power system characteristics, such as power flows, voltage levels, frequency balancing and reactive effects, are neglected.
- Investment costs, of e.g. building DERs and central storage, are neglected.
- The central storage is based on the characteristics of lithium-ion battery. Some storage characteristics are neglected, such as degradation and stand by losses.
- All efficiencies are considered constant.
- Uncertainties in DER production, electricity prices and demand are neglected, as all input time series are estimated based on historical data. In other words, assumed to be a perfect forecast model, where the hourly demand, production and prices are known prior to solving the problem.
- All building energy features and generation are assumed and designed to fit the case study and emphasis the aspects of the model. Hence, they are not installed at the actual buildings as of today.

3.2. Model formulation

A market design for a community of consumers and prosumers will mainly consist of trading decisions based on flexibility options, grid, DER surplus and local trade prices. A multi-step optimization method is required because the storage level at any given time step is dependent on the previous storage level. With hourly time step t these decisions are optimized over a time horizon T. The objective is to minimize the total cost of electricity for the community as a whole, while being subject to building energy feature, storage, trade, and supply constraints. With this overall cost minimization, the operation strategy is centralized for the community. The primarily scope is to determine the building electricity usage and value of P2P trade and shared on-site flexibility options for an industry site, in terms of peak shaving, power flows and cost reductions. Table 2 presents the sets, variables and parameters used in the mathematical model. All equations are true for all $t \in T$ and $b \in B$, if not otherwise specified.

3.2.1. The total cost of grid electricity for a Norwegian industry prosumer

Each user of the power grid, or consumer, is charged for the consumed energy and the usage of the grid. The cost of the consumed energy is the cost of the total amount of energy delivered from the chosen energy supplier in each billing period, which is based on the market spot price. The grid rent is given by the utility tariff charged by the local network company [31, 34]. With the widespread installation of Advanced Metering System (AMS), the Norwegian utility tariff system is moving from flat rate tariffs towards time-of-use pricing with peak demand charge [10, 35]. However, industrial consumers are already subject to a peak power demand charge, reflecting their high stress of the grid.

Table 2: Model nomenclature

	Description	**Unit**
Sets		
T	Set of time periods, $t \in T$	
M	Set of months, $m \in M$	
B	Set of buildings b and peers p in community, $b, p \in B$	
Scalars		
$c_{g,eng}$	Cost of energy term in utility tariff	NOK/kWh
$c_{g,fix}$	Fixed cost of utility tariff	NOK/mo
ψ_{P2P}	Distribution network losses and conversion of DG for P2P trading	-
Δt	Duration of the time step t	h
$P_{feed-in}^{max}$	Maximum power feed-in for prosumers	kW
$\overline{SOC}/\underline{SOC}$	Upper/lower limit for state of charge of central storage	p.u.
E^{nom}	Nominal capacity of central storage	kWh
η_{rt}	Round trip efficiency of central storage	-
η_{ch}/η_{dch}	Charging/discharging efficiency of central storage	-
η_{inv}	Efficiency of central storage inverter	-
P_{inv}^{nom}	Nominal power of central storage inverter	kW
$\eta_{ev,ch/dch}$	Charging/discharging efficiency of EV storage unit	-
E_{ev}^{nom}	Nominal storage capacity of EVs	kWh
$P_{ev,charger}^{num}$	Nominal power of EV charger	kW
E_{start}/E_{end}	Stored energy in EV when arriving/leaving work	p.u.
EV_{num}	Number of EVs parked during work hours	-
Parameters		
$P_{dem}^{(t,b)}$	Demand of building b in time step t	kW
$P_{DER}^{(t,b)}$	Distributed energy production of building b in time step t	kW
$c_{g,SP}^{(t)}$	Wholesale spot price in time step t	NOK/kWh
$c_{g,peak}^{(m)}$	Price of peak power term of utility tariff in month m	NOK/kWp/mo
$c_{feed-in}^{(t)}$	Price received for grid feed-in in time step t	NOK/kWh
$c_{LS}^{(b)}$	Penalty of load shifting for building b	NOK
$c_{p2p}^{(t,b)}$	Price of electricity in the local market for building b in time step t	NOK/kWh
$c_{ch}^{(t)}$	Price of charging the shared storage in time step t	NOK/kWh
$c_{dch}^{(t,b)}$	Price of discharging the shared storage for building b in time step t	NOK/kWh
$w^{(t)}$	Binary stating if time step t is within working hours or not	-
Variables		
$P_{g,buy}^{(t,b)}$	Grid consumption of building b in time step t	kW
$P_{g,peak}^{(m,b)}$	Peak power demand of building b in month m	kWp
$P_{g,sell}^{(t,b)}$	Power grid feed-in of building b in time step t	kW
$P_{ch}^{(t,b)}/P_{dch}^{(t,b)}$	Power charge/discharge of shared storage of building b in time step t	kW
$P_{allch}^{(t)}/P_{alldch}^{(t)}$	Sum of all power charge/discharge to shared storage in time step t	kW
$E^{(t)}$	Shared storage energy level in time step t	kWh
$P_{imp}^{(t,b)}$	P2P electricity purchase of building b in time step t	kW
$P_{imp,p}^{(t,b\leftarrow p)}$	P2P electricity purchase of building b from peer p in time step t	kW
$P_{exp}^{(t,b)}$	P2P electricity sale of building b in time step t	kW
$P_{exp,p}^{(t,b\rightarrow p)}$	P2P electricity sale of building b to peer p in time step t	kW
$E_{ev}^{(t)}$	Total EV storage unit level in time step t	kWh
$P_{ev,ch}^{(t,b)}/P_{ev,dch}^{(t,b)}$	Power charge/discharge to EV storage of building b in time step t	kW
$P_{ls,sh}^{(t,b)}/P_{ls,dem}^{(t,b)}$	Load shifted/rescheduled of building b in time step t	kW
$E_{ls}^{(t,b)}$	Shifted power level of building b in time step t	kWh
$P_{curtail}^{(t,b)}$	Curtailed DER of building b in time step t	kW

The Norwegian industrial consumer utility tariff consists of a fixed term, energy term, and power term. The fixed term is a fixed yearly or monthly charged cost $[NOK/mo]$, covering e.g. grid investments and government taxes. The energy term is given in $[NOK/kWh]$ and reflects the cost of grid usage, e.g. losses. Finally, the power term is a fixed or seasonal dependent cost charged for the highest peak power demanded during a month, given in $[NOK/kWp/mo]$.

In January 2017 the prosumer agreement was introduced, allowing prosumers to sell their surplus energy to the market without being subject to the same feed-in utility tariff as larger producers. The feed-in power limit is 100 kW and prosumers are usually paid the market spot price [32].

The total cost of grid electricity of the Norwegian industry site prosumer buildings for each monthly billing period is presented in Eq. (1).

$$\begin{aligned} c_{g,tot}^{(m,b)} &= \sum_{t \in m} (c_{g,SP}^{(t)} \cdot P_{g,buy}^{(t,b)} \Delta t + c_{g,eng} \cdot P_{g,buy}^{(t,b)} \Delta t) \\ &+ (c_{g,fix}^{(m)} + c_{g,peak}^{(m)} \cdot P_{g,peak}^{(m,b)}) - \sum_{t \in m} (c_{feed-in}^{(t)} \cdot P_{g,sell}^{(t,b)} \Delta t) \end{aligned} \tag{1}$$

The highest measured power drawn from the grid during an hour within month m is the peak demand $P_{peak}^{(m,b)}$ of building b in the given month, given by Eq. (2).

$$P_{g,peak}^{(m,b)} \geq P_{g,buy}^{(t,b)} \qquad , \forall \, t \in M \tag{2}$$

The power drawn from the grid by building b in time step t has to be a positive value, applied with Eq. (3).

$$P_{g,buy}^{(t,b)} \geq 0 \tag{3}$$

The prosumer agreement is met by applying Eq. (4), which limits the grid power feed-in from building b in time step t.

$$0 \leq P_{g,sell}^{(t,b)} \leq P_{feed-in}^{max} \tag{4}$$

3.2.2. Peer-to-peer trading rules

P2P energy trading within the industry site allows for flexible and direct energy trading between interconnected peers. Mechanisms must be developed to secure that the trades between the buildings follows the defined market rules. These P2P trade rules are based on the work of Lüth et al. [8]. The total exported P2P power of each building b in each time step t, is defined by Eq. (5).

$$P_{exp}^{(t,b)} = \sum_{p \neq b} P_{exp,p}^{(t,b \to p)} \tag{5}$$

Further, Eq. (6) establishes the total imported P2P power of each building b in each time step t.

$$P_{imp}^{(t,b)} = \sum_{p \neq b} P_{imp,p}^{(t,b \leftarrow p)} \tag{6}$$

The imported power of building b from peer p is provided by Eq. (7). Moreover, the equation ensures that the imported power of a building from a peer equals the exported power from the peer to the building including the community network losses.

$$P_{imp,p}^{(t,b \leftarrow p)} = \psi_{P2P} \cdot P_{exp,p}^{(t,p \rightarrow b)} \qquad , \forall\, p \neq b \tag{7}$$

The total sum of P2P traded power flows between buildings is given by Eq.(8), where the total exported power equals the total imported power within the community.

$$\sum_b \psi_{P2P} \cdot P_{exp}^{(t,b)} = \sum_b P_{imp}^{(t,b)} \tag{8}$$

3.2.3. Central community storage decisions

There are various available energy storage technologies, each with its advantages and drawbacks. As a bidirectional component, the energy storage can be charged and discharged, however not at the same time. The energy storage balance is ensured by Eq. (9), where the energy level is either decreased or increased in each time step. The energy level E at time step t is a function of the energy stored at time step $t-1$, which is the main reason for the employment of the multi-step optimization method. Seeing that the energy storage is a central community storage, the energy level is subject to the sum of all power flows from and to all industry site buildings.

$$E^{(t)} = E^{(t-1)} + \eta_{ch} \cdot \eta_{inv} \cdot \Delta t \cdot P_{allch}^{(t)} - \frac{1}{\eta_{dch} \cdot \eta_{inv}} \cdot \Delta t \cdot P_{alldch}^{(t)} \tag{9}$$

The sum of all power flows from and to all buildings in time step t are given by Eq. (10) and (11). As the storage can not charge directly from the grid, all storage power flows are local within the industry site.

$$P_{allch}^{(t)} = \psi_{P2P} \cdot \sum_b P_{ch}^{(t,b)} \tag{10}$$

$$P_{alldch}^{(t)} = \frac{1}{\psi_{P2P}} \cdot \sum_b P_{dch}^{(t,b)} \tag{11}$$

The conversion losses for the storage are taken into account by the charge and discharge efficiencies, of which the charge $P_{ch}^{(t,h)}$ and discharge $P_{dch}^{(t,h)}$ powers are subject to. The efficiencies depend on the current through the storage. However, for simplicity it is assumed that they are constant and calculated to be equal based on the round-trip efficiency η_{rt}, as in Eq. (12). The round-trip efficiency is referred to as the performance of the storage [36]. In addition, the charge and discharge powers are subject to the storage inverter efficiency η_{inv}.

$$\eta_{ch} = \eta_{dch} = \sqrt{\eta_{rt}} \tag{12}$$

The lower and upper capacity constraint in Eq. (13) limits the energy level in each time step. These limits keeps the storage in secure capacity ranges, thus avoiding damaging deep discharging or overcharging.

$$E_{nom} \cdot \underline{SOC} \leq E^{(t)} \leq E_{nom} \cdot \overline{SOC} \tag{13}$$

Where the storage state of charge (SOC) is a variable $\in [0, 1]$ [p.u.] which defines the level of stored energy in the storage at any given time. The SOC is expressed in Eq. (14) by the nominal storage capacity E_{nom} and the energy in the storage $E^{(t)}$. The minimum and maximum SOC are decided based on the preferable operation region of the storage. Fig. 2 illustrate a typical curve of the open circuit voltage as a function of SOC of a lithium-ion battery, where the profile is relative stable in the SOC range 20-90 % [36, 37].

$$SOC = \frac{E^{(t)}}{E_{nom}} \tag{14}$$

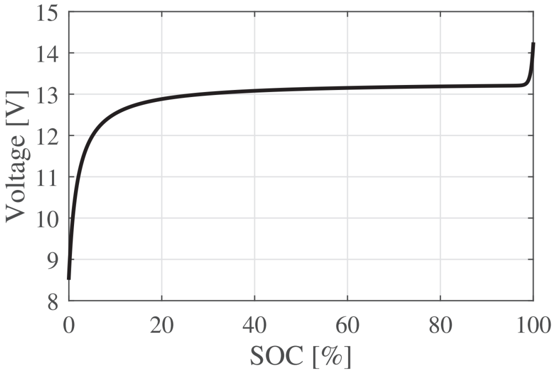

Figure 2: Typical lithium-ion battery open circuit voltage vs. SOC curve, extracted from [36].

Further, the sum of all storage charging and discharging power rates in each time step t are restricted by the nominal power of the storage inverter in Eq. (15) and (16). These limits are included to avoid high currents and over-voltages.

$$0 \leq P_{allch}^{(t)} \leq \eta_{inv} \cdot P_{inv}^{nom} \tag{15}$$

$$0 \leq P_{alldch}^{(t)} \leq P_{inv}^{nom} \tag{16}$$

It should be noted that solutions with simultaneously charging and discharging can occur in principle. However, they are mutually exclusive events in this model, as it will not be optimal due to efficiencies lower than 1 $p.u.$ [38, 39]. Hence, a constraint preventing this, e.g. $P_{ch}^{(t,b)} \cdot P_{dch}^{(t,b)} = 0$, is not needed.

3.2.4. Building flexibility feature constraints

Customer flexibility can be defined as any energy feature at the customer site that supports a net change in the energy consumed from the grid by the customer. Large consumers, such as industry buildings, often have extensive energy demand, high yearly peak demand and production processes that may be rescheduled in order to provide flexibility to the community [12]. There are different costs and market decisions associated with the various flexibility features, hence certain rules need to be defined.

Load shifting

Load shifting is the shifting of the normal demand pattern by rescheduling loads. A shiftable load for an industry building means in practice that the building is able and willing to move demand to a period of time when the demand is generally lower, i.e. by running a production process at a later time. Load shifting usually induce rescheduling costs, such as labor rescheduling, overtime pay or productivity losses, which will be represented by a penalty in the objective function.

For simplicity, the load shifting feature is modeled as a storage unit without losses. The available power shift for a building in time step t is limited to 10 % of the monthly peak demand. The same limit is defined for the hourly rescheduling power load, presented in Eq. (17). The available hourly load for shifting is assumed to be high for the industrial buildings due to their power consuming processes.

$$0 \leq P_{ls,sh}^{(t,b)}, P_{ls,dem}^{(t,b)} \leq 0.1 \cdot P_{g,peak}^{(m,b)} \qquad ,\forall\, t \in M \tag{17}$$

Eq. (18) presents the energy balance of the representative storage for a building b in time step t. The energy level $E_{ls}^{(t,b)}$ keeps track of the amount of load shifted.

$$E_{ls}^{(t,b)} = E_{ls}^{(t-1,b)} + P_{ls,sh}^{(t,b)} \cdot \Delta t - P_{ls,dem}^{(t,b)} \cdot \Delta t \tag{18}$$

Further, the energy level of a building b is limited to four time steps of maximum power shift, given by Eq. (19).

$$0 \leq E_{ls}^{(t,b)} \leq 4t \cdot 0.1 \cdot P_{g,peak}^{(m,b)} \cdot \Delta t \qquad ,\forall\, t \in M \tag{19}$$

In addition, a final storage limit is specified for the individual buildings, presented in Eq. (20). This limit makes sure all shifted load are rescheduled, hence the representative storage are fully discharged, within a given time step t. The time limit $d_{end}(t)$ typically represents the end of the day or workday.

$$E_{ls}^{(d_{end}(t),b)} = 0 \qquad ,\forall\, d_{end}(t) \in T \tag{20}$$

Electric vehicle parking lot

Vehicle-to-grid (V2G) is the bi-directional use of electricity stored in EV batteries. If the technology is made possible, V2G holds the promise of flexible and fast-responding storage for several grid services, such as; arbitrage, peak shaving and spinning reserves. With EVs brought together, this dual use of EV batteries can serve as an on-site storage unit for buildings. An industry site usually holds many employments, hence typically large parking lots. With

V2G technology installed at these parking lots, a storage representing the EVs parked is an alternative building flexibility option at an industry site.

The building EV parking lot is modeled as a joint storage unit, where Eq. (21) balances the overall storage energy level in time step t.

$$E_{ev}^{(t,b)} = E_{ev}^{(t-1,b)} + \eta_{ev,ch} \cdot \Delta t \cdot P_{ev,ch}^{(t,b)} - \frac{1}{\eta_{ev,dch}} \cdot \Delta t \cdot P_{ev,dvh}^{(t,b)} \tag{21}$$

Eq. (22) defines the upper and lower energy level limit, which is dependent on the average nominal EV battery capacity E_{ev}^{nom}, number of EVs parked during work hours EV_{num}, and SOC limits.

$$E_{ev}^{nom} \cdot EV_{num} \cdot \underline{SOC} \leq E_{ev}^{(t,b)} \leq E_{ev}^{nom} \cdot EV_{num} \cdot \overline{SOC} \tag{22}$$

The charge and discharge power rates are limited by the nominal capacity of the installed charger technology $P_{ev,charger}^{nom}$ and the number of EVs parked EV_{num}, presented in Eq. (23).

$$0 \leq P_{ev,ch}^{(t,b)}, P_{ev,dch}^{(t,b)} \leq P_{ev,charger}^{nom} \cdot EV_{num} \cdot w^{(t)} \tag{23}$$

Moreover, the binary parameter $w^{(t)}$, presented in Eq. (24), states if the current time step t lies within working hours or not. In other words, gives if the joint EV storage unit is available.

$$w^{(t)} = \begin{cases} 1, & \text{if t is working hour} \\ 0, & \text{otherwise} \end{cases} \tag{24}$$

Finally, an initial and final storage level limit are defined for each start and end of a workday, given by Eq. (25) and (26). These limits represents the arrival and leaving of EVs in the morning and the afternoon. E_{start} and $E_{end} \in [0, 1]$ represents the assumed average energy level in each EV battery when arriving and leaving work, respectively. Sperstad et al. [38] investigates the value of stored energy at the end of each planning horizon, and defines three operational strategies. Constraining the minimal amount of stored energy at the end of each day is recognized as the most common strategy in literature. However, this and human behavior are advantageous areas for further work regarding EVs and V2G.

$$E_{ev}^{(d_{start}(t),b)} = E_{ev}^{nom} \cdot EV_{num} \cdot E_{start} \qquad , d_{start}(t) \in T \tag{25}$$

$$E_{ev}^{(d_{end}(t),b)} \geq E_{ev}^{nom} \cdot EV_{num} \cdot E_{end} \qquad , d_{end}(t) \in T \tag{26}$$

3.2.5. Defining case specific market designs

The market design for the different industry site case studies are presented separately, in terms of objective function, power balance and decision constraints. For all considered market designs, the overall objective is to minimize the total cost of electricity for the whole industry site, however subject to constraints for varied shared community flexibility options.

Base Case

In the Base Case market design, with grid connection and building energy features, costs arise at the events of grid consumption and load shifting. Benefits arise when prosumers sell their excess electricity to the grid. Thus, the objective function in this case, Eq. (27), minimizes the total cost of grid energy and load shifting. Where the total cost of grid electricity during the optimization period is based on Eq. (1).

$$\begin{aligned}\min_{\substack{\forall t\in T\\ \forall m\in M\\ \forall b\in B}} C_{totBC} = \Bigg\{ \sum_{b}^{B} \Bigg(& \sum_{t}^{T} \Big[\Big(c_{g,eng} + c_{g,SP}^{(t)} \Big) \cdot P_{g,buy}^{(t,b)} \Delta t \Big] \\ & + \sum_{m}^{M} \Big[c_{g,fix}^{(m)} + c_{g,peak}^{(m)} \cdot P_{g,peak}^{(m,b)} \Big] \\ & - \sum_{t}^{T} \Big[c_{feed-in}^{(t)} \cdot P_{g,sell}^{(t,b)} \Delta t \psi_{P2P} \Big] + \sum_{t}^{T} \Big[c_{LS}^{(b)} \cdot P_{ls,sh}^{(t,b)} \Delta t \Big] \Bigg) \Bigg\}\end{aligned} \tag{27}$$

The cost minimization is subject to the grid constraints, Eqs. (2)-(4), the load shifting decisions, Eqs. (17)-(20), and the electrical vehicle joint storage unit constraints, Eqs. (21)-(26).

In addition, the instant balance between demand and supply has to be kept at all times in a power system, which implies that the total demand has to be equal to total supply at each node. The buildings $b \in B$ is considered to have diverse demand and on-site production profiles. The power balance equation ensures that this balance is met for each building b in each time step t, given in Eq. (28).

$$\begin{aligned} & P_{dem}^{(t,b)} + P_{g,sell}^{(t,b)} + P_{ev,ch}^{(t,b)} + P_{ls,dem}^{(t,b)} + P_{curtail}^{(t,b)} \\ & = P_{DER}^{(t,b)} + P_{g,buy}^{(t,b)} + P_{ev,dch}^{(t,b)} + P_{ls,sh}^{(t,b)} \end{aligned} \tag{28}$$

The parameter $P_{DER}^{(t,b)}$ is the total distributed energy production from DG at each building b in time step t. In addition, the demand $P_{dem}^{(t,b)}$ is also given as a parameter, while the grid power $P_{g,buy}^{(t,b)}$, peak power $P_{g,peak}^{(m,b)}$, grid feed-in $P_{g,sell}^{(t,b)}$, as well as the load shift $P_{ls,sh}^{(t,b)}$ are all variables.

Collaboration Case 1: P2P energy trade

In the first collaboration marked design, the industry site buildings have the opportunity to trade energy locally, in addition to operating the building energy flexibility features. Costs arise when a prosumer consumes grid energy, practice load shifting or imports power from an industry site peer. In addition to the benefits from grid feed-in, a building exporting power to a peer earns money. As the amount one peer pays another peer earns, the total community money transition cancel out. However, these P2P trade costs affects the optimal solution of the individual buildings and are therefore included in the objective function nevertheless, Eq. (29).

$$
\begin{aligned}
\min_{\substack{\forall t\in T\\ \forall m\in M\\ \forall b\in B}} C_{totC1} = \Bigg\{ C_{totBC} + \sum_{b}^{B} \Bigg(\sum_{t}^{T} \Bigg[c_{p2p}^{(t,b)} \cdot P_{imp}^{(t,b)} \Delta t \frac{1}{\psi_{P2P}} \Bigg] \\
- \sum_{t}^{T} \Bigg[\sum_{p\neq b}^{B} c_{p2p}^{(t,p)} \cdot P_{exp,p}^{(t,b\rightarrow p)} \Delta t \Bigg] \Bigg) \Bigg\}
\end{aligned}
\tag{29}
$$

This cost minimization is subject to the same system constraints as the Base Case objective, along with the P2P energy trading constraints, Eqs. (5)-(8). The trade power flows will affect the power balance of each building b in time step t, hence the related power balance constraint is presented in Eq. (30).

$$
\begin{aligned}
&P_{dem}^{(t,b)} + P_{g,sell}^{(t,b)} + P_{exp}^{(t,b)} + P_{ev,ch}^{(t,b)} + P_{ls,dem}^{(t,b)} + P_{curtail}^{(t,b)} \\
&= P_{DER}^{(t,b)} + P_{g,buy}^{(t,b)} + P_{imp}^{(t,b)} + P_{ev,dch}^{(t,b)} + P_{ls,sh}^{(t,b)}
\end{aligned}
\tag{30}
$$

Where the P2P import $P_{imp}^{(t,b)}$ and export $P_{exp}^{(t,b)}$ are variables.

Collaboration Case 2: P2P energy trade and central community storage

In the second collaboration market design for the industry site, costs emerge at three events: grid consumption, discharging of the central storage and P2P import. Benefits arise when prosumers export electricity to peers, receive compensating for charging the shared industry site storage or sell power to the main grid. The objective function with the additional on-site flexibility option is presented in Eq. (31).

$$
\begin{aligned}
\min_{\substack{\forall t\in T\\ \forall m\in M\\ \forall b\in B}} C_{totC2} = \Bigg\{ C_{totC1} + \sum_{b}^{B} \Bigg(\sum_{t}^{T} \Big[c_{dch}^{(t,b)} \cdot P_{dch}^{(t,b)} \Delta t \Big] \\
- \sum_{t}^{T} \Big[c_{ch}^{(t)} \cdot P_{ch}^{(t,b)} \Delta t \Big] \Bigg) \Bigg\}
\end{aligned}
\tag{31}
$$

The central energy storage operation is limited by the constraints in Eqs. (9)-(16). The charging $P_{ch}^{(t,b)}$ and discharging $P_{dch}^{(t,b)}$ powers are variables, and are added to the power balance constraint in Eq. (32).

$$
\begin{aligned}
&P_{dem}^{(t,b)} + P_{g,sell}^{(t,b)} + P_{exp}^{(t,b)} + P_{ch}^{(t,b)} + P_{ev,ch}^{(t,b)} + P_{ls,dem}^{(t,b)} + P_{curtail}^{(t,b)} \\
&= P_{DER}^{(t,b)} + P_{g,buy}^{(t,b)} + P_{imp}^{(t,b)} + P_{dch}^{(t,b)} + P_{ev,dch}^{(t,b)} + P_{ls,sh}^{(t,b)}
\end{aligned}
\tag{32}
$$

4. A Norwegian industrial site: model implementation and data

The system under investigation is an industry site located in central Norway. The model data involve characteristics and demand profile of each building, the attributes of distributed flexibility and generation (DG) technologies, community storage aspects and all the related electricity prices. Demand and production time series, along with grid utility tariff prices and aspects, are historical time series and information provided by the utility company NTE Nett AS[1].

A model horizon of one year with a time resolution of one hour is considered in order to capture the seasonal characteristics of building demand, solar PV generations and prices, i.e. $T = 8760$, $\Delta t = 1\text{h}$ and $M = 12$. All data sets cover the year of 2017.

4.1. Demand profiles

The load data for the industrial site is composed of five different industrial buildings, i.e. $B = 5$. The electrical demand for each building can be supplied by either the grid or local community generation and flexibility. In general, industrial buildings have higher electrical consumption than residential buildings and often the financial possibility to invest in local DER. Consequently, industrial consumers are often the first to employ new technology. The chosen industrial buildings are differentiated in terms of area of business and size, hence the demand profiles vary both in magnitude and pattern. Table 3 gives an overview of the characteristics of the industrial buildings[2]. We highlight the following features and assumptions:

Table 3: Information about the different industrial buildings.

	Building 1	**Building 2**	**Building 3**	**Building 4**	**Building 5**
Area of business	Construction material production	Mechanical workshop	Food processing	Food processing	Forestry
Yearly demand $[kWh/yr]$	1 170 000	250 000	1 400 000	360 000	2 800 000
Yearly peak demand $[kWp/yr]$	345	157	261	115	789
Roof top area $[m^2]$	5 500	2 000	6 000	6 000	9 000
Assumed energy features	PV, CHP and load shifting	EVs during work hours	CHP and load shifting	PV	PV and CHP

- **B1**: The construction material production industry consists of a wide range of companies involved in the mining, quarrying, and processing of raw materials used for buildings and constructions. Hence, construction materials include materials such as; cement, wood, bricks, glass, aluminum, plastics, etc. A large part of the production costs comes from energy consumption and pollution costs. Due to high electricity consumption and a relative constant base

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[1] Company information at: www.nte.no

[2] Due to confidentiality reasons, more detailed information regarding the buildings where not available

load, the building is assumed to have roof top solar PV and electrical supply from CHP as DG. Further, it is assumed that some production process can be shifted during work hours, thus load shifting is included as an additional flexibility resource.

- **B2**: A mechanical workshop is a business within the iron- and metal-industry, performing services such as; shipbuilding, forging, welding, mechanical work, etc. A decentralized storage is added to the building to provide some energy flexibility. The storage unit represents EVs parked at a parking lot outside the building, serving vehicle-to-building (V2B) operations.
- **B3**: The food processing industry consist of businesses producing food, mineral water and other articles. In other words, articles consumed by humans. The industry covers a series of industrial activities directed at the processing, conversion, preparation, preservation and packaging of food articles. Today, the industry has become highly diverse in terms of size and efficiency, ranging from small and traditional businesses that are highly labor intensive to larger, mechanized and capital-intensive industrial producers. In Norway, this industry is the largest continental-industry. With a steady demand for heat and power, many food-manufacturing sites are ideally suited for CHP. With high demand and somewhat constant base load, CHP and load shift are assumed DERs for the building.
- **B4**: This food processing industrial building have a fairly even electrical demand throughout the year, even during the summer, in terms of base load and power peaks. As the summer moths actually have higher power peaks than the winter months, it is assumed to have a great need of cooling[3]. Based on this and the large roof top area, the building is assumed to have a relative large solar PV roof top installation.
- **B5**: Forest industry is a common category for all industry employing lumber as raw material, such as saw-mills, planing-mills and all wood processing industry. The forest product industry uses much energy from woody biomass and is a leader in using CHP to produce electricity. According to an analysis performed by the International Energy Agency (IEA) [40], CHP supplies 20-60 % of the electricity requirements for the pulp and paper industry in several countries. Hence, the building DERs are assumed to be a CHP covering the large base load and a solar PV system installed at the large roof top.

4.2. Distributed generation and flexibility

The substantial electricity demand and power peaks of the industrial buildings, incentives investing in DERs. In addition, having a green image is becoming increasingly important for today's industry. Two examples of commercial buildings in central Norway with periodical excess power, due to large PV systems, are Powerhouse Brattørkaia [42] and ASKO [41]. Powerhouse Brattørkaia is Norway's biggest and newest energy-positive building, where solutions for

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[3] Such as the ASKO facility in Trondheim. ASKO is Norways largest grocery wholesaler [41].

trading excess PV generation directly to neighbouring buildings are being considered. ASKO is Norway's largest grocery wholesaler with 9000 m^2 installed PV system and hydrogen production at the facility in Trondheim. Based on these trends and the industry information, the building DG and flexibility are assumed in order to facilitate building excess power in some periods, to study P2P energy trading at an industry site.

Solar PV

Historical solar PV production data for the year 2017 was provided by NTE Nett AS for a PV system located in central Norway. The time series are hourly production data from the system with installed capacity of 45.7 kWp and total annual solar production of 29.6 MWh. The individual building PV systems are based on these historical data, PV system characteristics and building roof top areas. The total annual solar production calculated for building 1, 4 and 5 are 118.3, 118.3 and 266.1 MWh, respectively.

Combined heat and power

CHP systems are highly efficient, making use of the heat which would otherwise be wasted when generating electrical or mechanical power. The size of the CHP plant can be based on several considerations, e.g. baseline electricity or thermal output. In this paper, gas fired CHP units are used to supply the base electricity demand of some industrial buildings. The hourly electricity output of the CHP in building 1, 3 and 5 are 45, 60 and 110 kWh, respectively. The CHPs are not operated during the summer holiday, when the production is lowered or stopped and the outdoor temperature is higher. Further, the fuel costs are neglected.

Load shift

Load shifting assumes some degree of demand elasticity. That is, the load is shed based on costs and availability of loads as long it is recovered at a later point in time. Flexible loads and processes in industry are typically: heat and cooling processes, inert diffusion processes, mass transport and logistics [12, 43]. Load shifting is enabled to provide flexibility to the buildings, and is modeled as a loss less storage unit. As shifting a production process from the original production schedule is an inconvenience, the demand is shifted at a high variable cost for the building. The total available load reduction in a time step t is 10 % of peak demand and the maximum amount of shifted load not rescheduled is four times the available load reduction.

Table 4 gives the period of time the loads can be shifted (and recovered) and the related variable cost. Due to little information regarding the production processes in the buildings, the costs are based on the electricity prices, Gils's [44] presentation of variable costs of different technologies and Angized et al. [12] characteristics of identified flexible loads.

Table 4: Overview of building load shift characteristics: time period and related variable cost.

	Building 1	**Building 3**
Time period	Work hours	24 hours
Penalty $[NOK/kWh]$	0.4	1.2

Electric vehicle parking lot

A storage unit, representing EVs parked at an employee parking lot, is serving as V2G flexibility for building 2. In this paper, the parking lot is assumed available for all interested employees of the industry site, and that an average of 600 cars are parked there during work hours. According to Statistics Norway (SSB), EVs constituted 5.1 % of the Norwegian passenger car stock at the beginning of 2018 [45]. Hence, the assumed number of EVs are 30. The number of EVs are expected to increase extensively [46], making the V2G technology highly relevant for communities in the near future.

The average storage capacity of the EVs is based on the three most common EVs in Norway in 2017: Nissan Leaf, Volkswagen e-Golf and Tesla S [47]. These holds lithium-ion (Li-ion) batteries with capacities of 24-60, 24-36, and 60-100 kWh, respectively. As a result, the nominal storage capacity for all the EVs are set to 50 kWh, with a round-trip efficiency of 96 %. Today, there is a clear market demand for EVs with more storage capacity, which is evident in the market growth of different EV models and for the EV models entering the market. EV manufactures commonly set the SOC window of the Li-ion batteries to 20-90 %, due to lifetime aspects such as battery degradation [48].

The charging time and battery power rates are also dependent on the charger technology, which again is dependent on the available voltage level at the desirable location. The voltage level at the industrial buildings is 400 V, hence semi high-speed EV chargers of 20 kW with one hour charging are assumed for the parking lot.

The storage unit of EVs is available during work hours, which are weekdays from 8 am to 4 pm. Implemented with the binary parameter $w(t)$, stating if the given time step t is a work hour or not. When the EVs arrive for work the average storage level is assumed to be 60 % of nominal capacity. A survey of Norwegian households with EV, performed by Sæle et al. [49] in 2018, shows that 70 % of the households normally charge their EV at home and only 21 % daily at the office. For that reason, the average minimum amount of stored energy in the EVs at the end of each workday is set to 70 % of nominal capacity. Assuming the EV owners in average increases the storage level 10 % during a work day and are willing to make their EV available for V2G services. Human behavior and the value of end storage level are advantageous areas for further work regarding EVs.

