Design and Evaluation of a Local Energy Market

A case study of Chalmers University Campus

Master's thesis in Innovative and Sustainable Energy Engineering

GRACE SHAMMAS

DEPARTMENT OF SPACE, EARTH & ENVIRONMENT

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2021
www.chalmers.se

MASTER'S THESIS 2021

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Master's Thesis 2021
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Cover: Wind visualization constructed in Matlab showing a surface of constant wind speed along with streamlines of the flow.

Typeset in LaTeX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2021

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Abstract

The need to decarbonize the energy system, in addition to the falling costs of renewable energy sources, electric vehicles, and other technological advances, has presented opportunities to resolve the limitations and costs of the current electrical grid that have become apparent. Amongst other concerns, renewable technologies have resulted in imbalances in the network and constraints due to the lack of clear strategies and planning. Researchers are thus exploring the fundamental re-engineering of the electricity services industry in a way that will systemically change the way that electricity is generated and traded. The proper management of distributed energy resources (DER) could bring various benefits, through its application in a local energy market (LEM). The study aims to design and model a local energy market within Chalmers University of Technology based on the theory of energy markets in the available literature. The local energy market was designed to trade multiple energy carriers to locate and unlock potential synergies, with the main focus on electricity and heat trading. The purpose of this study is to identify the challenges and opportunities of local energy markets and assess their economic feasibility from the perspective of the market participants. The LEM was designed and modeled in Python and simulations were conducted for different scenarios to analyze their effects on participant behavior and subsequent market clearing.

In an attempt to decarbonize the energy system, a popular trend is to electrify everything, as long as electricity is generated in a low-carbon manner. This results in a substantial elevation of electric demand on the electrical grid. The execution of a LEM within Chalmers University of Technology was found to ease the strain on the external grid and district heat network (DHN) during periods of peak demand, by acting as additional generators. Also, in response to the local market's partial self-sufficiency, energy costs were reduced and better controlled within the LEM. In the base case, there were no benefits seen in regards to reduced electricity prices, as internal generation did not satisfy demand. Regarding heat, however, costs were reduced up to an average of 52% in the winter and 100% in the summer. The first sensitivity case scenario analyzed the benefits of increasing the capacities of the solar PV and CHP units. No electricity price reductions were seen in the winter, however, costs did drop up to an average of 13% in the summer. For heat, costs dropped up to an average of 53% and 100%, for winter and summer, respectively. The second sensitivity case analyzed the impact of electricity price fluctuations on the LEM, and the system proved to be reliable and provide cost stability.
Nevertheless, under all scenarios investigated, the simulated market was found to be consistently dependent on the external electricity grid to meet the needs of the consumers. The pricing relationship with surrounding markets was deemed to be

a major concern if the market model were to be applied in practice and is briefly discussed.

Keywords: Local Energy Market, Energy Market, Day-Ahead Market, Market Clearing, Bid-dependency, Energy system integration, Distributed Energy Resources, Energy Storage

Acknowledgements

There were many who helped me throughout the writing of this thesis, and I would like to take a moment to thank them.

First and foremost, I am extremely grateful for my supervisor David Steen, for his invaluable advice and continuous support during my thesis. His knowledge and vast experience have been of great encouragement and inspiration. I would also like to show gratitude to Ali Fotouhi, Nima Mirzaei Alavijeh, Sanna Syri and Tuan Anh Le, for their guidance and contributions to my study.

Finally, I must express my very profound appreciation to my family for providing me with unwavering support throughout my academic career and through the process of researching and writing this thesis. This paper stands as a testament to your unconditional love and encouragement.

Thank you.

Grace Shammas, Gothenburg, August 2021

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Nomenclature

Sets

BES Battery energy storage
CHP Combined heat and power
CO_2 Carbon dioxide
COP Coefficient of performance
DER Distributed energy resources
DH District heating
DHN District heating network
FGC Flue gas condenser
HP Heat pump
LEM Local energy market
PV Photovoltaics
RES Renewables energy sources
SOC State of Charge
TES Thermal energy storage

Constants

η_{bes} Charging and discharging efficiency of battery energy storage
η_b Efficiency of biomass boiler
η_{CHP_b} Efficiency of CHP boiler
$\eta_{CHP_{tr}}$ Electrical Efficiency of CHP turbine
η_{fgc} Efficiency of flue gas condenser
η_{tes} Charging and discharging efficiency of thermal energy storage
$COP_{k,absc}$ Cooling coefficient of performance
COP_q Coefficient of performance of heating
$EN_{cap_{bes}}$ Energy capacity of battery [kWh]
$EN_{cap_{tes}}$ Energy capacity of thermal energy storage [MWh]
f_{price} price of biomass[SEK/kWh]
$K_{min_{absc}}$ Minimum cooling capacity[kW]
$loss_{tes}$ loss in thermal energy storage
$P_{cap_{bes}}$ Power capacity of battery [kW]
$P_{cap_{HP}}$ Coefficient of performance of cooling
$P_{cap_{HP}}$ Power capacity of heat pump [kW]
p_{tax} transmission fees and incorporated taxes for importing electricity from external grid
$Q_{cap,absc}$ Cooling capacity of absorption chiller [kW]
$Q_{cap,b}$ Heat capacity of boiler [kW]
Q_{cap,CHP_b} Heat output capacity of CHP boiler [kW]

$Q_{cap,CHP_{tr}}$ Heat output capacity of CHP turbine [kW]
$Q_{cap,fgc}$ Heat capacity of flue gas condenser [kW]
$Q_{cap_{ch,tes}}$ Charging capacity of thermal energy storage[MW]
$Q_{cap_{dis,tes}}$ discharging capacity of thermal energy storage[MW]
RD_b Ramp Down capacity of boiler [kW]
RU_b Ramp Up capacity of boiler [kW]
SOC_{min} Minimum state of charge of battery energy storage
Parameters
e_{price} expected price of electricity [SEK/kWh]
$h_{price_{ex}}$ Export heat price to the district heating network [SEK/kWh]
$h_{price_{im}}$ Import heat price from the district heating network [SEK/kWh]
k_{absc} Cooling production from absorption chiller [kW]
K_{demand} Cooling demand[kWh]
P_{demand} electricity demand [kWh]
P_{PV} Forecasting production from PV panels [kW]
q_b Heat production from biomass boiler [kWh]
Q_{demand} Heat demand[kWh]
q_{fgc} Heat production from flue gas condenser [kWh]
Variables
k_{HP} Cooling provided by the heat pump[kWh]
$lambda_D$ Bidding price for consumers
$lambda_G$ Bidding price for suppliers
$p_{charge_{1,2}}$ Charging power of the 2 batteries [kW]
$p_{CHP_{tr}}$ Power production in turbine [kWh]
$p_{discharge_{1,2}}$ Discharging power of the 2 batteries [kW]
P_D Bidding quantity for consumers
$p_{grid_{ex}}$ Power exported to external grid [kW]
$p_{grid_{im}}$ Electricity imported from external grid [kWh]
P_G Bidding quantity for suppliers
p_{HP} Electricity consumed by the heat pump[kWh]
q_{absc} Supplied heat from driving chiller [kWh]
$q_{b,fgc}$ Heat from boiler and flue gas condenser [kWh]
q_{charge} Heat charge from thermal energy storage [kWh]
$q_{CHP_{b2g}}$ Heat produced from boiler to the grid [kWh]
q_{CHP_b} Heat production in boiler [kWh]
$q_{CHP_{htr}}$ Recovered heat from turbine to the grid [kWh]
$q_{CHP_{tr}}$ Heat sent to turbine [kWh]
q_{CHP} Heat production in the CHP unit [kWh]
$q_{DH_{ex}}$ Heat exported to district heat network [kWh]
$q_{DH_{im}}$ Heat imported from district heat network [kWh]
$q_{discharge}$ Heat discharge from thermal energy storage [kWh]
q_{fuel_b} Fuel Input to the biomass boiler [kWh]
$q_{Fuel_{CHP_b}}$ Fuel input to the CHP boiler [kWh]
q_{HP} Heat provided by the heat pump[kWh]
$SOC_{bes_{1,2}}$ State of charge of the 2 batteries [%]
SOC_{tes} State of charge of the thermal energy storage [%]

v_D	unitary benefit for consumers
v_G	unitary benefit for suppliers
y_D	Generation level for consumers
y_G	Consumption level price for suppliers

1

Introduction

1.1 Background & Motivation

A prevalent challenge in the 21st century is decarbonization, whilst filling the gap between energy supply and demand with clean, reliable and inexpensive energy. According to the UN Intergovernmental Panel on Climate Change (IPCC), decarbonization is defined as the decline in average carbon intensity of primary energy [1]. The rate of decarbonization has become a great priority in recent years due to the growing threat of climate change. In 2015, world leaders agreed to work together to adverse the impacts of climate change and reduce greenhouse gas emissions. This resulted in what is now known as the Paris Agreement. The agreement sets the goal of "holding the increase of global average temperature to well below 2°C above pre-industrial levels" and further extending this intention to limiting "the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change" [2]. In October 2018, studies by the IPCC confirmed that at the world's current emission rate, the global average temperature is likely to rise to the 1.5°C threshold as early as 2030 [3]. Thus, emissions must be reduced at a faster rate than ever before.

In response, significant alterations to the current energy system are being universally encouraged in many economies, in anticipation of steering away from the conventional energy source of fossil fuels and mitigating dangerous anthropogenic interferences with the climate [4]. This includes a significant increase in renewables, the electrification of large energy sectors that are currently reliant on fossil fuels, rapid technical advancements in sectors such as negative emission technologies (extracting CO_2 from the air), and implementing other mitigating factors such as carbon taxes. However, the process is not so well defined. The deviation to intermittent renewable energy sources (RES) is bringing disruptive, yet necessary, change to the global energy landscape at an accelerating pace, thus presenting new challenges to the entire power grid. Renewables, such as wind and solar, vastly complicate the management of the grid, for they are weather dependent and are not able to ramp up and down as needed, thus creating an urgent need for flexibility. As a result, resources that can ramp up and down, or otherwise compensate for natural fluctuations, are critical in a grid with a lot of renewables [5]. Additionally, energy demand is consistently rising as a result of economic growth, the electrification of transportation and heat, population expansion, and the industrialization of developing countries. These changes, in addition to technological advances, such as electrical vehicles and energy storage devices, have presented further obstacles to the traditional structure of energy transportation and the electricity market. The grid is stressed out, and in the midst of climate instability, the demand for local resilience is on the rise. This has created unprecedented opportunities to rethink the way that energy systems operate and how to incorporate innovative technologies to improve public health and reduce ecological damage; ensuing in the exploration towards a fundamental re-engineering of the electricity services industry. As a result, decarbonization, decentralization and digitalization, commonly known as the 3 D's, have become the prominent pillars towards a future green energy economy [6].

A solution that encompasses all 3 D's, and has been gaining recent momentum, is the integration of RES locally as distributed generation (DG), whilst energy generation, trading, storage, and consumption are coordinated via a local energy market (LEM). The concept aims at diverting from the conventional archetype of a centralized and supply-side oriented future, based on large-scale generation and transmission, and moving towards more local structures, relying on smaller scale distributed energy resources in the distribution grid [7]. The energy sector reform also exploits the increased intelligence and declining costs of information and communication technology (ICT) [5]. As sensors and processors become more affordable, it will become easier to monitor exactly what is happening in a distribution grid down to the individual device level, and to communicate that information in real time via the web [5]. More data can be created, and information and energy can be managed more intelligently thanks to artificial intelligence and machine learning [5].
The implementation of LEMs would greatly affect electrical power systems with strongly different management, coordination, resource mix and market models, as the futuristic grid structure inclines towards decentralized smaller generation, powered by cleaner generation sources [4]. Such a futuristic grid will permit bidirectional power flow as it is anticipated that integration of electrical vehicles, prosumers, and energy storage in the energy market will be able to aid in load management and grid support services. A local energy market could prove to be fundamental in providing reliable and sustainable energy to a society, whilst potentially decreasing power losses, energy costs, and quantity of imported power, thus, increasing overall system efficiency.

These benefits, however, have yet to be verified via real-world applications. Chalmers University of Technology already contains several fossil-free local production units, and thus, there is a strong incentive to design and model a local energy market model within the campus. Doing so enables the evaluation of LEM operation and associated benefits to the University, as well as the other actors in the energy market. This study embodies the research and modelling of a LEM at Chalmers University of Technology, using Python.

1.2 Aim

The overall goal of this research is to create a local energy market at Chalmers University of Technology's Johanneberg campus that efficiently utilizes available resources by integrating multiple energy carriers and determining out how to maximize their potential benefits via effective energy management. Three energy carriers (electricity, heat, and cooling) will be investigated, with a main focus on the electricity and heat markets. The model will be coded on Python using Chalmers campus data.

1.3 Objectives

In order to meet the aforementioned goal, the following objectives must be met:

1. Define the network framework for local energy trading
2. Design the structure for submitting bids
3. Construct a computational model for market clearing
4. Execute a case study using Chalmers campus data
5. Test model under various scenarios

1.4 Specific Tasks

Figure 1.1 presents a brief overview of the approach employed in order to achieve the objectives of the study.

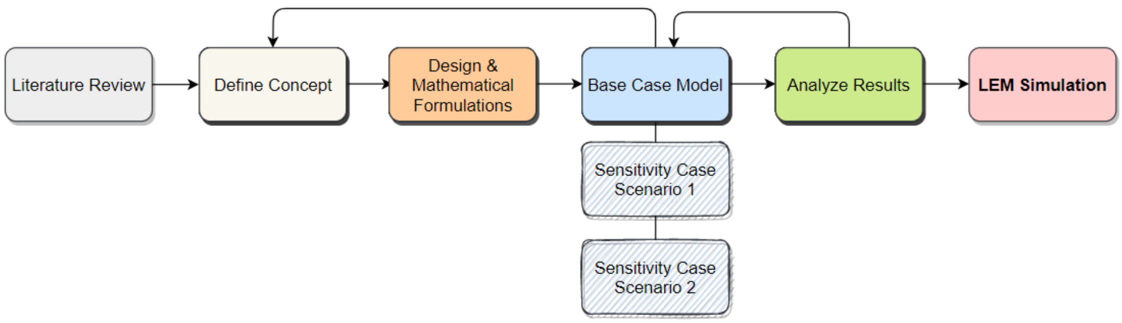


Figure 1.1: Simple Schematic of Research Tasks. *Adapted from [8]*

A preliminary literature review will be conducted to attain a deeper understanding of LEMs and the general procedure of designing a market for local energy trading. Once a clear concept of the project is determined, the LEM is able to be designed to meet project objectives. Mathematical formulation construction and coding could thus begin, and the concept definition can be regularly modified if found to be too complex or infeasible [8]. The computational model will be implemented on Python and the linear optimization problems shall be solved using the gurobi solver. The overall model will be simulated and evaluated based on four weeks of data – one week in January, April, June, and October respectively, to signify the different seasons. Results will then be critically analyzed to ensure they are realistic and sensible. If not, the model shall be adjusted once again by either altering constraints or input parameters. Following the design and evaluation of the base case, a sensitivity analysis will be conducted to determine how the model will perform under various scenarios.

1.4.1 Local Energy Market Design Framework

The main principles of the local energy market designed in this thesis are:

- The model follows an auction-based design that optimizes available resources and facilitates flexibility
- All participants have an equal influence on the market
- A simultaneous and interconnected clearing of multiple energy carriers is conducted
- Energy is traded locally while also interacting with external markets

1.5 Scope and Limitations

This project will focus on Chalmers campus and uses available historical data from the internal grid at Johanneberg campus. This historical data consists of building demand and Solar PV production, which will be used as forecasts and assumed to be accurately predicted. The local market is simulated using the obtained data and the energy technologies are separated into different players. The simulated market will only clear for electricity and heat, which will be discussed in further detail in Section 3. Technical aspects such as voltage, frequency, etc. will not be modelled. Only energy trading and market services will be incorporated.

1.6 Thesis Outline

The thesis consists of six chapters, including the introduction. These chapters are summarized below:

Technical Background: This chapter describes the concept of local energy markets and highlights some of the energy sources currently utilized on campus that will be implemented in the study.

Mathematical Formulation and LEM Design Methodology: This chapter describes the methodology behind the design of the LEM, how the input data was used, and the mathematical formulation of the optimization problem that was solved. It also introduces the sensitivity scenarios and their objectives.

Results: This chapter illustrates the results obtained from the different scenarios. An analysis and discussion of the results is also conducted.

Conclusion: This chapter emphasizes the main conclusions of the study, followed by potential future work proposals.

2
Technical Background

The design of a local electricity market is largely dependent on the characteristics and objectives of the participating actors. This chapter embodies the research and general design of local energy markets and associated technologies. Section 2.1 will illustrate the concept and fundamentals of local energy markets, including associated benefits and challenges. Section 2.2 introduces a typical procedure for designing a market for energy trading, followed by a brief look into how electricity and heat is currently traded in Gothenburg, via Nord Pool and the district heating system, respectively, in Sections 2.3 and 2.4. Section 2.5 highlights the energy sources that will be utilized in the project's design, based on the current network on Chalmers campus.

2.1 Local Energy Markets

An energy system is a network that consists of energy generation, transportation and consumption. The electricity sector can thus be segregated into 4 dimensions: generation, transmission, distribution, and markets/selling. Historically, utilities in the electricity sector used to be vertically integrated, such that several of these services were owned by the same company. The electricity sector became a monopoly and electricity prices had to be regulated. In order to facilitate greater competition, in the 1990s, many countries transitioned towards competitive segments with many actors (generation and retail), and non-competitive segments controlled by a single actor (transmission and distribution). This is commonly known as vertical unbundling [9] [10]. The integration of private players, and increased competition between the actors, incentivized efficiency, and reduced energy costs. Today's grid consists of huge generating stations that typically produce energy using coal, gas, nuclear, and as of lately, renewable energy sources like wind and solar. Energy is then delivered to the end-user through the grid. However, with increasing demand and environmental concerns, the energy system is being examined once again.

Technological advancements have provided new opportunities to provide clean energy and integrate prosumers in the energy system. A prosumer is defined as an actor who consumes and produces energy. An example of a prosumer is a homeowner who utilizes rooftop solar PV systems to meet some or all of their electricity needs, whilst also being able to sell excess energy to the main grid. Prosumers act as an additional source of renewable energy, aids in reducing network losses and peak loads, increases efficiency, and improves demand response and consumer engagement in the energy system [11]. However, the effects of incorporating these changes on the network cannot be neglected. The combined factors of growing amounts of distributed energy resources (mainly intermittent renewable sources), new demands (e.g. electrical vehicles, heat pumps, ect.), required bidirectional power flow with prosumer integration, and increasing number of players/competition, network problems such as congestion will result. In addition, despite the push for more market participants and competition, the energy market in Europe has become dominated by big companies through legislative restrictions influenced by generation size and legal stipulations [12]. The various restrictions and requirements prevent small-scale actors from participating in the energy bidding process [12]. However, in November 2016, the European Commission (EC) pushed forward the "Clean Energy for all Europeans" policy package [13]. According to Mendes et al. (2018), the policy enables Europeans more control over their energy consumption through active involvement in the European Union energy system and utilization of local available renewable energy sources [13]. The EC is projecting that all European electricity will be carbon free by the year 2050. For Europe to reach their 2050 carbon free goal; the energy market requires prosumers and/or other local generating bodies to take advantage of local available renewable energy sources [13]. Overall, the developments in the energy market paved the way for the establishment of local energy markets [13]. LEMs empower small local players to participate in integrated short-term energy markets, trading amongst an auction-based online platform and building a balance between local generation and consumption [14]. Energy sources, loads, and energy storage units operate together locally with or without support from the central electric grid. A LEM is comprised of energy sources used to generate power to provide to a load or to be stored when profitable [15]. Additionally, energy efficiency is significantly increased in a LEM because energy is more often consumed near the generation source. Therefore, less distribution/transmission losses are experienced because the electricity does not need to travel as far, overall improving the energy efficiency [16]. Typical LEMs will still maintain connection to the central grid to meet very high-power demand spikes.

There are many benefits from implementing a LEM, primarily serving as a tool to reduce carbon emissions and mitigate climate change [15]. The LEM system can minimize peak loads, as well as transition between energy carriers based on availability, allowing for greater flexibility and security [17]. When grid stability and performance challenges arise, the local market can aid in stabilizing the overall network. This is primarily related to the electricity market, which is more prone to issues of grid stability and quality; however, identical problems could arise in the case of a district heating network [17]. Typically, a LEM consists of many power generating and storage sources ranging in size, all contributing to the required load. Therefore, the LEM has many options to meet demand or fix energy imbalances through a combination of generation, reserves, and external grids. As previously mentioned, energy efficiency is significantly higher in a LEM, as energy is generated and utilized in the same geographical location, subsequently reducing energy costs.

Although LEMs provide a lot of opportunities and benefits, they have many technical and economical requirements that serve as barriers. The main technical barrier is that the overall technical maturity required for a LEM is not widely adopted and is still being researched and developed [13]. For example, there are many types of energy storage systems, such as fuel cells, batteries, and thermal systems that are still in the development phase and require time and research before they can be commonly used in industry. Micro-grids are still experiencing many technical challenges that are being examined in both research and industry [13]. Examples of these challenges involve achieving a connection to the grid, specifically when incorporating bi-directional flow [15]. From an economic standpoint, a present challenge is the cost and payback period of renewable energy power plants. Typically, renewable energy power projects have a high initial capital cost, which can result in quickly steering away the attention of investors [13]. Customers may prioritize investments with lower capital costs to reduce the payback period, even though it may result in more operational costs in the long run [15]. Additionally, the investment and development of LEMs could result in a decrease in grid market revenues, which would lead to higher electricity prices and higher grid fees for prosumers. However, a vital asset to operating a successful LEM is the connection to buy and sell to the grid or other distribution networks. Therefore, owners or companies that provide centralized generation will need to adapt and reconstruct their business models for a new market equilibrium to be met that will benefit both the grid and the LEM [13]. Moreover, due to their limited size, another limitation of a local energy market is that the advantages of a more efficient system may not be substantial enough to compensate for the expenses of running the market or the social costs of increasing market complexity [18]. However, LEMs can range in sizes and features, thus the feasibility of local energy markets is extremely case-specific [18]. Lastly, a LEM requires a refined market model, which typically requires advanced and reliable technology. Even though these requirements could be deemed as a barrier, technology and automation is continuously improving as companies and industries are incentivized to prioritize the development of smart grid technologies consisting of energy efficiency appliances and automation technology [15].

Ownership varies amongst local energy markets. Specifically, privately owned local energy is a profit-making independent power plant managed to provide minimal operational cost while using renewable energy sources [15]. Meanwhile, community-owned local energy focuses on saving money for the community by reducing electricity bills and promoting the reduction in burning fossil fuels. One of the main objectives for all LEMs is to ensure profits for the different participants [16]. The LEM must be consistently lucrative to keep the participants interested, otherwise they will sell and buy energy elsewhere. With a successful market model, a LEM is a very attractive concept that has proven to be economically and environmentally profitable as more and more people and communities are investing in them daily.

In addition to electricity, heating and cooling are also important energy carriers in a LEM. Renewable district heating and cooling are not only cost-effective and energy efficient, but similarly important in reaching overall sustainability and energy efficiency targets [18]. The district heating (DH) system can specifically be further utilized as a balance resource for the electric power system by coupling the sectors, to mitigate in production capacity [18].

2.2 Designing a Local Energy Market

Electricity is inherently difficult to store in vast quantities and in a cost-effective manner. Additionally, the increasing importance of intermittent generation has resulted in increasing volatility in market prices. Thus, energy markets are critical to ensure that demand is always met in a reliable and cost-effective manner. In order to design a proper market for trading multiple energy carriers, the market players and their objectives must be clearly established, in addition to the type of market clearing that will be conducted. A visual representation of the general market design procedure can be seen in Figure 2.1 below.

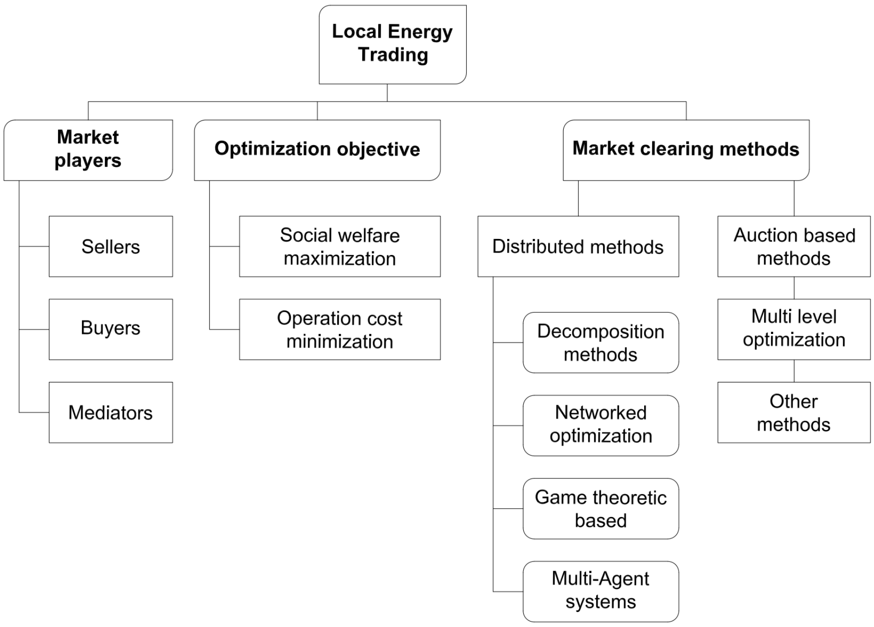


Figure 2.1: General Procedure of Market Design for Local Energy Trading. *Adapted from [19]*

To design a LEM, three main questions must be answered: who are the market players, what is the optimization objective, and what market clearing method(s) will be utilized? Sellers are market players with the capability of generating or storing energy, while buyers demand energy from local generators. The function of a mediator differentiates based on the type of market, but is commonly responsible for collecting offering/bidding parameters (prices and amounts) from different players to maximize social surplus [19].

Social welfare is defined as “the net benefits from energy consumption and generation based on the utility of dispatchable demand” [20]. The objectives of social welfare maximization and operation cost minimization will be discussed in further detail in the following chapter.

There are various types of clearing methods, with the auction-based market being the most recognized, and thus, the focus in this study. An auction-based market clearing is a negotiation mechanism that is facilitated by an intermediary. The intermediary can be either a real agent or an automated set of rules.

2.2.1 Auction-based Market

Based on microeconomics, a general market is based on supply-side and demand-side. Supply refers to the availability of goods and/or services in the marketplace – as the price of a product increases, supply raises as producers are willing to manufacture since it is increasingly profitable. The term demand is used to characterize a strong desire for a specific product, when there is enough purchasing power and/or power to make the decision to purchase. A critical component of a market design are the wholesale markets and subsequent balancing tools that are implemented to maintain an equilibrium between supply and demand. In order to ensure perfect competition, no participant should be able to affect the market price.
Generally, in an energy market, suppliers and consumers place their bids, which are sorted in an ascending and descending order, respectively. The intersection defines the final trading price (spot-price), also known as the "market equilibrium", and will thus be the set price for a unit of energy that everyone pays or gets paid at that specific time. In such a market, the participants should not have the power to influence the outcome of the price in an auction. A visual representation of this phenomena can be seen below.

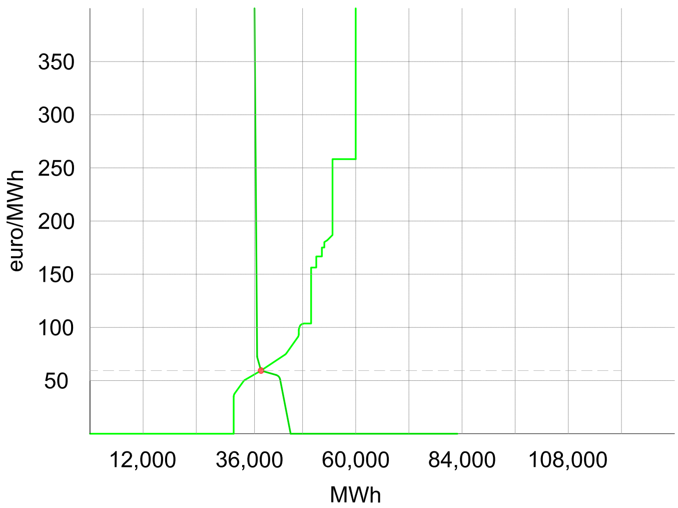


Figure 2.2: Supply and Demand Curve. *Adapted from [21]*

Initially, the demand curve is relatively inflexible, as consumers such as hospitals, industrial plants, refrigerators and other appliances need to run at virtually any cost. Afterwards, the curve becomes less rigid as demand side agents become more responsive to price signals. At this point, when supply price increases, demand will decrease, and vice versa. The primal goal of the market is to maximize social welfare, while considering network constraints provided by transmission system operators, such that participants end up paying less for energy and suppliers generate revenue from production.

2.2.2 Marginal Pricing Modeling Approach

In order to evaluate the revenue of producers and the risks they face, studies conducted in literature have typically considered a "marginal cost bidding." Although this form of bidding does not always apply, such as during scarcity hours for instance, the approach has advantages regarding simplicity, limited data, and reduced assumptions in respect to market participant bidding strategies. Marginal costs refer to any additional costs associated with producing one more unit of energy – mainly fuel costs, CO_2 costs, and start-up costs. When participants initially bid based on their short-term marginal cost of generation, high costs of energy can be mitigated, and energy is distributed in a more efficient manner [22]. Moreover, bidding at a higher price than marginal costs can result in the loss of potential profits, without any considerable benefits [22]. When applying the theoretical model of a perfectly competitive day-ahead market, it is evident that the generator with the highest marginal costs sets the clearing price. When the bids are sorted in ascending order, starting from the producer with the cheapest marginal costs, and compared with demand, the last generator will earn zero profits, while the remaining generators will earn profits equal to the difference between the market clearing price and their own marginal costs. Hence, there is no incentive for generators to bid prices above their marginal costs as the likelihood of the bid to be executed will decrease. This ascending list of generators based on marginal costs is generally known as a "merit order curve," as shown in 2.3 below.