4.3. Central energy storage

The shared energy storage is modeled as a Li-ion battery, which is the most widespread battery energy storage system (BESS). The nominal storage capacity is 1 MWh, with a round-trip efficiency of 96 %. Further, the SOC operating interval was explained in the model formulation and set to 20-90 %. The battery inverter transforms AC power from the buildings to DC power when charging, and vice verse when discharging. The size is typically matched to provide the nominal power of the battery, and is set to 333.33 kW with an efficiency of 98 %. Initial storage level is set to the minimum SOC. The final storage value is not specified, as it will no affect the results noticeably with the one year time horizon. For simplicity, some assumptions are made regarding the storage characteristics, such as no degradation, constant efficiencies, no stand-by-losses and a C-rate of 0.33[4].

4.4. Electricity prices

A prominent part of the market designs and rules are defining the various electricity prices, both for exchange with the main grid and local community prices. The optimization and comparison of the different setups are highly dependent on these prices.

Grid electricity prices

As described in Section 3.2.1, the total cost of grid electricity for an industrial prosumer consist of three parts: the cost of energy supplied from the chosen energy supplier, the utility tariff of the local grid owner, and the revenues from selling excess power. The total cost was presented in Eq. (1).

The market spot price is decided by Nord Pool, which operates the Northern European electric power exchange market [50]. The industrial site is located in central Norway, hence the hourly day-ahead spot prices for the price-area Trondheim is employed. Nord Pool's historical data are open and available for all [51], and time series for the year 2017 are used. The spot prices are trending towards higher and more fluctuating prices, which might contribute to increase the value of on-site flexibility and P2P energy trading.

The industrial consumer utility tariff, including the peak power demand charge, was described in detail in Section 3.2.1. The related data are set by the local network company, which for the given area in central Norway is NTE Nett AS. All the buildings are connected at the same voltage level and related utility tariff data are presented in Table 5 [52]. The buildings are invoiced at the high voltage side, hence they are subject to a high voltage tariff. However, the voltage level at the buildings are 400 V, as they own the low voltage grid themselves.

Table 5: Industrial consumer utility tariff, with data from NTE Nett AS [52].

Type	**Fixed Term [NOK/yr]**	**Energy Term [NOK/kWh]**	**Power Term [NOK/kWp/mo]**
High voltage	14811[5]	0.0424	70

---

[4] The assumed C-rate means that the battery can charge or discharge all available energy in three hours within the limits of the inverter.

In the case of excess power from DERs or flexibility features, prosumers have the opportunity to sell power to the grid. With the new prosumer agreement, described in Section 3.2.1, this revenue depends on the sales agreement between the prosumer and the local energy supplier. Prosumers usually receive the hourly area market spot price $[NOK/kWh]$ for feed-in electricity. Hence, the buildings receive the market spot price for the energy delivered to the distribution grid (after community network losses).

P2P prices

A reasonable price level for the P2P prices is between the grid consumption price and the grid feed-in price, to promote power flows at local level [1, 9]. Lüth et al. [8] argues that the P2P energy trade prices should reflect the willingness of each individual prosumer to pay for an extra unit of electricity, in other words the shadow prices of each prosumer. For that reason, the P2P trade prices are set to the willingness to pay for each building in the Base Case, with no possibility to trade locally or use the central storage. Which is analogues to the clearing price method of Abbaspourtorbati et al. [53], where the dual prices of the energy balance equations are the clearing prices.

The P2P trade prices are calculated by minimizing the cost of each building in the Base Case setup. The optimal solution provides a dynamic willingness to pay, i.e. marginal price, for each building in each time step. The monthly fixed utility tariff cost is not included in the marginal price calculation, as this is a cost the buildings have to pay regardless of the grid consumption in time step t. Hence, it does not affect the willingness to pay. In addition, the P2P energy is traded locally within the industry site, thus the grid usage cost in total should not be included. In peak demand periods the willingness to pay is high as the cost of increasing the monthly peak power is so extensive, due to the utility peak demand tariff. To reflect this, an individual penalty, based on the monthly peak power utility cost, is added in the marginal price calculation in time steps where the grid power consumption is higher than a certain threshold. This threshold is set for the individual building in each month and defines peak power periods in the P2P price calculation. Fig. 3 visualizes the grid consumption with this threshold in an arbitrary week. Hence, the willingness to pay in these time steps are increased.

Central storage prices

The charging of the shared community energy storage should be compensated. It is reasonable that the price a building receive when charging the storage is equal to the price for selling electricity to the distribution grid. Thus, the compensation price is set to the market spot price, and the buildings receive this price for the power leaving the building (before community network losses).

The discharging of the shared community energy storage is priced according to the individual building willingness to pay, i.e. building P2P price, and an

---

[5] Equals 1234.25 NOK per month

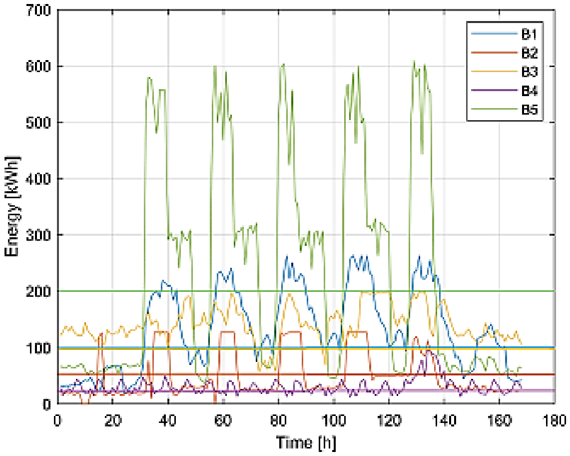


Figure 3: Visualization of the building grid consumption power threshold defining peak power periods in the P2P price calculation in arbitrary winter week.

additional fee. This fee is added to avoid simulations charging and discharging by the same building, i.e. unfavorable price arbitrage, and to incentive P2P trade. The fee is set equal to the charging price. As a result, the discharging prices are dynamic individual prices for each building.

5. Results

The presented linear multi-stage optimization models are implemented in the optimization environment General Algebraic Modeling System (GAMS) [54] and solved using the CBC solver. All system parameters are read from Excel and all results are loaded back to Excel and MATLAB. A one year system simulation of Case 2 took approximately 100 sec on a computer with 64-bit Windows 10 Education, Intel® Core™ i7-7600U 2.80 GHz CPU and 16 GB of RAM.

The effectiveness of the system operation is evaluated by the sum of the objective function, i.e. the total cost of the whole industry site, and the individual costs of each building. A lower value of the total cost implies a more effective strategy for operating flexibility resources and employment of P2P trade. The usage and value of P2P energy trade and on-site flexibility are assessed by comparing and studying the various market designs.

5.1. Base Case: Flexible buildings

With the configuration and market design of the Base Case (BC), the supply-demand decisions are obtained decentralized at each individual building, without P2P collaboration or shared flexibility within the industry site. In other words, the building DERs (PV, CHP, EV and LS) are optimally scheduled to supply the individual building demand, with grid power consumption covering

Table 6: Total results for the three industry site system configurations.

	Base Case *(Reference)*	**Case 1** *(P2P trade)*	**Case 2** *(P2P & storage)*
Total costs [NOK]	***2,334,921***	***2,175,170***	***2,077,326***
Total cost of grid consumption	2,360,882	-7.5 %	-12.0 %
Cost of peak power	1,017,800	-15.0 %	-25.6 %
Cost of UT energy term	162,860	-1.9 %	-2.1 %
Cost of UT fixed term	74,055	0 %	0 %
Cost of energy spot price	1,106,166	-1.9 %	-1.9 %
Revenues of selling to the grid	27,069	-65.3 %	-87.1 %
Yearly peak demand [kWp]	1,412	-7.0 %	-19.5 %
Grid consumption [kWh]	3,841,049	-1.9 %	-2.1 %
Power sold to grid [kWh]	110,346	-67.0 %	-87.9 %
Curtailed power [kWh]	15,711	-100 %	-100 %
P2P export [kWh]		206,208	260,537
Central storage charge [kWh]			56,894
Yearly peak shave [kWp]		99	275
Total savings [NOK]		***159,751***	***257,596***
Total savings [%]		***6.8 %***	***11.0 %***

the remaining electricity demand. In the case of excess power, the power are sold to the grid or curtailed. Further, the BC is considered the reference case when analyzing the results from the other market designs.

The BC is investigated in terms of simulations of various length and seasonal characteristics, and the total industry site results are summarized in Table 6. Based on the results and simulation trends, following observations are made:

- Each building maximizes the self-consumption of their building DER and minimizes the grid consumption.
- Excess power mainly occurs during the summer in times of high irradiation on the PV systems. The amount of power sold to the grid is 110,346 kWh, while 15,711 kWh exceeds the prosumer limit and are curtailed.
- Load shifting brings some degree of demand elasticity to B1 and B3. The feature is employed to shave the peak power demand and the load is rescheduled according to the wholesale price. Further, the available time period for rescheduling and the LS penalty affects and reduces the usage of the load shifting feature for demand response.
- The EV parking lot storage at B2 is operated to perform peak shaving, as well as price arbitrage based on the spot prices. However, the total building demand for B2, and thus the cost of energy, sees a large increase, due to the hard constraints on the initial and final storage level of a workday. Consequently, the EV storage brings some flexibility to B2, though the building demand is considerably increased.

As the industrial buildings are assembled to represent an industry site in this study, all the demanded electricity is consumed from the grid in the present situation. In the present situation, the total cost of electricity is 3.3 mill NOK and the total grid consumption 5.9 mill kWh, which are 28.8 % and 35.3 % higher than for the BC, respectively.

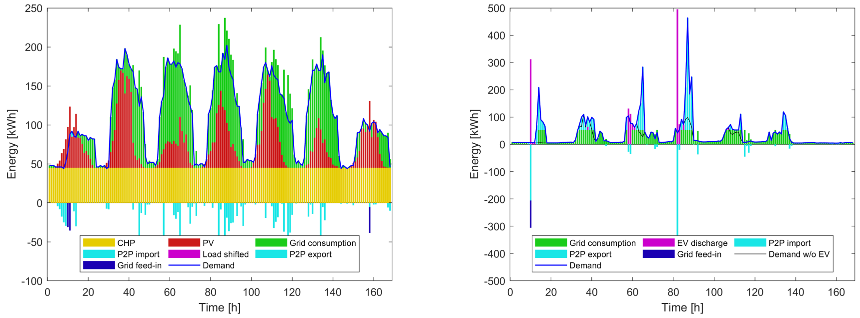
5.2. Case 1: P2P energy trade

The first collaboration case, Case 1 (C1), allows for local energy trade, in addition to the market features of BC. The P2P mechanism allows the prosumers to sell their surplus or stored energy from DERs and extra procurement from the main grid in the local industry site market.

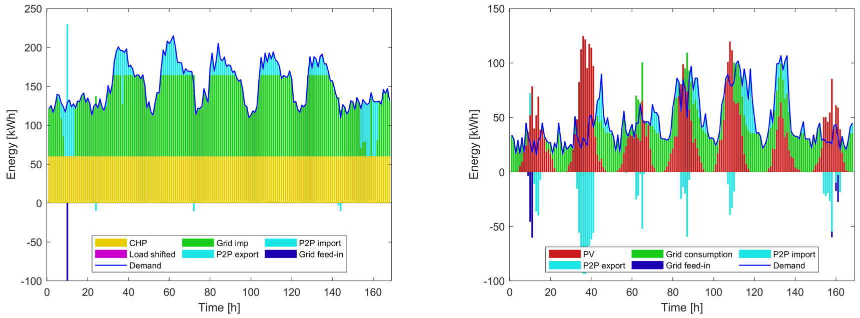
Simulating the optimization model based on the market rules of C1, the total cost of electricity for the industry site is minimized. Hence, the optimal system operation minimized the total amount of energy consumed from the grid. Each building consumes their own DG and then covers any remaining demand by buying the next cheapest electricity available in the market, thus from peers or the grid. Consequently, the day-to-day system operation and energy source composition of each building varies. Fig. 4 presents the supply-demand decisions of an arbitrary summer week in 2017 (week 24 in June), illustrating how each building covers its demand, operates building flexibility and trades. Following observations are seen from the simulation and figures:

- P2P trade reduces the grid consumption and make the industry site more flexible.
- The EV storage of B2 are used more rapidly, due to price arbitrage operation by the whole industry site based on the wholesale prices. The recharging power peaks at the end of the workday are covered by P2P trade, hence these B2 grid power demand peaks are shaved.
- The industry site perform price arbitrage in terms of buildings consuming extra power from the grid in low-price periods, up to the optimal peak power of the given month, and trades with peers.
- Excess grid power is traded to shave the power peaks of peers, with the peak demand charge as the key driver. Hence, P2P trade covers great share of the peaks.

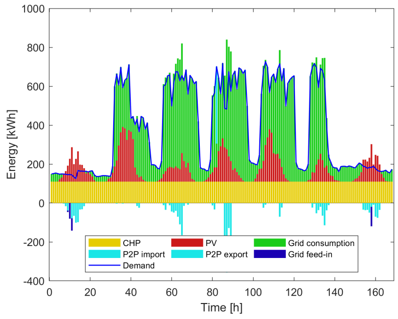
The arbitrary week shows how the industry site collaborates using P2P trade to cover the building demand and shave power peaks during the summer. The buildings with times of generation surplus, thus buildings with installed PV systems: B1, B4 and B5, export the most P2P energy. B2 and B3 imports most of the P2P trade, as mainly price takers with the highest willingness to pay. As the chosen week presents a good supply from the PV systems, the P2P trade primarily consist of DG surplus. The generation varies among the seasons, and the amount of extra consumption from the grid penetrating the P2P export are higher in periods of less generation. These results are also driven by the centralized solution method, where the total cost of electricity is minimized for the whole industry site. This affects the P2P power flows to a great extent, where the industry site go to great lengths to keep the monthly peak power for each building as low as possible. Making it optimal for a building to consume



(a) B1: Construction material production (b) B2: Mechanical workshop



(c) B3: Food processing (d) B4: Food processing



(e) B5: Forestry

Figure 4: Supply-demand results for Case 1 with P2P trade in arbitrary summer week.

extra grid power, up to the lowest monthly peak for trading, to help a peer shave its peak.

The total industry site results for the C1 market are summarized in Table 6, giving following insights:

- The grid consumption is reduced 1.9 %, while the total cost of grid consump-

tion is reduced 7.5 %. Due to a more flexible industry site utilizing volatile price signals and shaving peaks.
- The cost of peak power is reduced 15 % and the total highest peak is shaved 99 kWp due to P2P trade.
- No power is curtailed and the grid feed-in is reduced 67 %.
- The total system savings by the introduction of P2P trade is 159,751 NOK (6.8 %).

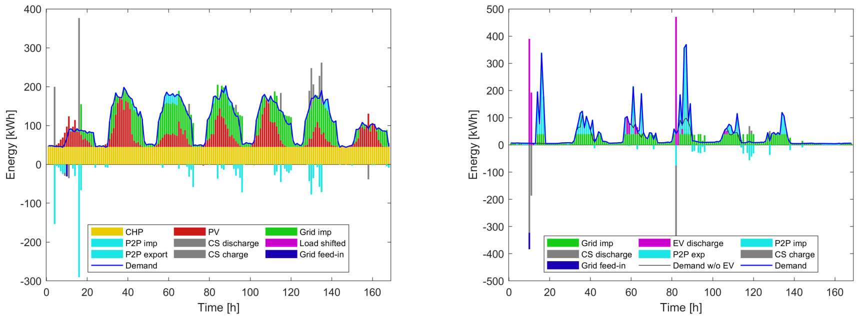
5.3. Case 2: P2P energy trade and central storage

The second collaboration case, Case 2 (C2), includes a shared community energy storage and P2P energy trade, in addition to the market features of BC. The market rules and prices are the same as for the C1 market, further the prosumers can utilize the central storage according to local charging compensation and discharging prices. The storage can be charged by prosumers excess power of DERs and additional procurement from the distribution grid, yet the storage cannot charge directly from the grid.

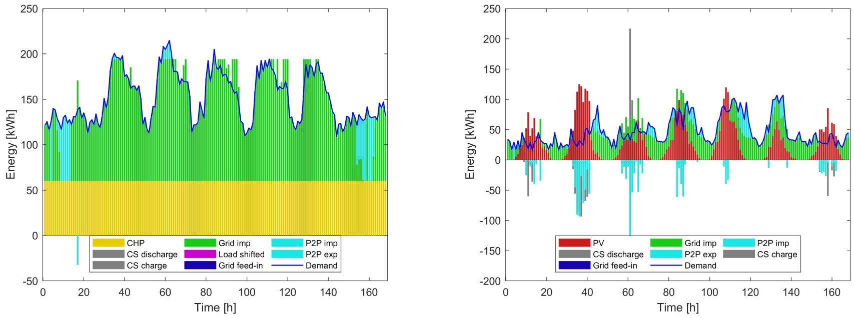
Simulating the C2 market design, the yearly system operation for each building are slightly different. The individual supply-demand decisions of each building in the same summer week in 2017 (week 24 in June) are presented in Fig. 5. Following insights are gained from the simulation and figures:
- The shared storage is employed to cover the building demand and to shave peaks.
- P2P trade and the shared storage reduces the grid consumption and make the industry site more flexible.
- The monthly grid consumption peaks are significantly reduced for each building throughout the year.

The figures illustrates how P2P trade and the shared storage are used to cover building demand and shave power peaks for the overall industry site. The supply-demand power flow patterns have changed, where B2 and B3 contribute with more P2P energy export. This is viable for B3 in week 24, where the building consume extra grid power for trading. The centralized control method also affects the operation of the shared energy storage. The building with the lowest discharging price tends to discharge a large amount in a time step, and trade this power to peers. Hence, the overall system performs price arbitrage and shave peaks.

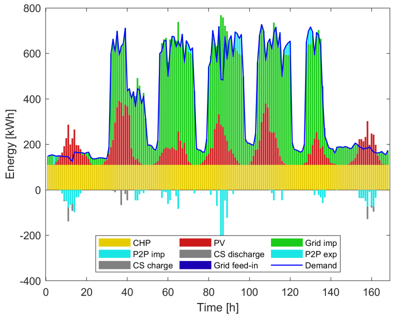
The total industry site results for the C2 market are summarized in Table 6, and the following are observed:
- The grid consumption and total grid cost are reduced 2.1 % and 12.0 %, respectively. Hence, the industry site has become considerably more flexible to exploit volatile spot prices and shave peaks.
- The cost of peak power and the total highest peak are reduced 25.6 % and 275 kWp, respectively, due to the shared storage and P2P trade.
- The grid feed-in is now reduced 87.1 % from BC, which means that near all generation is employed locally.
- The amount of P2P trade is increased 54,331 kWh from C1.



(a) B1: Construction material production (b) B2: Mechanical workshop



(c) B3: Food processing (d) B4: Food processing



(e) B5: Forestry

Figure 5: Supply-demand results for Case 2 with central storage and P2P trade in arbitrary summer week.

- The total system savings by introduction shared storage and P2P trade are 257,596 NOK (11 %). Compared to C1, this represents additional savings of 97,845 NOK (4.2 %).

5.4. Evaluation of the participation willingness

As the demand and installed capacity of DERs vary among the individual buildings, the total cost of electricity is vary for each industry site building. The proposed market designs define rules for the local collaboration within the industry site. With different degree of flexibility and production, the benefits of engaging in a joint community differ among the buildings. For prosumers to cooperate in P2P energy trading there must be an incentive to join the community. As such, the benefits of each single prosumer counts, as well as the overall benefits of the whole industry site. To evaluate the participation willingness and to see what provides the most benefit to whom, the total cost of electricity is evaluated per building in each of the designs.

Table 7 presents the total cost of electricity and savings compare to BC for each building in the market designs. The total cost of electricity is decreased for all buildings in C1 and C2, with distinctly higher savings in C2. In C1, P2P trade leads to a minimum saving of 4.4 % compared to the BC. While for C2, savings are more evenly distributed among the buildings, with a minimum of 7.0 %. As primary a price taker, EV storage holder by day and consumer by night, B2 sees large savings in both collaboration cases. B4 has the most excess production and sees the largest savings, due to no curtailment, favorable local trade and peak shaving. Further, the PV owners, B1, B4 and B5, profits to a great extent from implementing the share storage in C2. The buildings obtain benefits due to P2P import and export leading to price arbitrage, peak shaving and increased self-consumption, overall making the industry site more flexible. Further, this elaborates how the defined market designs, in terms of pricing schemes and rules, are key driver for the results.

Table 7: Total cost of electricity and total savings referred to BC for each building in each system configuration.

	BC: reference	**C1: P2P**		**C2: P2P & Shared storage**	
	Tot costs [NOK]	Tot costs [NOK]	Tot savings	Tot costs [NOK]	Tot savings
B1	422,847	404,073	4.4 %	378,984	10.4 %
B2	201,494	176,569	12.4 %	172,827	14.2 %
B3	443,605	413,391	6.8 %	412,649	7.0 %
B4	182,655	147,645	19.2 %	140,137	23.3 %
B5	1,083,698	1,033,493	4.6 %	972,728	10.2 %

Zhou et al. [9] and Long et al. [1] defines a participation willingness index, which measures the percentage of the prosumers who obtain more benefits after participating in P2P collaboration. The index is measured by the proportion of the prosumers who have lower cost of electricity compared to only procuring from the wholesale market, given by Eq. 33. In this participation evaluation, investment costs are not evaluated. However, compared to the BC, the industry site do not need any investments to enable P2P energy trading.

$$PI = \frac{N_{Lowercost}}{N} \cdot 100\% \tag{33}$$

Seeing that all buildings have lower cost of electricity in both C1 and C2, all buildings (PI = 100 %) obtain benefits with P2P collaboration and have an incentive to participate in the industry site community.

6. Conclusions

In this study, the value of P2P energy trading in combination with various on-site generation and flexibility resources are investigated for a Norwegian industrial site. Two local energy market designs are proposed, with the objective to minimize the total cost of electricity for the industrial site as a whole. An additional scope has been the system operational impact of the utility tariff peak power charge in combination with P2P energy trading.

The results reveal that P2P energy trading is able to bring substantial economic benefits to the industrial site, as well as to the individual customers. With yearly net savings for the whole industrial site of 6.8 % and 11.0 % in the C1 and C2 markets compared to base case, respectively. As such, all buildings have a willingness to participate. The self-consumption is considerably increased with the local building collaboration, with no power curtailment and a reduction in grid feed-in of 67.0 % and 87.1 %.

Further, it is demonstrated that using P2P energy trading for peak shaving purposes are highly beneficial. The total cost of peak power is reduced 15.0 % in C1 and 25.6 % in C2, with the substantial peak demand as key driver. As a result, peak shaving is by far the largest contributor to the net cost savings. The shared storage in the C2 market enables a large increase in peak shaving. An interesting finding is that the results are greatly driven by the centralized solution method, where the total cost of electricity is minimized for the whole industrial site. Consequently, the market design is the main driver of the results.

This study demonstrates the benefits of integrating P2P energy trading at an industrial site and P2P trading in the presence of a utility tariff peak power charge. Consequently, the operational trends and results in the thesis bring novel results to the subject of P2P energy trade. It should be noted, there are many key enablers and barriers remaining in the field, such as advances in DERs and ICT, digitization, legal and regulatory obstacle and consumer willingness to share energy.

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Chapter 4

Further Elaboration of the Industrial Site Data and Solution Method

As the paper in Chapter 3 is limited in terms of length, this chapter is included to provide some further understanding and details regarding the presented solution method, industry site data and assumptions.

4.1 The Modelling Software

The presented mathematical models are implemented and solved in the optimization environment GAMS. An overview of the complete model formulation for each case study are presented in Appendix A. All system parameters are read from Excel. The results from solving the optimization model are loaded back to Excel and Matlab, to enable further modification and revision of the results in order to produce presentable graphs and plots.

GAMS is a high-level modeling system for mathematical programming and optimization. The environment is equipped for complex and large scale modeling applications, where the models are easily adapted to new cases and simulations. GAMS is specifically designed for modeling linear, nonlinear and mixed integer optimization problems, and contains a large amount of integrated high-performance solvers. In addition, the model is independent of the solver. This means that several solvers can be tested for the same model formulation, which reduces the risk of being limited by the solver [39].

Moreover, the mathematical models are formulated in a way that is very similar to the mathematical descriptions, namely an algebraic modelling language. As a result, the language is easy to understand and use. This is opposite to matrix data structure languages, where equations and constraints must be translated into matrices. Today, algebraic modeling is considered the most productive way of implementing optimization models and decomposition methods for optimization problems. Finally, the solution report from the solver, with the outputs and results, are easy to read and transfer to other programs. As described, GAMS introduces several benefits for implementing the model. Nevertheless, the widespread usage may be limited to some extent, as it is commercial and academic licensed [39].

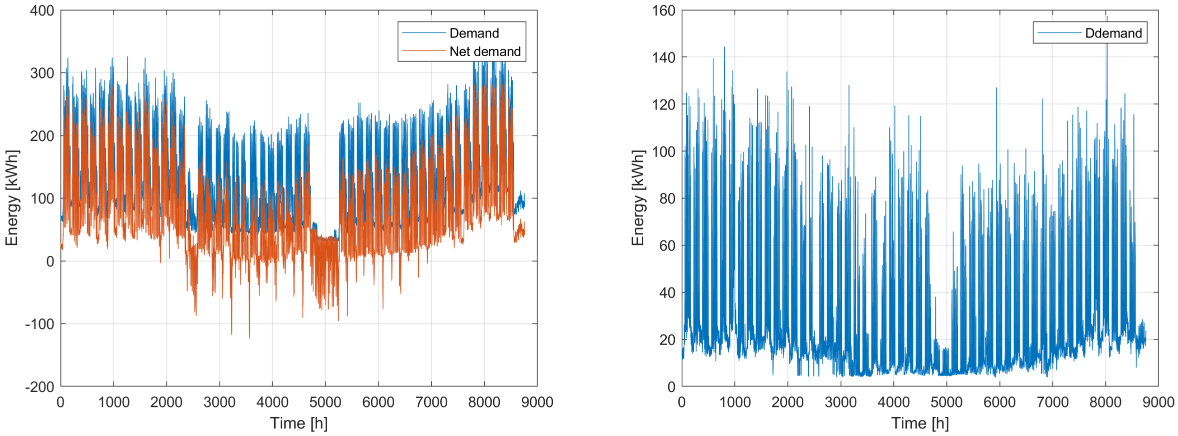
4.2 The Norwegian Industrial Site

The Norwegian industry site was described in detail in the paper presented in Chapter 3. In order to be able to analyze the data and system behavior in further detail, this section provides plots and some additional remarks regarding the industry site data.

4.2.1 Building Demand Profiles

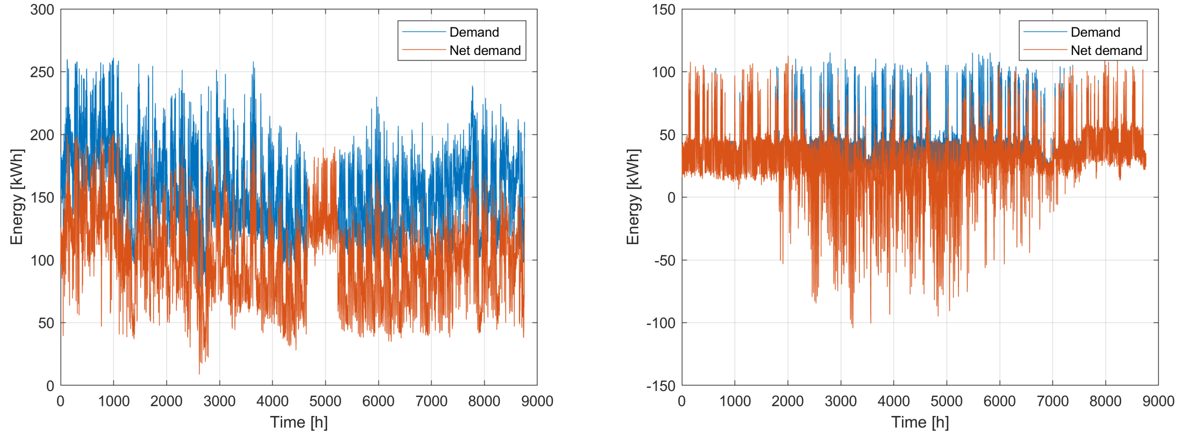
As described in Section 4 in the paper, the system under investigation consist of five industrial buildings, customers of NTE Nett AS, assembled to represent an industry site case study. The industrial buildings are differentiated in terms of area of business and size, hence the demand profiles are different both in magnitude and pattern. The area of business and building characteristics were presented in the paper, while comparison and details regarding the demand patterns will be presented in this section. It should be noted that power with negative value in the following figures represent excess power or power leaving the building.

The demand time series are visualized in Figure 4.1, where the demand is the original building demand in 2017 provided by NTE Nett AS. Moreover, the net demand is the original demand including the distributed generation of the given building, i.e. CHP and PV. The most prominent difference between the demand profiles is the magnitude. B1 in Figure 4.1a and B2 in Figure 4.1b have very similar demand patterns, except for the dimension. As seen from the figures, both buildings have lower demand during the summer months compared to the winter. The demands are at its lowest in the middle of the summer, which can assumed to be a production stop during the summer holiday. The demand curves are diminish parallel to warmer weather, and increasing as the season gets colder towards winter. Hence, a logical explanation could be the need for heating.



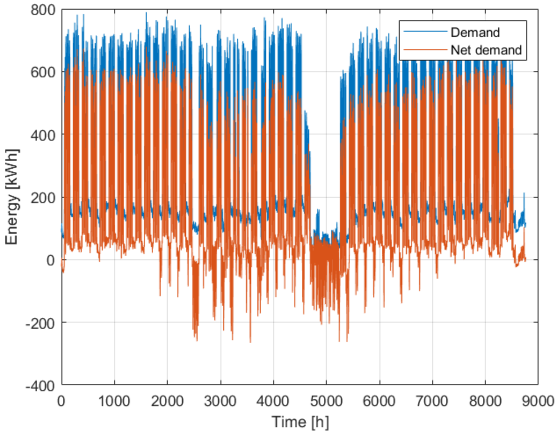
(a) Building 1: Construction material production

(b) Building 2: Mechanical workshop



(c) Building 3: Food processing

(d) Building 4: Food processing

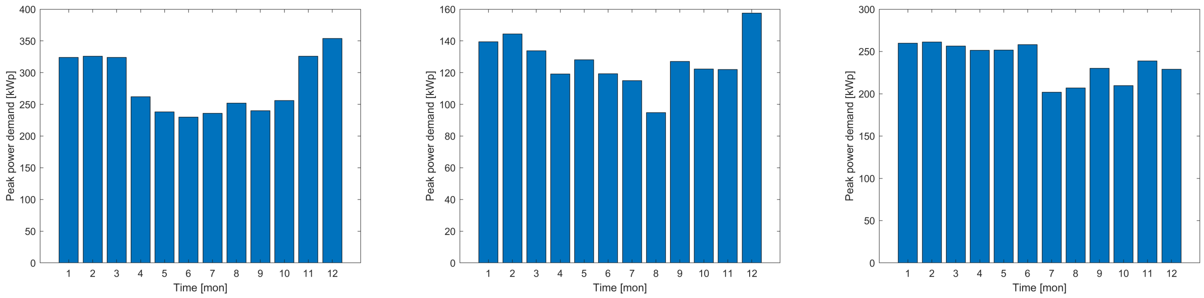


(e) Building 5: Forestry

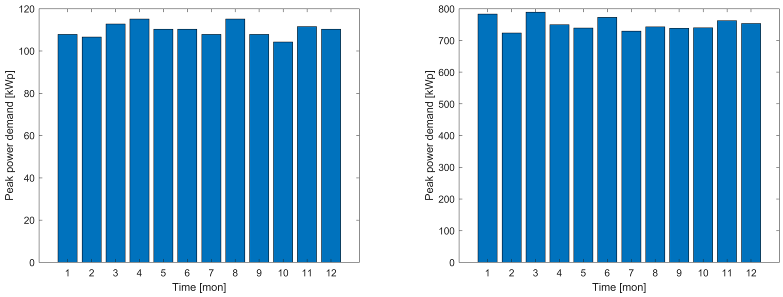
Figure 4.1: Demand and net demand profiles for each building, based on data from NTE Nett AS.

B3 and B4, in Figures 4.1c and 4.1d respectively, are both food processing industrial buildings. Compared to the other buildings, the demand patterns are slightly more even throughout the year. The base loads are higher and more prominent, especially for B4. In addition, these building do not have the period of production stop during the summer. B5 in Figure 4.1e stands out with much higher annual demand and demand profile than the other buildings.

Moreover, the monthly peak power demands of each building can be seen in Figure 4.2. It should be noted that these peak power demands are from the original system without any DER, storage or P2P energy trading. The figures visualize how the industrial buildings have high peak power demand throughout the year. B1 and B2, in Figures 4.2a and 4.2b respectively, have lower peaks during the summer compared to the winter months, while the rest of the buildings have fairly even peaks the whole year. As the peak power term in the industry consumer utility tariff is considerable, peak shaving may present large savings for the industrial buildings.



(a) Building 1 **(b)** Building 2 **(c)** Building 3



(d) Building 4 **(e)** Building 5

Figure 4.2: Monthly peak power demand for the original industrial buildings in 2017

4.2.2 Distributed Generation Time Series

The solar PV and CHP characteristics where presented in the paper. This section presents the PV production pattern and some additional remarks regarding the DG production and net demand.

Figure 4.3 presents the historical solar PV production data provided by NTE Nett AS, which is used to produce the individual PV production patterns for the buildings with installed PV system. As seen from the figure, the generation is higher during the summer and lower during the winter, which agrees with typical yearly sun condition patterns. The solar PV production is higher during the summer due to more irradiation. Seeing that the data is historical data actually measured in central Norway, daily changes in weather are accounted for. For this reason, the production is intermittent with large day-to-day changes, due to e.g. shading from clouds.