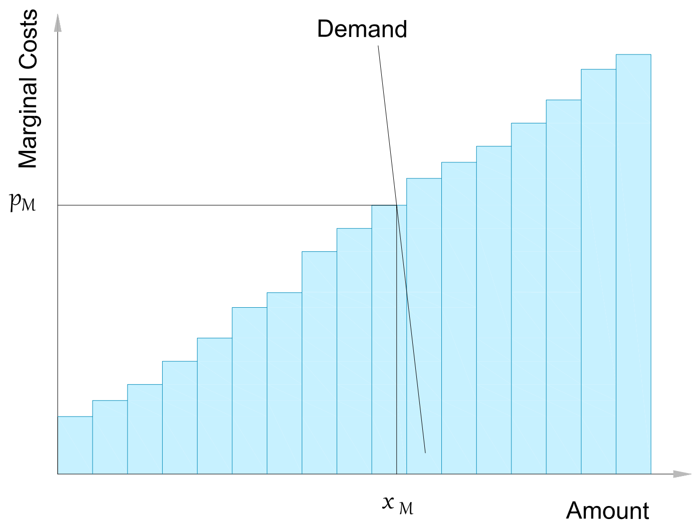


Figure 2.3: Merit-Order in a Perfectly Competitive Market. *Adapted from [22]*

The width of each unit represents the power it can supply, and a demand curve can be integrated into the merit order to determine the cost of energy. When energy is generated from renewables or 'baseload' plants with very low marginal costs, they will have a bidding price of practically zero, hence receiving the highest profits. As renewable energy bids increase, the clearing price will subsequently decrease by shifting the merit order tot the right, as seen in the Figure 2.4 below. Consequently, more expensive units will no longer be part of the energy mix. [21]

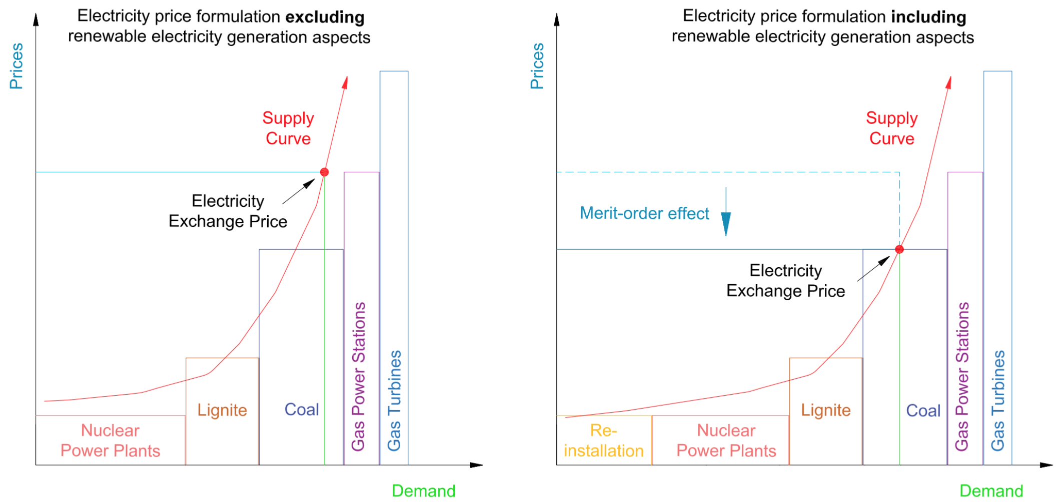


Figure 2.4: Shift in Merit Curve due to RES Supply. *Adapted from [23]*

2.3 Nord Pool

In Europe, Nord Pool runs the leading power market, where energy is sold between producers and retail companies, as well as large electricity customers. Some trade agreements do not pass through the market, due to prearranged trade set exclusively between two parties, also known as bilateral trade – but often prices used in such trades are bound to the spot market prices. Electricity markets are generally organized into different time horizons. One of the most critical markets is known as the "day-ahead market." In a Nord Pool day-ahead market, actors can sell or buy energy for the next day, during 12-36 hour intervals, in a closed auction. This provides guidance to generators and system operators, and aids in dictating how much power should be produced and from where it will be obtained. The market receives the bids, then calculates the hourly price whilst balancing supply and demand. Participants are then obligated to physically deliver or consume according to their cleared bids. Other markets, such as the "inter-day market," simultaneously operate making fine balancing adjustments closer to delivery time.
Participants with temporal storage typically bid to optimize profits based on expected production, and participants whom emit must consider CO_2 permits in their pricing. Price zones are typically created in consideration of network constraints. [24]

2.4 Gothenburg District Heating System

Heating residential, industrial, and commercial buildings using district heating (DH) is both efficient and environmentally friendly, as heat can be generated in a centralized location using innovative technology and environmentally acceptable materials, as opposed to each building having its own heating system [25]. District heating, however, is a natural monopoly. Due to the high infrastructural investments required, it is more economically efficient for a single business to generate a particular quantity of production within a geographic market, rather than several firms [25]. The main objective of district heating is to meet customer heat demand (typically space and water heating) by utilizing local fuel or heat resources that would otherwise be wasted [26]. Gothenburg's district heating system is particularly unique compared to other typical district heating systems, both in Sweden and the rest of the world. This is mainly due to the system's prioritization of excess heat from refineries in the area and waste incineration, to supply a large extent of demand [27]. The remaining base and intermediate demand is met by Göteborg Energi's heat only boilers (fueled by oil, biomass or natural gas), combined heat and power plants (fueled by biomass or natural gas), or heat pumps.
District heating can be divided into two parts: distribution and production. Having two parallel distribution networks is inefficient from an economic standpoint, and as a result, district heating distribution in Gothenburg is a natural monopoly, operated by Göteborg Energi [25]. Göteborg Energi also has a monopoly in regards to heat production, as the company has bilateral contracts with industries and owns most of the production units, which is then supplied to the customers.

2.5 Distributed Energy Resources

In the following section, different technologies that were utilized in the design of the Chalmers local energy market are briefly described.

2.5.1 Solar (PV)

Solar power can be harnessed using a system made up of multiple photovoltaic cells, also referred to as PV cells. PV cells produce energy by converting photons from sunlight into an electric current with a process called the photovoltaic effect [28]. The solar cells are composed of a p-type semiconductor and an n-type semiconductor, which create a p-n junction when combined [29]. The p-n junction allows for current to flow in one direction, forming an electric field. Photons are defined as "a particle representing a quantum of light or other electromagnetic radiation" [30]. When the electromagnetic radiation from the photon hits the PV cell, energy from the photon is transferred to an atom of the semiconducting material in the p-n junction. Electrons in their excited state are free to move through the conducting material, leaving behind a "hole" in the valence band. The movement of the electron creates two charge carriers, an electron-hole pair. However, due to the presence of the electric field from the p-n junction, electrons and holes move in the opposite direction as expected, creating a current in the cell [29]. The electricity can be sent to available batteries to be stored or used in the form of direct current (DC). However, the electricity utility grid operates and requires alternating current (AC). Therefore, most solar panel systems will be met with a DC to AC inverter before the electricity is sent to the grid or used to meet local demand [31]. A solar panel consists of many solar cells encapsulated within a material to protect the cells from the environment. Solar panels can be mounted on buildings, rooftops or anywhere with available space. Multiple solar panels can be used together to form a solar farm or park.

2.5.2 Combined Heat & Power (CHP)

Gas and steam turbine technology alone has a lower efficiency than an equal power output reciprocating engine. Different technologies have been implemented to improve gas and steam turbine efficiencies. Combined heat and power (CHP) systems use high temperature and pressure to send steam or gas through a turbine to generate both heat and electricity. Capturing almost all possible heat losses, actual CHP plants have utilisation factors of 85-90 percent [32]. A CHP plant consists of multiple technologies working together to generate heat and electricity. A fuel source, combustion engine, boiler, steam or gas turbine, heat recovery unit and generator are some of the major components [33]. The total efficiency for CHP plants is usually as high as 80 percent, as heat is lost through the boiler flue stack [32]. Additional heat losses occur when transferring heat to the consumers [32]. Every CHP system includes a mechanism for thermal heat recovery that would otherwise be wasted [33]. The overall system allows for very efficient electricity and heat production in comparison to conventional plants along with fewer emissions. Therefore, CHP plants are a very feasible option in the energy industry.

2.5.3 Boiler

An industrial grade boiler is a system that is usually made up of a combustion furnace, a vent stack and waterwall furnace tubes [34]. Combustion of various fuels in the furnace releases heat which is transferred to the water in the waterwall furnace tubes. The water evaporates, generating pressurized superheated steam which will then be sent to a turbine for electricity generation. The high-pressure turbine exhaust can be recycled back into the boiler for reheating [34]. Once cooled down, the steam or hot water can also be used for residential heating purposes, such as heating a house. Coal, oil, natural gas, and biofuels are common fuels to combust in a boiler [34]. These style boilers do produce flue gas, which can be scrubbed, incinerated, or vented.

2.5.4 Heat Pumps

A heat pump is an electronic device that transports heat from a low temperature location, referred to as a heat source, and moves it to a high temperature destination, known as a heat sink [35]. According to the second law of thermodynamics, heat flows from high temperature regions to lower temperature regions. A great example of this principle is when heat from inside a building is lost to the outside during cold winter months. To counteract the natural flow of heat, a heat pump utilizes

electrical energy to pump energy from a cold location to a warm location, essentially warming the inside of a house during cold winter months [35]. Heat pumps are mostly used to heat and sometimes cool buildings [16]. There are many different types of technologies that provide a heat pumping function, with the type of energy input being either in the form of heat or work. Excluding absorption coolers, air-to-air, water source and geothermal are the three conventional types of heat pumps [36].
The most common type of heat pump is air-to-air, also known as air source heat pumps, typically used to transfer heat between the inside of a building and the outside air. During the heating cycle, heat is extracted from the ambient air and pumped indoors. The liquid refrigerant first travels via the expansion device, where it is converted to a low-pressure liquid/vapour mixture [35]. The refrigerant next travels to the evaporator coil. The evaporator coil is outside in ambient conditions, allowing heat to transfer from outside to the refrigerant as it moves through the coil [35]. The liquid refrigerant acquires heat from the environment and boils, transforming into a low-temperature vapour [35]. This vapour travels to the accumulator through the reversing valve, where it gathers any residual liquid before entering the compressor [35]. The vapour is then compressed, which reduces its volume and causes it to heat up [35]. As directed by the reversing valve, the hot gas flows to the indoor coil, which serves as the condenser [35]. The refrigerant condenses into a liquid as the heat from the hot gas is transmitted to the interior air [35]. The liquid is pumped back into the expansion mechanism, and the cycle begins again [35]. The indoor coil is positioned near the furnace in the ducting [35]. This energy transfer cycle can be reversed to provide cooling when required, such as during summer months [35].
The earth or ground water are commonly used as sources of heat for a heat pump to pull from during the winter. The two locations can also act as a reservoir in the summer when removing heat from inside a building [35]. Water source or ground source (geothermal) heat pumps can achieve higher efficiencies and are relatively cheaper to operate due to the ground or nearby water temperatures staying consistent all year long. However, these types of heat pump systems are generally more expensive to install and require appropriate subsoil, landscape and location to be deemed feasible [35].

2.5.5 Absorption Chiller

Absorption coolers, also known as absorption heat pumps, are essentially air-sourced heat pump driven by a heat source instead of electricity. Natural gas, propane, solar-heated water, or geothermal water are the most common heat sources used in absorption heat pumps [37]. Absorption coolers use an ammonia-water absorption cycle to provide cooling and heating to residential or industrial areas. Pure ammonia in the liquid state produces a cooling effect, which is used to absorb heat and cool down a room or building. The ammonia evaporates once the heat is absorbed. This is all performed in the evaporator component of the absorption cooler. [38] The gaseous ammonia travels to the absorber where it is absorbed by unsaturated water. The absorption of ammonia will produce small amounts of heat, which is usually captured with a heat sink [39]. The now strong aqueous solution of ammonia is pumped at high pressure to the generator to be heated. Using an external heat source, the generator heats the ammonia-water solution and vaporizes the ammonia. However, the ammonia vapor can consist of five to ten percent water, therefore a rectification column can be used to reduce the concentration of water vapour significantly. Lastly, the high-pressured ammonia vapour passes through a coil where it is condensed by cool water. The now liquid ammonia passes through an expansion valve on its way to the evaporator, which causes its temperature and pressure to significantly decrease. Once it enters the evaporator, the refrigeration process repeats itself. [38] The added advantage that absorption coolers offer is the ability to operate with any heat source and they can offer a significant amount of cooling.

2.5.6 Energy Storage

Energy storage systems provide a solution to intermittent renewable energy generation by acting as backup supply or backup storage to balance the demand and supply within a short-term notice [40]. One of the most common forms of energy storage is batteries. Lithium-ion batteries provide one of the highest energy dense storage technologies along with high discharge capabilities and long service life [41]. Lithium-ion batteries are taking over the electric vehicle industry and have made portable electronics ubiquitous due to their high energy dense storage capabilities [42]. Another popular benefit to lithium-ion batteries is the longevity it offers in comparison to other popular batteries. Other prevalent batteries such as nickel-cadmium and nickel-metal hydride have a property known as memory effect. Memory effect is defined as a battery gradually losing its service life by repeatedly being charged when it is only partially discharged. Lithium-ion batteries have no memory effect, and therefore, commonly have longer service lifes than other rechargeable batteries. [18] Lithium-ion batteries have the capability of storing electricity produced in excess from intermittent renewable energy sources. Once stored, the energy can be used as backup in events where the demand exceeds the available supply from the intermittent renewable sources. Overall, long lasting and energy dense rechargeable batteries provide significant benefit and operational flexibility, especially within a microgrid.

Thermal energy storage is another popular method of energy storage that is gaining popularity as multiple forms are being optimized and implemented globally. Even though it is being used more and more often every day, according to Ibrahim Dincer, thermal energy storage could be considered the first form of energy storage ever created. Thermal energy storage systems date back to when early civilization was harvesting ice and storing it for later use. Today, thermal energy storage technologies are being used in many applications, such as district heating, industrial processes, and even in residential and industrial buildings. There are two main types of thermal energy storage currently being used, sensible and latent. Sensible heat storage deals with simply increasing or decreasing the temperature of the storage medium, which can then be used as a heat source when required. Popular sensible heat storage medium is water or rock, however, there is a wide range of choices depending on the temperature range and application. [43] For example, the ground is an ideal medium for storing large quantities of heat for long durations. Therefore, underground caverns or underground storage tanks are being used as sensible thermal storage facilities that can hold heat for multiple months of the year. [44] Latent heat storage is the capture of heat produced during the phase change of a compound, for example, water/ice, or salt hydrates. Latent heat is produced from a compound through a phase change, during this period, heat can be added or removed without affecting the compound's temperature. Very large amounts of energy can be produced through phase changes, resulting in high thermal storage capacities. [45] Latent and sensible heat storage methods are being used increasingly and studied everyday as they offer efficient, simple and cost-effective methods for storing excess heat. Depending on the application, a combination of the two may offer the most effective thermal energy storage option available to date. [46]

2.5.7 Ramping

Technical constraints are vital to consider and include in simulations when designing theoretical energy systems. Ramp rate is defined as the rate at which a power plant can increase or decrease output, which is quantified as a measure of operational flexibility. Ramp rate is usually expressed as megawatts per minute. Flexibility is critical when operating a plant to provide grid support while dealing with variable loads. Ramp rate depends on plant capacity, operating conditions and available technology that can be implemented to reduce start up time and increase ramp rate. [47] Batteries and demand response are two common techniques that can be used to improve flexibility when dealing with a limited ramp rate.

3
Mathematical Formulation and LEM Design Methodology

The following chapter will present the methodology behind simulating an energy market that makes the most effective use of Chalmers University's local resources. This includes a description of how the work was conducted, what data and assumptions were used, and the mathematical formulation of the optimization problem that was solved for the modeling of the market. Finally, a sensitivity analysis was performed on the base case scenario to test the model under various scenarios.