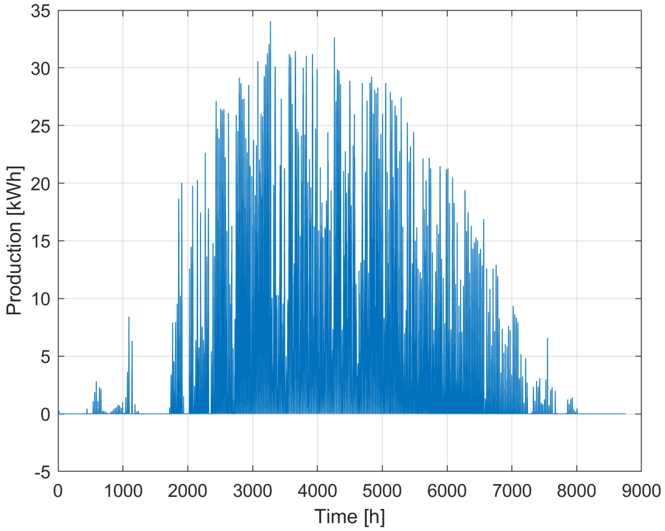
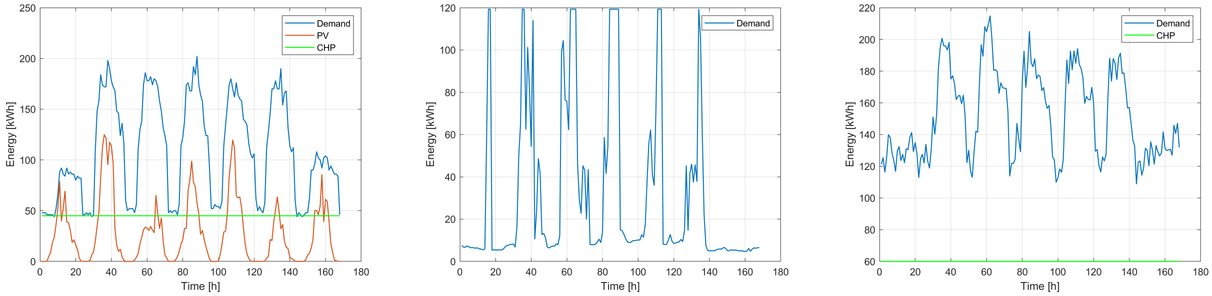


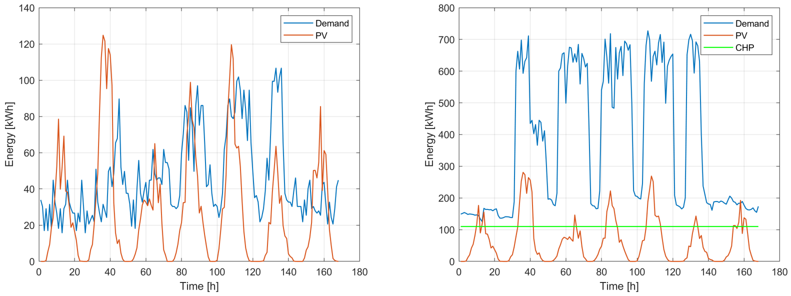
Figure 4.3: Historical production of a PV system with installed capacity of 45.7 kWp, based on data provided by NTE Nett AS.

The net demand of each building are presented in Figure 4.1, which is a product of the original demand and any CHP electrical production and solar PV production. The distributed flexibility features, EV parking lot and load shifting, are not included in the net demand, since the related variables are decided by solving the optimization problem. Further, the net demand visualizes any periods of excess power for the individual buildings. Excess power occur in the time steps where the net demand is below zero. Seeing that the CHP covers the base load, the demand patterns are shifted vertically downwards, as observed for B1, B3, and B5 in Figures 4.1a, 4.1c, and 4.1e, respectively. Further, the buildings with periods of excess power are B1, B4, and B5. These periods arise mainly during the summer in time steps where the demand is low or shifted by CHP and the PV production is high, visualized in Figures 4.1a, 4.1d, and 4.1e. Typically, CHP enables and leads to more frequent excess power when combined with solar PV for buildings with a high base load, as for B1 and B5.

The PV production typically exceeds the demand in periods of low demand and peak production, e.g. weekends during the summer. This pattern is analogous to the ASKO facility in Trondheim[1], which is an industrial building located in central Norway. With a great need for cooling during the summer, their power demand peaks are reduced by the installation of a 1.4 MWp rooftop PV system of 9500 m^2. The periods of excess power mainly occur in periods of low activity at the facility and much irradiation[2].



(a) Building 1 **(b)** Building 2 **(c)** Building 3



(d) Building 4 **(e)** Building 5

Figure 4.4: Building demand and generation in arbitrary summer week (week 24).

Figure 4.4 presents the demand at each building and any electrical production from CHP and solar PV in an arbitrary summer week (week 24). Figures 4.4a and 4.4e for B1 and B5, respectively, shows how the total building production is dependent on the CHP electrical production to exceed the demand. During the winter the irradiation is much lower, hence the demand is considerably higher than the production, even with CHP. For B4 the solar PV production alone exceeds the demand during the summer months, seen in Figures 4.4d and 4.2d.

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[1] ASKO is Norway's largest grocery wholesaler [40] and was described in the paper.

[2] Information provided through email correspondence with Roger Sæther at ASKO Trondheim.

The remarks presented above are important concerning the system utilization of the available flexibility options, thus how P2P trade and decentralized and centralized on-site flexibility can bring benefits. If the production do not exceed the demand for any buildings, there are no excess power to trade or charge the central storage. Thus, industry site collaboration may not be of any value, as the remaining industry site demand would have to be consumed from the grid. On the other hand, if the difference between off-peak and peak electricity prices are high and/or the individual building peak demand patterns diverge, the on-site flexibility can be operated to perform price arbitrage and peak shaving.

4.2.3 Nord Pool Spot Prices

Detailed price information was given in Section 4 in the paper. This section presents some additional visualizations and remarks regarding the trends and seasonal differences in the Nord Pool spot prices.

As the industry site is located in central Norway, the hourly day-ahead spot prices for the price-area Trondheim were employed. Nord Pool's historical data is open and available for all, and Figure 4.5 shows the hourly spot prices for the years 2015-2018 [41]. The figure illustrates some trends towards higher and more fluctuating prices, which might contribute to increase the value of on-site flexibility and P2P energy trading, as described in Section 2.2.2.

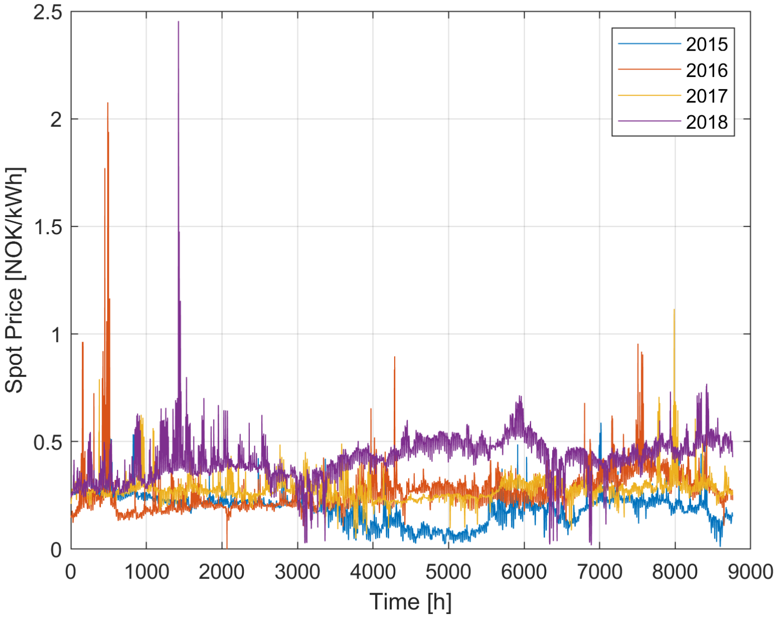
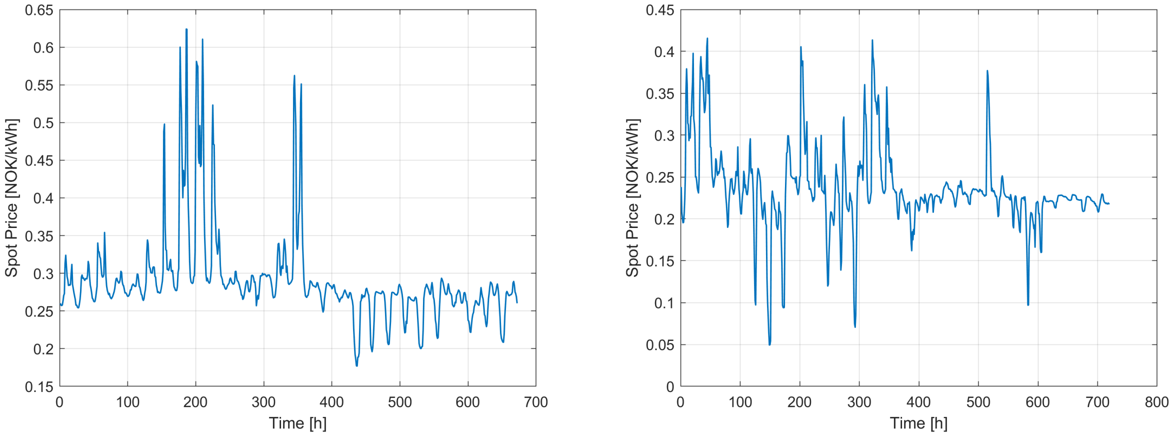


Figure 4.5: Hourly spot prices in Trondheim, based on data from [41].

Figure 4.6 presents the spot prices for two arbitrary months in 2017; winter and summer. The spot prices are higher during the winter month compared to the summer month, which conforms with the average winter and summer spot prices being 0.29 and 0.26 NOK per kWh, respectively. Further, the figures shows some tendencies toward more fluctuating prices during the summer, which may be a result of higher penetration of intermittent RES.



(a) February

(b) June

Figure 4.6: Nord Pool spot prices in Trondheim in arbitrary months in 2017, based on data from [41].

Chapter 5

The Material Behind the Results and Further Analyses

In Section 5 in the paper, the main system and market results were presented. The paper gave a well-arranged overview of the main results of each system configuration and market design, along with comparison and discussion. This chapter is included to provide the complete material behind these results and analyses, and some further results, sensitivity analyses and remarks. Moreover, this chapter is an important part of the thesis in order to present sufficient study of the optimal system operations and the value of P2P energy trade.

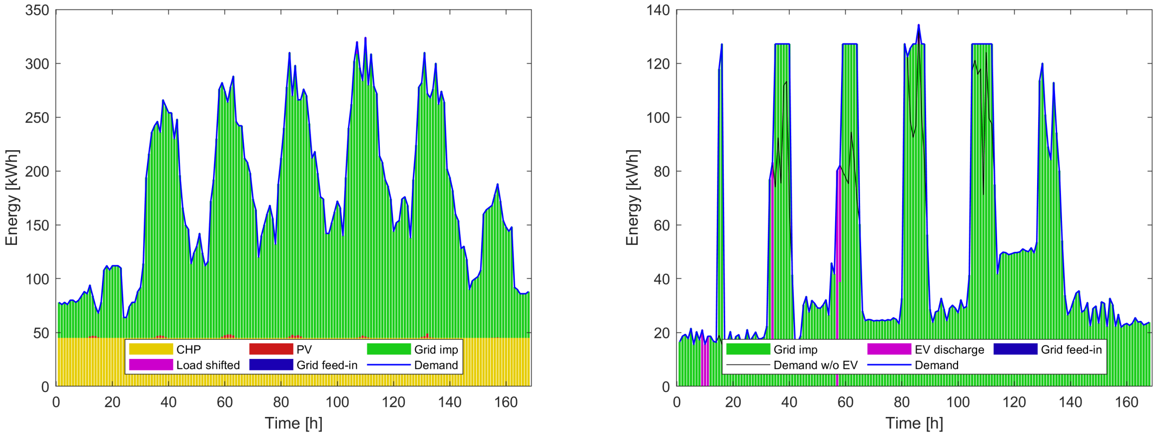
It should be noted that every power flow leaving a building are considered negative in the figures to follow. For each system configuration, supply-demand decisions are visualized for an arbitrary winter and summer month for each building in Appendix C. These additional plots are provided to emphasis the seasonal trends stated for the summer and winter weeks presented in the paper and later in this chapter, and are not further commented.

5.1 Base Case: Flexible Buildings

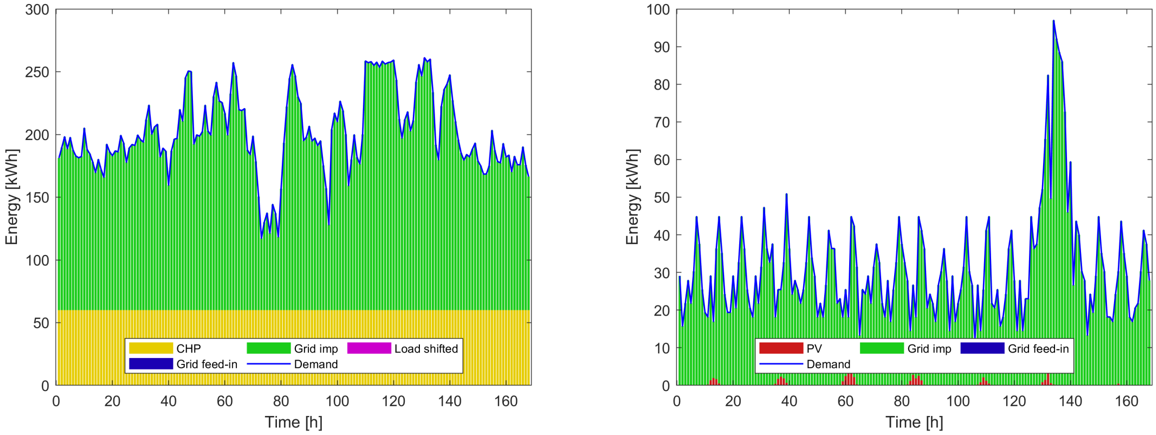
The one-year optimal system operation of the market rules of the BC minimizes the total cost of electricity in the industry site, hence the grid consumption is minimized. As there are no collaboration opportunities in this system configuration, each building maximizes the self-consumption of their building DER and buys the remaining demand from the grid. In times of excess power, the electricity is sold to the grid and curtailed in the few time steps where the excess power exceeds the prosumer feed-in limit.

Figure 5.1 shows the system operation in terms of hourly power flows for the different buildings for an arbitrary winter week. These figures illustrate how the building demand is covered and confirms the maximization of DER self-consumption, as there are no grid feed-in. Hence, it is more profitable to consume building generation than to sell the power to the grid. Moreover, load shifting as a building flexibility feature is employed by B1 and B3 to shave peaks, and are further elaborated in Section 5.1.1.

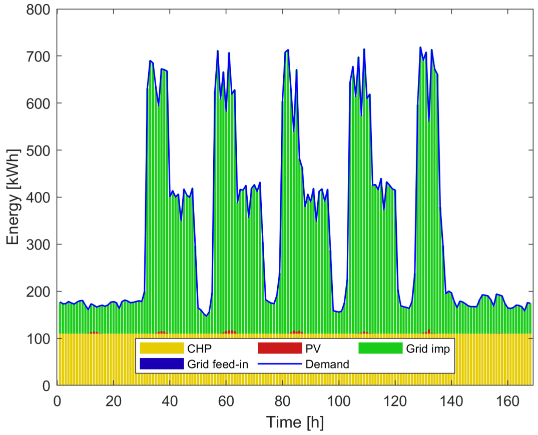
Figure 5.2 presents the supply-demand decisions for each building during an arbitrary summer week. It is evident that self-consumption is prioritized in the operation of DERs during summertime, as stated for the wintertime. Excess power occurs in times of high irradiation on the PV systems and are fed to the grid, as illustrated in Figures 5.2a, 5.2d and 5.2e. Excess power exceeding the prosumer feed-in limit is curtailed, e.g. for B5 in hour 10 in Figure 5.2e. Curtailed power is a direct loss of power for the related building and industry site. B2, in Figures 5.1b and 5.2b, utilizes the EV storage unit for peak shaving and demand cover, which are further examined in Section 5.1.2.



(a) Building 1 **(b)** Building 2

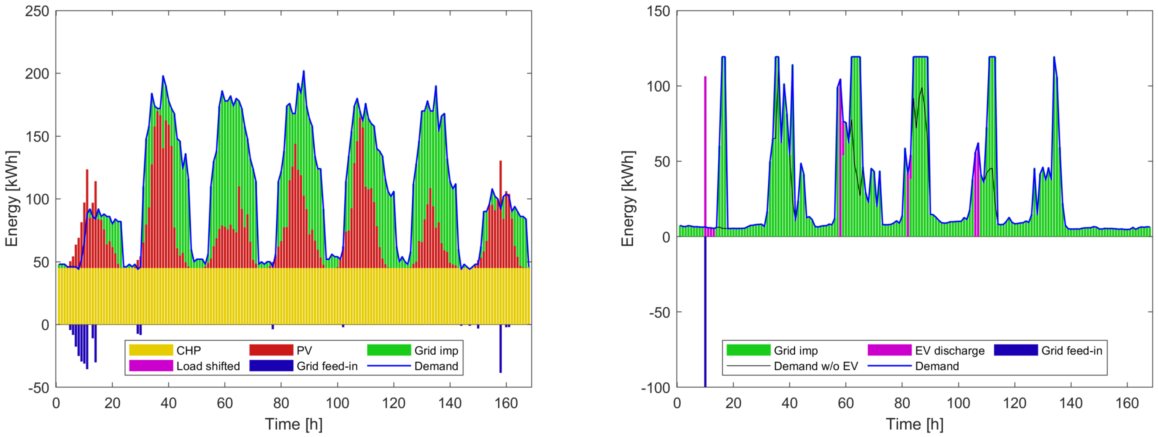


(c) Building 3 **(d)** Building 4

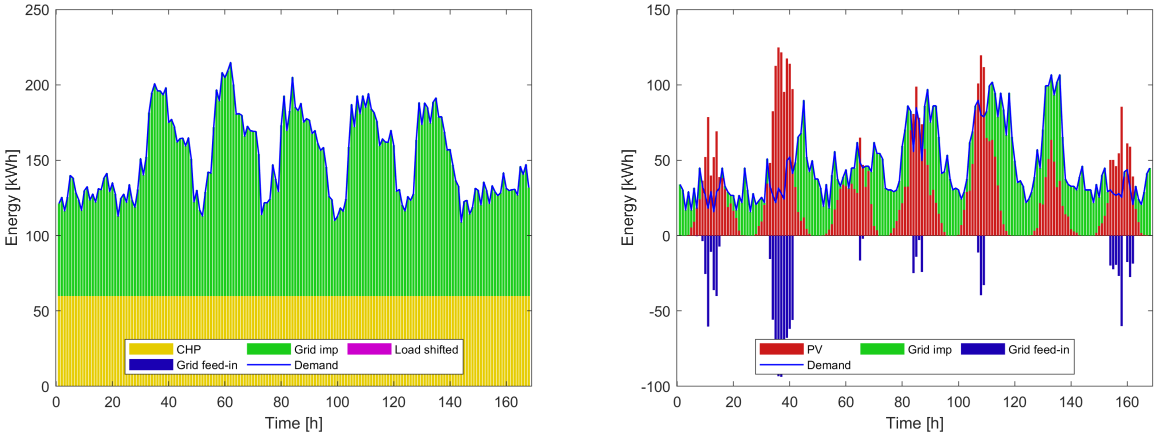


(e) Building 5

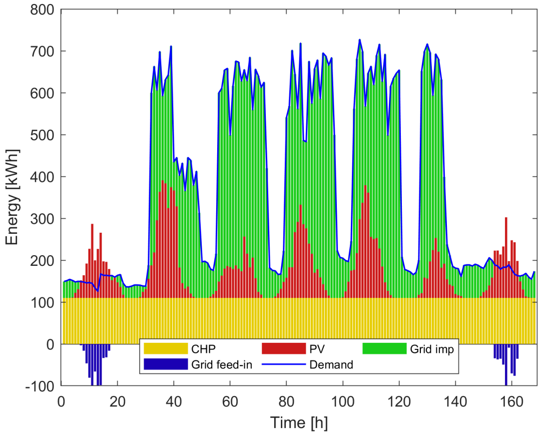
Figure 5.1: Supply-demand results for the Base Case market for a winter arbitrary week (week 6).



(a) Building 1 **(b)** Building 2



(c) Building 3 **(d)** Building 4



(e) Building 5

Figure 5.2: Supply-demand results for the Base Case market for a summer arbitrary week (week 24).

The total results for the industry site and the individual buildings in the BC market are presented in Table 5.1. This table summarizes the most important results and are used as a reference and basis for interpreting the value of P2P energy trade and share on-site flexibility in the system setups under study.

Table 5.1: Base Case results, where costs are given in KNOK.

Base Case *(Reference)*	**Industry site**	**B1**	**B2**	**B3**	**B4**	**B5**
Total costs	***2,335***	***423***	***201***	***444***	***183***	***1,084***
Total cost of grid consumption	2,361	427	202	443	190	1,098
Cost of peak power	1,018	178	93	143	86	518
Cost of UT energy term	163	30	12	38	12	72
Cost of UT fixed term	75	15	15	15	15	15
Cost of energy spot price	1,106	205	82	248	78	494
Revenues of grid feed-in	27	5	0.2	0	8	15
Yearly peak demand [kWp]	1,412	289	132	199	113	679
Grid consumption [kWh]	3,841,049	701,685	281,881	888,981	276,676	1,691,825
Grid feed-in [kWh]	110,346	18,548	538	0	30,717	60,544
Curtailed power [kWh]	15,711	158	0	0	6	15547
Demand by grid [%]	64.2 %	60.0 %	97.2 %	64.4 %	76.0 %	60.8 %
Demand by DER [%]	35.8 %	40.0 %	2.8 %	35.6 %	24.0 %	39.2 %

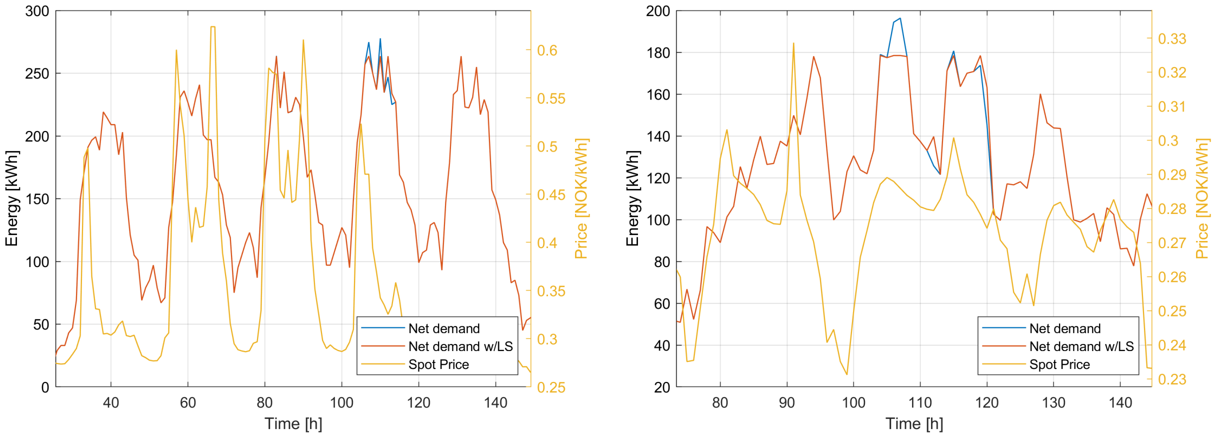
5.1.1 Load Shift

The load shifting flexibility feature brings some degree of demand elasticity to B1 and B3. As a result, load is shed based on costs and availability, and recovered at a later point in time. Load shifting is used for peak shaving, to avoid increasing the highest monthly peak power and the related peak demand cost. This is evident for B1 in Figure 5.1a, where the two peaks around hour 110 are shaved.

In order to be able to study the operation of the load shifting feature in detail, the results in arbitrary weeks are presented for B1 and B3 in Figures 5.3a and 5.3b, respectively. By studying these figures, several interesting facts are observed:

- The main contribution from load shifting is shaving the peak power demand. For example, B1 shaves the peak 11.2 kWp in hour 105 to avoid increasing the highest peak power in February and the related peak demand charge. In addition, the load is rescheduled to a time of lower spot price. The savings from performing this one load shift amounts to 781 NOK, where the load shift penalty is subtracted. The calculation is shown in Appendix B.1.

- The shifted load is rescheduled to a possible time step where the wholesale spot price is as low as possible, as further explained below.
- The rescheduling flexibility, with regards to the available time period for rescheduling, affects the results. B3 have a longer period for rescheduling, hence the building is more flexible to reschedule at time steps with more favorable spot prices. In Figure 5.3b, B3 shaves the peak in hour 105 and reschedules in hour 115 where there is a dip in the spot price curve. In comparison, B1 reschedules only 5 and 2 hours after shaving the two highest peaks in Figure 5.3a.
- The savings from performing demand response based on the spot price is lower than the load shift penalty. Hence, price arbitrage based on the spot price is not profitable and the load shift feature is not employed to a great extent.
- The total amount of shifted load throughout the year for B1 and B3 are 244 and 1029 kWh, respectively.



(a) Load shift B1 in week 6

(b) Load shift B3 in week 9

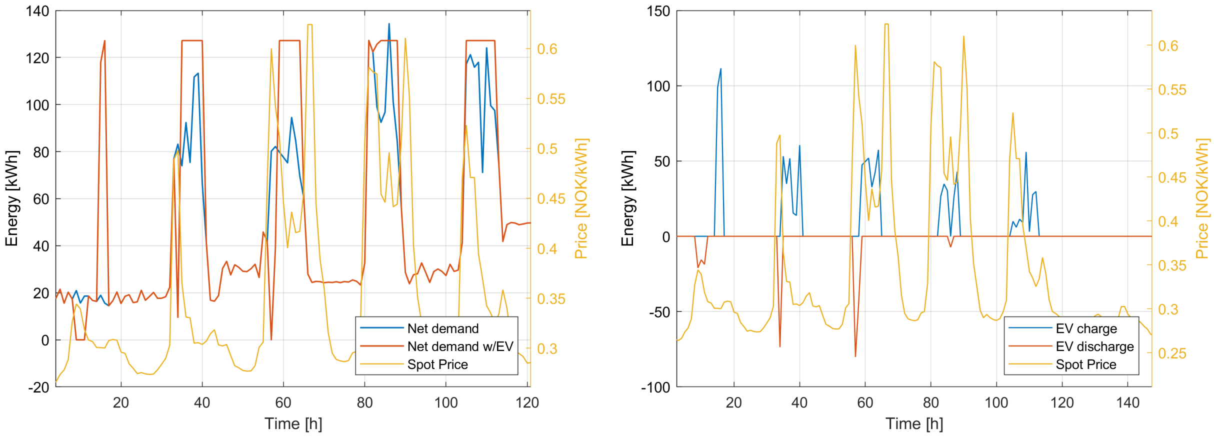
Figure 5.3: Load shift in arbitrary winter weeks.

5.1.2 EV Parking Lot

The EV parking lot at B2 represents a hard-constrained decentralized energy storage at building level, and brings some degree of flexibility to B2. The hard constraints are related to the start and end of a workday, where the initial storage level is fixed and the final storage level is a minimum amount. The system operation for B2 with EVs were displayed in Figures 5.1b and 5.2b. As the only alternative for covering the EV charge in the BC is to buy power from the grid, the EV charging power flows are shown as grid consumption in the figures. Detailed system operation and related spot prices are shown in Figure

5.4. Based on these figures, following observations are made:

- During hours of peak power demand, the EV storage is operated to some extent perform peak shaving. For example, the EV storage is discharged around hour 90 to shave the peak. Hence, B2 is able to reduce its total yearly cost of peak power, by employing the flexibility of the EV storage.
- However, the net demand and thus the cost of energy for B2 sees a large increase, due to the hard constraints on the storage level. The EV's are assumed partly discharged when they arrive to work, and the EV owners requests in average some charging during work hours. Due to these assumptions, B2 are delivering power to the EVs in a somewhat short period of time, which is a workday. Hence, the total energy demand for the building is actually increasing in BC. In Figure 5.4a, the net demand without EV storage is compared to the net demand with EV storage, which show how the demand is considerably increased.
- The EV storage is used for price arbitrage operation, based on the spot prices, as seen in Figures 5.4a and 5.2b. The storage is discharged in periods of high spot prices, and charged, when possible, in low price periods. This is especially evident in periods of volatile prices. Figure 5.4b illustrate how the EV storage charging and discharging are performed at the best possible spot price.



(a) Net demand with and without EV

(b) EV storage operation

Figure 5.4: EV storage operation in week 6.

5.1.3 The Present Situation

As described in the paper and Chapter 4, the industrial buildings are assembled to represent a modern industry site in this thesis. Today, the buildings are separately consuming all their demanded electricity from the grid. In other words, in the present situation the buildings have no installed distributed electricity production or flexibility features, or have any opportunity to trade energy locally. The industry site DERs were included to create a case study in this thesis, and are based on trends in today's industry.

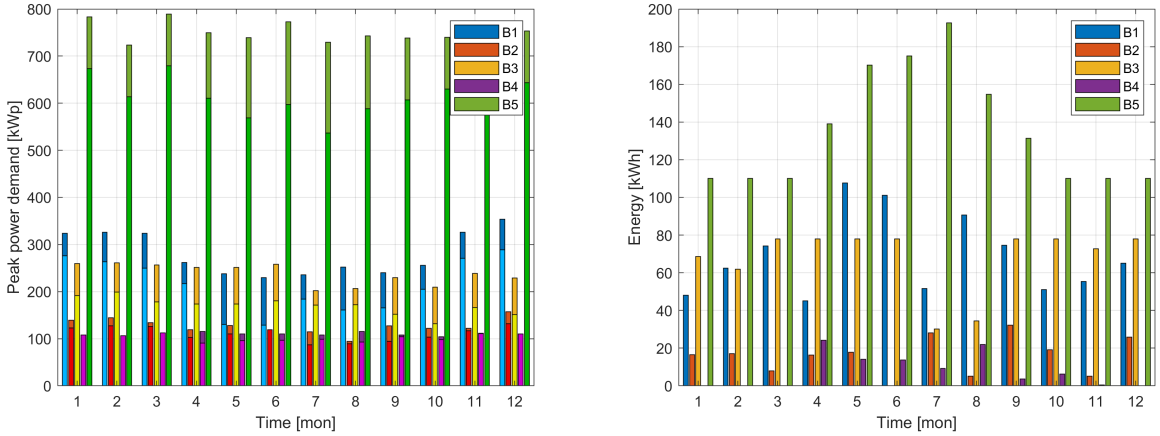
The cost of electricity in the present situation are calculated based on the grid price data provided in the paper and shown in Table 5.2. These costs are included to provide the correct starting point and some additional remarks for the BC results. As seen from the table, the cost of peak power contributes with a substantial amount to the total cost of electricity for the industry site and the individual buildings. In fact, the cost of peak power is an average of 40.3 % of the total cost of each building. Comparing the total industry site results in the BC, the total costa reduction of 28.8 % is seen for the total costs, 19.6 % for the peak costs and 35.3 % for the grid consumption.

Table 5.2: The present situation.

	Total cost [KNOK]	**Total cost of peak** [KNOK]	**Grid consumption** [kWh]
Industry site	3,282	1,266	5,939,670
B1	635	236	1,169,438
B2	203	107	244,252
B3	657	200	1,379,901
B4	225	92	364,221
B5	1,561	632	2,781,857

Figure 5.5 presents the monthly peak power demand for each building in the BC compared to the present situation. In Figure 5.5a the BC are the lowest peaks (brightest color). Moreover, the monthly peak power reduction for each building are shown in Figure 5.5b. B1, B4 and B5 have the highest reduction in peak power in the summer months, due to production in the PV systems. For B3, the reduction is fairly even throughout the year, due to the electricity production of the CHP. With the EV parking lot as the only DER, B2 have the most variable peak power reduction. The largest peak power reduction of each building provides savings of 7,530, 2,258, 5,453, 1,697 and 13,477 NOK the given month, chronically. Consequently, reducing the peak power presents considerable savings.

The grid owner has to build the distribution lines according to the highest peak power drawn from the grid throughout the year, i.e. sufficient grid capacity to supply the coldest winter day. Therefore, the yearly peak power and the potential reduction of this could be of great interest to the grid owner as well. The yearly peak power of each building in the BC are given in Table 5.1.



(a) Monthly peak power in BC and present situation

(b) Monthly peak reduction in BC

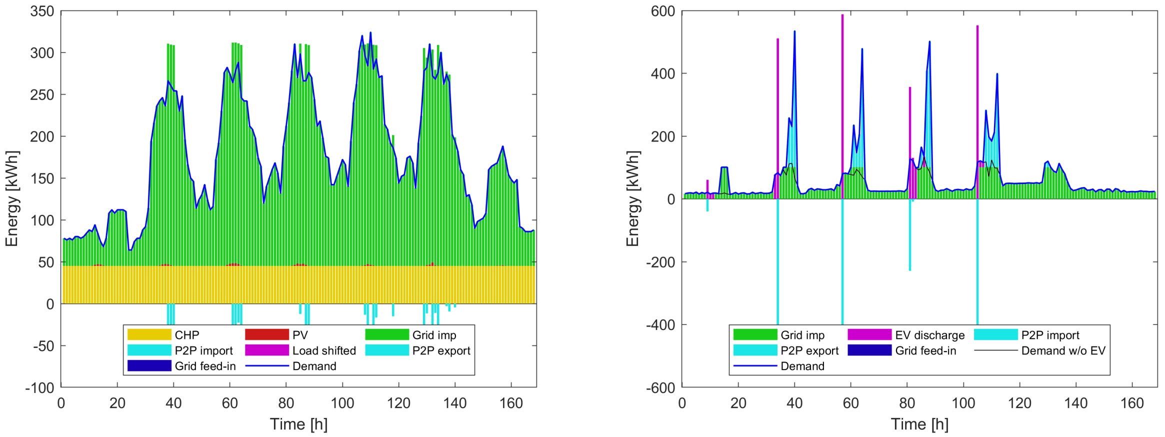
Figure 5.5: Monthly peak reduction for the Base Case market compared to the present situation.

5.2 Case 1: P2P Energy Trade

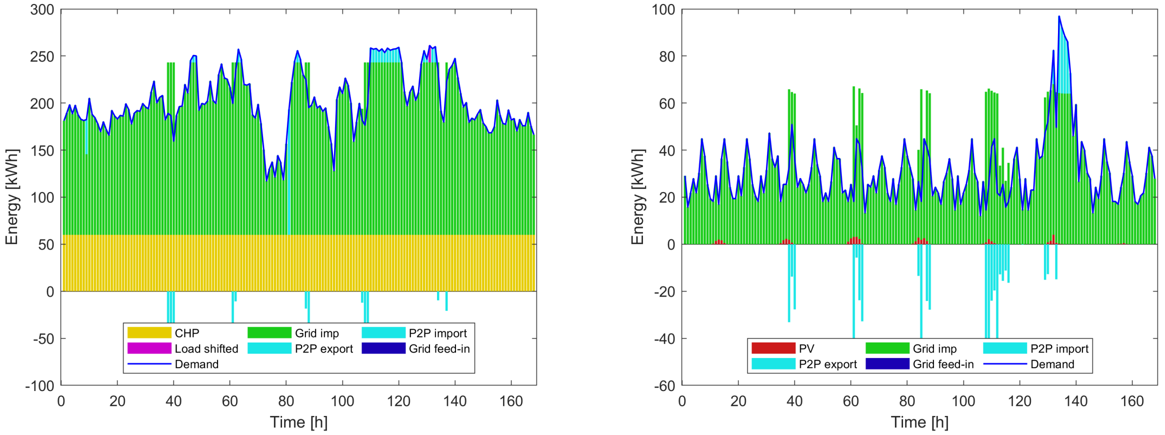
The main results and key findings for the C1 market design were presented in the paper. In this section, the detailed results and material from the model simulation will be presented.

The system operation in terms of supply-demand decisions for each building in an arbitrary summer week, were presented in the paper. Figure 5.6 illustrates the supply-demand power flow results and the related wholesale prices for an arbitrary winter week (week 6 in February). The DG production is unchanged from the BC, however the optimal operation of the grid consumption, flexibility usage and grid feed-in are changed in the presence of P2P energy trade. This is especially evident when comparing the figures. Instead of only prioritizing coverage of own demand and selling in times of excess power, the buildings are more elastic and collaborate to minimize the total cost of electricity for the whole industry site. The yearly optimal system operation for each building, including the P2P trades, are presented in Appendix C.2.1.

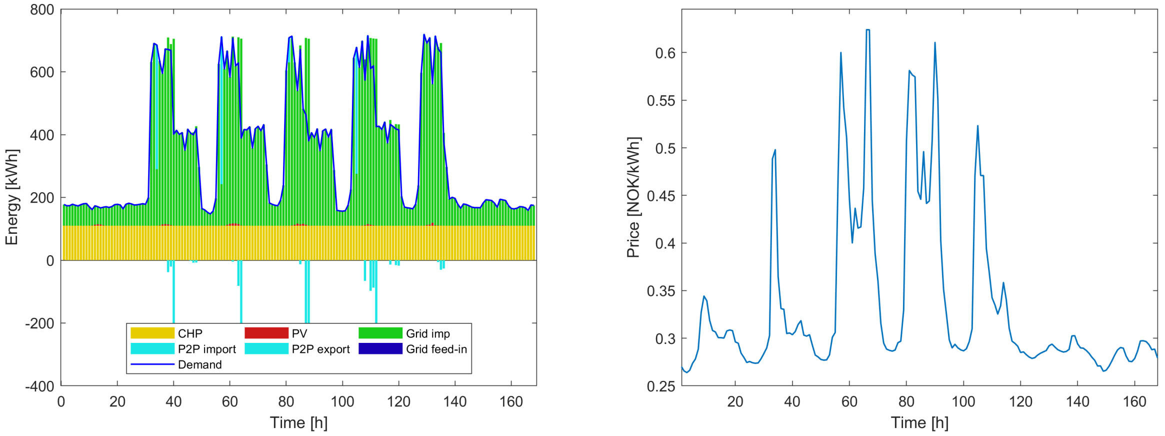
The EV storage is used more rapidly in C1 in terms of more frequent charge and discharge, illustrated in the yearly system operation for B2 in Figure C.3c in Appendix C.2.1. Comparing the storage utilization in Figure 5.6b to the spot prices in Figure 5.6f, it is evident that the storage is used for price arbitrage. In peak cost periods, the storage is discharged to cover the demand in B2 and trade large amounts of energy to peers, i.e. around hour 60 in week 6. Further, imported P2P energy covers most of the recharging, to provide the required final storage level at the end of the workday, in both seasons. This P2P energy is



(a) Building 1 **(b)** Building 2



(c) Building 3 **(d)** Building 4

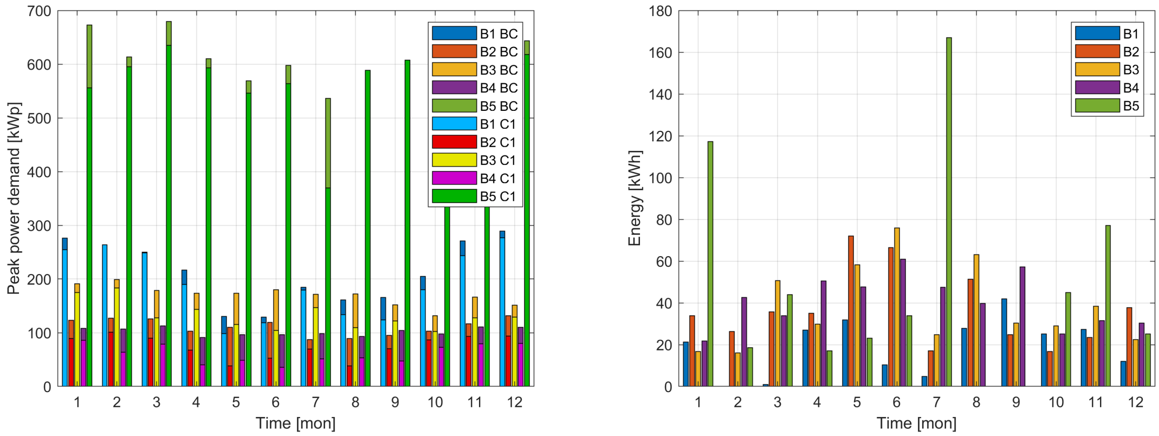


(e) Building 5 **(f)** Spot prices

Figure 5.6: Supply-demand results for the Case 1 market and related wholesale prices for a winter arbitrary week (week 6).

provided by buildings consuming extra grid power during off-peak price periods, if possible. As a result, the industry site as a whole employs the EV storage for price arbitrage. The recharging represents power peaks for B2 and by covering this with P2P trade the peaks are shaved, and the cost of peak power is not increased. The yearly optimal operation of B2 is visualized in Figures C.3c and C.3d in Appendix C.2.1, where the peak shaving and frequent P2P import are evident. Consequently, the EV storage unit provides flexibility to the industrial site in the presence of P2P collaboration.

In addition to utilizing the EV storage unit for price arbitrage, the buildings procures extra electricity from the grid to perform price arbitrage by trading with peers. In other words, the buildings consumes extra power from the grid in low-price periods, up to the optimal peak power of the given month, to sell to peers. As such, the buildings take advantage of the spot price fluctuations and the fact that peak power charge is charged for the monthly peak, regardless of how many times the peak amount of power are consumed. The building performing price arbitrage and trading sees cost revenues, while the peer buying power shaves its peak and buys cheaper electricity, thus benefits from the trade as well. As an illustrating example, B5 consumes 30 kW extra in hour 134 in week 6, which is traded to B4. The total system savings of this operation is 1,969 NOK in the given hour, as B4 shaves its peak in the given hour by buying from B5 instead of from the gird and B5 performs price arbitrage. The calculation is shown in Appendix B.2.



(a) Monthly peak power C1 compared to BC

(b) Monthly peak reduction in C1

Figure 5.7: Monthly peak reduction for the Case 1 market compared to the Base Case.

The results are also driven by the centralized solution method, where the total cost of electricity is minimized for the whole industry site. This centralized control further incentive the trading of extra grid power, with the extensive peak power charge as the key driver. The industry site go to great lengths to keep the monthly peak power for each building as low as possible. Making it optimal for a building to consume extra grid power up to the optimal monthly peak regardless of the wholesale price, to prevent other buildings from increasing their monthly peak. This is visible in all presented figures, where Figure 5.6d is an evident example. Thus, peak shaving is highly prioritized for the site. Further, the centralized solution method also affects the P2P power flows to great extent. The individual buildings do not necessarily trade with the highest bidder, but with the peer that minimizes the cost for the whole industry site.

The effect of peak shaving is further analyzed in Figure 5.7. Figure 5.7a visualizes the monthly peak power in C1 compared to BC for each building, while Figure 5.7b shows the amount of peak power shaved in each month. By the introduction of P2P energy trade in the market design, the largest peak reduction in one month for each building are chronically: 42, 72, 76, 62 and 167 kWp. The related cost savings are: 2,940, 5,040, 5,320, 4,340 and 11,690 NOK.

The total results for the industry site and individual buildings are presented in Table 5.3, and important findings are given below.

Table 5.3: Results for the C1 market with P2P energy trade, with the percentage change compared to the BC market.

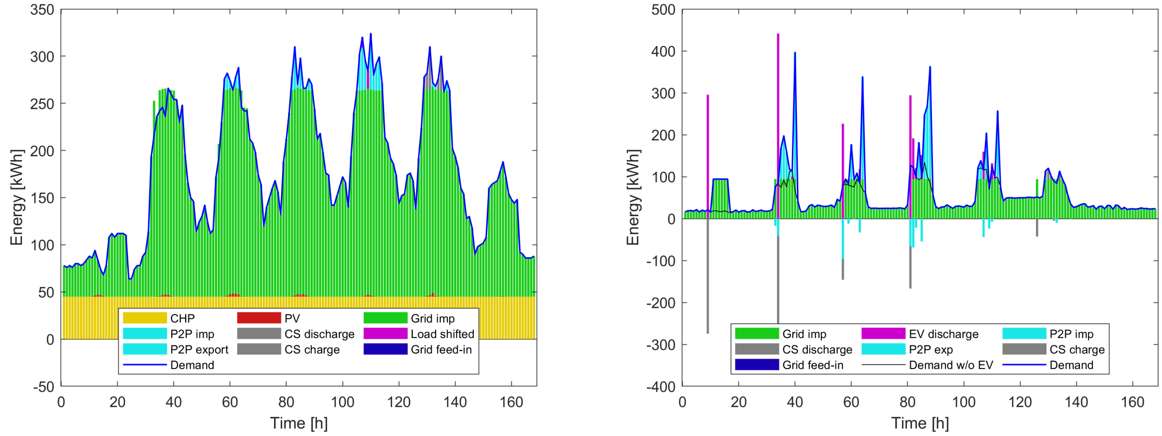
Case 1	**Industry site**	**B1**	**B2**	**B3**	**B4**	**B5**
Total costs [NOK]	***2,175,170***	***404,232***	***176,612***	***413,320***	***147,571***	***1,033,435***
Total cost of grid consumption	-7.5 %	-2.7 %	-21.6 %	-13.1 %	-18.3 %	-2.6 %
Cost of peak power	-15.0 %	-9.1 %	-33.1 %	-22.3 %	-39.9 %	-7.7 %
Cost of UT energy term	-1.9 %	2.0 %	-13.1 %	-9.4 %	-0.7 %	2.1 %
Cost of UT fixed term	0 %	0 %	0 %	0 %	0 %	0 %
Cost of energy spot price	-1.9 %	1.8 %	-13.7 %	-9.2 %	-0.7 %	2.0 %
Revenues of selling to the grid	-65.3 %	-66.6 %	74.6 %	247.0 %	-67.9 %	-67,3 %
Yearly peak demand [kWp]	-7.0 %	-4.2 %	0 %	-8.0 %	-23.6 %	-6.5 %
Grid power bought [kWh]	-1.9 %	2.0 %	-13.1 %	-9.4 %	-0.7 %	2.1 %
Power sold to grid [kWh]	-67.0 %	-68.2 %	89.8 %	815.0 %	-68.6 %	-68.6 %
Curtailed power [kWh]	-100 %	-100 %	0 %	0 %	-100 %	-100 %
P2P export [kWh]	206,208	34,372	23,324	6,390	31,362	110,760
P2P import [kWh]	190,537	7,593	61,476	90,554	12,193	18,720
Yearly peak shave [kWp]	99	12	0	16	27	44
Total savings [NOK]	***159,751***	***18,614***	***24,882***	***30,908***	***35,083***	***50,263***
Total savings [%]	***6.8 %***	***4.4 %***	***12.3 %***	***7.0 %***	***19.2 %***	***4.6 %***

- The yearly grid consumption for the total system is reduced 1.9 %, while the total cost of grid consumption is reduced 7.5 %. This is due the industry site being more flexible and thus exploit volatile price signals and shave peaks. B2 has the highest reduction, as the building goes from being primary a price taker to a more active entity at the industry site.
- There is no curtailment and the feed-in power is extensively reduced. Hence, more power is consumed locally in the industry site and the main grid is less stressed.
- The highest yearly peak power for the industry site is reduced with a total of 99 kWp and the cost of peak power is reduced 15 %. Hence, this year the required distributed network capacity from the grid owner is reduced. B4 have the highest reduction in the yearly peak power costs, thus 39.9 % reduction.
- The total amount of P2P trade is 206,206 kWh. The buildings with installed PV system, with times of generation surplus, are the biggest contributors. With no excess power, B2 and B3 imports most of the P2P trade, as they mainly are price takers. Approximately 16,000 kWh (7.6 %) of the exported P2P trade is lost due to line losses.
- The total yearly system savings by the introduction of P2P trade is 159,751 NOK (6.8 %).

5.3 Case 2: P2P Energy Trade and Shared Storage

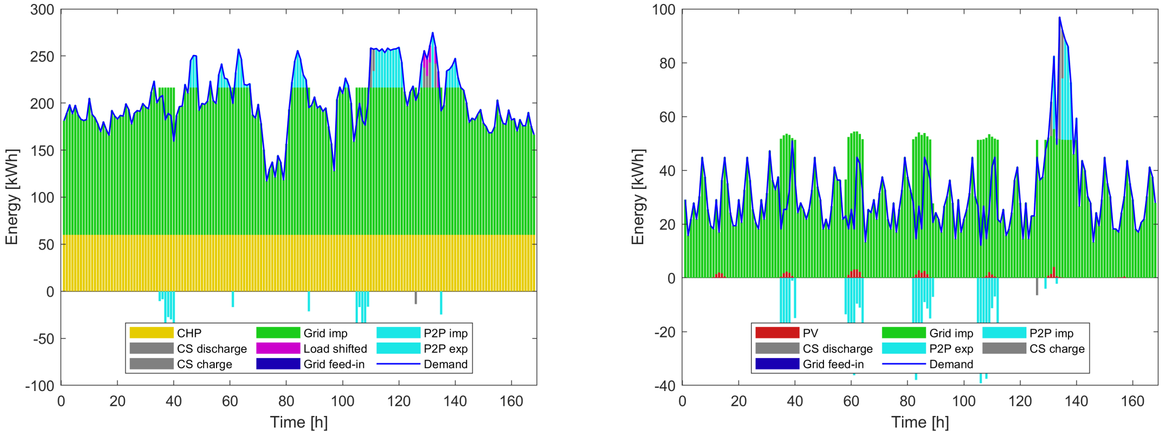
The main results for the C2 market were presented in Section 5.3 in the journal paper. This section gives the material behind the results and some additional findings, with emphasis on the system operation when the shared energy storage is implemented. The system operation in terms of supply-demand decisions for each building in week 6 are presented in Figure 5.8, while illustrations for week 24 were presented in the paper. With the shared storage, the buildings are more elastic and cooperative towards minimizing the total cost of electricity for the whole industry site.

The supply-demand decision figures show that the shared storage is utilized to shave the power peaks and cover demand, in addition to the P2P energy trade feature. The buildings consume extra grid power for trading more frequently compared to C1, however in smaller amounts. As a result, the monthly peak power of each building are further decreased in this market design. This is evident for the yearly optimal system operation of each building presented in Appendix C.3.1, which includes the power flows of P2P trades and shared storage charge and discharge.



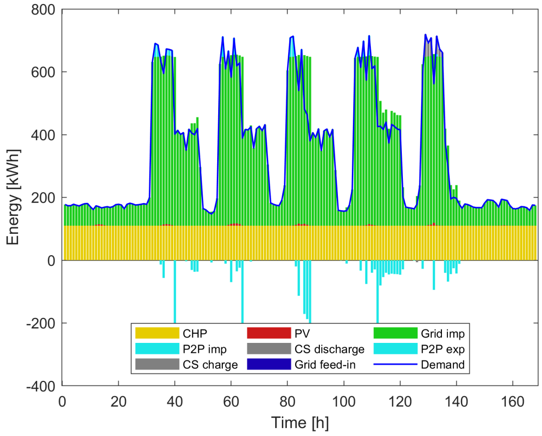
(a) Building 1

(b) Building 2



(c) Building 3

(d) Building 4



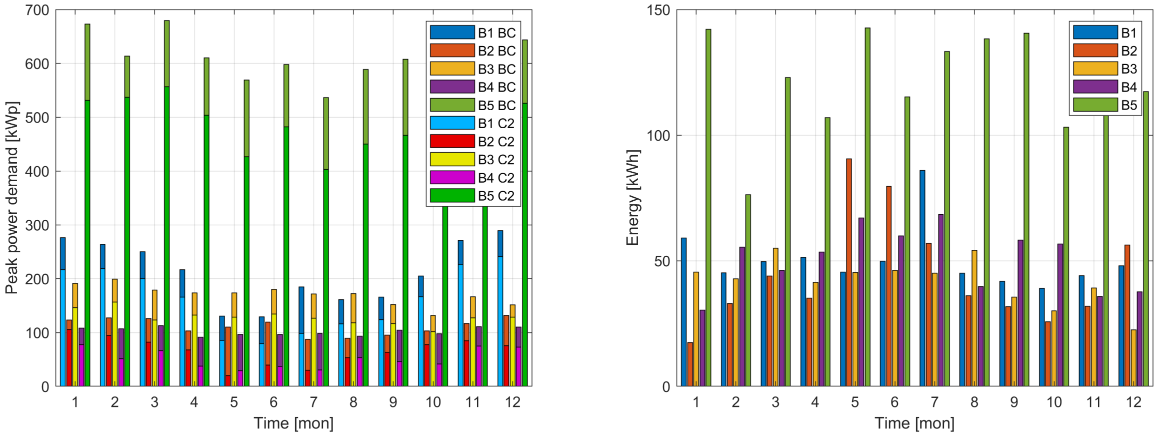
(e) Building 5

Figure 5.8: Supply-demand results for the Case 2 market for a winter arbitrary week (week 6).

The building flexibility features (EV and LS) are employed more often, thus bring increased value and flexibility to the industry site in C2. The EV parking lot storage of B2 are more frequently charged and discharge, as it can be discharged to charge the shared storage for later use in periods of high demand or price. The load shifting at B1 and B3 are a bit more utilized to shave peaks, as displayed around hour 130 in Figure 5.8c.

In time steps with large amounts of storage discharge, the discharging is often done by the building with the lowest discharging price in the given time step. A recurring event is that the discharged power is traded directly to peers in the same time step. As a result, the discharging building uses the storage for price arbitrage, through buying cheap power from the storage and exporting it to peers at higher prices. The buying peers also see a lower price, as their P2P willingness to pay in the time step is lower than their cost of discharging the shared energy storage. Consequently, the total cost of electricity for the whole industry site is minimized in the given time step. However, this discharging operation is inefficient and more power is lost due to line losses, compared to the demanding buildings discharging the shared storage directly themselves. For example, during hour 60 in week 24 in the paper B4 discharges the shared storage and gains excess power, which is directly traded to B1, B2 and B3. As a result, B4 sees revenues from price arbitrage and the peers gain benefits from shaving their peak at a lower cost than their discharging price.

From these simulations and results, it is evident that the operation of the shared storage also is affected by the central control method. The overall industry site is operated to minimize the total cost electricity, with the extensive peak power charge as the key driver.



(a) Monthly peak power in C2 and BC **(b)** Monthly peak reduction in C2 compared to BC

Figure 5.9: Monthly peak reduction of each building in the Case 2 market compared to the Base Case.

The effect of peak shaving is further analyzed in Figures 5.9a and 5.9b. Compared to the peak powers of BC, the peaks are further reduced with the implementation of the shared storage. The monthly peak power of each building are more evenly shaved throughout the year and considerably reduced, which are viable when compared to the peak reduction in C1 in Figure 5.7b.

The total results for the industry site and individual buildings in C2 compared to BC are given in Table 5.4, and important findings are presented below.

Table 5.4: Results for the C2 market with P2P energy trade and shared central storage, with the percentage change compared to the BC market.

Case 2	**Industry site**	**B1**	**B2**	**B3**	**B4**	**B5**
Total costs [NOK]	***2,077,326***	***378,950***	***172,911***	***412,646***	***140,128***	***972,691***
Total cost of grid consumption	-12.0 %	-9.3 %	-25.8 %	-12.8 %	-23.1 %	-8.4 %
Cost of peak power	-25.6 %	-23.8 %	-40.4 %	-24.6 %	-49.6 %	-19.8 %
Cost of UT energy term	-2.1 %	1.2 %	-15.3 %	-7.8 %	-1.9 %	1.7 %
Cost of UT fixed term	0 %	0 %	0 %	0 %	0 %	0 %
Cost of energy spot price	-1.9 %	1.1 %	-15.3 %	-7.4 %	-1.5 %	1.8 %
Revenues of selling to the grid	-87.1 %	-79.8 %	-54.6 %	0 %	-87.7 %	-89.5 %
Yearly peak demand [kWp]	-19.5 %	-16.6 %	-19.8 %	-21.5 %	-31.1 %	-18.1 %
Grid power bought [kWh]	-2.1 %	1.2 %	-15.3 %	-7,8 %	-1.9 %	1.7 %
Power sold to grid [kWh]	-87.9 %	-81.4 %	-51.6 %	0 %	-88.4 %	-90.0 %
Curtailed power [kWh]	-100 %	-100 %	0 %	0 %	-100 %	-100 %
P2P export [kWh]	260,537	43,005	25,027	18,421	44,497	129,587
P2P import [kWh]	240,736	17,111	81,222	81,875	22,865	37,664
Central storage charge [kWh]	56,894	10,887	14,021	1,340	9,756	20,890
Central storage discharge [kWh]	44,804	12,810	1,874	7,226	9,587	13,305
Yearly peak shave [kWp]	275	48	26	43	35	123
Total savings [NOK]	***257,596***	***43,896***	***28,582***	***31,582***	***42,527***	***111,008***
Total savings [%]	***11.0 %***	***10.4 %***	***14.2 %***	***7.1 %***	***23.3 %***	***10.2 %***

- The yearly grid consumption for the total system is reduced 2.1 %, while the total cost of grid consumption is reduced 12.0 %. Compared to C1, the total cost is reduced additional 27,950 NOK.
- The feed-in power is reduced 87.9 %, and there is no curtailed power. The generation surplus of the buildings with PV systems, B1, B4 and B5, are almost completely consumed locally.
- The yearly peak power of each building are extensively reduced. For the industry site as a whole it is reduced with 275 kWp and the cost of peak power 25.6 %. B5 has the largest reduction in one month at 123 kWp, while B4 see the largest reduction in total cost of peak power with 49.6 %.
- The total amount of P2P trade is 260,537 kWh, an increase of 54,331 kWh from C1. Buildings with

periods of excess generation are still exporting the most, and primarily price takers, B2 and B3, are still importing the most P2P energy. However, B3 exports more and is the only building with a reduction in P2P import.

- The total amount of energy charged to the central storage is 56,894 kWh. The buildings with generation surplus charges and discharges close to the same amount of power, while B2 charges more than it discharges and B3 discharges more than it charges. Approximately 27 % of the power is lost in the charge and discharging process.
- The total yearly system savings by the introduction of P2P trade and shared storage is 257,596 NOK (11.0 %). Compared to C1 with the pure P2P implementation, the savings have increased 97,845 NOK (4.2 %).

5.4 Price Sensitivity Analyses

Sensitivity analyses are carried out in order to investigate how the price parameters affect the optimal solution. The market design results showed that the cost of electricity have large impact on the results, hence sensitivity analysis are performed for: the spot prices, the peak demand tariff and P2P energy prices.

5.4.1 Nord Pool Spot Prices

The spot prices in the Norwegian market are trending towards more volatile price patterns with higher peaks, as described in Section 2.2.2 and visualized in Section 4.2.3. Due to the increasing penetration of fluctuating RES and increasing linkage to the European market. Therefore, it is important to investigate how the system operates under these price trends and how the optimal solution is affected.

The Elspot day-ahead prices for four different price areas in the Nord Pool Spot Market in 2017 are presented in Figure 5.10, showing the specter of different price scenarios in the power market. The figures visualize how the spot prices in Trondheim[1] are relative stable compared to the prices in Sweden (SE1), Finland (FI) and Denmark (DK1). The wholesale prices in Finland are especially volatile, with high peaks throughout the year. In Denmark (DK1) the market show hours of negative spot prices, which is

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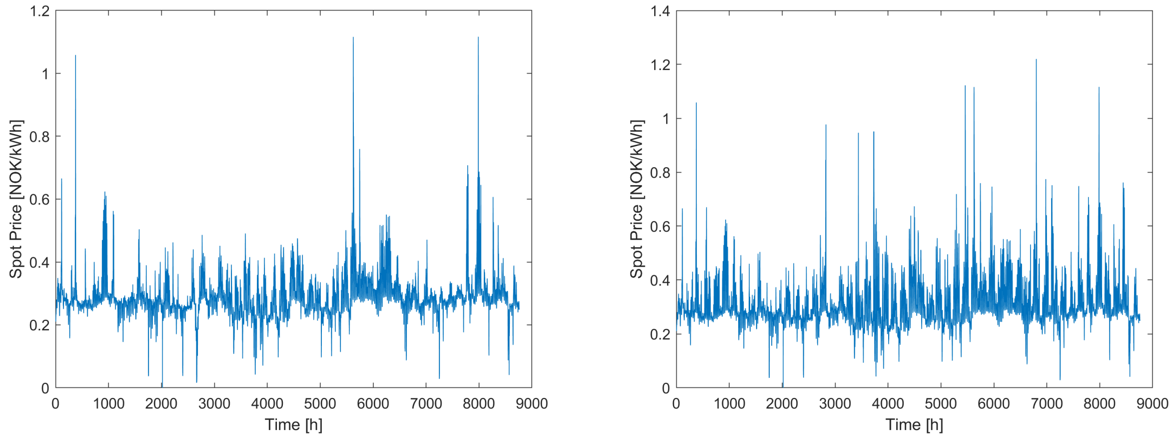
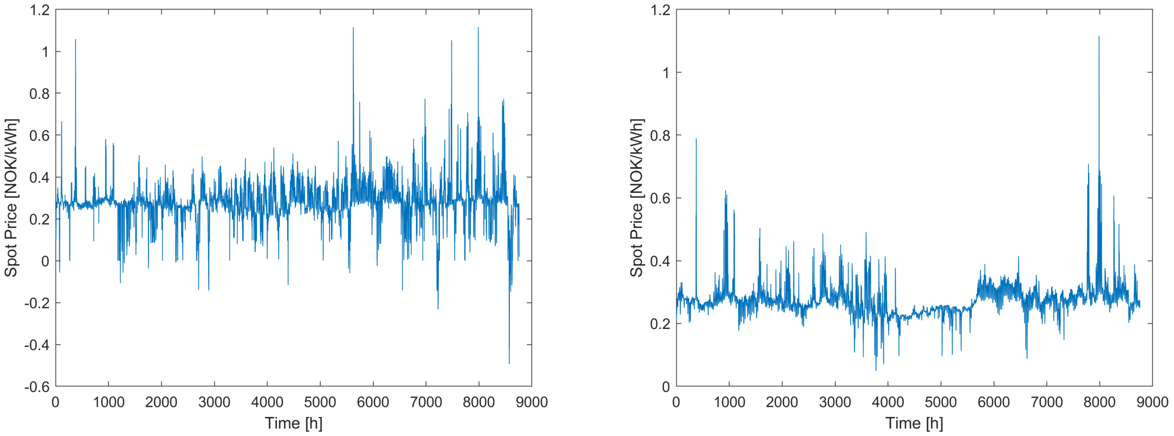
[1] The spot prices employed in all previous case studies.



(a) Sweden (SE1)

(b) Finland (FI)



(c) Denmark (DK1)

(d) Norway (Trondheim)

Figure 5.10: Spot prices for different areas in the Nordic market, based on data from [41].

a phenomenon that occurs when power generation from inflexible sources exceeds the demand. Due to inflexible sources, such as RES and thermal power plants, cannot be shut down and restarted in a quick and cost-efficient manner. This poses a potential problem regarding the instant supply-demand balance, as it is more cost-efficient for a producer to produce with losses than to shut down. Although generation from RES is promoted through a tariff in Denmark, negative prices are an incentive for producers to invest in flexibility resources [42]. As of today, this is not a realistic phenomenon in Norway, due to the large share of fast ramping hydropower generators.

System analysis have been carried out for each market design for the different market spot prices. Recall how the grid feed-in and local industry site prices, i.e. the individual P2P prices, storage charging compensation and individual storage discharge prices, are dependent on the wholesale spot prices. Table

5.5 presents the total system costs, total P2P export and savings compared to BC in each market.

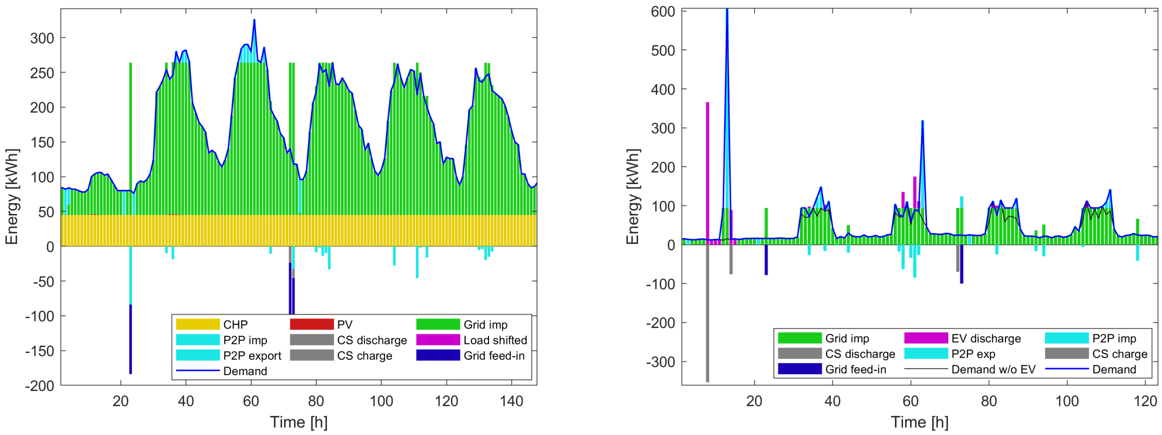
Table 5.5: Total system costs and savings with different spot prices.

	Trondheim	**SE1**	**FI**	**DK1**
Total system costs [KNOK]				
BC (Reference)	2,335	2,389	2,489	2,370
C1	2,175	2,228	2,326	2,209
C2	2,077	2,131	2,229	2,110
Total P2P export [kWh]				
C1	206,208	226,796	273,317	269,526
C2	260,537	273,088	307,435	311,563
Total savings [KNOK]				
C1	160 *(6.8 %)*	160 *(6.7 %)*	163 *(6.6 %)*	160 *(6.8 %)*
C2	258 *(11.0 %)*	258 *(10.8 %)*	260*(10.5 %)*	259 *(10.9 %)*

The following main insights are seen from the table and simulations of the SE1 and FI markets:

- With higher and more volatile spot prices, the total system costs are increased for all markets with SE1 and FI market prices compared to the Trondheim results. For instance, the increase is 2.3 % and 6.6 % for BC in SE1 and FI, respectively.
- The total P2P export is increased for both C1 and C2, as more price arbitrage is performed with P2P trade. Hence, the buildings consumes extra grid power in periods of low prices to trade to peers, exploiting the volatile spot prices.
- B2, with the EV parking lot, is primary a price taker in BC. With the spot prices in SE1 and FI, the building becomes a more active entity at the industry site in C1 and C2, with increased amount of price arbitrage operations with the EVs.
- As a price taker, B3 see a small decreasing in the total savings compared to in the Trondheim market. The same is found for the PV owners, B1, B4 and B5, as the production from solar PV and building demands are inelastic.
- The total amount saved by implementing P2P energy trade and the shared storage (C1 and C2) are close to unchanged, however the percentage savings are somewhat lowered due to the increased costs. Consequently, the system is already minimizing the grid usage by employing the available on-site flexibility as much as possible with the Trondheim spot prices.

The same trends are seen for the market designs with the DK1 spot prices. However, the system opera-



(**a**) Building 1

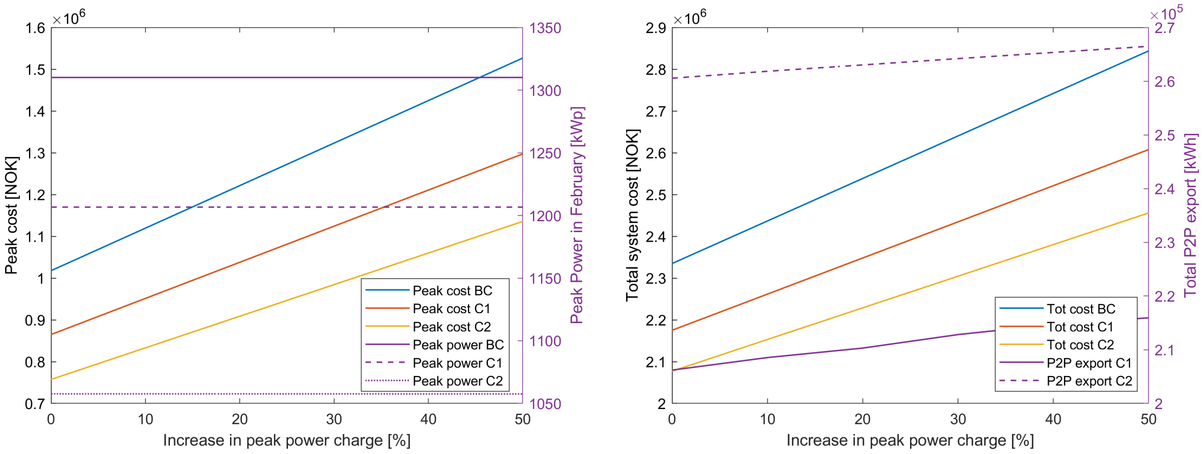
(**b**) Building 2

Figure 5.11: Supply-demand decisions for B1 and B2 in Case 2 with the DK1 spot prices in week 8.

tion is evidently changed in some time steps, namely the times of negative prices which are seen in Figure 5.10c. When the spot prices are negative it is economically attractive to consume as much power from the grid as possible, without exceeding the highest peak of the given month, and sell it to peer, central storage or back to the grid in the same time step. The first two events are not system efficient, while the third is not possible in real life as grid feed-in has to come from DERs. These events are visualized for B1 in C2 around hour 20 and 70 in Figure 5.11a. As a result, the total amount of P2P energy trade and grid feed-in are considerably increased in C1 and C2 with the DK1 spot prices, in addition to the central storage usage in C2, compared to the Trondheim spot price results. The EV storage at B2 is further employed for price arbitrage, presented for B2 in C2 in Figure 5.11b. The EVs are discharges to a great extent ahead of negative prices to charge the central storage, cover building demand or trade to peers, and the recharged at negative prices within work hours.