3.1 Methodology

An extensive literature review was primarily conducted to get a deeper understanding of the fundamentals of local energy markets, market modelling and energy markets. The campus network presented by Alavijeh et al. [48] was used as a benchmark in comprehending the university's current energy set up and utilization. The literature review aided in forming the foundation of the market model design, as different design options were considered, leading to the implemented design which best satisfied the purpose of the thesis. Data was gathered from Chalmers campus, and the proposed model was then implemented in an optimization problem using Python, based upon current technology available on campus. The model was designed to reflect a day-ahead market and was broken down into two segments: the bidding stage and the market clearing stage. The market model consisted of 7 active actors - 5 generators and 2 consumers. Of the 5 generating actors, 2 of them placed bids reflecting the energy that could be imported from the external electric grid and DHN, assumed to be Nord Pool and Göteborg Energi. The remaining 3 generating actors placed bids reflecting energy produced with Johanneberg campus. These actors would bid based on the marginal cost of production of each technology, and manipulate bid quantities to maximize their overall individual profits throughout the time period examined. The 2 consumers placed bids reflecting demand from both Johanneberg and Lindholmen Campus. These actors and their bidding strategies will be discussed in greater detail in Section 3.3. The local energy market underwent hourly market clearing in order to maximize social welfare per hour. The model ran for 4 periods, a week in January, April, July, and October, to encompass every season. After critically analyzing the results obtained from the general model, altered versions of the simulation were investigated to determine how the market players and the market itself would behave under different scenarios. The results were analyzed, compared, and discussed to highlight the opportunities and challenges of a local energy market.

3.2 Input Data

A successful market model is determined based on its ability to clear the market for adequate energy transactions and prices, maximizing overall social welfare. For this study, the trading period will be based on one hour intervals, as commonly performed in realistic energy markets. For an enhanced understanding of the market design and formulations, a simplified overview of the network based on Alavijeh et al.'s campus network, is provided in Figure 3.1 [48].

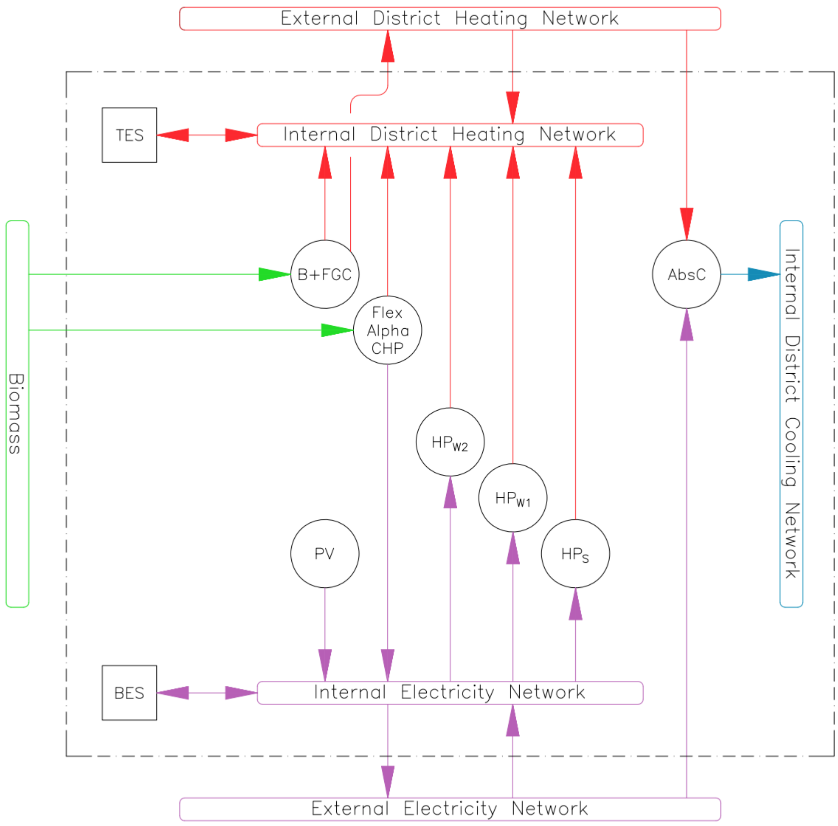


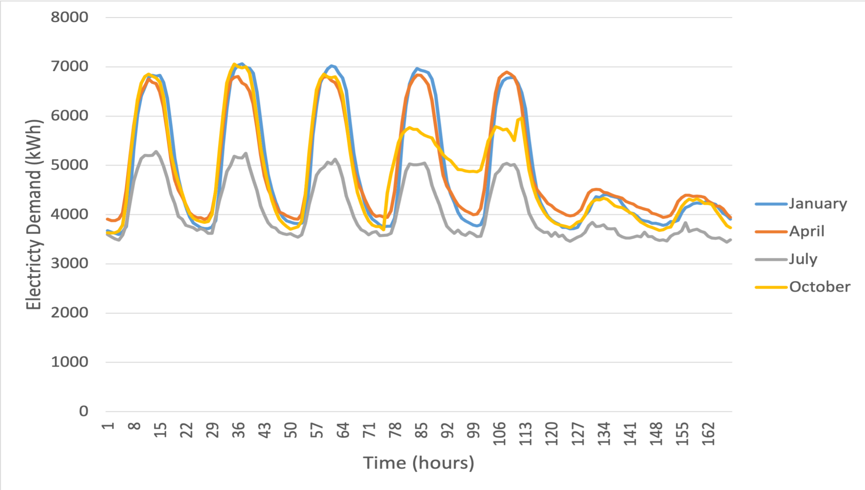
Figure 3.1: Local Energy System Structure. *Adapted from [48]*

The market solver will perform based on data provided regarding internal consumption and generation, and external network prices. For simplicity, it was assumed that all forecasts were accurate and would not deviate prior to physical energy delivery. In this section, utilized data and assumptions will be discussed.

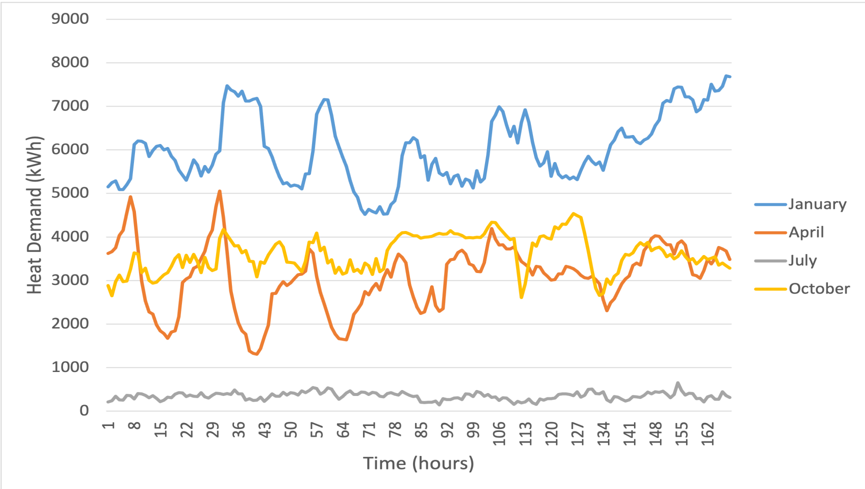
3.2.1 Consumption Data

The main demand side participants of the market are buildings situated within the Chalmers Johanneberg campus. These buildings include offices, lecture halls, study areas, research facilities, the library, and some commercial areas such as cafés [17]. Forecasted energy demand and consumption will be based on 2016-2017 building usage profiles. Consumption within the Johanneberg campus will be represented as a single actor who will place bids to ensure the hourly demand of the buildings are being met. Chalmers' Lindholmen campus will not be included in the internal market, however, local production could be sold to the Lindholmen campus for a profit, as will be discussed later in this chapter. Bids from the Lindholmen campus will be placed by a separate agent.

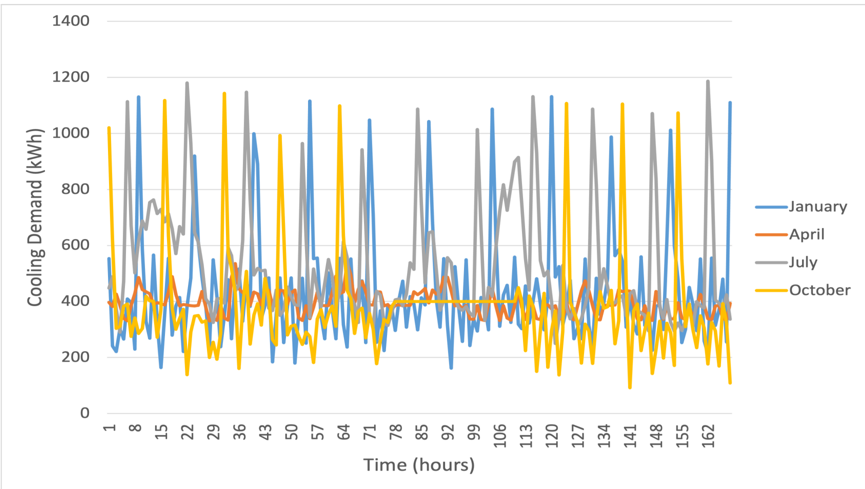
Aforementioned, the model is simulated during four periods, one week for every season. This is done to achieve accurate results as loads and solar PV production will vary considerably over the year. Figure 3.2 illustrates the total Johanneberg electricity, heat and cooling demand profiles for each of the time frames investigated. The magnitudes of electricity, heat, and cooling demand within the weeks investigated are also shown in Table 3.1. Lindholmen demand is assumed to be 1/3 of Johanneberg's internal demand. All data was obtained from [48].



(a) Electricity profile



(b) Heating profile



(c) Cooling profile

Figure 3.2: Electricity, Heat, and Cooling Demand Profiles [48]

Table 3.1: Magnitudes of Johanneberg Electricity, Heat, and Cooling Demand [48]

	Maximum (kWh)	Minimum (kWh)	Average (kWh)
Electricity	7062.34	3441.47	4676.44
Heating	7699.86	139.20	3262.60
Cooling	1186.67	91.90	433.08

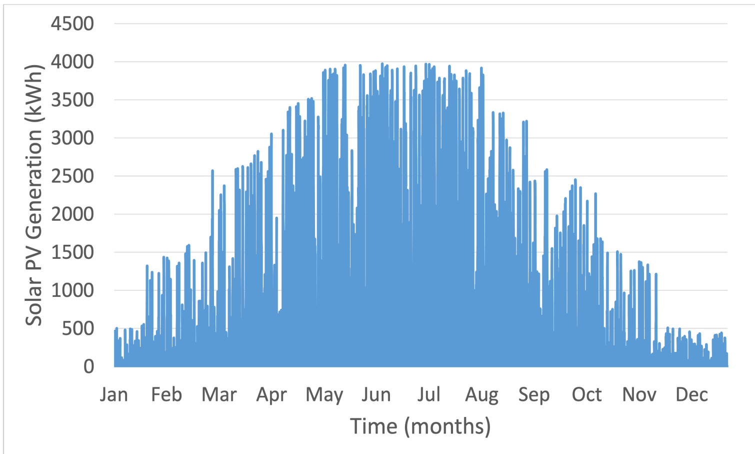
Seasonal, weekly, and day-to-day variations in energy consumption are all factors to consider when analyzing demand profiles. Unusual occurrences, such as severe weather conditions, might significantly impact demand. The increase and decrease in energy demand is generally known as peaks and valleys, respectively. The electricity demand profiles of the buildings were seen to vary, most notably with two buildings, Kemi and MC2, consuming a majority of the electricity. The demand is generally higher during weekdays, but also fluctuates over the course of a day. Electricity demand is also noted to reduce during the summer months, which can be allocated to the warmer climate and reduction of students and staff on campus. A similar pattern can be seen in the heat demand profile.
Heat demand has a strong link to the outdoor temperature, such that demand decreases with increasing temperature. Both heat and electricity profiles were noted to have comparably lower peaks and valleys in the summer season.
The cooling demand was seen to vary amongst the buildings, with the Kemi building requiring the most cooling. Most buildings demand cooling throughout the year, while some mainly during the summer months [49].

3.2.2 Local Generation

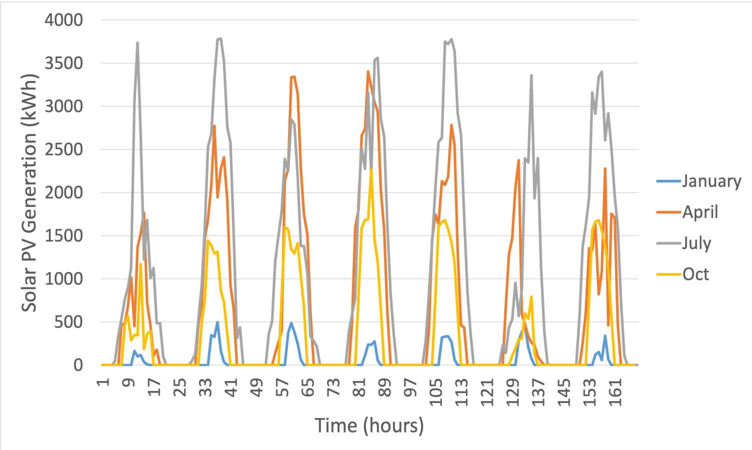
The local electricity, heating and cooling generation systems designed for the study were based on existing technologies utilized at Chalmers University, and their respective characteristics. This section illustrates all the input parameters of the energy technologies utilized, all which are based on the study conducted by Alavijeh et al. [48].

3.2.2.1 Solar PV

Renewable technologies are strongly affected by meteorological conditions, thus manipulating the intermittent feed-in of solar power into the market. Data for solar PV generation is thus based on the assumption that historical generation records can be utilized as “real-time” hourly PV generation. Based on a prior study conducted at Chalmers University, the capacity of campus PV generation data was moderately increased in the study for more noteworthy results [49]. Figure 3.3 shows the enhanced production profile of solar PV 2016-2017 (a), as well as for each of the weeks assessed (b). As expected, solar PV generation is significantly higher during the day and summer months.



(a) 2016-2017 profile



(b) Weekly profile

Figure 3.3: Solar PV Generation Profile [48]

3.2.2.2 Battery Energy Storage

In accordance with [48], Chalmers' network contains 2 battery energy storage units with respective power capacities and energy capacities of 100 and 50 kW, and 200 and 100 kWh. Both storage units have a charge and discharge efficiency of 95% and must maintain a minimum state of charge of 0.2. Table 3.2 summarizes the characteristics of both energy storage units.

Table 3.2: Characteristics of Battery Energy Storage (2 Units) [48]

Input Parameter	Value
Power capacity of BES ($Pcap_{bes}$)	100 and 50 kW
Energy capacity of BES ($ENcap_{bes}$)	200 and 100 kWh
Charging/Discharging Efficiency of BES (η_{bes})	0.95
Minimum state of charge of BES (SOC_{min})	0.2

3.2.2.3 Combined Heat & Power

The CHP unit at Chalmers is set to use wood chips as its primary fuel. The fuel cost is thus assumed to be 0.14 SEK/kWh [50]. Aforementioned, the CHP unit consists of a boiler and a turbine, and is able to generate both heat and electricity simultaneously to the electricity and district heating networks. Heat is initially produced via the boiler. The system then regulates how much of that heat is sent to the local district heat network ($Q_{CHP_{b2g}}$), and how much is sent to the turbine ($Q_{CHP_{tr}}$), making electricity production very flexible. In this study, it is assumed that any heat that is not converted into power can be recovered and redirected to the local district heat network ($Q_{CHP_{htr}}$). The following schematic provides an overview of the total energy production from the CHP unit.

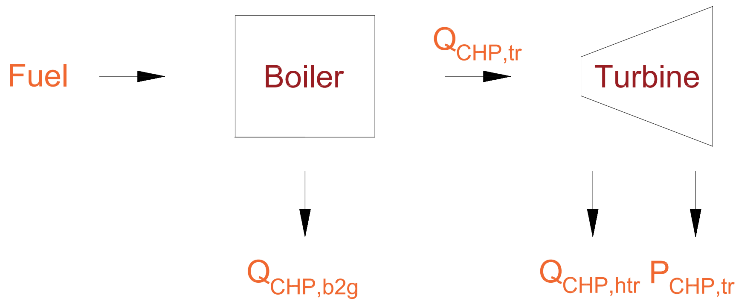


Figure 3.4: CHP General Schematic

As all generation units, production from the CHP unit is limited based on its maximum capacity, which is set to 6000 kW and 800 kW for the boiler and turbine, respectively. Efficiencies for the boiler and turbine are 77% and 17%, respectively. The CHP unit also has a ramp up and down capacity of 1000 kW, limiting the change of energy flow from one time unit to the next. This mitigates changes in production and flow in the grid, ensuring control of frequency and security of supply [51]. Table 3.3 summarizes all the technology characteristics of the CHP unit.