5.4.2 Peak Power Charge

Due to the vast penetration of energy demanding entities, such as EVs, the power demand in the power systems of today is increasing. As the capacity of distribution network has to be sufficient to deliver the highest power draw from the grid throughout the year, this can lead to a great need for costly line investments. The peak power demand is considered a possible way of giving price signals to consumers to shave peaks and shift loads, thus reduce the stress of the grid. Hence, increasing the already existing industry peak power charge could incentive more peak shaving. The cost of peak power is a large part of the industry site electricity bill, and affected the system results to a great extent. Therefore, simulations have been carried out for each market design subject to percentage increase in the peak power demand charge, to see how the system operation and costs are affected.



(a) Yearly peak cost and peak demand in Feb **(b)** Total system costs and P2P export

Figure 5.12: Sensitivity to percentage change in the peak power demand charge.

Figure 5.12 show the system sensitivity to a gradually percentage change in the peak power charge $c_{g,peak}$, from the initial value to a 50 % increase. Figure 5.12a presents the same simulation for the yearly cost of the peak power and the peak power demand in February as a function of percentage increase in $c_{g,peak}$ for each market design. The total system cost and total P2P energy export for the whole year, are shown in Figure 5.12b. The following insights are obtained:

- The peak power demands in February are close to constant, which also were the result throughout the year. This indicates that the optimal solution of each market design already shaves the peak powers as much as possible with the present peak demand charge. Hence, all the on-site flexibility and collaboration are operated for the industry site to shave the power peaks. In other words, the peak shaving is limited by the usable capacity of the on-site flexibility, collaboration and inflexible system parameters.
- The total cost of peak power increases for each market design, as expected. For a 50 % increase in $c_{g,peak}$, the total cost of peak power for are 50.00 %, 49.96 % and 49.92 % for BC, C1 and C2, respectively. Hence, the increases are close to directly correlated, which are expected due to the previous observation.
- The total cost of the system is strongly affected by peak power charge for each market design. As for the peak power costs, the costs increases linearly, where the increase for BC is a bit higher than for C1

and C2. For a 50 % increase in $c_{g,peak}$ the total system costs are increased 21.8 %, 19.9 % and 18.2 %, respectively.

- With an increase of 50 % in the peak power charge, the total cost savings of a pure P2P energy trade implementation is 236,214 (8.3 %). In C2, with P2P trade and the shared storage, the total cost savings is 387,871 (13.6 %).
- The amount of energy exported to peers are increased 4.7 % in C1 and 2.3 % in C2 with a 50 % increase in the peak power charge.

Summarized, the peak demand charge at toady's level constitute an extensive cost for the industry site. For this reason, the industry site are already operating all DER, shared storage and P2P energy trade to shave the peaks as much as possible in each system configuration. An increase in the peak demand charge gives a large increase in the total cost of electricity, due to the direct cost of peak power. However, it do not affect the optimal operation of the systems considerably.

5.4.3 P2P Energy Trade Prices

The individual P2P energy trading prices reflects the buildings willingness to pay for electricity. In addition to defining the prices on the P2P trades, the shared storage prices are given by the P2P prices and spot prices. Therefore, the local energy flows and the value of local collaboration are affected by these prices. As such, it is important to see how changes in these prices, while keeping other prices and parameters constant, could affect the optimal results. In the following analysis, simulations have been carried out for decreasing and increasing P2P prices.

Table 5.6: The total system costs and percentage system savings compared to BC subject to percentage change in the P2P prices.

Change in P2P prices [%]	**Total system costs [NOK]**		**Total savings**	
	C1	*C2*	*C1*	*C2*
-50	2,175,170	2,073,138	6.8 %	11.2 %
-30	2,175,170	2,074,875	6.8 %	11.1 %
0	2,175,170	2,077,326	6.8 %	11.0 %
30	2,175,170	2,079,661	6.8 %	10.9 %
50	2,175,170	2,081,162	6.8 %	10.8 %

Figure 5.13 and Table 5.6 presents the system sensitivity to a gradually percentage change in the P2P

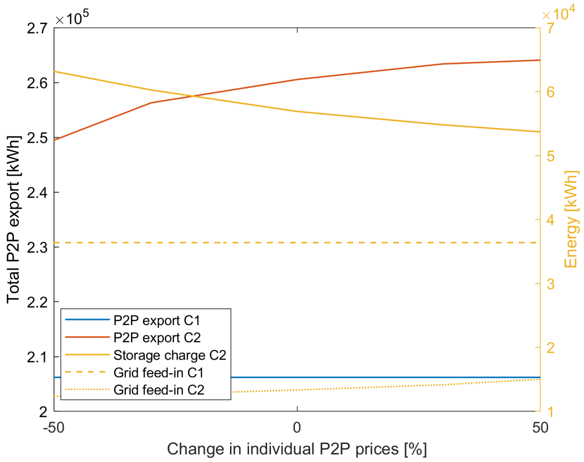


Figure 5.13: Local power flows and grid feed-in sensitivity to change in the individual P2P energy trading prices.

prices, from decrease to increase. The change in total local power flows out of the buildings, in terms of total P2P export and shared storage charging, and grid feed-in in C1 and C2 are presented in Figure 5.13[2]. Table 5.6 show how the total system costs and total savings are affected in C1 and C2. The following observations are made:

- The total optimal solution of the whole industry site is not sensitive to percentage changes in the P2P prices in the C1 market. However, the power flows and optimal solutions of the individual buildings are affected. For instance, the P2P export of the PV owners decreases, while it increases for B2 and B3 with higher P2P prices. The same trends are seen for the total system savings.
- The total system savings compared to BC is constant 159,128 kWh (6.8 %) for C1. While for the C2 market, the total system savings with 50 % decrease and increase in the individual P2P prices are 261,161 kWh (11.2 %) and 253,137 kWh (10.8 %). Namely, a 2 % increase and decrease from the initial savings (11.0 %).
- The total P2P export is similar for all P2P prices in C1. For a 50 % increase in the P2P prices, the P2P export in C2 is increased 3,533 kWh from the initial value and the total shared storage charging is decreased 3,192 kWh. While for a 50 % reduction, the P2P export is decreased 11,084 kWh and the storage charging is increased 6,271 kWh. As the shared storage discharging prices is a function of the P2P prices, the storage usage is directly affected by changes in the P2P prices. As expected, the costs and revenues of P2P trading are directly influences by the price changes.

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[2] BC is not included, as the P2P prices are the willingness to pay in the BC and the prices are not present in the BC.

- The grid feed-in C2 see a small linear increase from the lowest to the highest P2P prices in C2.
- The total system costs in C2 are increased 0.18 % and decreased 0.20 % with a 50 % increase and decrease in P2P prices, respectively.

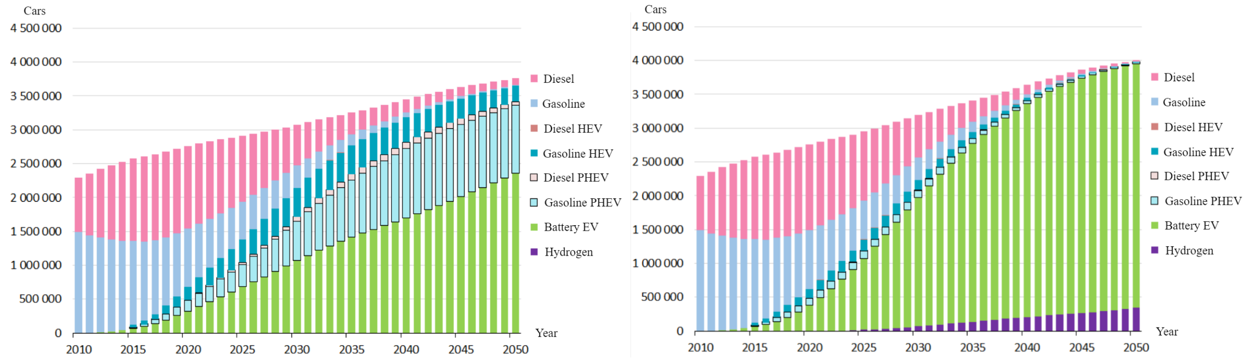
Further, Lüth et al. [1] argues that P2P export and import will cancel out, thus the costs and revenues of trading, in the objective function for the total industry site. Therefore, this approach was tested for C1 and C2. The simulations showed that even though the total costs cancel out the power flows are affected, in terms of which peers buys and sells the P2P energy.

It should be noted that there are other ways of designing the P2P prices and local market structure. As such, other structures and pricing schemes could impact the results to a great extent. The focus of this analyses have been on the implemented market designs.

5.5 Future Scenario Simulation: The Industrial Site with EVs in 2030

As the power system and power market are evolving, along with technology developments, a future scenario simulation of the system configurations are highly relevant. While the sensitivity analyses presented above gives an insight regarding the system operational tendencies when changing one price parameter at the time, the other parameters are kept constant during the analysis. In this section, the system configurations are simulated for one year using parameter values corresponding to future trends for the year 2030.

In 2016 the Norwegian Institute of Transport Economics (TØI) presented trend projections for the Norwegian stock of passenger vehicles, illustrated in Figure 5.14 [43]. These projections show the great potential that will lie in V2G technology in the near future. According to the electrification trends used by NVE, 50 % of the Norwegian car fleet will be electrified in 2030 [44]. Further, the projection in Figure 5.14b is based on a ultra-low emission policy scenario and technology development trends, shows how the electrification can happen faster than predicted by NVE. Based on this, it is assumed that all the buildings have a joint EV energy storage unit serving V2G flexibility, equivalent to the unit at B2. As the V2G technology holds the promise of flexible and fast-responding storage services, it is assumed that it is desirable for all the buildings to offer EV parking in the 2030 scenario. As the focus of this implementation is the operational trends with decentralized EV storage units, in addition to the amount of uncertainties regarding the number of EVs and EV characteristics of the future, the EV parking lot characteristics are not changed.



(a) Based on the passenger vehicle trends for the years 2010-2015.

(b) Based on ultra-low emission policy scenario and technology development.

Figure 5.14: The evolution trends in the Norwegian stock of passenger vehicles, modified from projection figures in [43].

Further, the electricity price are changing, as described in Section 2.2. The utility tariff are currently under the loop and the Norwegian spot prices are expected to become higher and more volatile. Therefore, the peak demand tariff is increased by 20 % and the day-ahead spot prices in SE1 are employed[3] in the 2030 scenario.

The yearly system operation is optimized for each market design in the assumed 2030 scenario, with all other parameters kept unchanged. Table 5.7 presents the total results of the industry site in each case study in the 2030 scenario.

5.5.1 Base Case

As an EV storage unit is located decentralized at each building in the 2030 scenario, the building supply-demand decisions include the optimal operation of the storage. With this, the buildings have the option to employ the storage during the workday. Hence, the buildings goes from being primary inflexible price takers in the present BC to somewhat flexible and active entities in the 2030 scenario. Further, the BC in the 2030 scenario is considered the reference case when analyzing C1 and C2 and the value of P2P energy trading and shared storage in 2030.

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[3] Recall how the grid feed-in and local industry site prices, i.e. the individual P2P prices, storage charging compensation and individual storage discharge prices, are dependent on the wholesale spot prices.

Table 5.7: Total results for the three industry site system configurations in the 2030 scenario.

	Base Case	**Case 1**	**Case 2**
Total costs [NOK]	***2,622,795***	***2,468,877***	***2,383,655***
Total cost of grid consumption	2,650,248	-6.5 %	-9.9 %
Cost of peak power	1,207,047	-12.5 %	-20.3 %
Cost of UT energy term	168,947	-1.8 %	-1.9 %
Cost of UT fixed term	74,055	0 %	0 %
Cost of energy spot price	1,200,199	-1.4 %	-1.3 %
Revenues of selling to the grid	29,264	-63.0 %	-83.0 %
Yearly peak demand [kWp]	1,385	-4.6 %	-13.2 %
Grid power bought [kWh]	3,984,603	-1.8 %	-1.9 %
Power sold to grid [kWh]	104,222	-66.5 %	-85.6 %
Curtailed power [kWh]	13,007	-100 %	-100 %
P2P export [kWh]		165,285	180,241
Central storage charge [kWh]			62,889
Yearly peak shave [kWp]		64	182
Total savings [NOK]		***153,918***	***239,140***
Total savings [%]		***5.9 %***	***9.1 %***

When comparing the total industry site results for the 2030 scenario BC in Table 5.7 to the present BC, following observations are made:

- The total cost of electricity for the whole industry site is increased 12.3 %. Where the total cost of wholesale electricity and peak power have increased 8.5 % and 18.6 %, respectively. Based on the 2030 spot prices being higher and more volatile and the increase in peak power charge, these results are as expected. However, the cost of peak power is lower than the percentage increase of the peak demand charge (20 %).
- The total amount of grid feed-in and curtailed power are reduced 5.6 % and 17.2 %, respectively. Which is a direct consequence of the buildings having some flexibility in BC in the 2030 scenario, thus are able to store excess generation for later usage. As such, more power is consumed locally.
- The highest yearly power peak of the total industry site is reduced 27 kWp, thus the buildings employ the EVs for peak shaving. The monthly peak shaving are the reason why the total cost of peak power is not identical to the percentage increase of the peak power charge. Further, B5 is able to shave the monthly peak power throughout the year, and represents most of the yearly reduction above.
- The total consumption from the grid is increased 143,554 kWh (3.74 %). Due to the hard constraints on the initial and final storage level, corresponding to the EVs arriving and leaving work, the EV storage

bring an increase in the individual building demand. Hence, the EV storage bring flexibility to the buildings at the cost of increased demand.

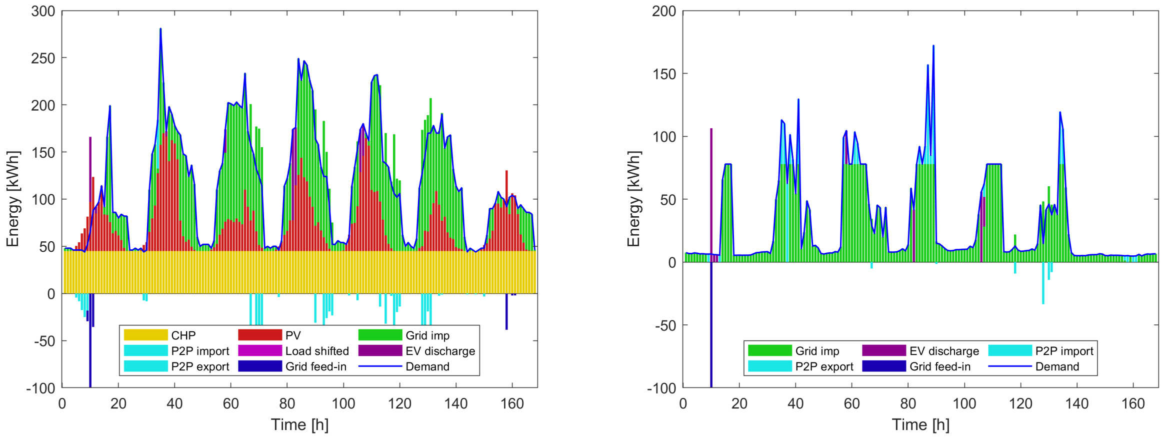
- The EV storage units are used for price arbitrage operation by the individual buildings, based on the spot price. Consequently, each building are able to exploit the volatile spot price to some degree during workhours.

5.5.2 Case 1 and 2

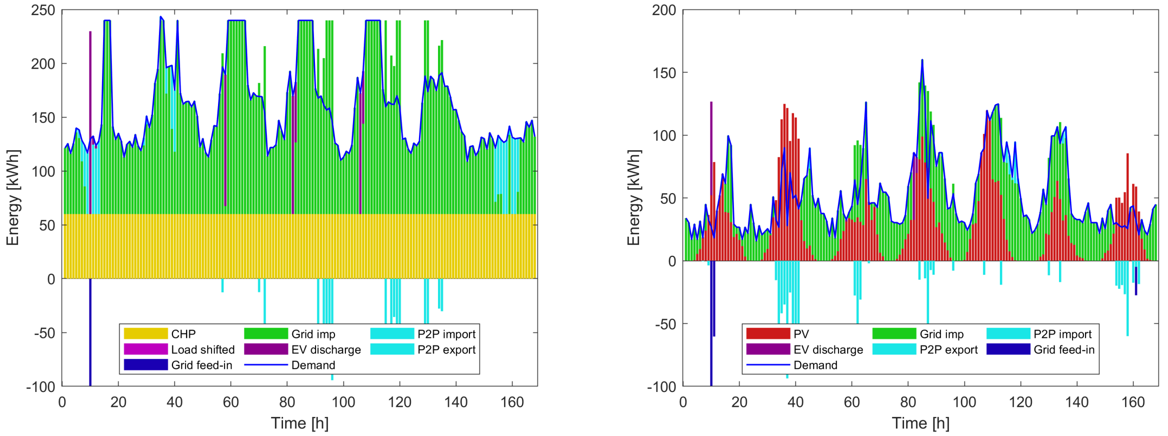
In this section, the results for C1 and C2 in the 2030 scenario are presented, with emphasis on the system operational changes compared to the BC in the 2030 scenario and the results from present scenario. It should be noted, as the energy demand of the buildings increased in the BC, due to the EV storage implementations, so the correlated willingness to pay have increased. Hence, the individual P2P prices are higher in the 2030 scenario. Consequently, the individual discharging prices of the central storage are increased. In addition, both the charging compensation and discharging prices of the central storage are a function of the spot price, which are higher and more volatile.

Figure 5.15 presents the supply-demand decisions for C1 and the related spot prices in a summer week (week 24 in June) in the 2030 scenario, illustrating in detail how each building covers its demand, operates the EV storage, DERs and trades. The figures show the operational trends for the EVs, which were found to be close to equal for C1 and C2. The following observations are seen from the figures:

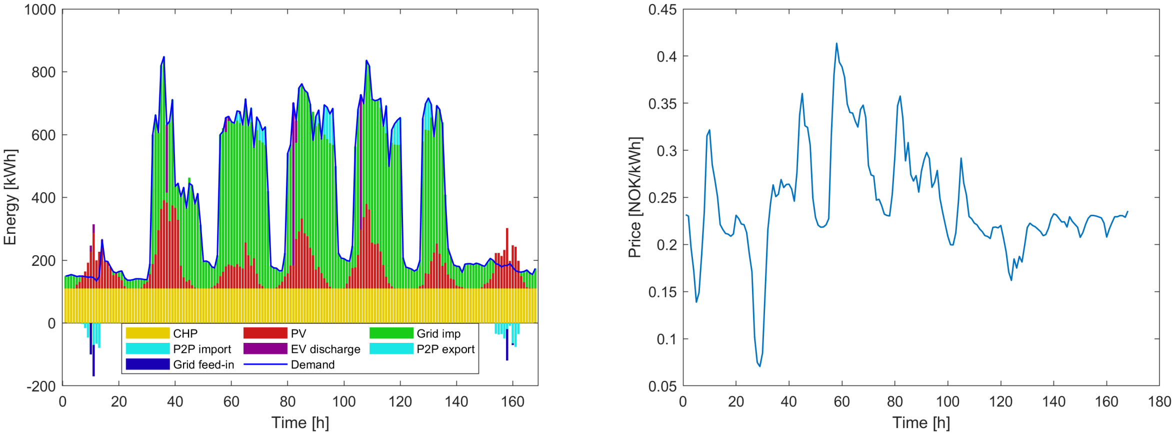
- The EV storage units are employed for price arbitrage. The discharging energy covers building demand, traded to a peer, sold to the grid or charged to the central storage (in C2). For instance, the buildings discharges the EVs to cover demand at the peak spot price in hour 80, and recharges at lower spot prices. At the peak price in hour 10, B2 and B3 discharges the EVs to sell to the grid, while the rest of the buildings feed-in coinciding excess DG production. The price arbitrage operation using the EVs are limited by the hard constrains on the EV storage level and period of availability that is a workday.
- The energy demand of each building are increased compared to the present scenario, especially during the workday. This is evident when comparing the figures to the summer week illustrations for C1 in the paper.
- As for the present scenario, the buildings import extra power from the grid, up to the optimal monthly peak power, and trades to peers. Hence, power demand peaks are shaved by P2P collaboration, e.g. for



(**a**) Building 1 (**b**) Building 2



(**c**) Building 3 (**d**) Building 4



(**e**) Building 5 (**f**) Spot prices

Figure 5.15: Supply-demand results for the Case 1 market and related wholesale prices for week 24 in the 2030 scenario.

B2 in Figure 5.15b.

- Compared to the present scenario, DG owners consume more of their own production, due to the increased building demand and flexibility. As PV production is inelastic and generates power when the sun shines during the day, production is consumed by the building to charge the EVs during the workdays.

Table 5.7 presents the total system results for C1 and C2 compared to the BC in the 2030 scenario, thus the value of implementing P2P collaboration and shared storage. Based on these results and the operational trends shown in Figure 5.15, the following observations are made:

- The total grid consumption is reduced 1.8 % and 1.9 %, while the total cost of grid consumption is reduced 6.5 % and 9.9 % in the C1 and C2 markets, respectively. Due to the P2P collaboration and shared storage making the industry site more flexible to exploit volatile price signals and shave peaks.
- The cost of peak power is reduced 12.5 % in C1 and 20.3 % in C2.
- No power is curtailed and the grid feed-in is reduced 66.5 % and 85.6 % in C1 and C2, respectively.
- The total system savings by the introduction of P2P trade in C1 is 153,918 NOK (5.9 %), while the total system savings by combining P2P trade with a shared storage in C2 is 239,140 NOK (9.1 %) in the 2030 scenario.

Comparing the 2030 scenario results for C1 and C2 to the present scenario, the following insights are obtained:

- The total demand of each building are increased. Hence, the total grid consumption of each building are increased 3.9 % in both C1 and C2. The hard constraints on the EV storage units limits the the employment of the storages to a relatively short period. During a workday, the EVs must be charged to a higher storage level than when they arrive in the morning. In addition, the buildings have their highest demand during workhours, as they are industry consumers.
- The buildings prioritize self-consumption to a greater extent. With the increased demand and DG owners now having some on-site flexibility during the workday, a larger part of the DG production is self-consumed. Hence, there is less excess production for trading throughout the year.
- The total amount of energy charged to the shared storage is increased 5,995 kWh in the 2030 scenario. The buildings with installed PV system, B1, B4 and B5, provides most of the charging power.

- The amount of P2P energy traded are reduced for both C1 and C2 in the 2030 scenario compared to the present situation. In the present scenario, it was optimal for the buildings to consume extra power from the grid up to the monthly peak power demand for trading with peers. As the EV charging often coincides with the periods of high building demand and self-consumption is increased, the amount of excess power available for trading is decreased.
- The buildings are not able to shave their monthly peak power demands as much in the 2030 scenario C1 and C2 compared to in the present scenario, even with the increased peak demand charge. This is especially evident in the C2 market, where the peaks were considerably shaved for each building throughout the year, as seen from the figures in Appendix C.3.1. The reason for this is composed by all the operational aspects highlighted above. The on-site production is inelastic, the flexibility of the added EVs are limited and brings additional demand, and amount of excess power for trading is decreased. Hence, the peak power demand is limited by the usable flexibility and collaboration capacity of the industry site.
- The total system savings in C1 are lowered 5,833 kWh (0.9 %) and 18,456 kWh (1.9 %) in C2 compared to the total savings in the present scenario. This can be seen in context with the aspects presented above. In addition, there were some peak shaving in the 2030 scenario BC compared to the present scenario, as presented in Section 5.5.1. As the buildings are more flexible and active entities with the EVs in the 2030 BC. This influences the total savings, seeing that the related BC in the scenario is the reference when calculating the total savings, the peak power charge represents a considerable cost, and the peak shaving are limited by the available system flexibility.

Chapter 6

Discussion

The purpose of this study is to investigate whether enabling P2P energy trading at an industry site with installed DERs could provide benefits for the industry site as a whole and the individual buildings. As the industrial buildings are subject to a peak power charge, an additional goal is to evaluate how the industry site employ utilize the P2P trading mechanism and on-site flexibility. In this chapter, the results and analyses in Chapter 5 and Section 5 in the paper are discussed, as well as validity of the models and assumptions.

6.1 The Case Studies

6.1.1 The Base Case

The simulation results from the BC showed that the total industry site demand is supplied by 64.2 % power from the distribution grid and 35.8 % by on-site building DERs. In addition, 110,346 kWh is fed to the grid and 15,711 kWh is curtailed. The proposed flexibility options and on-site DG allows the industrial buildings to gain benefits by optimal scheduling of the resources and reduces the procurement from the grid, which coincide with a study of large consumers by Angizeh et al. [18]. The industry site DERs and flexibility features in BC were assumed and included to create a case study in this thesis. Hence, they are not installed at the actual buildings as of today. Consequently, the simulation results are most likely system dependent. Thus, depending on the system configuration and related characteristics, such as penetration level of DG, demand patterns, the available DER technologies and degree of demand response.

As such, how reasonable and the feasibility of the assumed industry site DERs, are important aspects when looking at the simulation results. The implemented DER technologies are based on trends in the industry today and are designed to fit the case study, as described in Section 4 in the paper. The high costs of electricity and the increasingly importance of a green image incentives investing in DERs, where Powerhouse Brattørkaia [45] and ASKO [40] were highlighted as examples from the industry in central Norway. To obtain the BC from the present alternative[1], rather large investments for DG technology, V2G technology and technical smart grid equipment must be realized. The related investment costs could have a considerable impact on the outcome. However, compared to the BC, the industry site do not need any investments to enable P2P energy trading. The focus of the study have been the operational value of the presented local market features, thus the investment costs of the markets have not been addressed in this thesis. Moreover, the investment costs of DERs, such as energy storage and PV, have exponentially decreased over the past years. Further, the wholesale price of electricity is still quite low in Norway compared to other countries. Consequently, the energy demand is primarily met by electricity from the distribution grid in the power system of today. However, spot prices are trending towards higher and more volatile electricity and the utility tariffs are up to evaluation, as described in Section 2.2.

6.1.1.1 Load shift

The load shifting feature of B1 and B3 are employed for peak shaving. Likewise, Zhou et al. [46] also found that DR actions by commercial buildings shave the load profile at peak hours with price-based DR programs. However, the load shifting feature is only somewhat employed in this study. The simulation results and calculated example in Section 5.1.1 showed how the savings from demand response, i.e. shifting load, based on the spot price is lower than the load shift penalty. As a result, price arbitrage operations based on the spot price is not profitable. Moreover, the yearly amount of shifted load for B1 is 244 kWh and 1029 kWh for B3, where B3 is able to reschedule shifted load throughout the day at a lower penalty. Hence, the load shifting usage is limited by the costs and degree of rescheduling freedom.

Due to little information regarding the production processes and related costs in the buildings, the load shifting characteristics were based on load patterns and literature. As such, further work related

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[1] The buildings of today, without any DERs installed.

to the industry site demand response should be to expand the feature and fit the related characteristics to detailed building information. Further, a full smart grid setting is assumed to enable load shifting. GridBeyond [47] in UK and Island delivers a platform which finds flexibility in industrial energy usage for savings, revenues and sustainability using machine learning technology. The platform controls and optimizes energy consumption for participation in demand side response programs and smart energy services.

6.1.1.2 EV parking lot

The simulation results revealed that the EV storage unit at B2 brought some degree of flexibility to the building, in terms of peak shaving and price arbitrage. However, the net demand and thus the cost of electricity are increased due to the hard constraints on the storage level. Further, V2G technology is assumed at the building, operating the interface of the building and EV parking lot. There is still key barriers and challenges related to the implementation of V2G, for instance battery degradation, market regulations, infrastructure, communication complexity and consumer acceptance. In this subject, some reviews focus on the technology and markets, while others push for attention to the end-user and social side of the technology [48].

6.1.2 Case 1 and 2: Industrial Site Collaboration

The simulation results reveal that P2P energy trading is able to bring economic benefits to the industrial site, as well as to individual customers. With yearly net savings of 6.8 % and 11.0 % for the whole industrial site in C1 and C2, respectively. Lüth et al. [1] found that a pure implementation of P2P trade leads to savings of 22 % and 10 % in their two case studies of storage combined with P2P trade in a community of prosumers in the UK, with prices based on hourly real-time pricing. In the last case, a central storage is shared between the houses, leading to net savings of 24 %. Long et al. [5] found that P2P energy sharing is able to reduce the energy cost of the community by 30 % compared to the conventional peer-to-grid trading, with a supply-demand ratio based pricing mechanism for P2P trades and flat rates for grid buying and selling prices. In comparison, these articles consist of communities with residential customers with higher penetration of DG production, and do not consider the peak power term in the utility tariff. Further, the results are most likely system dependent. As the results are heavily dependent on system characteristics, such as the penetration level of DG, available on-site flexibility, price levels and schemes, demand patterns and market designs. However, the articles have in common that the implementation of P2P energy trading brings significant net savings to the community. As such, comparing to other articles with different system setups are important to see the trends in literature and the specter of community solutions.

The P2P energy trade concept is a novel subject in the literature. At the time of this thesis, no literature to be found have studied P2P energy trade among industrial customers. Compared to residential customers they have high demand, large power peaks, different demand patterns and large investments. Therefore, there are little literature in the academia for direct comparison of the results. Further, they are subject to the peak demand charge in the industry utility tariff, which have shown to affect the system results to a great extent. As such, no literature to be found have studied P2P energy trade in combination with a peak demand charge. Seeing that the utility tariff in Norway are up to evaluation, the results are highly relevant for residential customers, as well as industrial customers. Consequently, the operational trends and results in the thesis bring novel results to the subject of P2P energy trade.

6.1.2.1 Peak shaving and price arbitrage with P2P energy trading

The simulations results from C1 and C2 show that using P2P energy trading for peak shaving purposes are highly beneficial. With the substantial peak demand as key driver, for the industry site as a whole the cost of peak power is reduced 15.0 % in C1 and 25.6 % in C2. Further, the peak shaving are also considerable for each building, with the total peak power cost reduction ranging from 19.8 % to 49.6 % in C2. As a result, peak shaving is by far the largest contributor to the net cost savings in both C1 and C2.

Further, the results reveal that the buildings buys extra energy from the grid to trade directly to peers at favorable prices, achieving benefits and helping the peers shave their. As such, the industry site performs peak shaving by exploiting the variations in prices and building demand and DG production. Hence, this implies that P2P energy trade provides benefits even without on-site DER and excess production. This is interesting results, as it was initially expected that only excess DG generation would be traded locally. However, buying from the grid and trading to a peer in the same time step, could be seen as a system inefficient operation. The same is seen for the central storage operation in C2, where one building discharges the storage and trades to a peer in the time step. This highlights a potential problem in the model. In this study, the physical power system characteristics are neglected. As such, simulating the system configurations including these characteristics are important further work. With a single metering system and the same contract for importing and exporting power, this is not physically possible. However, with two meters and two separate contracts this phenomenon could be possible. In order to simulate a more realistic scenario, a constraint saying that the power exported to peers, the central storage and fed to the grid must come from excess DG production could be implemented in the model. However, this will make the industry site less flexible and reduce the savings of peak shaving using P2P collaboration. In the work of Lüth et al. [1], P2P energy trading and central storage charging are limited to only excess DER generation. In comparison, the study have a higher penetration level of DG and residential prosumers and consumers, thus more excess production.

Due to the historical dynamic spot prices the buildings are able to perform price arbitrage, thus exploiting the price variations in the power market. Compared to BC, the grid consumption is reduced 1.9 % in C1, while the total cost of grid consumption is reduced 7.5 %. Further, the energy term in the utility tariff is a flat rate today. A new network utility tariff structure is under development for residential customers today, hence it is realistic that the industry utility tariff will see some changes as well. As a result, the industry sites' ability to perform price arbitrage could have increased value in the near future, with an utility tariff based on real-time pricing.

6.1.2.2 Central solution method

The simulations reveal that the results are driven by the centralized solution method, where the total cost of electricity is minimized for the whole industry site. With the extensive peak power charge as the key driver, the centralized solution method incentives the operation where buildings consumes extra grid power for P2P trading. Hence, the industry site go to great lengths to keep the monthly peak power of each building as low as possible. The centralized solution method also affects the P2P power flows to great extent. Further, the operational pattern of the central storage, namely the discharging power of one building is traded to a peer in the same time step, is also related to the central control and the individual discharging prices of the buildings. The individual buildings due not necessarily trade with the highest bidder, but with the peer that minimizes the cost for the whole industry site. Looking at the building perspective, this might be a model weakness and affect the willingness to participate in P2P collaboration. However, the evaluation of the participation willingness in Section 5.4 in the paper show that all buildings obtain benefits and have a motivation to participate in the joint industry site.

With the central solution method, all information are assumed available and known to all participants in the industry site. Further, a full smart grid setting in an advanced level of digitization is assumed. In such a full P2P market, the market participants directly negotiate with each other without third-party supervision. Hence, the collaboration is built on transparency and a willingness to share data. As such, the industry site is able to optimize the operation schedule for each building to find the optimal solution for the industry site as a whole. On the other hand, the strategy possesses some disadvantages regarding the sharing of information, personal security and fairness of economic gains. To face these challenges in communities and smart grids, the literature proposes for instance the use of decentralized optimization techniques [4, 12, 37]. These make it possible to explicit define individual problems for each participant, while guaranteeing their privacy. Moreover, each building only share the power and price they are willing to trade, without revealing preference, utility curve and DER characteristics. Accordingly, this is an important direction for further work.