Table 3.3: Characteristics of Combined Heat & Power Unit [48]

Input Parameter	Value
CHP boiler capacity ($Qcap_{CHP_b}$)	6000 kW
CHP turbine capacity ($Qcap_{CHP_{tr}}$)	800 kW
Efficiency of CHP boiler (η_{CHP_b})	0.77
Electrical Efficiency of CHP turbine ($\eta_{CHP_{tr}}$)	0.17
Ramp Up Capacity of boiler (RU_b)	1000 kW
Ramp Down Capacity of boiler (RD_b)	1000 kW

3.2.2.4 Biomass Boiler & Flue Gas Condenser

Similar to the CHP unit, the biomass boiler also uses wood chips as its primary fuel, with the same fuel cost of 0.14 SEK/kWh [50]. The flue gas condenser is utilized to capture and recover heat that was not absorbed from the boiler. The maximum capacity and efficiency of the biomass boiler and flue gas condenser is 8000 kW and 77%, and 1000 kW and 50%, respectively. Changes in the boiler's output is also limited to the ramp-up and ramp-down limits of 1000kW. Table 3.4 summarizes all the technology characteristics of this unit.

Table 3.4: Biomass Boiler & Flue Gas Condenser Technology Characteristics [48]

Input Parameter	Value
Biomass boiler capacity ($Qcap_b$)	8000 kW
Flue gas condenser capacity ($Qcap_{fgc}$)	1000 kW
Efficiency of biomass boiler (η_b)	0.77
Efficiency of flue gas condenser (η_{fgc})	0.5
Ramp Up Capacity of boiler (RU_b)	1000 kW
Ramp Down Capacity of boiler (RD_b)	1000 kW

Due to limits within the network structure of the university, exported heat to the external DH network is limited to the output of the biomass boiler [48].

3.2.2.5 Thermal Energy Storage Tank

In accordance with [48], Chalmers' thermal energy storage tank has a charging and discharging heat capacity of 11 MWh/h and 23 MWh/h, respectively. It has an energy capacity of 39 MWh and a charging/discharging efficiency of 95%. Table 3.5 summarizes the characteristics of the thermal storage unit.

Table 3.5: Characteristics of Thermal Energy Storage Tank [48]

Input Parameter	Value
Charging capacity of TES ($Qcap_{ch,tes}$)	11 MWh/h
Discharging capacity of TES ($Qcap_{dis,tes}$)	23 MWh/h
Energy capacity of TES ($ENcap_{tes}$)	39 MWh
Charging/Discharging Efficiency of TES (η_{tes})	0.95
Losses in TES ($loss_{tes}$)	0.01

3.2.2.6 Absorption Chiller

The absorption chiller allows for system flexibility by utilizing heat from the district heating network to generate cooling for the district cooling system. The unit only operates during the months May through October, during the cooling season, at a minimum operation limit of 200 kW. Due to the design of the network, the chiller only receives heating from the external district heating network, at a capacity of 2300 kW. The coefficient of performance of the absorption chiller is 0.5. Table 3.6 summarizes all the technology characteristics of this unit.

Table 3.6: Absorption Chiller Technology Characteristics [48]

Input Parameter	Value
Absorption Chiller capacity ($Qcap_{absc}$)	2300 kW
Coefficient of Performance of Absorption Chiller ($COP_{k,absc}$)	0.5
Minimum Cooling from Absorption Chiller ($Kmin_{abs}$)	200 kW

3.2.2.7 Heat Pumps

By utilizing electricity to generate heat to the district heating network and cooling to the district cooling network, the heat pump units are situated between the three energy carriers (electricity, heating, and cooling). This connection, although providing flexibility and production efficiency, also results in restrictions regarding the load factor of the heat pumps in order to ensure balance between energy production and consumption. As seen in the campus' energy system structure in Figure 3.1, the system contains three heat pumps – one used in the summer (HP_S), and two used in the winter season ($HP_{W1,2}$). Table 3.7 summarizes the parameters of the heat pumps, including each unit's coefficient of performance for cooling (COP_k) and heating (COP_q).

Table 3.7: Technology Characteristics of All Heat Pumps [48]

Heat Pumps	Power Capacity ($Pcap_{HP}$)	COP_q	COP_k
Summer season heat pump (HP_s)	216 kW	3	1.8
Winter season heat pump 1 (HP_{w1})	216 kW	3	1.8
Winter season heat pump 2 (HP_{w2})	203 kW	3.1	2.19

3.2.3 Importing & Exporting Prices

When comparing local demand and generation data, a deviation between supply and demand is observed. In order to establish an energy balance and maximize profit, electricity and heating can also be purchased from, or sold to, the external electricity market or district heat network, respectively. Grid prices have a direct impact on the market and this section will present how these prices were defined.

3.2.3.1 Electricity Grid Price

For the simulation, it is assumed that all external electricity is purchased from Nord Pool, thus, grid prices are obtained from historical 2016-2017 Nord Pool day ahead market prices, for region SE3 – ensuring realistic grid prices and fluctuations [52]. The variation in Nord Pool electricity prices can be seen in Figure 3.5, below.

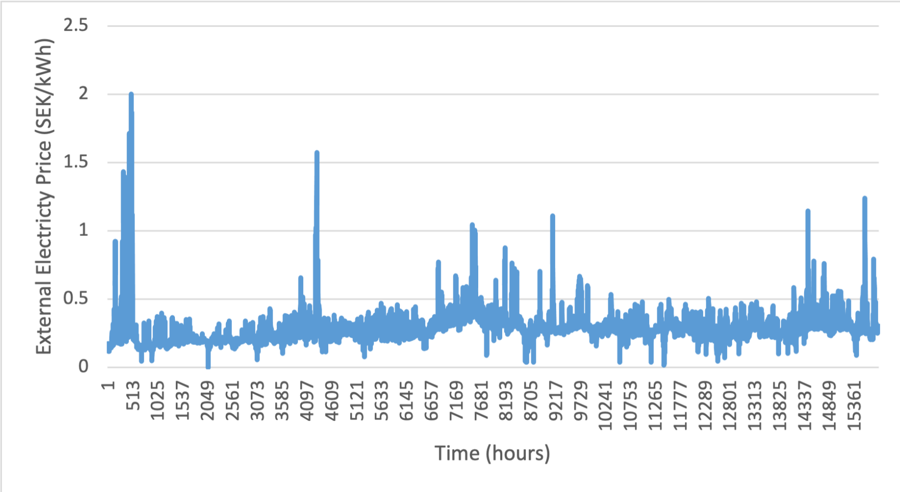


Figure 3.5: External Electricity Grid Price [52]

Operating a LEM does not directly signify cheaper energy prices, but the benefits are in the savings in ancillary and grid services. This is reflected in the model, for in addition to the price for the electricity, customers will pay a grid tariff when importing electricity, as a fee for transporting the energy. This fee is assumed to be 0.976 SEK/kWh in accordance with the Swedish Energy Markets Inspectorate [53]. Exporting heat from the LEM to the external grid is sold at the grid price with no additional cost, as an incentive for clean energy production. Energy exported to the Chalmers Lindholmen campus is assumed to be sold at a 10% discounted price from that of the external grid.

3.2.3.2 District Heating Network Price

With the intention of creating a dynamic interaction between the energy carriers, the hourly district heating prices are based on marginal prices of a typical generation mix in a Swedish district heating system, as shown in Figure 3.6 [48]. These prices include all additional service costs for importing the heat. The cost of external heat often differs depending on the season and hour, as it is subject to the utility used, input fuel, and demand. The summer periods typically use cheaper production methods, such as industrial waste heat, while winter peaks introduce more expensive facilities to meet the increasing energy needs that arise, such as thermal boilers, which have higher running costs [49]. In this way, the customer is also motivated to save energy during the winter as it is the most expensive time to produce.

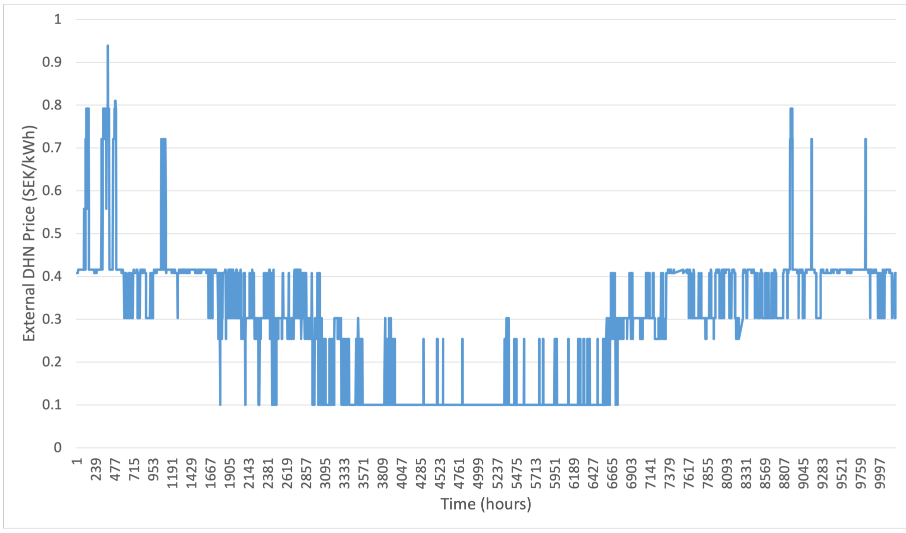


Figure 3.6: External DH Network Price [48]

As noted in literature, during the months of November to mid-April, exporting heat to the external DH network will have a set price of 0.3 SEK/kWh [49]. Otherwise, the value of exported heat is assumed to be zero due to the minimal heat demand [49]. Similar to electricity, heat exported to the Chalmers Lindholmen campus is sold at a 10% discounted price of that sold to the external DH network.

3.2.4 Assumptions

This model will represent a simplified market that is not analogous to reality, thus, assumptions are inevitable, and will consequently pose as the most imperative model limitations. Such assumptions include neglecting losses when distributing energy, and assuming perfect foresight, such that energy markets and loads are assumed to be optimally forecasted. Solar PV generation is assumed to be equal to past generation data. Other assumptions include the modeling of heat pumps, which have a fixed coefficient of performance (COP) factor. Additionally, both boiler units are assumed to have a ramping capacity rate of 1 hour, without any start-up costs. In consideration that energy produced on campus is clean, it is assumed that external grids are always willing to trade energy. Moreover, any potential impact of limited transfer capacities is neglected, insuring that market prices do not vary based on location, but only with time and energy carriers [18].
In order to simulate a feasible LEM case study, some site-specific limitations were neglected. For example, during the weekday working hours, realistically the biomass boiler and CHP units are generally not dispatchable as they are used for research purposes, however, it is assumed that in order to examine the practicality of an LEM at Chalmers, this can be disregarded. The base case is assumed to have no investment costs and demand side flexibility is neglected for simplicity.

3.3 LEM Market Model Formulation

By utilizing energy storage, flexibility and ability to switch between its different energy carriers, the Chalmers local energy market was designed to balance demand and supply, whilst reducing peak loads, and maximizing the usage of renewable energy, thus lowering both costs and the energy system's environmental effects [17]. The base model was modelled after the energy system of Chalmers University of Technology's Johannesburg campus, as presented in [48], with the purpose of using current energy investments as efficiently as possible.
In order to properly assess the feasibility of the model, the market trading timeline was set to align with the timeline for external markets. The problem was kept linear such that it can be solved via linear programming (LP) software. The energy technologies acting on the market were segregated and represented as 3 separate agents with the ability to trade within the internal and external energy markets. Agent 1 traded with the solar PV and 2 battery energy storage units, agent 2 generated energy via the CHP unit, the biomass boiler & flue gas condenser unit (B/FGC), and a thermal energy storage (TES) tank, and agent 3 encompassed all the heat pumps (HP) and the absorption cooler.

The trading process can be broken down into two segments: the preliminary stage and the market clearing stage – which can be further analyzed as follows: [17]

- Preliminary Stage:
  - Forecasting and estimation
  - Bid/Offer
- Production Stage:
  - Market Clearing
  - Execution

In the preliminary stage, market players make a forecast of what they believe their demand and production will be, and what the price for energy will be, in order to submit initial bids to the market. Forecasting aids in reducing or minimizing uncertainty, allowing agents to make effective bidding decisions in advance. Forecasting energy demand and supply can become quite complicated, as it is dependent on intermittent factors, such as meteorological conditions, the current state of the physical asset, future market prices, and the future demand for the physical asset itself. Based on these forecasts, and technical constraints, each agent can submit their bids based on marginal costs.
In the production stage, the day-ahead market is cleared prior to trading based on submitted bids, to reduce forecasting mistakes as participants can update their bids prior to delivery. This enhances precision, yet, has the potential to be a disadvantage for owners of larger production units as they won't be able to schedule their production ahead of time. This, however, is not a concern for this study, as the market is composed of various small-scale units. Once the market is cleared, market actors will be notified which transactions will take place at a set quantity and price.

Both stages of the trading process were simulated within the market solver such that the first part prepares the LEM for supplying energy, and the second part executes it by clearing the market and ensuring that enough energy is produced to meet demands. Since cooling will only be provided by agent 3, there is no competition for this energy carrier, thus, the case study will only include two markets: electricity and heating. The energy market activity diagram shown in Figure 3.7 presents a conceptual illustration of the simulation process when energy is traded within the market, for both energy carriers and their related services. The following subsections contain a more detailed examination of each segment in the market solver.

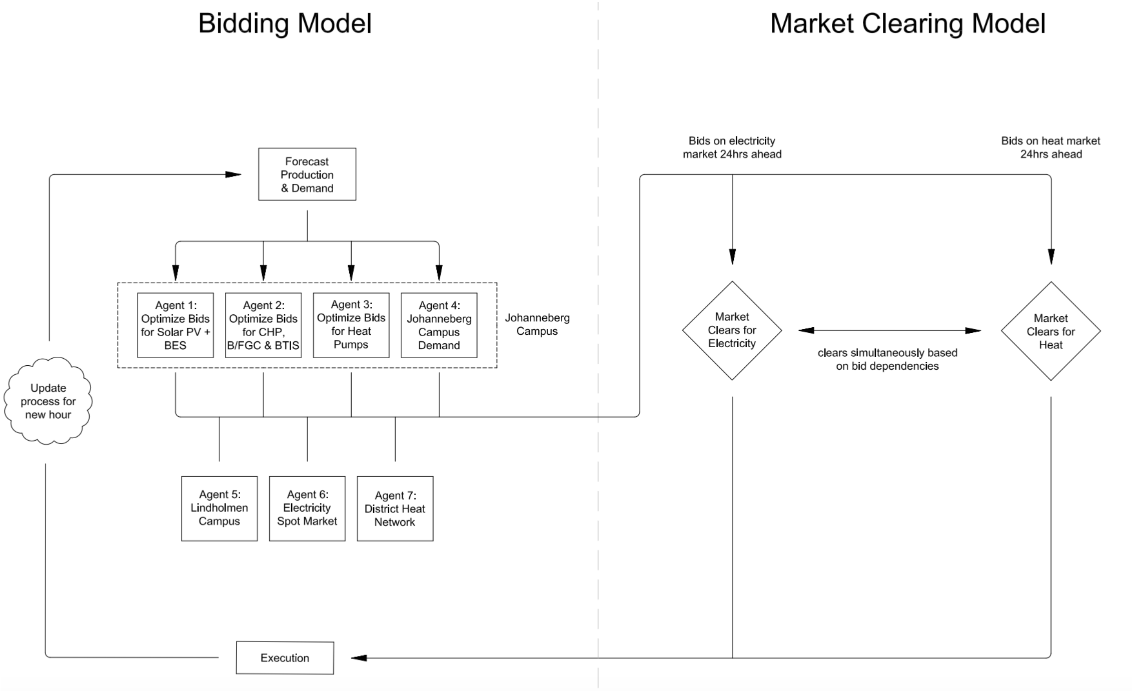


Figure 3.7: Energy Market Interaction Diagram. *Modified from [16]*

3.3.1 Bidding Model

The initial step of an energy market is forecasting. Aforementioned, forecasts in this study were based on historical data, assuming no equilibrium imbalances prior to market clearing. These forecasts include energy demands, solar PV production, and external energy network prices, per hour. Agents analyze forecasts and optimize strategies based on utility functions to generate offers accordingly. Such offers specify the energy carrier, the delivery-hour, the quantity (kWh) and the bid valuation (SEK/kWh).