6.1.2.3 Self-consumption

In the two collaboration cases, no power is curtailed and the grid feed-in is reduced 67.0 % in C1 and 87.1 % compared to the BC. As such, the implementation of P2P energy trading bring forth a higher level of self-consumption, which is in line with the findings in the work of Luth et al. [1] and Long et al. [5]. Further, the simulation results showed that full self-consumption is limited by the capacity of the flexibility in the industry site. As the PV systems are located at the same area, the PV systems produce power simultaneously and the industry site is not able to consume all the produced power locally. Consequently, it could be favorable to include DG with different seasonal production patterns than solar PV, e.g. a wind power plant. Long et al. [5] concluded that P2P energy sharing has a similar impact on raising the community's self-consumption, self-sufficiency and reducing energy costs as implementing batteries, but at a significantly lower investment cost.

6.1.2.4 Local industrial site prices

The cost of electricity form the distribution grid, in terms of utility tariff and wholesale prices, and the grid feed-in prices are actual time series provided by NTE Nett AS and Nord Pool. Although the feed-in tariff can provide basic motivation for P2P energy sharing, an appropriate internal pricing mechanism proved to be important. The local industry site prices are designed to fit the two system configurations, based three principles: 1) the internal prices should be bounded between the feed-in tariff and electricity prices of utility grid; 2) the principles of economics, the relation between price and supply-demand ratio is inverse-proportional; 3) the economic balance should always be guaranteed locally. Hence, it was important to take the system setup and its configurations into explicit consideration when designing the local electricity market. In the literature today, several bidding strategies and ways of implementing P2P energy trade in communities are emerging, which should be investigated for this industrial site.

6.1.2.5 The grid owner perspective

Due to the extensive peak shaving and local consumption, the distribution grid is relived of stress, especially in peak power periods. In addition, the grid consumption from the buildings are more periodically even. As the buildings collaborate to shave peaks, by consuming extra power up to their optimal peak power demand in the given month, the demand for grid power is smoothed for all buildings. Flatter power profiles are able to increase the utilization rate and operational efficiency of the power system equipment. Hence, shaving the yearly peak power demand could avoid or defer expensive network reinforcements. Further, the investment cost of a new line is always the opportunity cost of new technology if more capacity is needed. The investment cost is high, depending on factors such as useful lifetime, year of construction and the condition of today's line. In addition, at the request of increased line capacity, the industry buildings have to pay a substantial investment contribution to the grid owner. As a result, the yearly peak power shaving are of great interest to the both the industrial buildings and the grid owner.

From the grid owner perspective, a yearly peak power reduction is interesting with regards to savings related to line investments. Line investments are based on the demanded grid capacity, i.e. sufficient capacity to supply the coldest winter day, thus peak power reduction could decrease the necessary cross section of new lines. It should be noted that if the capacity of a line is reduced according to shaved peaks during reinforcements, the new line capacity cannot be exceeded. Hence, the buildings must be able to keep their peaks below this new capacity based on the shaved yearly peak demand. In principle, the grid is dimensioned based on the potential peak power of the customers. When lines are built or reinforced, the short-circuit current, voltage, losses and power flows are important characteristics to consider. If market mechanisms, such as P2P energy trading, reduces the considered yearly peak power, the cross section of the line might be reduced. In such an analysis, all the characteristics must be considered when comparing the power load of the original line and the line with reduced cross section. This will affect the socioeconomic and net saving analyses, as an increase in losses could neutralize the investment savings related to a line with lower cross section. However, if the original line is chosen, shaved peaks would still provide benefits in terms of reduced line losses and load and more effective usage. As such, more customers could be connected to the line, thus potentially avoid investing in an entirely new line. This is illustrated in an example in Table 6.1 for a hypothetical consumer with a peak power demand of 100 kWh/h. The consumer is connected to the bus through a 100 m cable at a voltage level of 400 V. The example show the impact of shaving the peak power 10 % for two different cross sections, revealing reductions in the cable losses, loads and operating currents[2]. For comparison, the yearly peak power of each building in the C2 market are shaved in the range of 16.6 % to 31.1 %, compared to the BC.

Table 6.1: Illustrating the affect a 10 % peak power reduction have on two 100 m cables with different cross section in the low-voltage distribution grid. The data is provided by NTE Nett AS.

Peak power [kW]	Cable cross section	Voltage [V]	Short-circuit current [A]	Losses [kW]	Load [%]	Operating current [A]	Investment costs [NOK]
100	50	384.5	2.198	4.56	103	154	10,167
100	95	393.1	4.043	2.18	68	151	12,551
90	50	386.4	2.198	3.66	92	138	10,167
90	95	394.1	4.043	1.76	61	135	12,551

With the emerging smart grids, microgrids, communities and grid cells, the future role of the grid owner in such local grids are under discussion. As a grid owner, NTE Nett AS sees the possibility in taking the role as the network operator in local grids, in terms of balancing the frequency, controlling the voltage level and perform grid reinforcements. Further, local market operator companies could possibly administer local energy markets[2].

6.2 Price Sensitivity Analyses

The price sensitivity analyses in Section 5.4 reveal that the system results are not very price sensitive. The electricity prices of today are already extensive for the industrial buildings. Therefore, the optimal solution are already employing all industry site flexibility, DG, P2P collaboration and shared storage to minimize the total cost of electricity. Hence, the optimal solution in terms of cost reduction operations, such as peak shaving and price arbitrage, are limited by the flexibility capacity of the industrial site. Another reason for the small operational changes, is the defined price scheme, where the prices are interconnected. Recall how the grid feed-in and local industry site prices, i.e. the individual P2P prices, storage

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[2] Information provided through correspondence with Andreas Hammer at NTE Nett AS.

charging compensation and individual storage discharge prices, are dependent on the wholesale spot prices. Lastly, all results are compared to the BC market results, which also sees changes when the spot prices and peak power charge are adjusted.

6.3 Assumptions and Shortcomings

Several simplifications and assumptions have been made in order to model the system configurations and market designs, which should be kept in mind when analyzing the results. All assumptions have been presented and explained throughout the thesis. In addition, the results and discussion have reveal some shortcoming's in the models. As such, key assumptions and shortcomings are summarized below:

- All demand and PV production data are historical measured time series, as well as the wholesale spot prices. Hence, perfect forecast models are assumed, neglecting uncertainties in DER production, electricity prices and demand. As a result, the hourly system operations are optimized using known values. In reality, demand, production and prices are affected by a range of external factors and are not known prior to solving. As such, a forecasting algorithm and stochastic optimization taking these factors into account should be implemented in the model.
- The optimization horizon is one year. To evaluate the value of P2P energy trading for an industry site and validate the findings, long term optimization should be simulated for each model.
- Power system characteristics are not implemented in the models. The models includes the demand and generation data for the buildings, however load flow analysis, the topology of the network and the impedance of branches are not considered. Such grid features influence the optimal operation of energy systems in reality, and should be implemented in the models. For instance, the phenomenon discussed in Section 6.1.2.1, where a building consumes extra gird power and trades to a peer in the same time step, might not be physically possible in reality.
- The central control method minimizes the total cost of electricity for the whole industry cite. The possible limitations related to this approach are discussed in Section 6.1.2.2.
- The local pricing schemes are designed to fit the markets. It should be noted that there are other ways of designing the P2P prices and local market structure. As such, other structures and pricing schemes could affect the results to a great extent. The focus of these analyses have been on the implemented market designs.

- Investment costs are neglected from models and analysis, as discussed in Section 6.1.1. It should be noted that compared to the BC, the industry site do not need any investments to enable P2P energy trading. Moreover, the investment costs for battery storages have exponentially decreased over the past years, making the implementation available to more consumers. However, the focus of this study have been on the operational value of the presented market features.
- Last but not least, local energy markets and P2P energy trading are still at an early stage, hence there are still many key enablers and barriers remaining. As such, there are still open questions when looking at the economic and technical modelling assumptions, thus the feasibility and value of the approach. What further economic details must be taken into account for the validation of local energy markets? What technical issues might arise? How will the widespread implementation of decentralized energy markets have on the exciting grid infrastructure? The main enablers for the rise of P2P markets are technological advances in DERs and ICT, digitization in the power system and consumers' desire to share their energy. On the other hand, the legal and regulatory obstacles are the main barriers to P2P market deployment, which are related to the long history of hierarchical and top-down organization in power systems. This thesis is meant to contribute to this novel field, by providing additional designs, results and insights in new possibilities to the academia, especially with regards to the industry perspective and Norwegian electricity prices.

Chapter 7

Conclusion and Recommendations for Further Work

7.1 Conclusion

In this thesis, the value of P2P energy trading in combination with various on-site generation and flexibility resources are investigated for a Norwegian industrial site. Two local energy market designs are proposed, with the objective to minimize the total cost of electricity for the industrial site as a whole. An additional scope is to study how the industrial buildings subject to a peak power charge in the utility tariff employ local flexibility and P2P trade. The optimization models, with the related system configurations and defined market rules, are developed based on multi-stage linear programming and simulated in GAMS. In this section, the most important findings and conclusions from the results and discussions are presented.

The results reveal that P2P energy trading is able to bring economic benefits to the industrial site, as well as to the individual customers. With yearly net savings of 6.8 % in a market design with P2P trading and 11.0 % in a market design with a shared storage in combination with P2P trading for the whole industrial site, compared to a base case market. As such, all buildings have a willingness to participate in the collaboration. The results also show that using P2P energy trading for peak shaving purposes are highly beneficial. The total cost of peak power is reduced 15.0 % and 25.6 % in the two case studies, with the substantial peak demand as key driver. Where the industrial site utilizes all available flexibility to shave the peaks as much as possible, thus the shared storage enables increased peak shaving. Therefore, peak shaving is by far the largest contributor to the net cost savings. Further, the buildings are able to perform price arbitrage by exploiting the price variations in the power market and local market prices using P2P trading. As such, the grid consumption is reduced 1.9 % in C1, while the total cost of grid consumption is reduced 7.5 %.

An interesting finding is that the results are driven by the centralized solution method, where the total cost of electricity is minimized for the whole industrial site. As such, all local flexibility, i.e. DERs, P2P energy trading capacity and shared storage, are operated according to the optimal solution for the total industrial site. With the extensive peak power charge as the key cost driver, the industrial site go to great lengths to keep the monthly peak power of each building as low as possible. As a result, the self-consumption of the DG production is significantly increased for the local markets, with no power curtailment and the grid feed-in is reduced 67.0 % and 87.1 % in C1 and C2, respectively. It should be noted, such market designs are built on transparency and a willingness to share data. From the grid owner perspective, peak shaving, local consumption and smoother demand patterns relive the distribution grid of stress. In turn, the operational efficiency of power system equipment are increased and could possible avoid or defer expensive network reinforcements.

As different market designs recently have emerged for residential communities, this master's thesis contributes to the field by providing several case studies related to industrial prosumers and P2P energy trading. Further, a new grid utility tariff is currently under development and no studies to be found in the literature have studied P2P energy trading in the presence of a peak power charge[1], thus related findings are highly relevant for both residential and industrial customers. Consequently, the operational trends and results in the thesis bring novel results to the subject of P2P energy trade.

7.2 Recommendations for Further Work

The suggestions for further work are presented below, based on the main shortcomings, discussion and literature.

- **Implement the power system characteristics.** The power system characteristics, such as power flows, voltage levels an frequency balance, are important for the validation of the results and value of P2P

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[1] At the time of the literature study for this thesis.

energy trading. As such, the models should be expanded to consider an actual representation of distribution grid infrastructure.

- **Decentralized control method.** The central solution method proved to be a main driver for the simulation results, as discussed in Section 6.1.2.2. To face these challenges in communities and smart grids, the literature proposes the use of decentralized optimization techniques [4, 12, 37]. These make it possible to explicitly define individual problems for each participant, while guaranteeing their privacy. Accordingly, this is an important direction for further work.
- **Consider a forecasting algorithm and stochastic optimization in the model.** As the model parameters are historical data, the stochasticity and forecast uncertainties are not accounted for in the models.
- **Implement the shared storage as an agent or independent entity.** The charging and discharging of the shared storage in the C2 market can originate from the same sources as the P2P trade. As such, the storage cannot act as an independent entity or agent and charge directly from the grid, due to interface difficulties of today regarding prices, ownership and market position. As an agent, with the ability to purchase and sell power directly to the distribution grid, the shared storage could possibly provide increased benefits to the industrial site. Multi-objective optimization was considered to facilitate the implementation. In addition, energy storage systems can reach their full economical potential when used for multiple applications, which is relevant in a study with all power system characteristics present.
- **Expand the grid owner perspective evaluation.** In Section 6.1.2.5, the value of shaving the yearly peak power is discussed with regards to savings related to line investments in the distribution grid. Expanding the presented calculation example to the industrial site and further analysis of potential grid investment savings, are an interesting direction for further work for NTE Nett AS. NTE Nett AS is interested in the role of a grid owner in such local markets, thus the industrial site study has great potentials for a future pilot project.
- **Expanding the implementation of EVs.** The hard constraints on the initial and final storage level of the EVs at the parking lot have proved to be limiting and lead to increased power demand. Sperstad et al. [49] investigates the value of stored energy at the end of each planning horizon, and defines three operational strategies. The optimal storage level at the end of each planning horizon depends on the possible realization of uncertainties in future planning horizons. For the EVs, the end value function will depend on the grid price and the EV owners willingness to leave with more or less power than they arrived with. With such an implementation, the end of workday energy level E_{end} is included

in the objective function and determined by the optimization model. Further, human behavior is an important aspect of the V2G application and an advantageous area for further research regarding EVs.

- **Bidding strategy for the local energy market.** A strong driver of the results are the local pricing schemes for the P2P energy trading and shared storage. As such, other strategies and ideas for market rules, such as bidding strategies, should be explored.
- **Exploring the coordination with the existing wholesale and retail markets.** Local energy markets and P2P energy trading are still at an early stage, hence there are still many key enablers and barriers remaining which have to be addressed before local energy markets can become widespread.
- **Trading with a nearby wind power plant.** As the DGs are co-located and generated power simultaneously, the industrial site do not reach 100 % self-consumption. In Section 6.1.2.3, the inclusion of DG with different seasonal production patterns than solar PV was suggested. The possible trading with a nearby wind power plant was explored, but was out of the scope in this thesis due to the time limit that is a semester. This was inspired by ASKO, which aims at being net self-provided with renewable energy in the country, and has invested in 5 wind mills. The industrial site could collaborate with a nearby wind power producer to gain benefits to both parties. Then mechanisms are needed to determine the amount of power and when the industry site buys and the wind power plant sells, which could be based on the electricity prices and the feed-in utility tariff of the producer and multi-objective optimization.

  The producer electricity prices

  The producer FiUT was described in Section 2.2.3. The fixed term and energy term practiced by NTE Nett consist of the terms given in Equation 7.1 and 7.2, where the fixed NVE amount is 0.0134 NOK/kWh as of 2019 [33].

$$\textit{Fixed term [NOK/kWh]} = \text{Average yearly production the last 10 years} \cdot \text{fixed NVE amount} \tag{7.1}$$

$$\textit{Energy term [NOK/kWh]} = \text{Actual production} \cdot \text{Marginal loss rate}^{2} \cdot \text{Spot price} \tag{7.2}$$

Further, a producer usually receive the area spot price for the energy delivered to the grid.

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[2] In Norwegian: Marginaltapssatsen (MTP)

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Appendix A

Model Formulation Overview

The complete model formulation for all cases, with the objective function and all equations and constraints, are given in this appendix.

A.1 Base Case

$$\min_{\substack{\forall t\in T\\ \forall m\in M\\ \forall b\in B}} C_{totBC} = \left\{ \sum_b^B \left(\sum_t^T \left[\left(c_{g,eng} + c_{g,SP}^{(t)} \right) \cdot P_{g,buy}^{(t,b)} \Delta t \right] + \sum_m^M \left[c_{g,fix}^{(m)} + c_{g,peak}^{(m)} \cdot P_{g,peak}^{(m,b)} \right] \right. \right.$$

$$\left. \left. - \sum_t^T \left[c_{feed-in}^{(t)} \cdot P_{g,sell}^{(t,b)} \Delta t \psi_{P2P} \right] + \sum_t^T \left[c_{LS}^{(b)} \cdot P_{ls,sh}^{(t,b)} \Delta t \right] \right) \right\}$$

s.t.

$$\begin{aligned}
P_{dem}^{(t,b)} + P_{g,sell}^{(t,b)} + P_{ev,ch}^{(t,b)} + P_{ls,dem}^{(t,b)} + P_{curtail}^{(t,b)} - P_{DER}^{(t,b)} - P_{g,buy}^{(t,b)} - P_{ev,dch}^{(t,b)} - P_{ls,sh}^{(t,b)} &= 0 \\
E_{ls}^{(t,b)} - E_{ls}^{(t-1,b)} - P_{ls,sh}^{(t,b)} \cdot \Delta t + P_{ls,dem}^{(t,b)} \cdot \Delta t &= 0 \\
E_{ls}^{(d_{end}(t),b)} &= 0 \\
E_{ev}^{(t,b)} - E_{ev}^{(t-1,b)} - \eta_{ev,ch} \cdot \Delta t \cdot P_{ev,ch}^{(t,b)} + \frac{1}{\eta_{ev,dch}} \cdot \Delta t \cdot P_{ev,dvh}^{(t,b)} &= 0 \\
w^{(t)} &= 0 / 1 \\
E_{ev}^{(d_{start}(t),b)} &= E_{ev}^{nom} \cdot EV_{num} \cdot E_{start} \\
P_{g,sell}^{(t,b)} &\leq P_{feed-in}^{max} \\
P_{ls,sh}^{(t,b)}, P_{ls,dem}^{(t,b)} &\leq 0.1 \cdot P_{g,peak}^{(m,b)} \\
E_{ls}^{(t,b)} &\leq 4 \cdot 0.1 \cdot P_{g,peak}^{(m,b)} \\
E_{ev}^{(t,b)} &\leq E_{ev}^{nom} \cdot EV_{num} \cdot \overline{SOC} \\
P_{ev,ch}^{(t,b)}, P_{ev,dch}^{(t,b)} &\leq P_{ev,charger}^{nom} \cdot EV_{num} \cdot w^{(t)} \\
E_{ev}^{(d_{end}(t),b)} &\geq E_{ev}^{nom} \cdot EV_{num} \cdot E_{end} \\
E_{ev}^{(t,b)} &\geq E_{ev}^{nom} \cdot EV_{num} \cdot \underline{SOC} \\
P_{g,peak}^{(m,b)} &\geq P_{g,buy}^{(t,b)} \\
P_{g,buy}^{(t,b)}, P_{g,sell}^{(t,b)}, P_{ls,sh}^{(t,b)}, P_{ls,dem}^{(t,b)}, E_{ls}^{(t,b)}, P_{ev,ch}^{(t,b)}, P_{ev,dch}^{(t,b)} &\geq 0
\end{aligned}$$

A.2 Case 1: P2P Energy Trading

$$\min_{\substack{\forall t\in T\\ \forall m\in M\\ \forall b\in B}} C_{totC1} = \left\{ C_{totBC} + \sum_{b}^{B} \left(\sum_{t}^{T} \left[c_{p2p}^{(t,b)} \cdot P_{imp}^{(t,b)} \Delta t \frac{1}{\psi_{P2P}} \right] - \sum_{t}^{T} \left[\sum_{p\neq b}^{B} c_{p2p}^{(t,p)} \cdot P_{exp,p}^{(t,b\rightarrow p)} \Delta t \right] \right) \right\}$$

s.t.

$$\begin{aligned}
P_{dem}^{(t,b)} + P_{g,sell}^{(t,b)} + P_{exp}^{(t,b)} + P_{ev,ch}^{(t,b)} + P_{ls,dem}^{(t,b)} + P_{curtail}^{(t,b)}& \\
-P_{DER}^{(t,b)} - P_{g,buy}^{(t,b)} - P_{imp}^{(t,b)} - P_{ev,dch}^{(t,b)} - P_{ls,sh}^{(t,b)} &= 0 \\
E_{ls}^{(t,b)} - E_{ls}^{(t-1,b)} - P_{ls,sh}^{(t,b)} \cdot \Delta t + P_{ls,dem}^{(t,b)} \cdot \Delta t &= 0 \\
E_{ls}^{(d_{end}(t),b)} &= 0 \\
E_{ev}^{(t,b)} - E_{ev}^{(t-1,b)} - \eta_{ev,ch} \cdot \Delta t \cdot P_{ev,ch}^{(t,b)} + \frac{1}{\eta_{ev,dch}} \cdot \Delta t \cdot P_{ev,dvh}^{(t,b)} &= 0 \\
w^{(t)} &= 0 / 1 \\
E_{ev}^{(d_{start}(t),b)} &= E_{ev}^{nom} \cdot EV_{num} \cdot E_{start} \\
P_{exp}^{(t,b)} &= \sum_{p\neq b} P_{exp,p}^{(t,b\rightarrow p)} \\
P_{imp}^{(t,b)} &= \sum_{p\neq b} P_{imp,p}^{(t,b\leftarrow p)} \\
P_{imp,p}^{(t,b\leftarrow p)} &= \psi_{P2P} \cdot P_{exp,p}^{(t,p\rightarrow b)} \\
\sum_{b} \psi_{P2P} \cdot P_{exp}^{(t,b)} &= \sum_{b} P_{imp}^{(t,b)} \\
P_{g,sell}^{(t,b)} &\leq P_{feed-in}^{max} \\
P_{ls,sh}^{(t,b)}, P_{ls,dem}^{(t,b)} &\leq 0.1 \cdot P_{g,peak}^{(m,b)} \\
E_{ls}^{(t,b)} &\leq 4 \cdot 0.1 \cdot P_{g,peak}^{(m,b)} \\
E_{ev}^{(t,b)} &\leq E_{ev}^{nom} \cdot EV_{num} \cdot \overline{SOC} \\
P_{ev,ch}^{(t,b)}, P_{ev,dch}^{(t,b)} &\leq P_{ev,charger}^{nom} \cdot EV_{num} \cdot w^{(t)} \\
E_{ev}^{(d_{end}(t),b)} &\geq E_{ev}^{nom} \cdot EV_{num} \cdot E_{end} \\
E_{ev}^{(t,b)} &\geq E_{ev}^{nom} \cdot EV_{num} \cdot \underline{SOC} \\
P_{g,peak}^{(m,b)} &\geq P_{g,buy}^{(t,b)} \\
P_{g,buy}^{(t,b)}, P_{g,sell}^{(t,b)}, P_{ls,sh}^{(t,b)}, P_{ls,dem}^{(t,b)}, E_{ls}^{(t,b)}, P_{ev,ch}^{(t,b)}, P_{ev,dch}^{(t,b)} &\geq 0 \\
P_{exp}^{(t,b)}, P_{imp}^{(t,b)}, P_{exp,p}^{(t,b\rightarrow p)}, P_{imp,p}^{(t,b\leftarrow p)} &\geq 0
\end{aligned}$$

A.3 Case 2: P2P Energy trading and Shared Energy Storage

$$\min_{\substack{\forall t\in T\\ \forall m\in M\\ \forall b\in B}} C_{totC2} = \left\{ C_{totC1} + \sum_{b}^{B}\left(\sum_{t}^{T}\left[c_{dch}^{(t,b)} \cdot P_{dch}^{(t,b)} \Delta t \right] - \sum_{t}^{T}\left[c_{ch}^{(t)} \cdot P_{ch}^{(t,b)} \Delta t \right] \right) \right\}$$

s.t.

$$\begin{aligned}
P_{dem}^{(t,b)} + P_{g,sell}^{(t,b)} + P_{exp}^{(t,b)} + P_{ch}^{(t,b)} + P_{ev,ch}^{(t,b)} + P_{ls,dem}^{(t,b)} + P_{curtail}^{(t,b)} & \\
- P_{DER}^{(t,b)} - P_{g,buy}^{(t,b)} - P_{imp}^{(t,b)} - P_{dch}^{(t,b)} - P_{ev,dch}^{(t,b)} - P_{ls,sh}^{(t,b)} &= 0 \\
E_{ls}^{(t,b)} - E_{ls}^{(t-1,b)} - P_{ls,sh}^{(t,b)} \cdot \Delta t + P_{ls,dem}^{(t,b)} \cdot \Delta t &= 0 \\
E_{ls}^{(d_{end}(t),b)} &= 0 \\
E_{ev}^{(t,b)} - E_{ev}^{(t-1,b)} - \eta_{ev,ch} \cdot \Delta t \cdot P_{ev,ch}^{(t,b)} + \frac{1}{\eta_{ev,dch}} \cdot \Delta t \cdot P_{ev,dvh}^{(t,b)} &= 0 \\
E^{(t)} - E^{(t-1)} - \eta_{ch} \cdot \eta_{inv} \cdot \Delta t \cdot P_{allch}^{(t)} + \frac{1}{\eta_{dch} \cdot \eta_{inv}} \cdot \Delta t \cdot P_{alldch}^{(t)} &= 0 \\
w^{(t)} &= 0 / 1 \\
E_{ev}^{(d_{start}(t),b)} &= E_{ev}^{nom} \cdot EV_{num} \cdot E_{start} \\
P_{exp}^{(t,b)} &= \sum_{p \neq b} P_{exp,p}^{(t,b\rightarrow p)} \\
P_{imp}^{(t,b)} &= \sum_{p \neq b} P_{imp,p}^{(t,b\leftarrow p)} \\
P_{imp,p}^{(t,b\leftarrow p)} &= \psi_{P2P} \cdot P_{exp,p}^{(t,p\rightarrow b)} \\
\sum_{b} \psi_{P2P} \cdot P_{exp}^{(t,b)} &= \sum_{b} P_{imp}^{(t,b)} \\
P_{allch}^{(t)} &= \psi_{P2P} \cdot \sum_{b} P_{ch}^{(t,b)} \\
P_{alldch}^{(t)} &= \frac{1}{\psi_{P2P}} \cdot \sum_{b} P_{dch}^{(t,b)} \\
P_{g,sell}^{(t,b)} &\leq P_{feed-in}^{max} \\
P_{ls,sh}^{(t,b)}, P_{ls,dem}^{(t,b)} &\leq 0.1 \cdot P_{g,peak}^{(m,b)} \\
E_{ls}^{(t,b)} &\leq 4 \cdot 0.1 \cdot P_{g,peak}^{(m,b)} \\
E_{ev}^{(t,b)} &\leq E_{ev}^{nom} \cdot EV_{num} \cdot \overline{SOC} \\
P_{ev,ch}^{(t,b)}, P_{ev,dch}^{(t,b)} &\leq P_{ev,charger}^{nom} \cdot EV_{num} \cdot w^{(t)}
\end{aligned}$$

$$
\begin{aligned}
E^{(t)} &\leq E_{nom} \cdot \overline{SOC} \\
P_{allch}^{(t)} &\leq \eta_{inv} \cdot P_{inv}^{nom} \\
P_{alldch}^{(t)} &\leq P_{inv}^{nom} \\
E_{ev}^{(d_{end}(t),b)} &\geq E_{ev}^{nom} \cdot EV_{num} \cdot E_{end} \\
E_{ev}^{(t,b)} &\geq E_{ev}^{nom} \cdot EV_{num} \cdot \underline{SOC} \\
P_{g,peak}^{(m,b)} &\geq P_{g,buy}^{(t,b)} \\
E^{(t)} &\geq E_{nom} \cdot \underline{SOC} \\
P_{g,buy}^{(t,b)}, P_{g,sell}^{(t,b)}, P_{ls,sh}^{(t,b)}, P_{ls,dem}^{(t,b)}, E_{ls}^{(t,b)}, P_{ev,ch}^{(t,b)}, P_{ev,dch}^{(t,b)} &\geq 0 \\
P_{exp}^{(t,b)}, P_{imp}^{(t,b)}, P_{exp,p}^{(t,b\rightarrow p)}, P_{imp,p}^{(t,b\leftarrow p)}, P_{allch}^{(t)}, P_{alldch}^{(t)} &\geq 0
\end{aligned}
$$

Appendix B

Calculations

B.1 Calculating the Revenues of Load Shifting

The revenues from peak shaving by performing load shifting are given as:

$$R_{LS} = c_{g,peak} \cdot (P^{(t,b)}_{g,peak,org} - P^{(t,b)}_{g,peak,new}) + P^{(t,b)}_{ls,sh} \cdot (c^{(t)}_{g,SP,org} - c^{(t)}_{g,SP,new}) \tag{B.1}$$

where $c_{g,peak}$ is the peak power charge, $P^{(t)}_{g,peak,org}$ the original peak demand, $P^{(t)}_{g,peak,new}$ the new peak demand after load is shifted, $P^{(t)}_{ls,sh}$ the amount of energy shifted, $c^{(t)}_{g,SP,org}$ the wholesale price at the time of load shift and finally the $c^{(t)}_{g,SP,new}$ is the wholesale price at the of rescheduling. The utility tariff energy term for energy usage is not included in the calculation, as this is fixed per kWh and will not vary in time.

The additional cost of performing load shifting is given as:

$$C_{LS} = c^{(b)}_{LS} \cdot P^{(t,b)}_{ls,sh} \tag{B.2}$$

where $c^{(b)}_{LS}$ is the load shift penalty cost of the related building.

The related parameter values of the load shifting example for building 1 in week 6 in February are listed in Table B.1.

Table B.1: Related parameter values for calculating load shift revenues for building 1.

	Value
$c_{g,peak}$	70
$c^{(t)}_{g,SP,org}$	0.47
$c^{(t)}_{g,SP,new}$	0.33
$c^{(b)}_{LS}$	0.40
$P^{(t,b)}_{g,peak,org}$	274.76
$P^{(t,b)}_{g,peak,new}$	263.56
$P^{(t,b)}_{ls,sh}$	11.20
t (load shifted)	971
t (rescheduled)	976

B.2 Calculating the Revenues of Peak Shaving by P2P Trading

The total system revenues from performing peak shaving by trading with a peer are given in Equation B.3. The benefits of the exporting building are due to the price arbitrage by P2P trade. The benefits of the importing building are the peak shave in the given time step, with the difference in energy costs withdrawn.

$$\begin{aligned} R_{PS} &= \text{Benefits of exporting peer} + \text{Benefits of importing peer} \\ &= \left\{ P^{(t,b\rightarrow p)}_{exp,p} \cdot \left(c^{(t,p)}_{p2p} - (c^{(t)}_{g,SP} + c_{g,eng}) \right) \right\} \\ &+ \left\{ P^{(t,b\leftarrow p)}_{imp,p} \cdot c_{g,peak} - P^{(t,b\leftarrow p)}_{imp,p} \cdot \left(c^{(t,b)}_{p2p} - (c^{(t)}_{g,SP} + c_{g,eng}) \right) \right\} \end{aligned} \tag{B.3}$$

where $P^{(t,b\rightarrow p)}_{exp,p}$ is the exported power from building to peer, $c^{(t,p)}_{p2p}$ the P2P willingness to pay of receiving peer, $c^{(t)}_{g,SP}$ the spot price, $c_{g,eng}$ the utility tariff cost of energy, $P^{(t,b\leftarrow p)}_{imp,p}$ the imported power of receiving peer, and finally $c_{g,peak}$ is the peak power charge. As the exporting building consumes extra grid power up to the optimal peak power of the month, the peak power demand of the building is not increased. Hence, the peak power charge is not included in the grid price for the exporting building. The utility tariff fixed term is not included in the calculation, as this is fixed and will not be affected by this operation for either building.

The related parameter values of the peak shaving by P2P trade example for building 4 and 5 in week 6 in February are listed in Table B.1. The difference in the exported and imported power is due to the line losses.

Table B.2: Related parameter values for calculating peak shaving revenues by P2P trade from building 5 to 4.

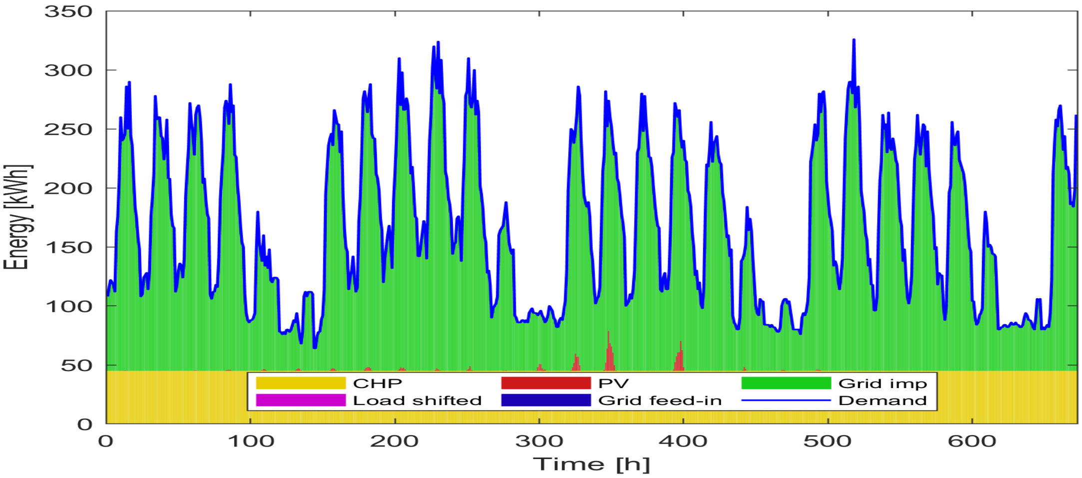
	Value
$c_{g,peak}$	70
$c_{p2p}^{(t,B4)}$	0.45
$c_{g,SP}^{(t)}$	0.29
$c_{g,eng}$	0.04
$P_{exp,p}^{(t,B5\rightarrow B4)}$	30.33
$P_{imp,p}^{(t,B4\leftarrow B5)}$	28.02
b (exporting)	5
b (receiving)	4
t	999

Appendix C

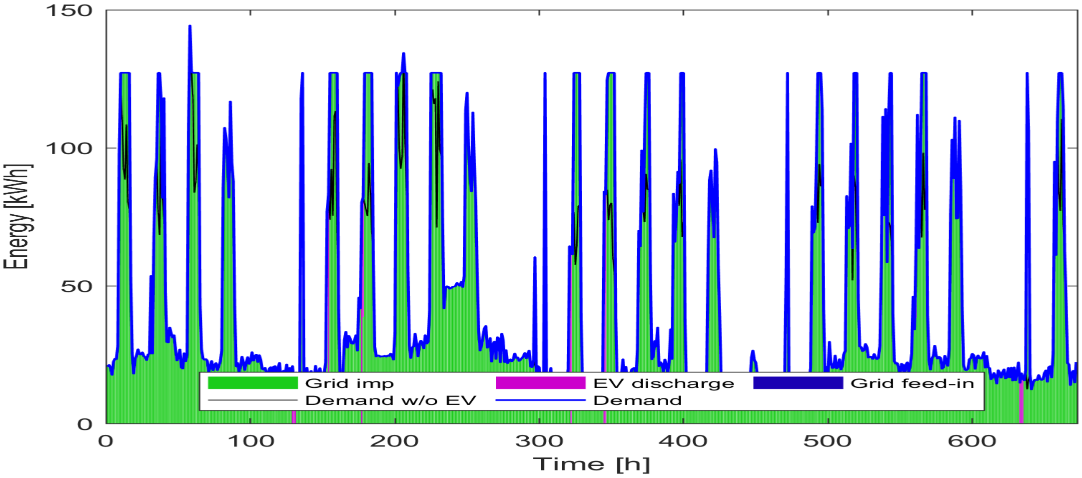
Complementary Result Plots

C.1 Base Case

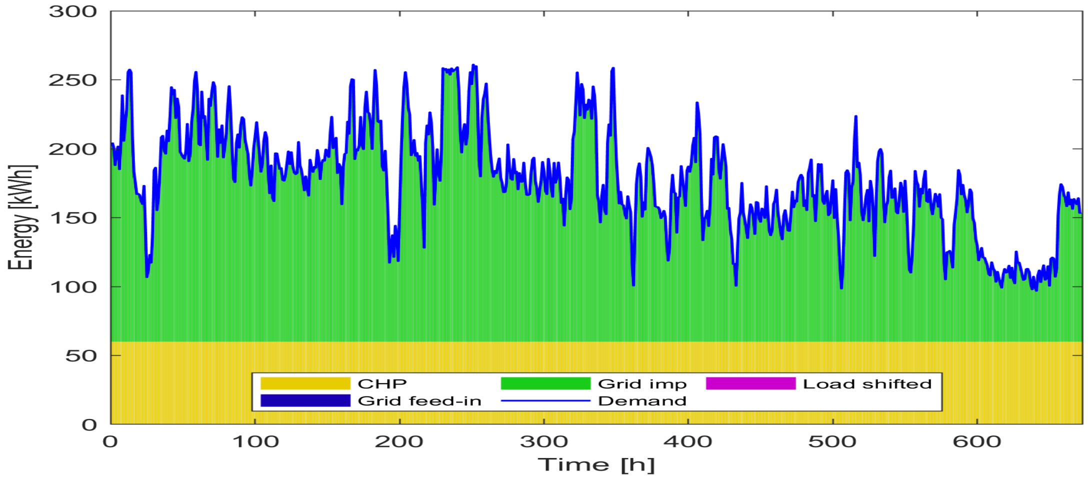
C.1.1 Supply-Demand Decisions in February



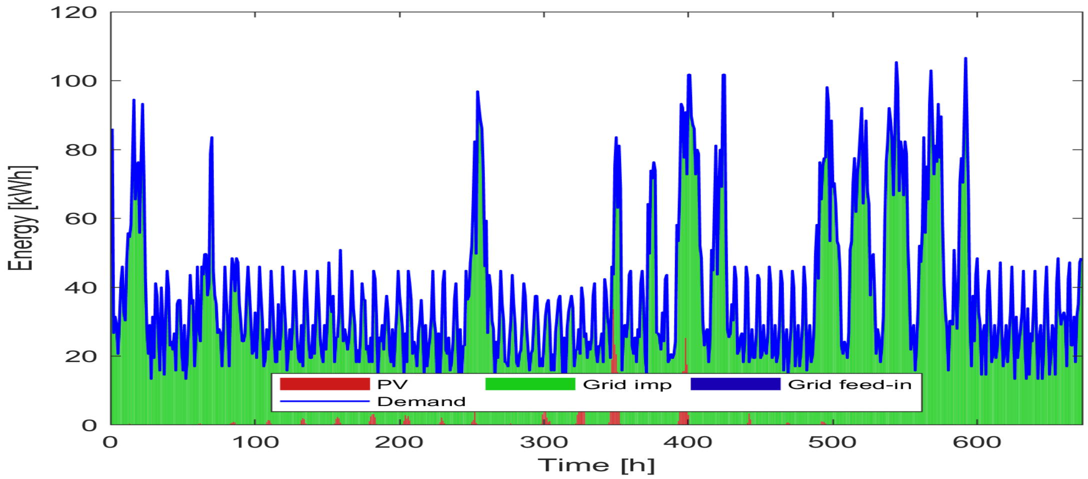
(a) Supply-demand building 1



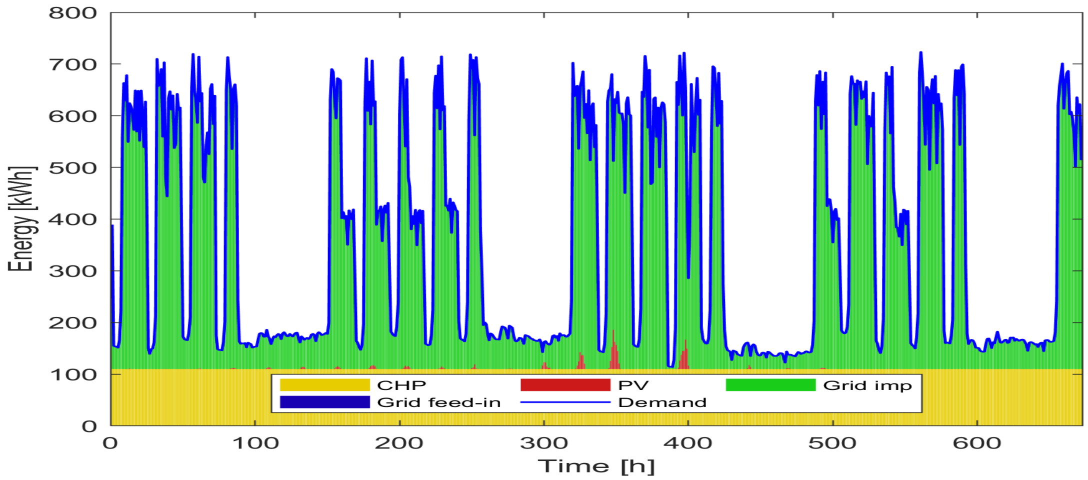
(b) Supply-demand building 2



(c) Supply-demand building 3



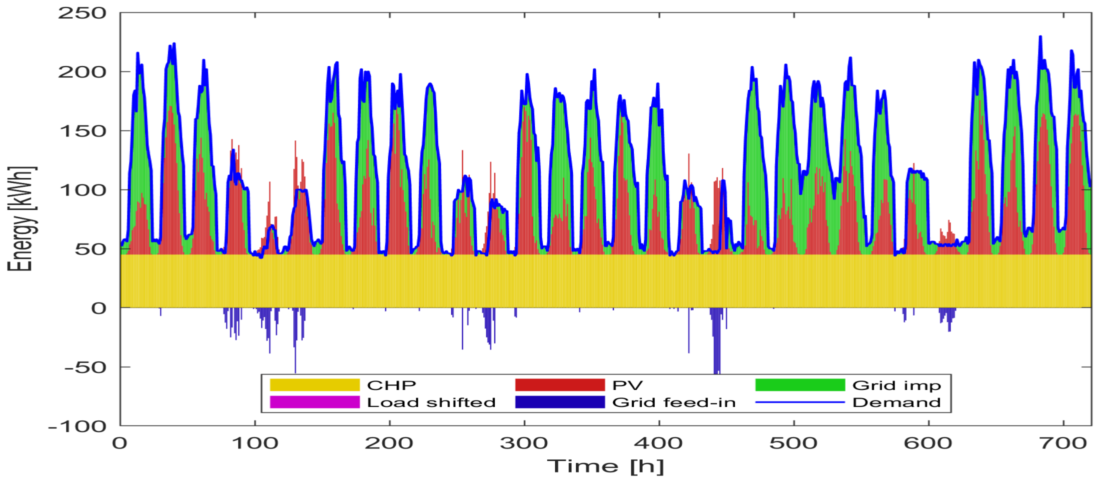
(d) Supply-demand building 4



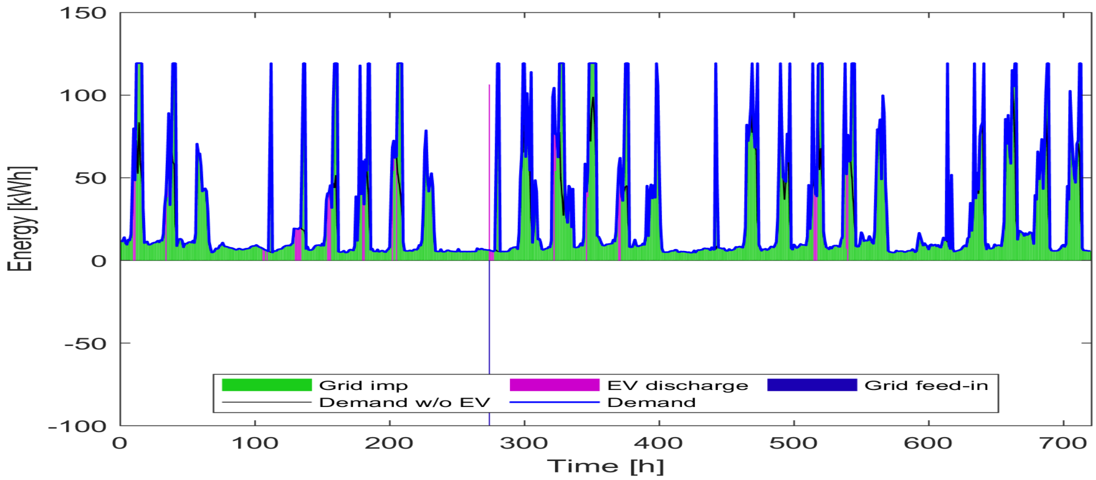
(e) Supply-demand building 5

Figure C.1: Demand cover for arbitrary winter month (February) for the Base Case market

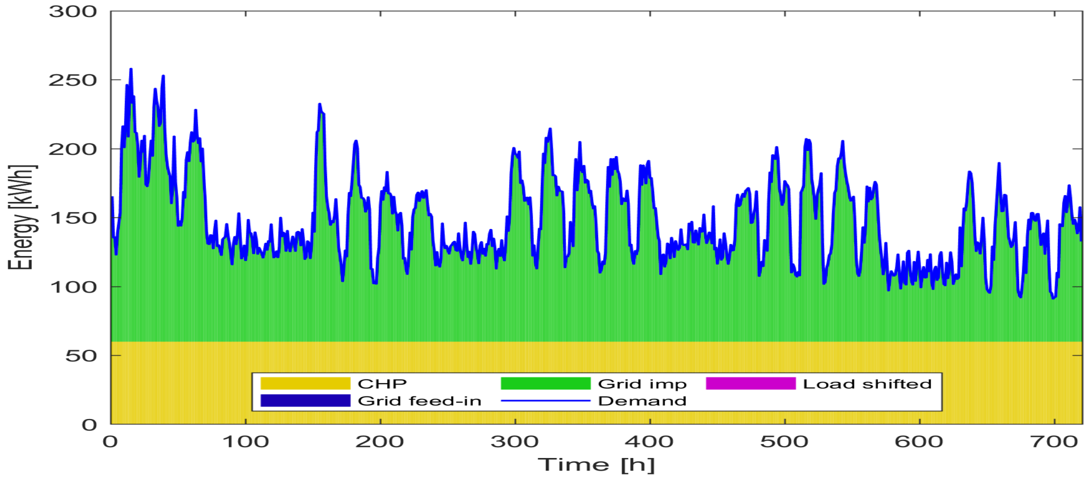
C.1.2 Supply-Demand Decisions in June



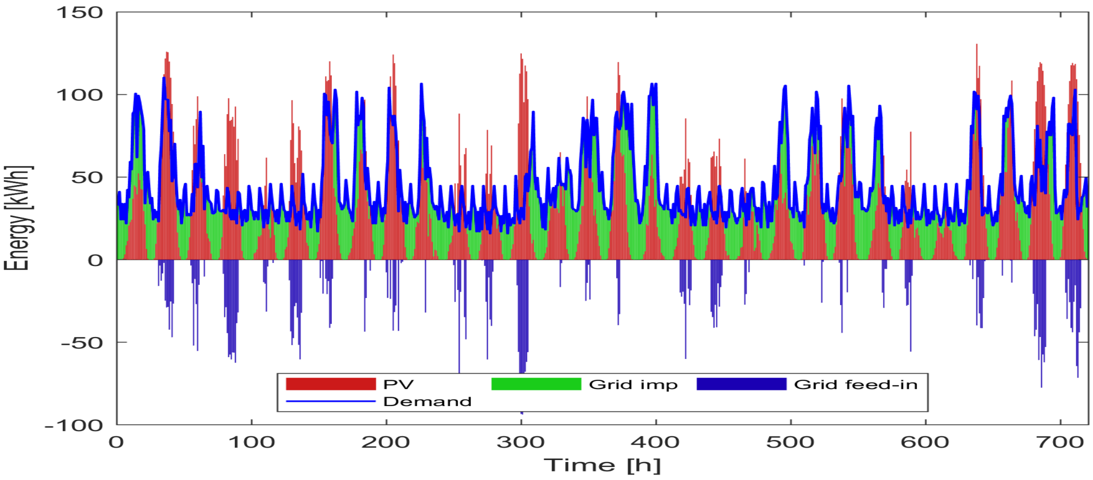
(a) Supply-demand building 1



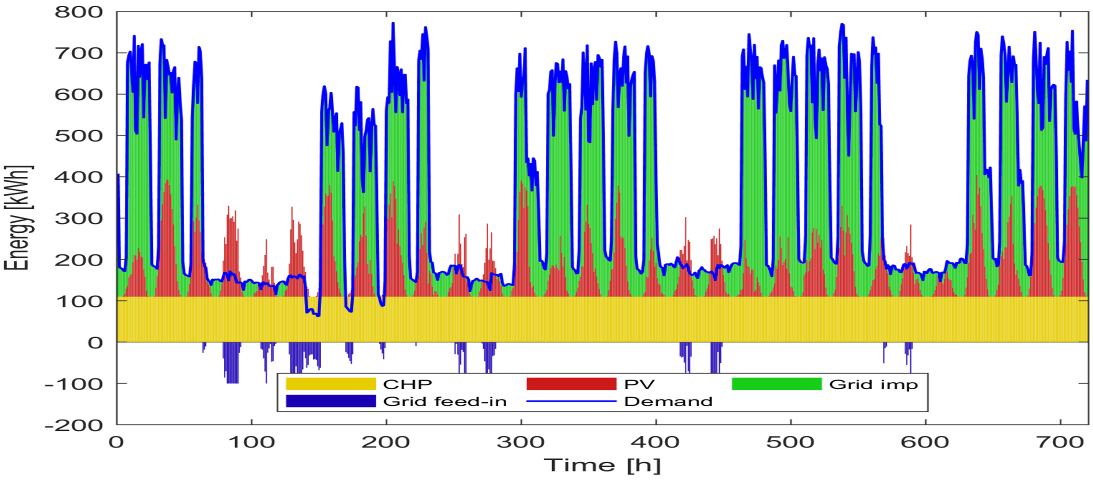
(b) Supply-demand building 2



(c) Supply-demand building 3



(d) Supply-demand building 4



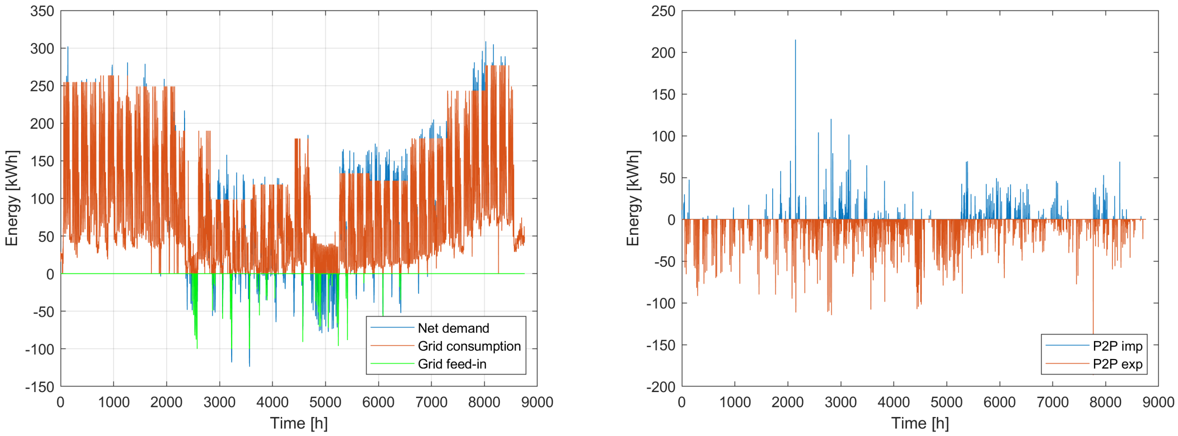
(e) Supply-demand building 5

Figure C.2: Demand cover for arbitrary summer month (June) for the Base Case market

C.2 Case 1: P2P Energy Trading

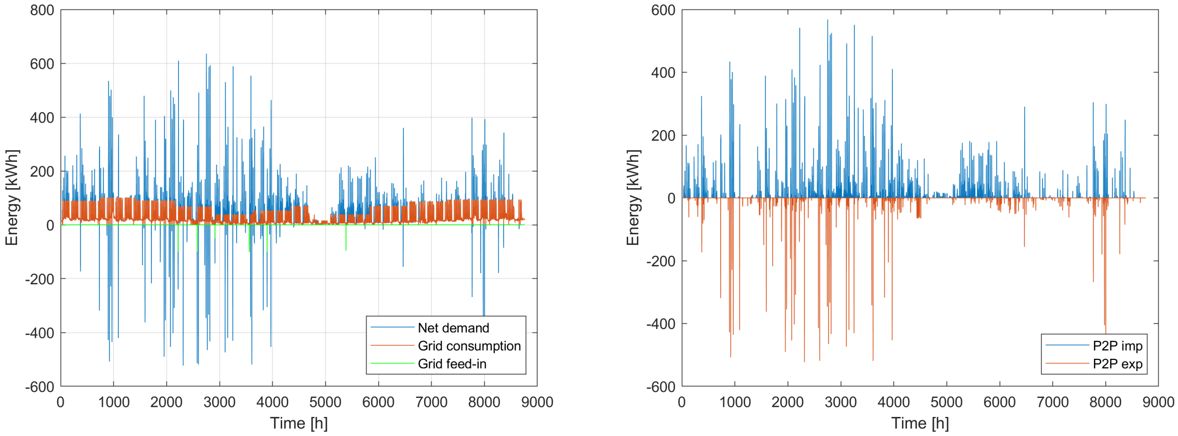
C.2.1 Yearly System Operation

In this section the yearly system operation for each individual building in the C1 market are presented. The net demand is the building demand including all production and operation of building DER.



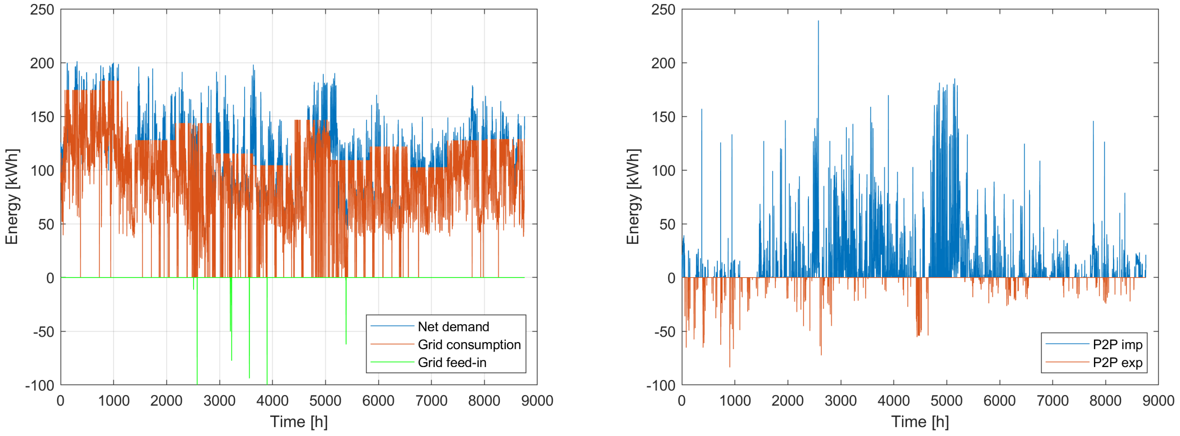
(a) B1: System operation

(b) B1: P2P trade



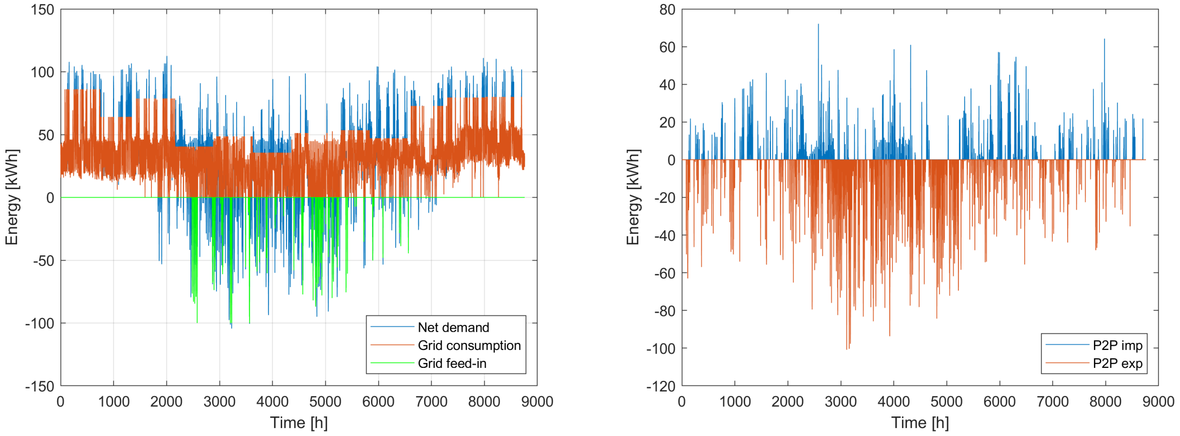
(c) B2: System operation

(d) B2: P2P trade



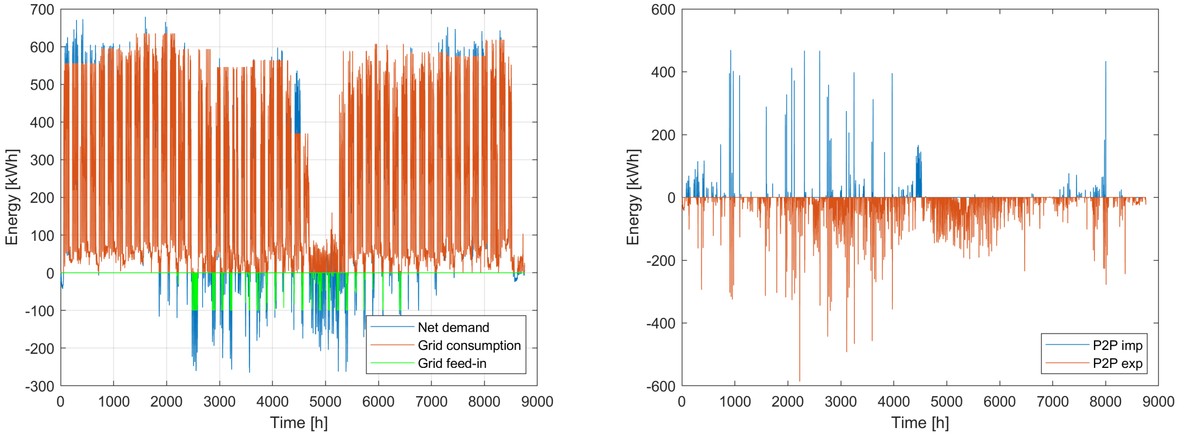
(e) B3: System operation

(f) B2: P2P trade



(g) B4: System operation

(h) B4: P2P trade

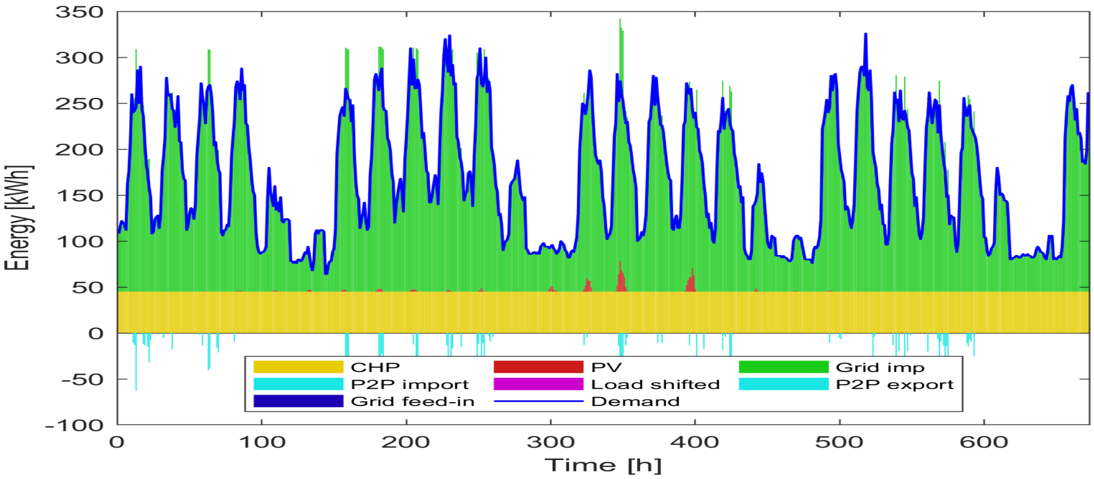


(i) B5: System operation

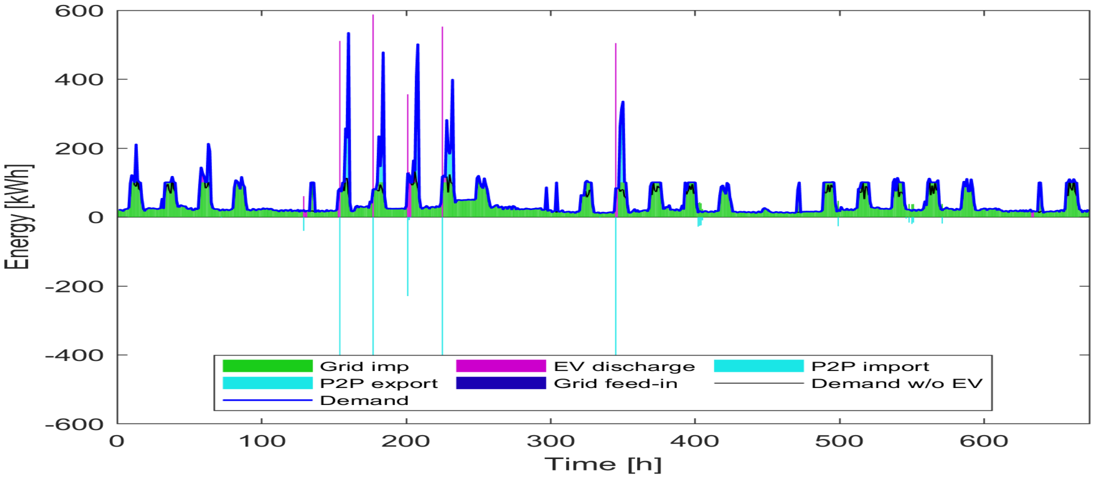
(j) B5: P2P trade

Figure C.3: System operation for each building in the Case 1 market for the whole year.

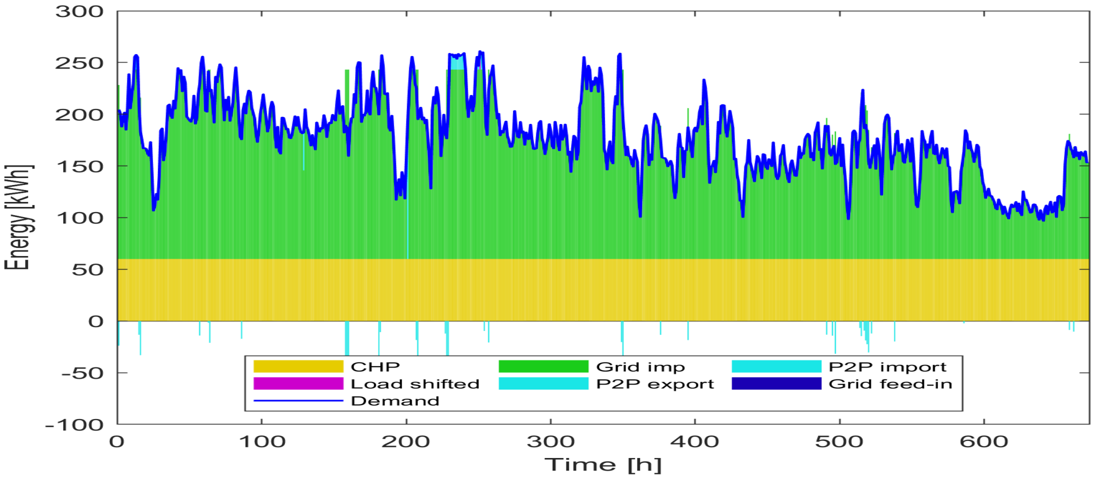
C.2.2 Supply-Demand Decisions in February



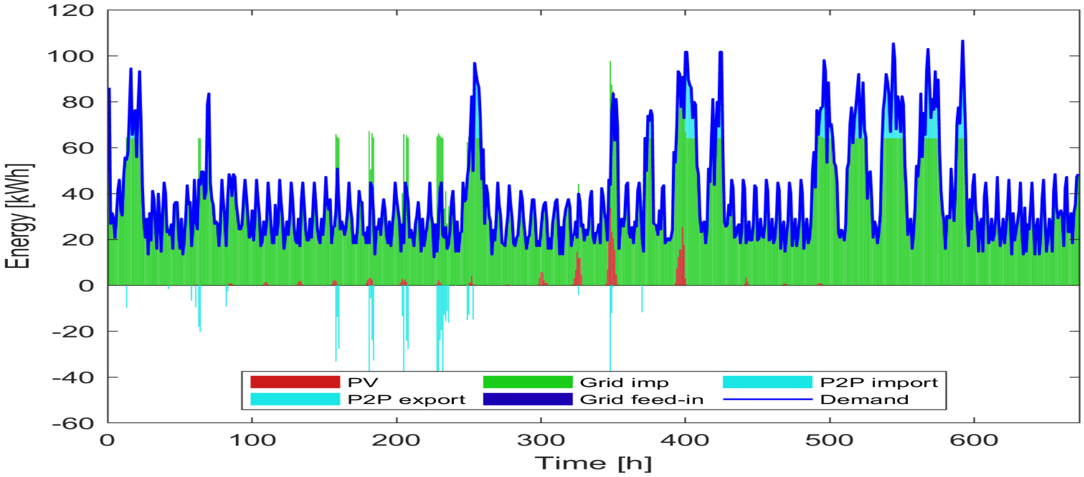
(a) Supply-demand building 1



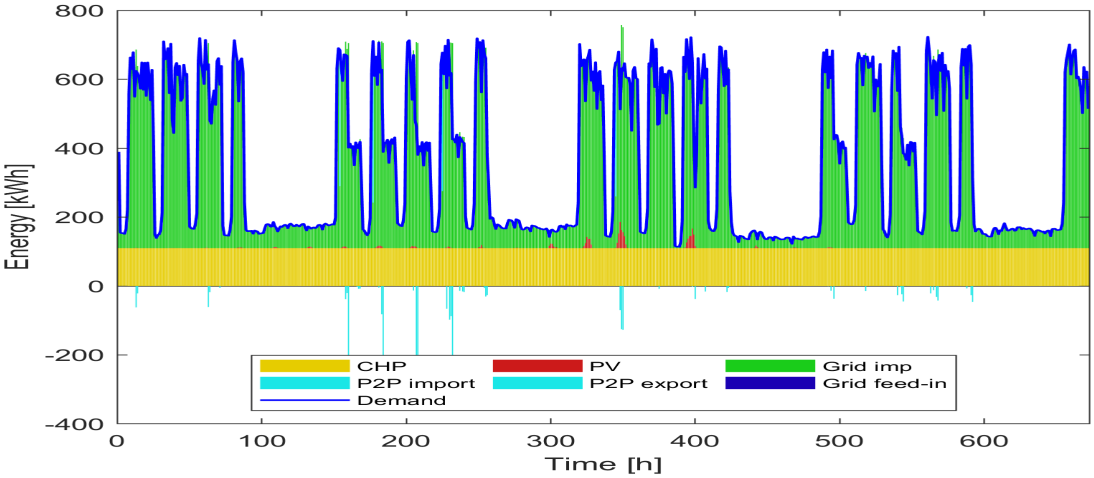
(b) Supply-demand building 2



(c) Supply-demand building 3



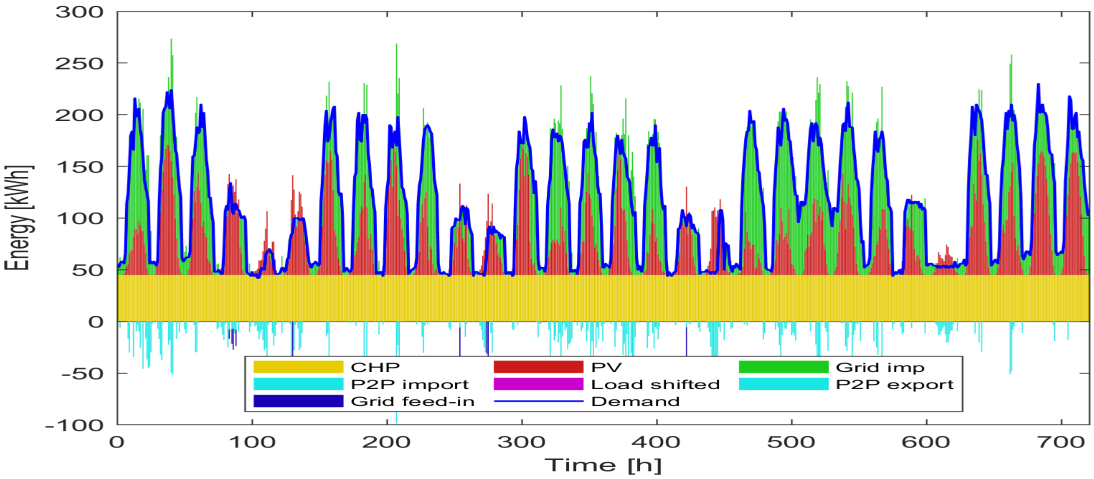
(d) Supply-demand building 4



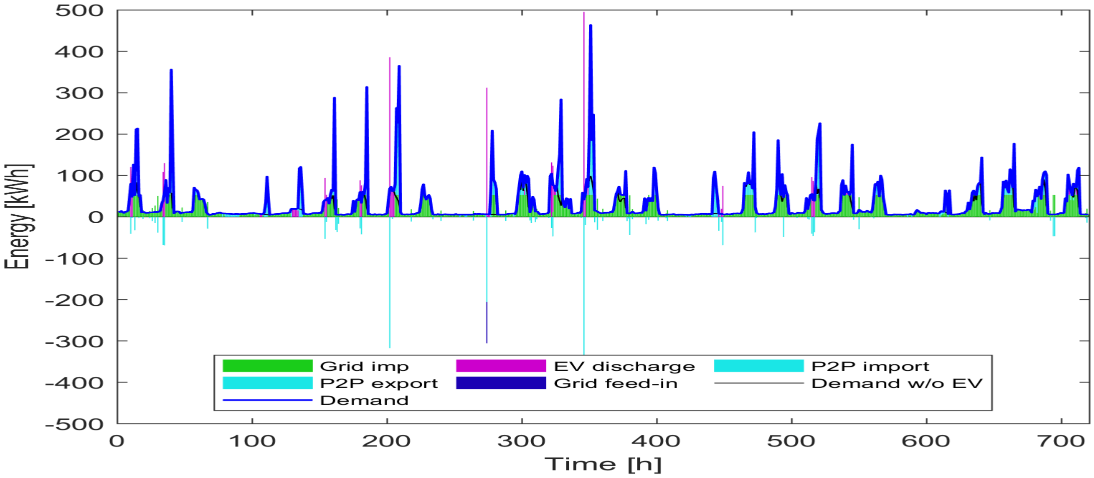
(e) Supply-demand building 5

Figure C.4: Demand cover for arbitrary winter month (February) for the Case 1 market