Energy is commonly traded like a commodity and is exchanged during distinct time periods with the same length for all energy carriers. Agents will submit separate bids for different time periods. The bidding model simulated is thus time-dependent and is solved repeatedly every 24 hours, to reflect a day-ahead market; however, the time period could be longer or shorter in reality. This strategy is simulated in the bidding model using the rolling horizon approach. The rolling-horizon approach allows for a more realistic representation of the bids placed by the market players, as they can adjust their bids and undergo market clearing closer to the physical delivery-hour, based on more precise forecasts. A simplified representation of the rolling horizon approach can be seen in Figure 3.8. In the bidding model, the bids undergo market clearing once per hour, shortly before delivery-hour. The model also contains a range of future hours in order for the market to handle dependencies over extended periods of time. The trading horizon is the total number of hours included in a market clearing. As reflected in the figure, the binding hours are the first 24 hours of inputted data in the trading horizon [18]. As the name suggests, these results are final, unlike the subsequent hours, referred to as advisory hours, which will be revised in the following simulated loop to better match updated forecasts [18].

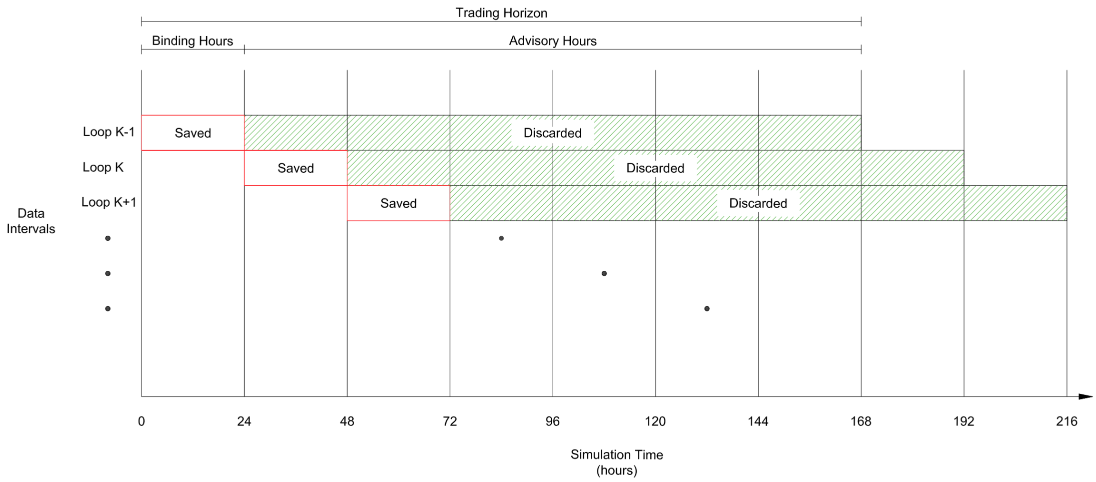


Figure 3.8: Simplified Rolling Horizon Diagram. *Modified from [54]*

This section will dive into the process of generating supply-side bid quantities that will maximize each agent's overall profit for the time period evaluated. Through tactful energy management of available units, each actor seeks to increase the likelihood of the market clearing its generation, in aims of increasing its profit or the social welfare. The derivations and equations in this subsection are adapted from [48].

3.3.1.1 Agent 1: Solar PV + Battery Energy Storage

Agent 1 can participate within the electricity market by offering energy produced via solar PV. With a zero-marginal cost of production, the renewable energy is prioritized in the order of dispatch. Agent 1's bidding strategy will thus be to optimize the ideal time to store energy, and subsequently when to discharge and sell that energy for a profit.

Objective function: Agent 1's objective is to maximize profit by selling electricity strategically. The optimization function is shown in equation 3.1.

$$Max \sum_{t=1}^{168} [p_{grid_{ex}}(t) \times e_{price}(t)] - [p_{grid_{im}}(t) \times (e_{price}(t) + e_{tax})], \quad \forall t \in \mathcal{T} \tag{3.1}$$

where $p_{grid_{im}}$ and $p_{grid_{ex}}$ represents the amount of electricity imported and exported from the external grid in kWh, respectively. e_{price} represents the expected price of electricity in SEK/kWh. This is set to the price of electricity from the external grid, as the current production capacity does not meet electrical demand, as will be discussed further in Chapter 4. e_{tax} refers to the transmission fees incorporated when importing energy from the external grid in SEK/kWh.

Energy Balance: The energy balance constraint is implemented to ensure demand is always met, as expressed in equation 3.2.

$$\begin{aligned} & p_{grid_{im}}(t) + P_{PV}(t) + p_{discharge_1}(t) + p_{discharge_2}(t) \\ = \; & P_{demand}(t) + p_{grid_{ex}}(t) + p_{charge_1}(t) + p_{charge_2}(t), \quad \forall t \in \mathcal{T} \end{aligned} \tag{3.2}$$

where P_{PV} and P_{demand} represent the forecasted solar PV production and electricity demand, respectively. $p_{discharge1,2}$ and $p_{charge1,2}$ represent the amount of energy discharged and charged within each of the two battery energy storage units.

Constraints: The battery energy storage units are limited to their respective energy capacities as shown in equations 3.3 and 3.4 .

$$SOC_{bes_{1,2}}(t) = SOC_{bes_{1,2}}(t-1) + \frac{p_{charge_{1,2}}(t) \times \eta_{bes} - \frac{p_{discharge_{1,2}}(t)}{\eta_{bes}}}{ENcap_{bes_{1,2}}}, \quad \forall t \in \mathcal{T} \tag{3.3}$$

$$SOC_{bes,min} \leq SOC_{bes}(t) \leq 1, \quad \forall t \in \mathcal{T} \tag{3.4}$$

Where the state of charge (SOC_{bes}) of each storage unit is related to its energy level in the previous time step, the amount it is charging (p_{charge}) or discharging ($p_{discharge}$), charging/discharging efficiency (η_{bes}), and respective energy capacity ($ENcap_{bes_{1,2}}$). In order to mitigate high degradation costs of the battery, and ensure reserve energy if needed, the state of charge of the batteries should not fall below 0.2.

The storage units should charge solely from PV production, as shown in equation 3.5).

$$0 \leq p_{charge_{1,2}}(t) \leq P_{PV}(t), \quad \forall t \in \mathcal{T} \tag{3.5}$$

Based on the optimization expressed, the model will return the desired amount of energy that Agent 1 should offer per hour and at which time steps the agent is prompted to store a specific quantity of energy for future offers.

3.3.1.2 Agent 2: Combined Heat & Power + Boiler & Flue Gas Condenser + Thermal Energy Storage

Agent 2 can participate in the electricity and heat market by offering heat produced by the CHP and B/FGC units, as well as electricity production from the CHP unit. The agent also contains a TES unit, which can be charged by both the CHP and B/FGC units. The agent will place a bid in the electricity market, and two bids in the heat market, based on the predicted cost of production from each unit, as will be further discussed in the following subsection. Agent 2's bidding strategy is to optimize its offered quantity in each market to maximize profit.

Objective function: Like Agent 1, Agent 2's objective is to maximize profits. As long as it is cost-effective to generate energy, the objective is typically met by reducing energy imports from the external system and increasing energy exports. Else, when energy prices are low, demand will be met by importing. In addition, costs associated with the amount of fuel used for each unit must also be considered, as shown in equation 3.6.

$$\begin{aligned} Max \sum_{t=1}^{168} [p_{grid_{ex}}(t) \times e_{price}(t)] - [p_{grid_{im}}(t) \times (e_{price}(t) + e_{tax})] + [q_{DH_{ex}}(t) \times (h_{price_{ex}}(t)] \\ -[q_{DH_{im}}(t) \times (h_{price_{im}}(t)] - [q_{fuel_{CHP_b}}(t) \times f_{price}] - [q_{fuel_b}(t) \times f_{price}], \quad \forall t \in \mathcal{T} \end{aligned} \tag{3.6}$$

where $h_{price_{im}}$ and $h_{price_{ex}}$ represent the expected price of importing and exporting heat, respectively. Expected prices are assumed to be equal to that of DHN price for simplicity, but to also to maintain hourly fluctuating prices, thus creating more dynamic interactions between the energy carriers. Similarly, $q_{DH_{im}}$ and $q_{DH_{ex}}$ represent the quantity of heat imported or exported to the grid. $q_{fuel_{CHP_b}}$ and q_{fuel_b} depict the quantity of fuel inputted into the CHP and boiler units, respectively, at a fuel price of f_{price}.

Energy Balance: Equations 3.7 and 3.8 are implemented to ensure demand is always met in both the electricity and heat markets.

$$p_{grid_{im}}(t) + p_{CHP_{tr}}(t) = P_{demand}(t) + p_{grid_{ex}}(t), \quad \forall t \in \mathcal{T} \tag{3.7}$$

$$\begin{aligned} q_{DH_{im}}(t) + q_{CHP}(t) + q_{b/fgc}(t) + q_{discharge}(t) \\ = Q_{demand}(t) + q_{DH_{ex}}(t) + q_{charge}(t), \quad \forall t \in \mathcal{T} \end{aligned} \tag{3.8}$$

where $p_{CHP_{tr}}$ represents the amount of power that is produced from the CHP's turbine. The amount of heat produced by the CHP and boiler + flue gas condenser units are depicted by q_{CHP} and $q_{b/fgc}$, respectively. Heat produced from the CHP unit is based on the heat produced from the boiler and sent to the district heat network, and the recaptured heat from the turbine ($q_{CHP_{htr}}$) (equation 3.9). q_{charge} and $q_{discharge}$ represent the amount of energy charged and discharged from the thermal energy storage tank, respectively.

$$q_{CHP}(t) = q_{CHP_{b2g}}(t) + q_{CHP_{htr}}(t), \quad \forall t \in \mathcal{T} \tag{3.9}$$

Constraints: Due to limitations of the current network structure, the amount of heat that can be exported is restricted to the output of the biomass boiler (equation 3.10).

$$q_{DH_{ex}}(t) \leq q_b(t), \quad \forall t \in \mathcal{T} \tag{3.10}$$

Aforementioned, in order to keep electricity production flexible, the system regulates how much of that heat is sent directly to the district heat network ($q_{CHP_{b2g}}$), and how much is sent to the turbine ($q_{CHP_{tr}}$) (equation 3.11). Based on equations obtained from [48], the amount of heat generated by the boiler (q_{CHP_b}) is proportional to the amount of fuel used ($q_{fuel_{CHP_b}}$) and the efficiency of the unit (η_{CHP_b}) (equation 3.12). Similarly, the amount of power that the turbine can output is determined based on the amount of heat it receives and its efficiency (η_{tr}) (equation 3.14).

$$q_{CHP_b}(t) = q_{CHP_{b2g}}(t) + q_{CHP_{tr}}(t), \quad \forall t \in \mathcal{T} \tag{3.11}$$

$$q_{CHP_b}(t) = q_{fuel_{CHP_b}}(t) \times \eta_{CHP_b}, \quad \forall t \in \mathcal{T} \tag{3.12}$$

$$q_{CHP_{htr}}(t) = q_{CHP_{tr}}(t) \times (1 - \eta_{tr}), \quad \forall t \in \mathcal{T} \tag{3.13}$$

$$p_{CHP_{tr}}(t) = q_{CHP_{tr}}(t) \times \eta_{tr}, \quad \forall t \in \mathcal{T} \tag{3.14}$$

Moreover, the amount of heat that can be produced from the CHP boiler and turbine is limited to their respective capacities as shown in equations 3.15 and 3.16. Additionally, the ramp-up (RU_b) and ramp-down (RD_b) limits restrict large deviations in the boiler's production between time steps (equation 3.17).

$$0 \leq q_{CHP_{tr}}(t) \leq Qcap_{CHP_{tr}}, \quad \forall t \in \mathcal{T} \tag{3.15}$$

$$0 \leq q_{CHP_b}(t) \leq Qcap_{CHP_b}, \quad \forall t \in \mathcal{T} \tag{3.16}$$

$$RU_b \leq q_{CHP_b}(t) - q_{CHP_b}(t-1) \leq RD_b, \quad \forall t \in \mathcal{T} \tag{3.17}$$

The amount of heat generated in the boiler (q_b) and flue gas condenser (q_{fgc}) is combined and analyzed as one ($q_{b_{fgc}}$), for the two components are in the same unit (equation 3.18). The amount of heat generated in the boiler is proportional to the amount of heat utilized and the boiler's efficiency (equation 3.19). Additional heat that is recovered from the flue gas condenser is equivalent to the heat not consumed by the boiler and flue gas condenser's efficiency (equation 3.20).

$$q_{b/fgc}(t) = q_b(t) + q_{fgc}(t), \quad \forall t \in \mathcal{T} \tag{3.18}$$

$$q_b(t) = q_{fuel_b}(t) \times \eta_b, \quad \forall t \in \mathcal{T} \tag{3.19}$$

$$q_{fgc}(t) = q_{fuel_b}(t) \times (1 - \eta_b) \times \eta_{fgc}, \quad \forall t \in \mathcal{T} \tag{3.20}$$

Similar to CHP's boiler unit, the biomass boiler is restricted to the same ramp-up and ramp-down limits (equation 3.21). The amount of heat that can be produced from the boiler and flue gas condenser is limited to their respective capacities (equations 3.22 and 3.23).

$$RU_b \leq q_b(t) - q_b(t-1) \leq RD_b, \quad \forall t \in \mathcal{T} \tag{3.21}$$

$$0 \leq q_b(t) \leq Qcap_b, \quad \forall t \in \mathcal{T} \tag{3.22}$$

$$0 \leq q_{fgc}(t) \leq Qcap_{fgc}, \quad \forall t \in \mathcal{T} \tag{3.23}$$

Constraints for the thermal energy storage tank are similar to that of the battery energy storage unit. The TES is also limited to its energy capacities as shown in equations 3.24 and 3.25 .

$$SOC_{tes}(t) = [SOC_{tes}(t-1) \times loss_{tes}] + \frac{q_{charge}(t) \times \eta_{tes} - \frac{q_{discharge}(t)}{\eta_{tes}}}{ENcap_{tes}}, \quad \forall t \in \mathcal{T} \tag{3.24}$$

$$0 \leq SOC_{tes}(t) \leq 1, \quad \forall t \in \mathcal{T} \tag{3.25}$$

Where the state of charge (SOC_{tes}) of the storage unit is related to its energy level in the previous time step, the amount it is charging (q_{charge}) or discharging ($q_{discharge}$), charging/discharging efficiency (η_{tes}), energy capacity ($ENcap_{tes}$), and losses ($loss_{tes}$).

The thermal storage unit can charge from both CHP and B/FGC production, as seen in equation 3.26.

$$q_{charge}(t) \leq q_{b/fgc}(t) + q_{CHP}(t), \quad \forall t \in \mathcal{T} \tag{3.26}$$

Based on the optimization expressed, the model will return the desired amount of energy that Agent 2 should offer for each unit, at each time step, in addition to which time steps the agent should store energy for future usage.

3.3.1.3 Agent 3: Heat Pumps + Absorption Chiller

Agent 3 represents the heat pumps and an absorption chiller, thus, the agent will participate as a generator in the heat market, but also as a consumer in the electricity market. Due to the layout of the network, the absorption chiller always obtains its heat input from the external district heat network to produce cooling within the internal network.

Objective function: Agent 3's objective is to maximize its profit by bidding at the highest probable value of clearing for the heat pumps, aware that clearing will be dependent on the price of electricity, as will be discussed in the next section. As seen in Figure 3.1, the absorption chiller can only obtain heat from the external network due to campus network constraints.

$$\begin{aligned} Max \sum_{t=1}^{168} -[p_{HP_n}(t) \times e_{price}(t)] - [q_{DH_{im}}(t) \times h_{price_{im}}] \\ -[q_{absc}(t) \times h_{price_{im}}], \quad \forall t \in \mathcal{T} \end{aligned} \tag{3.27}$$

where, HP_n represents any of the three heat pumps: HP_s, HP_{w1} and HP_{w2}.

Energy Balance: Equations 3.28 and 3.29 are implemented so that the agents aim to meet both heat and cooling demands.

$$q_{DH_{im}}(t) + q_{HP_n}(t) = Q_{demand}(t), \quad \forall t \in \mathcal{T} \tag{3.28}$$

$$k_{absc}(t) + k_{HP_n}(t) = K_{demand}(t), \quad \forall t \in \mathcal{T} \tag{3.29}$$

where k_{absc} refers to cooling from the absorption chiller.

Constraints: The amount of heat and cooling generated in each heat pump is related to its specific coefficient of performance and power input (equation 3.30 and 3.31). The amount of cooling generated in the absorption cooler is related to the cooling coefficient of performance and heat input (equation 3.32). The electricity input to the absorption cooler is comparably minimal, thus neglected.

$$q_{HP_n}(t) = COP_{q_{HP_n}} \times p_{HP_n}(t), \quad \forall t \in \mathcal{T} \tag{3.30}$$

$$k_{HP_n}(t) = COP_{k_{HP_n}} \times p_{HP_n}(t), \quad \forall t \in \mathcal{T} \tag{3.31}$$

$$k_{absc}(t) = COP_{k_{absc}} \times q_{absc}(t), \quad \forall t \in \mathcal{T} \tag{3.32}$$

Moreover, the amount of heat and cooling that can be produced from the heat pumps and absorption cooler is limited to their respective capacities as shown in equations 3.33 and 3.34. During the warmer months (May – October) the absorption chiller has a minimum operation limit of 200 kW (equation 3.35).

$$p_{HP_n}(t) \leq Pcap_{HP_n}, \quad \forall t \in \mathcal{T} \tag{3.33}$$

$$q_{absc}(t) \leq Qcap_{absc}, \quad \forall t \in \mathcal{T} \tag{3.34}$$

$$K_{absc}(t) \geq Kmin_{absc}, \quad \forall t \in \mathcal{T} \tag{3.35}$$

Based on the optimization expressed, the model will return the desired amount of electricity agent 3 should purchase/bid for in the electricity market, and the amount the agent should simultaneously offer in the heating market, at each time step.

3.3.1.4 Agent 4 & 5: Johanneberg & Lindholmen Campus Demand

Agents 4 and 5 place bids within the marketplace representing the electricity and heat demand from Johanneberg and Lindholmen campus, respectively. Aforementioned in subsection 3.2.1, Johanneberg campus demand will be based on historical consumption data, while Lindholmen campus will be assumed to be 1/3 of Johanneberg campus' demand.

3.3.1.5 Agent 6 & 7: Electricity Spot Market & District Heat Network

Agents 6 and 7 represent the external electricity grid and district heat network. As noted in subsection 3.2.3, heat and electricity prices were similarly based off historical prices obtained from Göteborg Energi and Nord Pool market data, respectively. It is assumed that remaining demand that can not be met by Agents 1, 2 and 3, can always be met by the external networks.

3.3.2 Local Energy Market Clearing Model

Following the bidding model, the market clearing portion of the simulation is utilized to connect the physical assets and facilitate energy trading. Once all the bids have been received, the market clearing portion of the model clears the market by identifying which bids will be accepted. This is done in a simultaneous and interconnected manner for both electricity and heat energy carriers, in order to leverage potential synergies.
The model is conducted as a two-sided auction, meaning both consumption and production biddings are considered in the same market clearing, ensuring equivalent clearing of both sides. The model also follows the guidelines of the uniform price auction, such that all accepted bids pay or receive at the market price. [18] The solver is based on standard economic theory that the objective of a market is to maximize the total system benefit, as shown as the area between cleared consumption and generation in the illustrated example in Figure 3.9. The equilibrium point is that which allows to maximize social welfare.

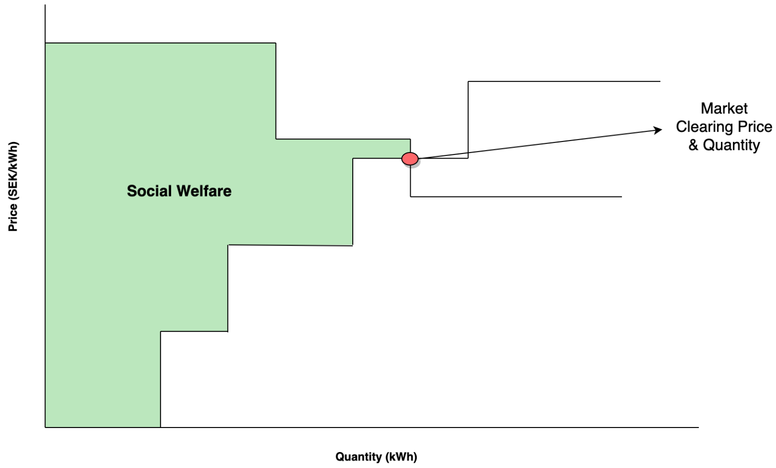


Figure 3.9: Market Clearing for Social Welfare

The market clearing can be solved by applying the duality property of linear programming problems. The objective of maximizing social welfare is written as shown in equation 3.36, where e and h represent the electricity and heat energy carriers, respectively. The objective function is subject to equation 3.37, such that demand must always equal supply, for each of the energy carriers separately. The generation and consumption level to optimize social welfare is constrained within equations 3.38 and 3.39, also for each of the energy carriers.

$$\max_{y_i^D, y_j^G} [\sum_i \lambda_i^D(t) y_i^D(t) - \sum_j \lambda_j^G(t) y_j^G(t)]_e + [\sum_i \lambda_i^D(t) y_i^D(t) - \sum_j \lambda_j^G(t) y_j^G(t)]_h, \quad \forall t \in \mathcal{T} \tag{3.36}$$

subject to:

$$\sum_j y_j^G(t) - \sum_i y_i^D(t) = 0, \quad \forall t \in \mathcal{T} \tag{3.37}$$

$$0 \leq y_i^D(t) \leq P_i^D(t), i = 1, ..., N_D, \quad \forall t \in \mathcal{T} \tag{3.38}$$

$$0 \leq y_j^G(t) \leq P_j^G(t), j = 1, ..., N_G, \quad \forall t \in \mathcal{T} \tag{3.39}$$

where D and G refer to demand and generation, respectively, and i and j represent the consumer and supplier agents, respectively. λ symbolizes the bidding valuation, while P and y symbolize the offered and cleared quantities, respectively. N represents the numbers of participants.
By completing the market clearing, the simulation generates a list of accepted offers for supply and demand side, and their respective cleared quantities. This is classified as the primal linear program. The price at which the market is cleared is generally equal to the highest-valued accepted bid valuation. It can be obtained through the duality of the linear program defined before, as shown in equations 3.40 through 3.44, where v_i^D and v_j^G are Lagrange multipliers representing the unitary benefits for the various demand and supply offers if the market is cleared at λ^S, in SEK/kWh. By solving the dual linear program, the system price and utility benefits on the demand and supply side can be determined.

$$\begin{aligned}\max_{\lambda^S, v_i^D, v_j^G} & [-\sum_j vj^G(t)P_j^G(t) - \sum_i v_i^D(t)P_i^D(t)]_e \\ +[-\sum_j vj^G(t)P_j^G(t) & - \sum_i v_i^D(t)P_i^D(t)]_h, \quad \forall t \in \mathcal{T}\end{aligned} \tag{3.40}$$

subject to:

$$\lambda^S(t) - v_j^G(t) \leq \lambda_j^G(t), j = 1, ..., N_G, \quad \forall t \in \mathcal{T} \tag{3.41}$$

$$-\lambda^S(t) - v_i^D(t) \leq -\lambda_i^D(t), i = 1, ..., N_D, \quad \forall t \in \mathcal{T} \tag{3.42}$$

$$v_j^G(t) \geq 0, j = 1, ..., N_G, \quad \forall t \in \mathcal{T} \tag{3.43}$$

$$v_i^D(t) \geq 0, i = 1, ..., N_D, \quad \forall t \in \mathcal{T} \tag{3.44}$$

It is vital that the energy market clearing is conducted in an interconnected and simultaneous manner, such that agents can create links between the bids of different energy carriers. Despite the fact that the different energy carriers are traded in the same market clearing, they are nevertheless considered as distinct commodities, thus, their individual market clearing prices do not need to be equivalent. Brolin et al.[18] introduces the concept of applying bid-dependencies as a mechanism to create such links, providing flexibility to the market amongst other advantages. The theory behind AND-dependencies was enforced in this study, affirming that bids are treated by the market as complements that need to be accepted or rejected in tandem [18]. Moreover, it allows for circumstances in which an uneconomical bid may be accepted, as long as the other bid connected within the same dependency compensates for it, generating an overall profit [18]. This is particularly applicable for the CHP and heat pump units, where partial clearing of bids may be necessary to ensure the same proportion of each bid clears the market. The amount of heat that can be cleared from the CHP turbine is dependent on the portion of electricity that is cleared. Similarly, the heat pump bids will only clear if the profit of selling heat exceeds that of purchasing electricity, in respect to the equipment's COP. Therefore, bids that include an AND-dependency have the following constraint:

$$\frac{y_{b_i}}{P_{b_i}} = \frac{y_{b_j}}{P_{b_j}}, \quad \forall (b_i, b_j) \in r, \quad \forall r \in R^{AND} \tag{3.45}$$

where b is the index of the specific technology the AND-dependency is set for.

With the objective of maximizing social welfare, an individual bid may be accepted even if it has a loss in one market, considering that the other bid in the same dependency compensates for it, generating an overall profit. By solving the complete market optimization, bids that should be accepted and those which should be rejected are listed, alongside the market clearing price, for each time-step and energy carrier. As the trading on the market is fully automated, there is no need for interaction between the end users apart from administration and operation.

3.3.2.1 Bid Valuation

The term valuation is utilized in preference to price, as a means to distinguish the difference between the bid prices offered by each technology, and the final prices that are obtained following market clearing. Theoretically, offer prices for generated energy are dependent on a technology's geographical position in the system, time, and energy carrier [17]. In this study, agents can place multiple offer prices, based on each unit's generation cost as a function of quantity c(q). To incentivise buyers to purchase energy locally, energy produced from the local market should not be priced significantly higher than that of the external market.

Determining the bid valuation for some participants is comparably simple, as they submit one bid per hour, at a specific quantity and energy carrier (supply or demand). This is specifically true for agent 1 (PV & BES units), agents 4 and 5 (demand bids from the buildings), agent 6 (the electricity grid), and agent 7 (the district heat network). These players cannot provide flexibility across time or energy carriers, and consequently, no bid dependencies are applied. Rather, in this study, solar PV generation will place an offer at a price of 0 SEK/kWh, as there are no additional operational costs to produce an extra unit of energy. The battery energy storage unit is charged by solar PV, with no operating costs, thus will bid jointly with solar PV when discharging to make a profit. Internal demand bids placed by agent 4 will be set at a high valuation to ensure the demand is always met. Bids for the Chalmers Lindholmen campus, however, will be set at 90% of the external grid price.

On the contrary, production from the CHP unit will be illustrated by 3 separate bids – heat generated directly from the boiler, captured heat from the turbine and electricity produced from the turbine. In this study, heat produced from the turbine is considered as a by-product and is thus offered at a price of 0 SEK/kWh. Conversely, the price for heat that is sent directly to the network from the boiler was calculated to be 0.19 SEK/kWh, based on equation 3.48, below.

$$\frac{f_{price}}{\eta_{CHP_b}} \tag{3.46}$$

CHP electricity offer price was calculated to be 1.09 SEK/kWh via the equation shown in 3.47:

$$\frac{f_{price}}{\eta_{CHP_b} \times \eta_{tr}} \tag{3.47}$$

Offer prices for heat produced from the boiler and flue gas condenser was calculated to be 0.16 SEK/kWh, as shown below.

$$\frac{f_{price}}{\eta_b + (1 - \eta_b) \times \eta_{fgc}} \tag{3.48}$$

Heat pumps offer energy at a valuation of 0 SEK/kWh, not to be confused as a maximum price, but to be seen in the context of the other bids in the AND-dependency [18].

For clarity, consider an example with HP_s, in which it consumes electricity and produces heat at a ratio of 30:90, and that the valuation for both the electricity purchase bid and the heat supply bid is set to 0. Thus, 2 bids are placed as demonstrated:

- Bid 1: (-30,0) for electricity
- Bid 2: (90,0) for heat

To understand why bidding is conducted in such a manner, the role of the actor must be assessed. Agent 3 aims to make a profit by obtaining the difference presented in 3.49 - acquired by simplifying 3.36 and adding the 0 valuations to clearly reflect agent 3's objective.

$$0 \leq [\sum_i \lambda_i^D y_i^D]_h - [\sum_j \lambda_j^G y_j^G]_e \tag{3.49}$$

Thus, it may be noted that the relation between the electricity price and heat price is that of concern, rather than the prices in absolute values. Therefore, upon examining the given example, as long as the prices fulfill the requirement of $\lambda_{jh}^G \geq \frac{30}{90} \times \lambda_{ie}^D$, the actor is satisfied, otherwise, the actor will not place a bid. Accordingly, the market clearing will only accept bids connected with the aforementioned AND-dependency if $\frac{y_{ie}^D}{30} = \frac{y_{jh}^G}{90}$, or $y_{jh}^G = \frac{90}{30} \times y_{ie}^D$, setting a constraint for how energy for the different carriers are consumed and produced. Results must also comply with the model's objective function when clearing, such that maximum social welfare is achieved. Therefore, bids will only clear if the market value in the clearing of supplying heating exceeds the market value (or market cost) of the consumed electricity. As a result, the objective of actor 3 is met if the bids are cleared, despite it being explicitly defined in the bidding stage, but implicitly through the clearing mechanism.[18]

Finally, no offers will be placed by the absorption chiller, as will be further discussed in the following section.

3.4 Sensitivity Analysis Scenarios

The focus of this chapter is to conduct a sensitivity analysis on the base case simulation to determine the dependency of the model output from model input. This paper analyzes the impact of increasing solar PV and CHP capacity on local energy trading. It also tests the effect of extreme price fluctuations within the external electric grid, on the local energy market.