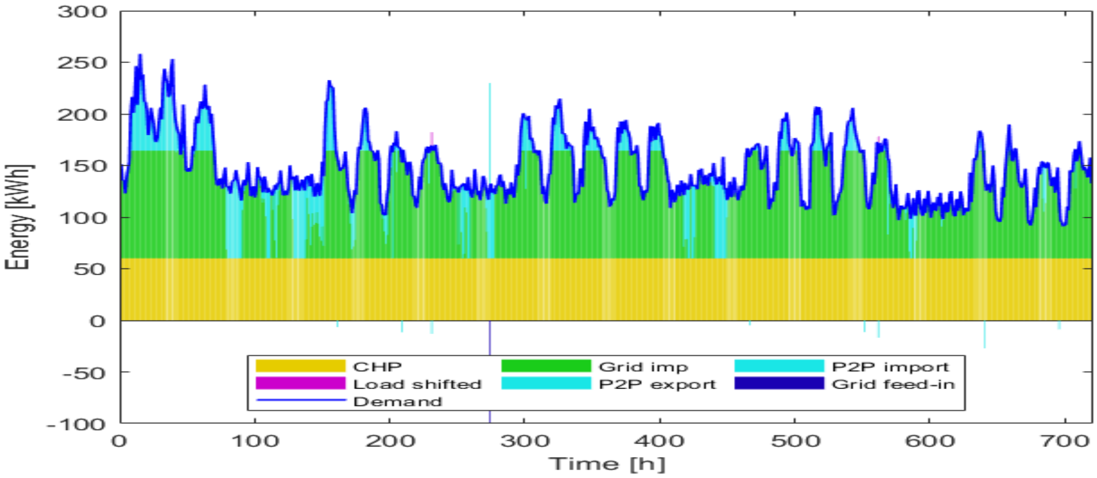
C.2.3 Supply-Demand Decisions in June



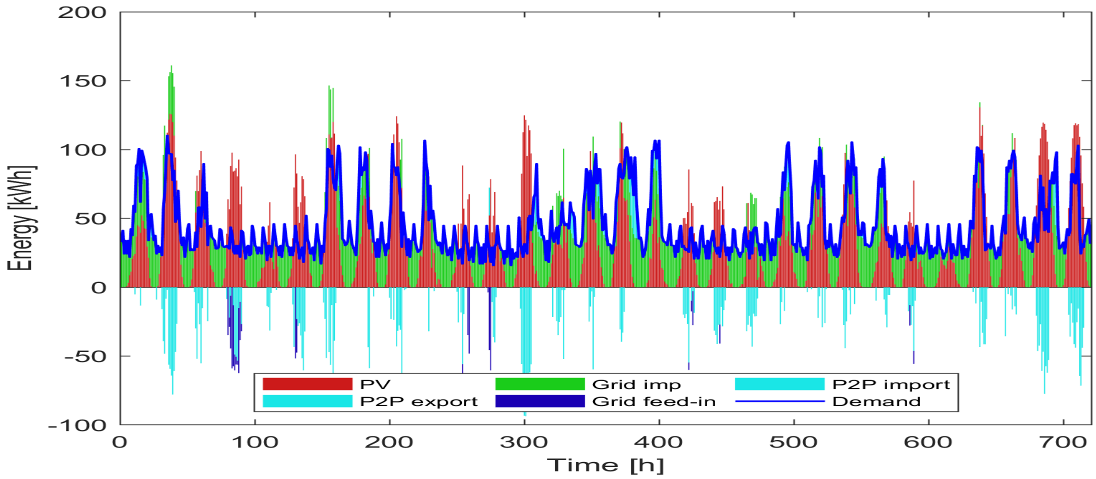
(a) Supply-demand building 1



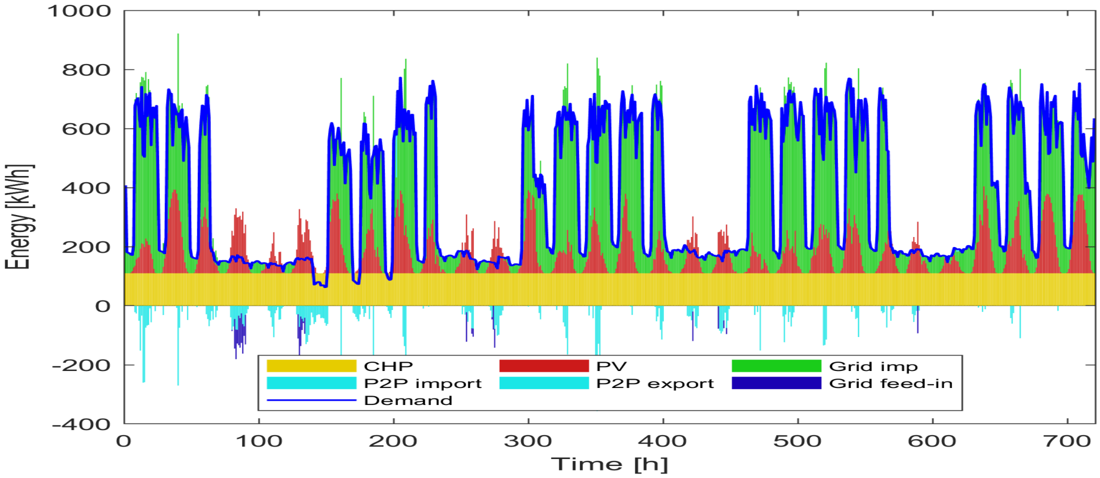
(b) Supply-demand building 2



(**c**) Supply-demand building 3



(**d**) Supply-demand building 4



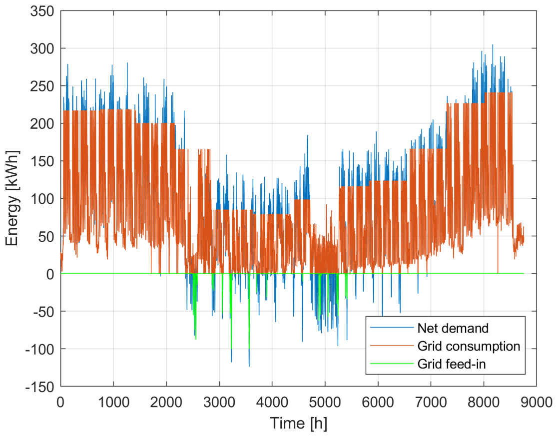
(**e**) Supply-demand building 5

Figure C.5: Demand cover for arbitrary summer month (June) for the Case 1 market

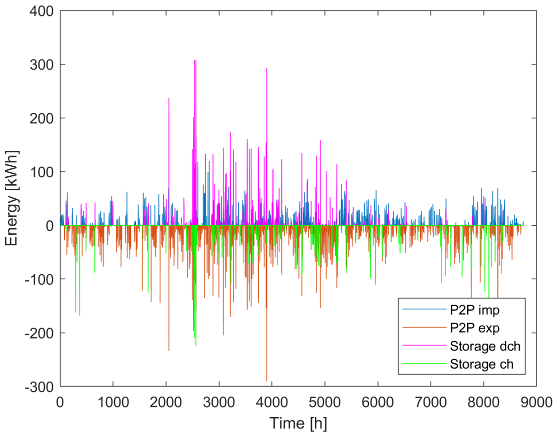
C.3 Case 2: P2P Energy Trading and Shared Energy Storage

C.3.1 Yearly System Operation

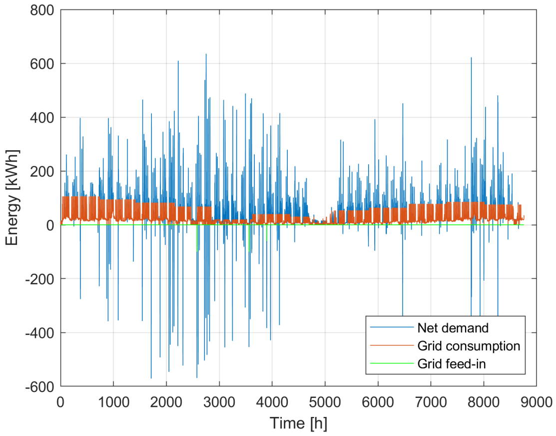
In this section the yearly system operation for each individual building in the C2 market are presented. The net demand is the building demand including all production and operation of building DER.



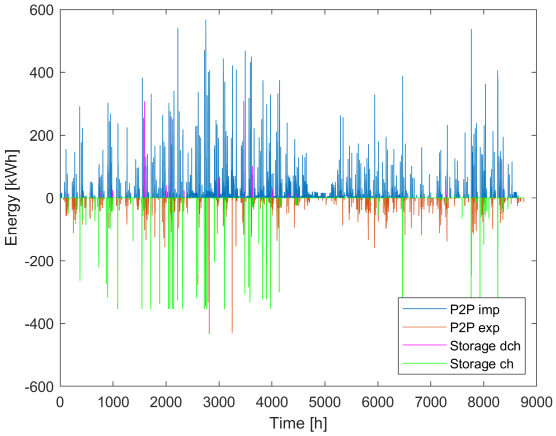
(a) B1: System operation



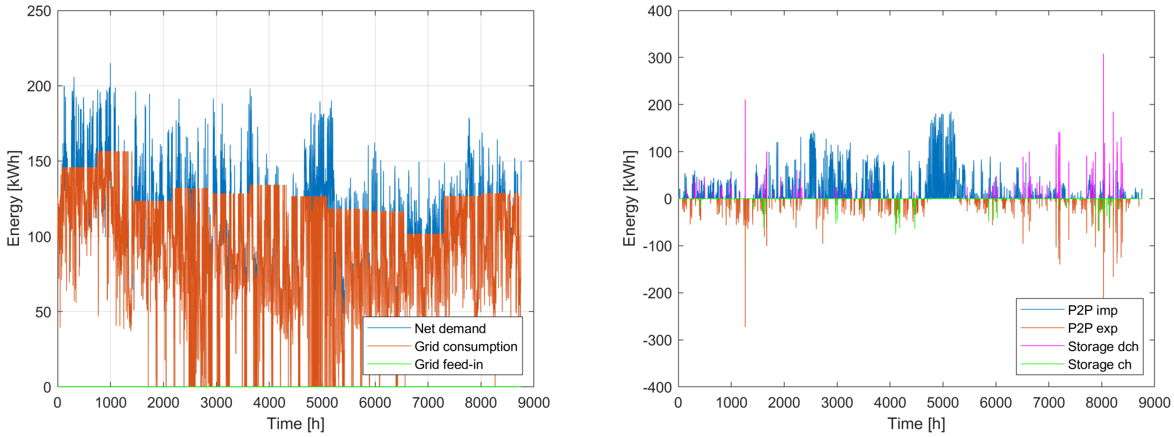
(b) B1: P2P and storage trade



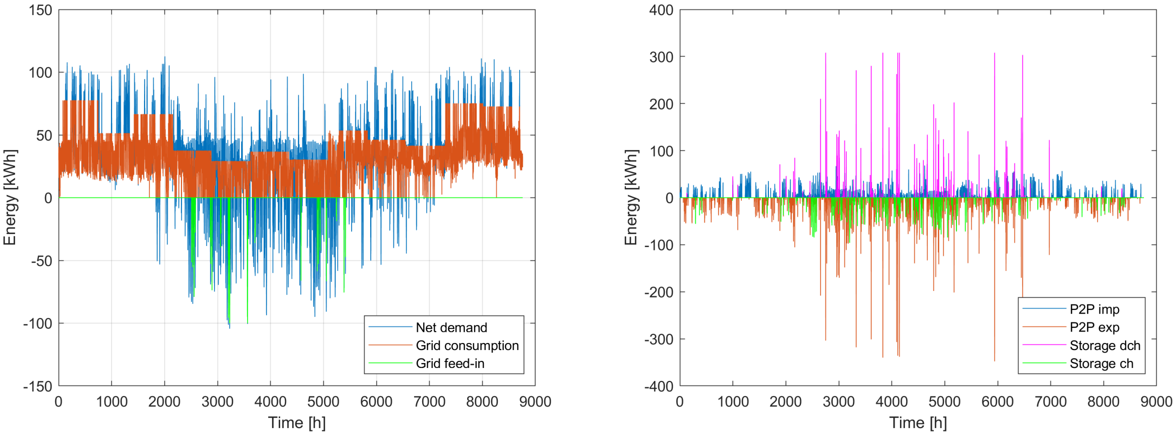
(c) B2: System operation



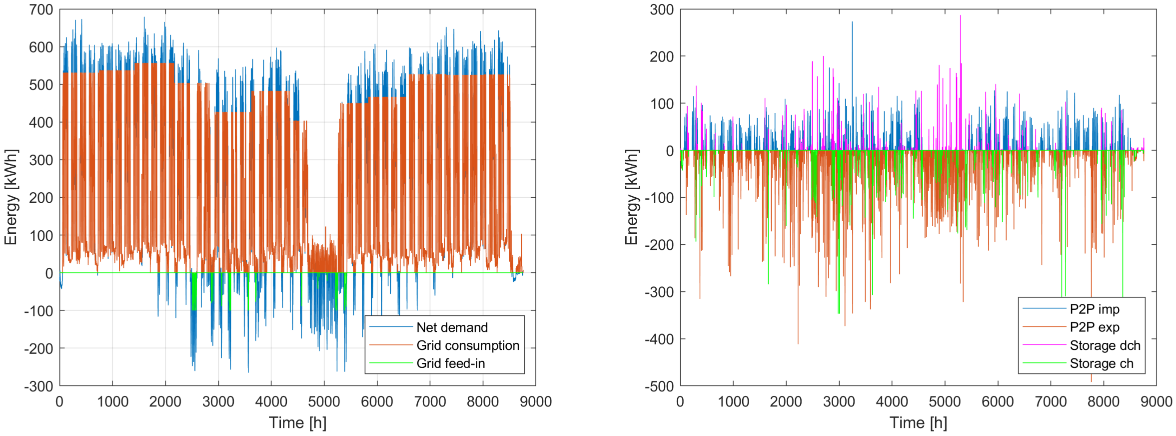
(d) B2: P2P and storage trade



(e) B3: System operation **(f)** B2: P2P and storage trade



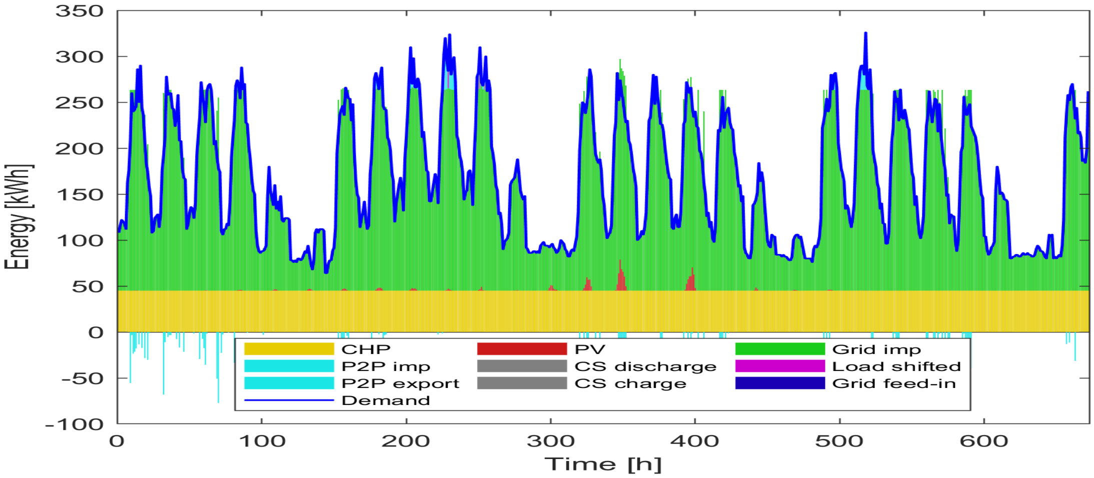
(g) B4: System operation **(h)** B4: P2P and storage trade



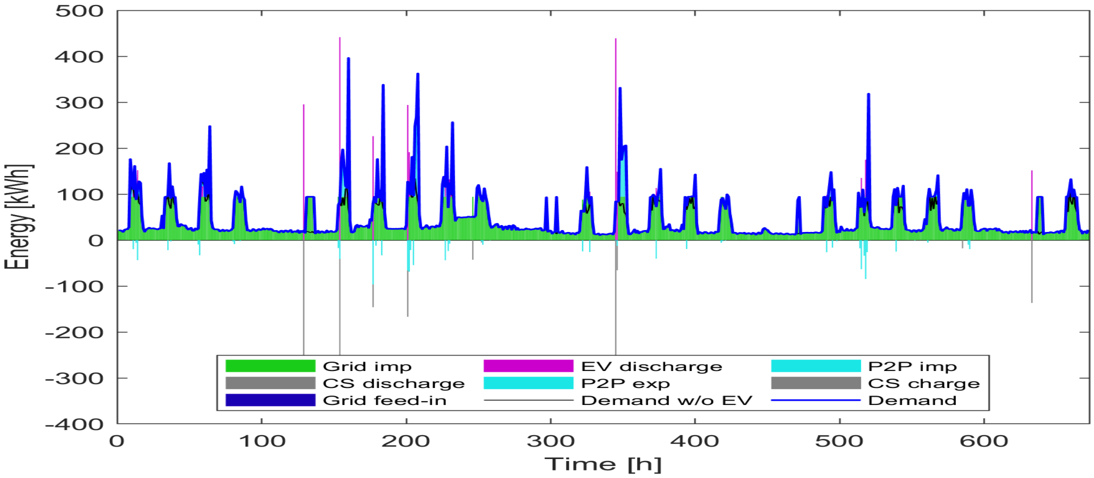
(i) B5: System operation **(j)** B5: P2P and storage trade

Figure C.6: System operation for each building in the Case 2 market for the whole year.

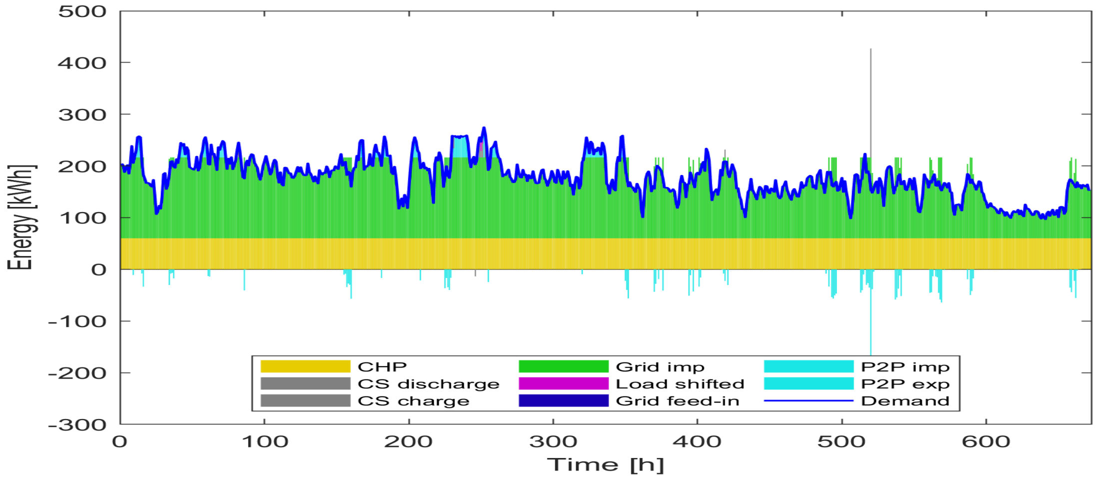
C.3.2 Supply-Demand Decisions in February



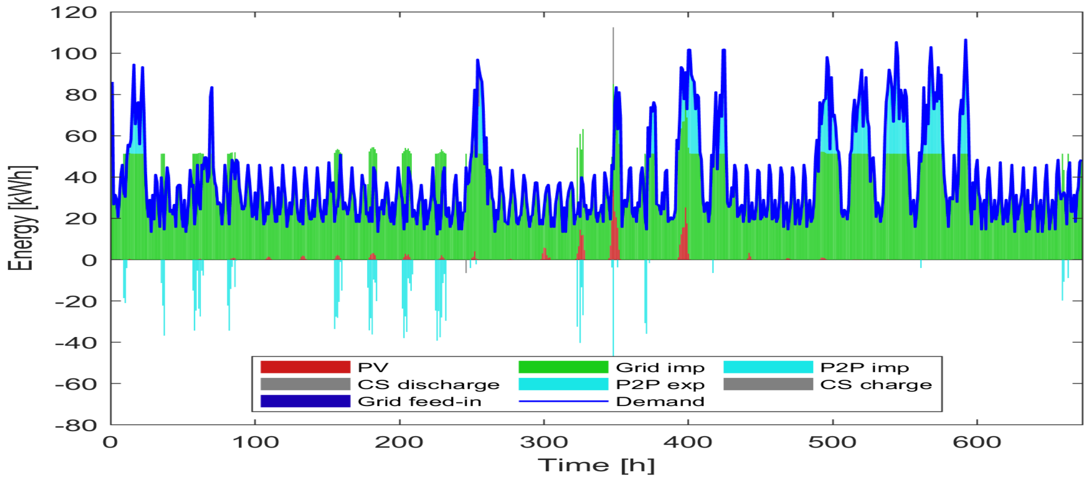
(a) Supply-demand building 1



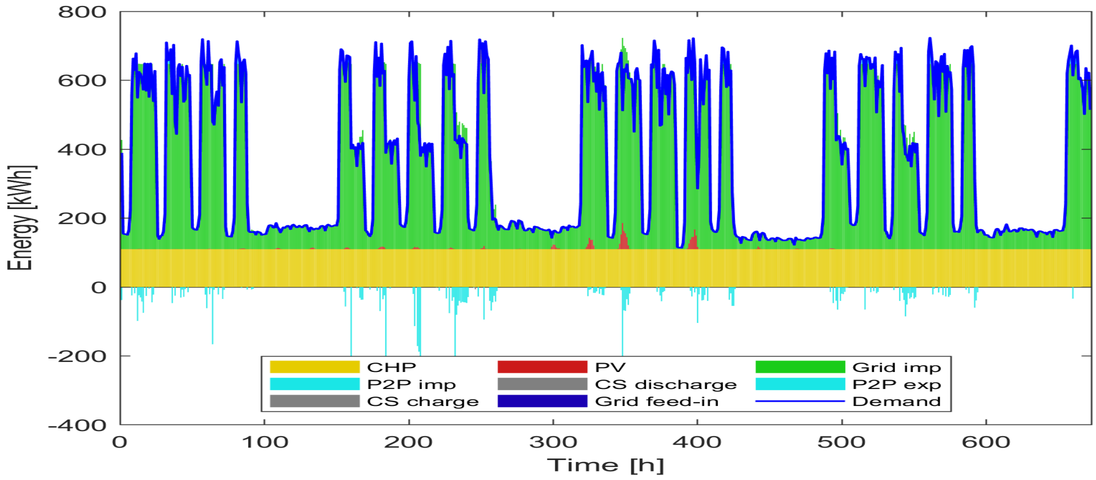
(b) Supply-demand building 2



(c) Supply-demand building 3



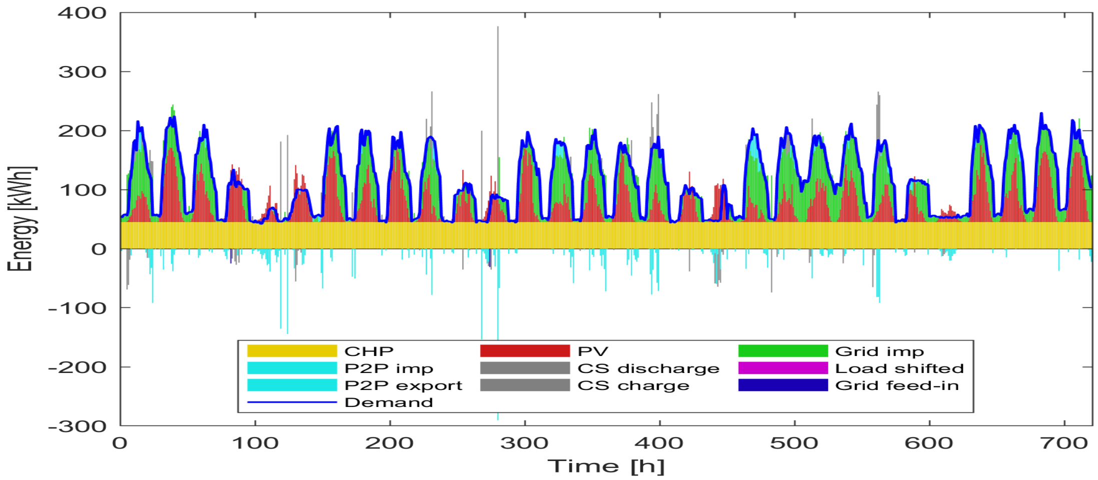
(d) Supply-demand building 4



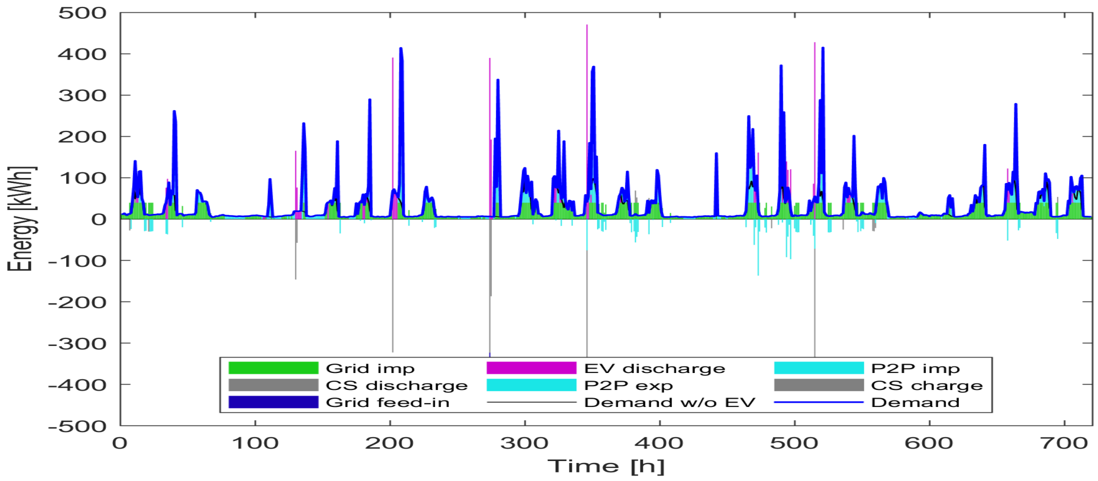
(e) Supply-demand building 5

Figure C.7: Demand cover for arbitrary winter month (February) for the Case 2 market

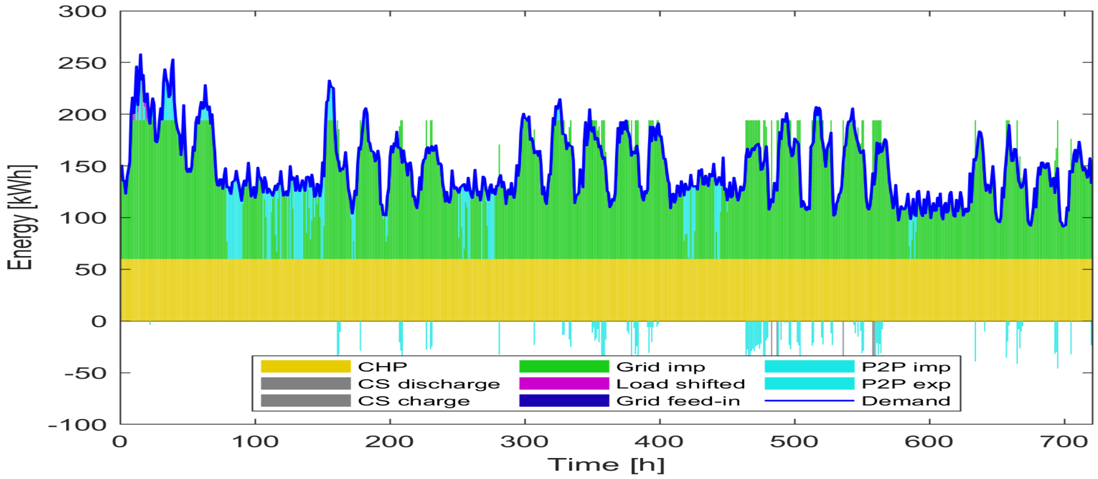
C.3.3 Supply-Demand Decisions in June



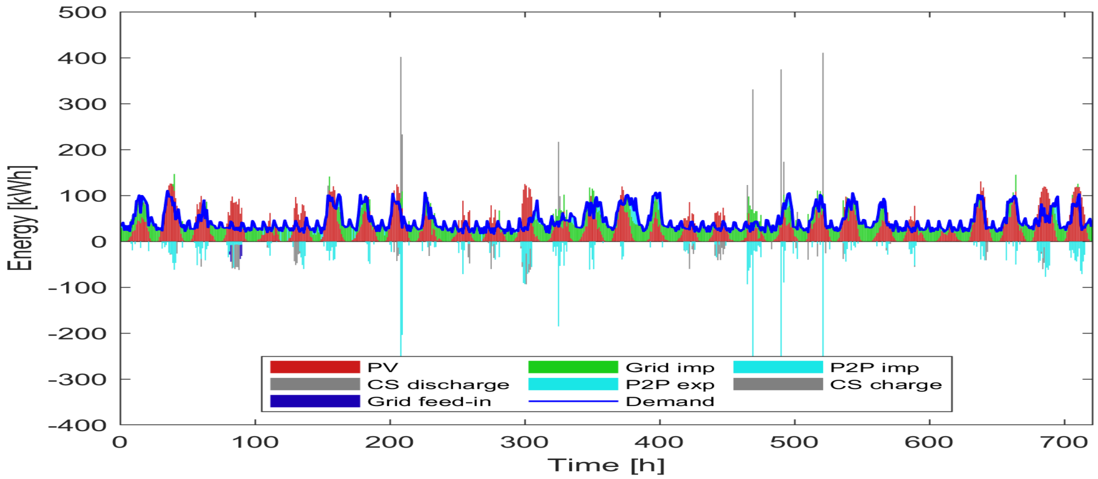
(a) Supply-demand building 1



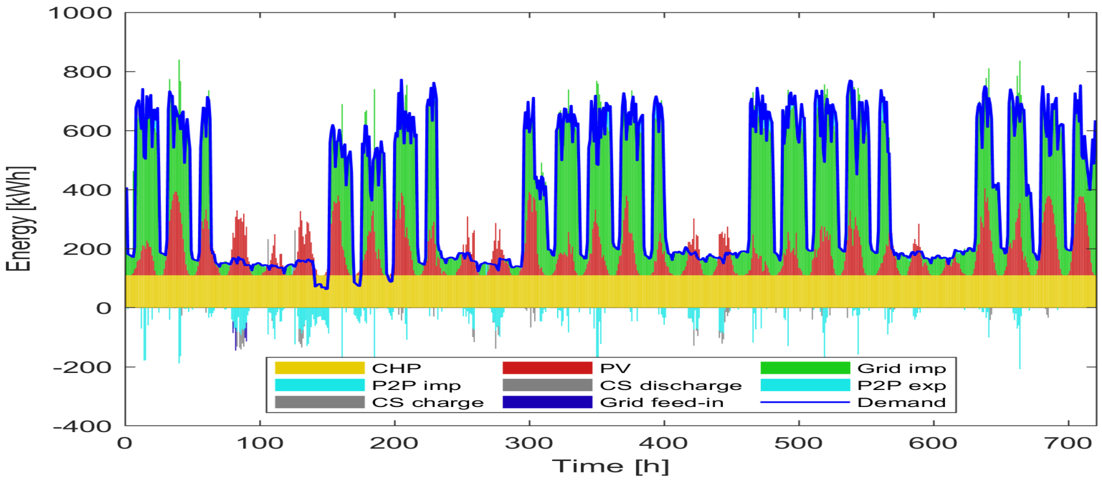
(b) Supply-demand building 2



(c) Supply-demand building 3



(d) Supply-demand building 4



(e) Supply-demand building 5

Figure C.8: Demand cover for arbitrary summer month (June) for the Case 2 market