3.4.1 Increased Solar PV and CHP Capacity

Over the past decade, the cost of solar PV panels has fallen dramatically. As technology advances, solar PV technology is expected to increase in efficiency and continue to become available at lower costs. Additionally, with the rise in electrical demand, investing in technologies that meet this demand has been become more plausible. This subsection will examine the effect of optimizing the base case energy mix by specifically increasing solar PV and CHP capacity, such that the Chalmers campus microgrid could meet more of its internal electricity demand, whilst accounting for associated investment costs. Determining the optimal expansion was conducted by developing an Optimized Capacity Modeling code on python. The code optimized investment quantities by considering annualized gain and annualized investments to obtain an overall profit. All base case scenario input parameters were included in this code, with the sole discrepancy being a year time frame. Additional input parameters can be seen in table 3.8 below. Average irradiance of the Chalmers campus solar panels was also utilized. Results of the Optimized Capacity Modeling code will propose new optimized capacities of the units, which are inputted into the base case and simulated.

Table 3.8: Additional Input Parameters for Optimized Capacity Modeling Code

Input Parameter	Value
Solar PV Investment Cost	14 196 SEK/kW [49]
CHP Investment Cost	28 419 SEK/kW [55]
Annuity Payment Factor	0.06

The annuity payment factor was calculated using equation 3.50 under the assumption the number of periods is 30, based on the predicted lifetime of the solar panels [49], and with an assumed discount rate of 5%.

$$\frac{r}{1-(1+r)^{(-n)}} \tag{3.50}$$

where r represents the discounted rate or interest rate, and n represents the number of periods in which payments will be made.

Objective function: The objective of the Capacity Model is to optimize the Chalmers microgrid energy mix by investing in the increase of Solar PV and CHP capacity, such that overall profit is maximized.

$$\begin{aligned}
&[p_{grid_{ex}}(t) \times e_{price}(t)] - [p_{grid_{im}(t)} \times (e_{price}(t) + e_{tax})] + [q_{DH_{ex}}(t) \times h_{price_{ex}}(t)] \\
&-[q_{DH_{im}}(t) \times h_{price_{im}}(t)] - [q_{fuel_{CHP_b}}(t) \times f_{price}] - [q_{fuel_b}(t) \times f_{price}] \\
&-[inv_{PV_{price}} \times annuity \times inv_{PV}] - [inv_{CHP_{price}} \times annuity \times inv_{CHP}], \quad \forall t \in \mathcal{T}
\end{aligned} \tag{3.51}$$

where $inv_{PV_{price}}$ and $inv_{CHP_{price}}$ represents the investment costs of solar PV and CHP, respectively, in SEK/kW. Similarly, inv_{PV} and inv_{CHP} represents the additional capacity of solar PV and CHP, respectively, in kWh.

Energy Balance: Like before, the energy balance constraints are implemented to ensure demand is always met, as expressed in equations 3.52 and 3.53.

$$\begin{aligned}
&percent_{irra}(t) \times inv_{PV}(t) + p_{grid_{im}}(t) + p_{CHP_{tr}}(t) + P_{PV}(t) + p_{discharge_1}(t) \\
&+p_{discharge_2}(t) = P_{demand}(t) + p_{grid_{ex}}(t) + p_{charge_1}(t) + p_{charge_2}(t), \quad \forall t \in \mathcal{T}
\end{aligned} \tag{3.52}$$

$$\begin{aligned} &q_{DH_{im}}(t) + q_{CHP}(t) + q_{b/fgc}(t) + q_{discharge}(t) \\ &= Q_{demand}(t) + q_{DH_{ex}}(t) + q_{charge}(t), \quad \forall t \in \mathcal{T} \end{aligned} \tag{3.53}$$

where $percent_{irra}$ represents the average percent irradiance from the solar panels, or percentage of total capacity generated, in kWh/m^2.

Constraints for all the technologies remain the same. Once the optimal investments were obtained, and the new solar PV and CHP capacities was determined, the base case model was simulated once again including the optimized alterations. Forecasting hourly solar power production based on the new investment was calculated as follows:

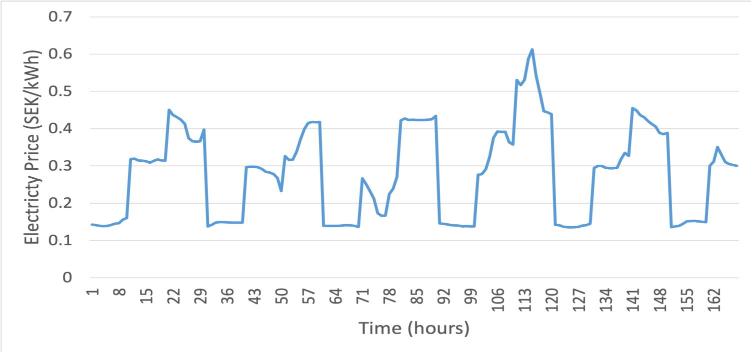
$$P_{PV}(t) + [percent_{irra}(t) \times inv_{PV}], \quad \forall t \in \mathcal{T} \tag{3.54}$$

The increase of BES capacity was not included as it was deemed not profitable. This was calculated under the assumption that the battery investment cost is approximately 6000 SEK/kWh [49], and with an annuity factor of 0.05. Assuming a full cycle (charging and discharging) always occurred when prices were extremely low and high at 0.1 and 2 SEK/kWh, respectively, it was concluded that the battery needed to undergo 158 cycles in a year to cover investment costs. Despite the assumptions reflecting a best-case scenario, with overall dynamic price fluctuations, this is still deemed too costly. Moreover, given the fact that the base case scenario only analyzes results via a course of a week, price fluctuations are clearly too minor to properly quantify any benefits of the investment.

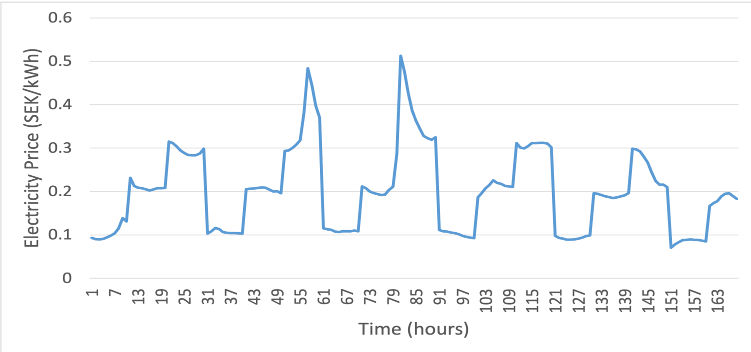
3.4.2 Price Fluctuation

One of the main benefits of a LEM, amongst others, is the ability to stabilize energy prices during hours that external price fluctuations are volatile. Due to the local market's partial self sufficiency and available storage units, energy costs can be reduced and better controlled within the LEM. The storage devices are particularly profitable during these instances, as energy can be stored when prices are low to be later utilized during price spikes. This not only aids in keeping prices low within the campus network, but also provides additional benefits by inducing less strain on the external networks, and offsets any external plants that utilize conventional fuels, such as fossil fuels. Transmission losses are also reduced due to on-site generation and consumption.

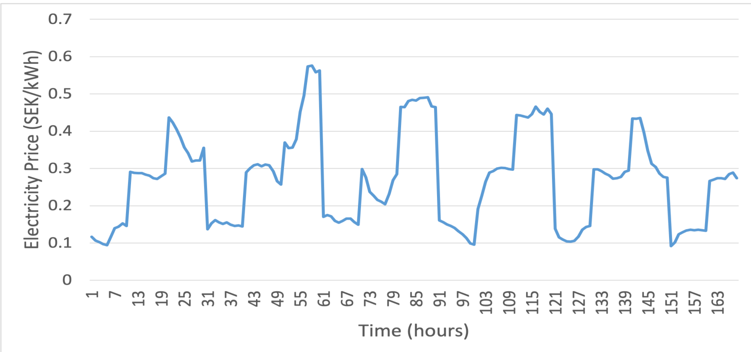
This scenario will explore the effect of major peaks and valleys, specifically within the external electric grid, and how the various factors of the model will react to such a deviation. Price fluctuations on the external electricity grid could occur for a number of reasons. For example, Denmark may start producing a large quantity of wind power, causing the electricity market prices to drop. Another instance could be that a large power plant unexpectedly goes offline, causing grid prices to surge for a period of time. External grid price fluctuations were exaggerated in this scenario within the span of a week for verification purposes. In the base case, the electricity market clearing price always reflected that of the external grid, since the campus network was never able to meet its own demand. Thus, the new optimal capacities obtained from the previous sensitivity scenario will be utilized. The new dynamic price profiles for each week assessed, can be seen in Figure 3.10, below.



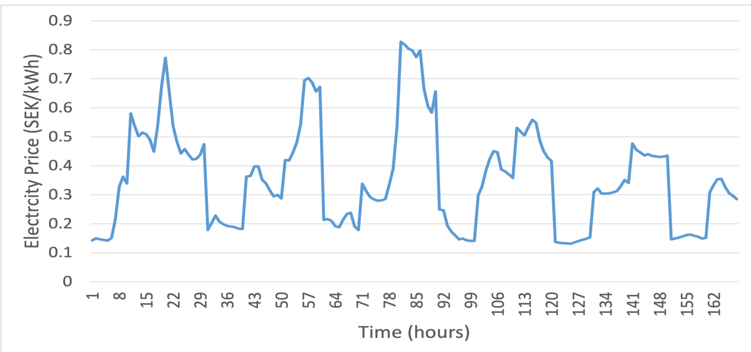
(a) January profile



(b) April profile



(c) July profile



(d) October profile

Figure 3.10: Major Price Fluctuations within External Electricity Grid

4

Results

The analysis of large-scale systems often result in complexities when interpreting market clearing results. Thus, for simplicity, a limited number of market participants, bids, and trading periods were modeled under various scenarios. This section presents the computed results from the base case simulation compared with the results from sensitivity analysis scenarios.

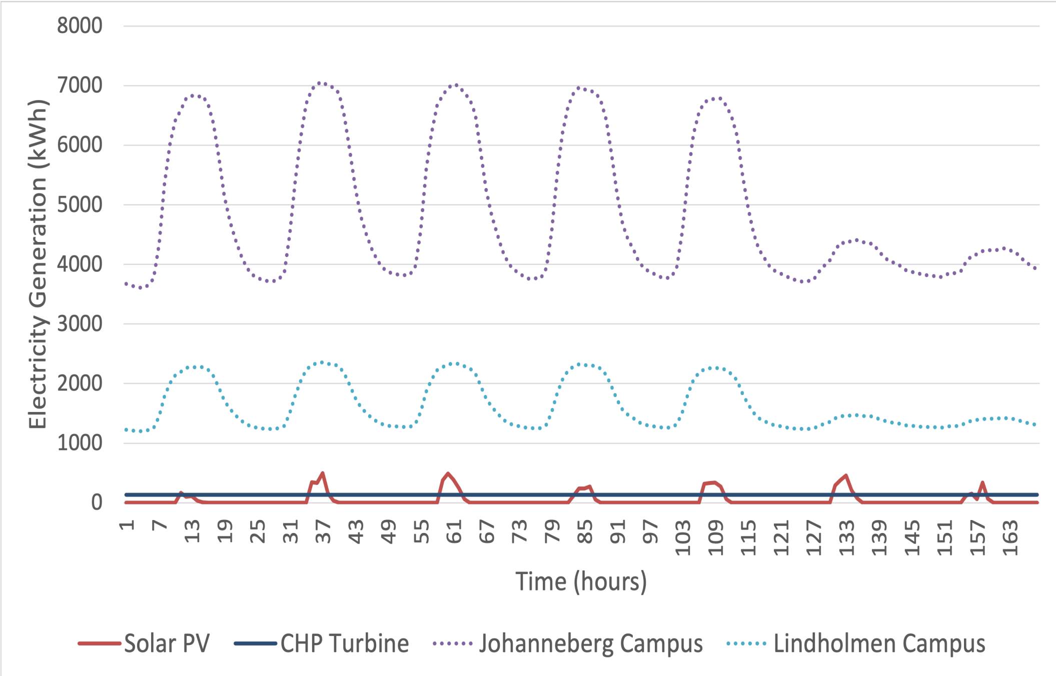
4.1 Base Case Market Model

The base case model represents, at best, a simplified version of a realistic energy trading market. The fundamental outputs of the local energy market are the quantity of local energy production, amount of consumption and storage, and the local market value of the energy. The overall consumption is partly pre-determined via forecasts based on campus historical data, as previously mentioned.

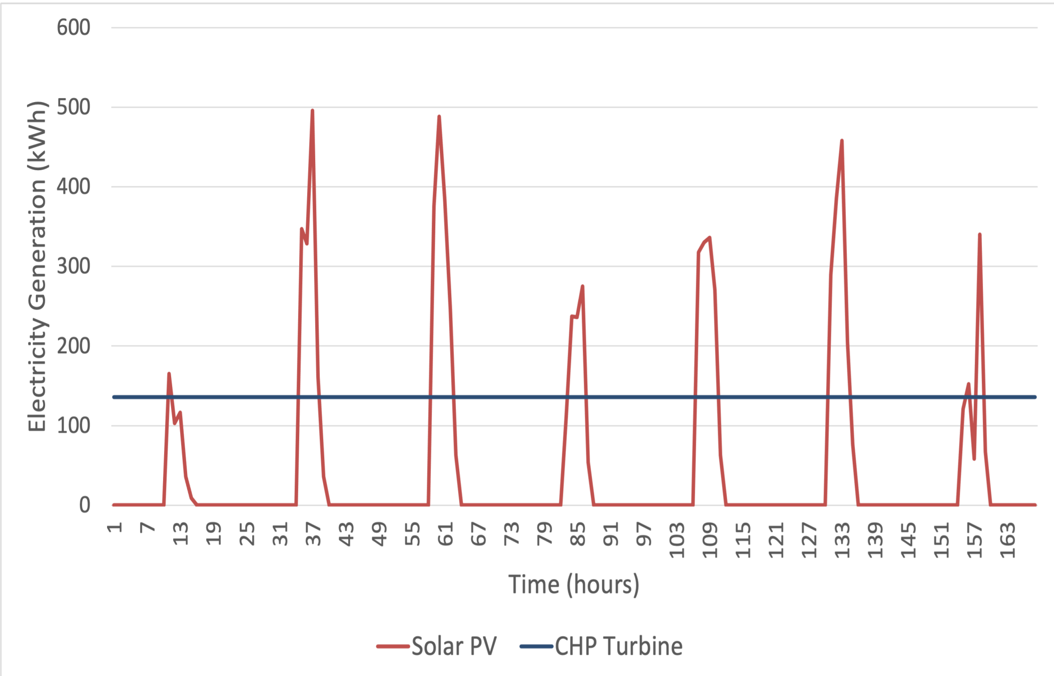
4.1.1 January - Winter Season

Of the four weeks assessed, January energy demand was noted to be considerably high, which is intuitive and expected. This is attributed to the increased desire for heating in buildings in response to the colder weather, and the heightened reliance in indoor lighting as it becomes darker outside for larger portions of the day. Electricity and heat bid quantities from actors within the campus microgrid can be seen in Figures 4.1 and 4.2. The probability of heat pump bids clearing is low, and thus not presented in the figures.

As predicted, PV production is low due to the limited hours of daylight, and demand is high, within the colder season. Despite the CHP turbine constantly running at full capacity, the amount of electricity the LEM can produce is substantially lower than needed to meet demand, as seen in Figure 4.1(a), and the remaining electricity must be obtained from an external electricity market. The BES units were not utilized during this period, as solar PV generation was low ad grid prices did not fluctuate to the degree that would render them effective. When also accounting for the energy losses that occur when charging and discharging the BES units, implementation was determined unprofitable. It is important to note that this conclusion is a product of the short time period assessed. If a longer period were to be evaluated, utilization of the BES units will likely be advantageous with more dynamic meteorological parameters, like outdoor temperature and solar radiation, and varying external electricity prices.



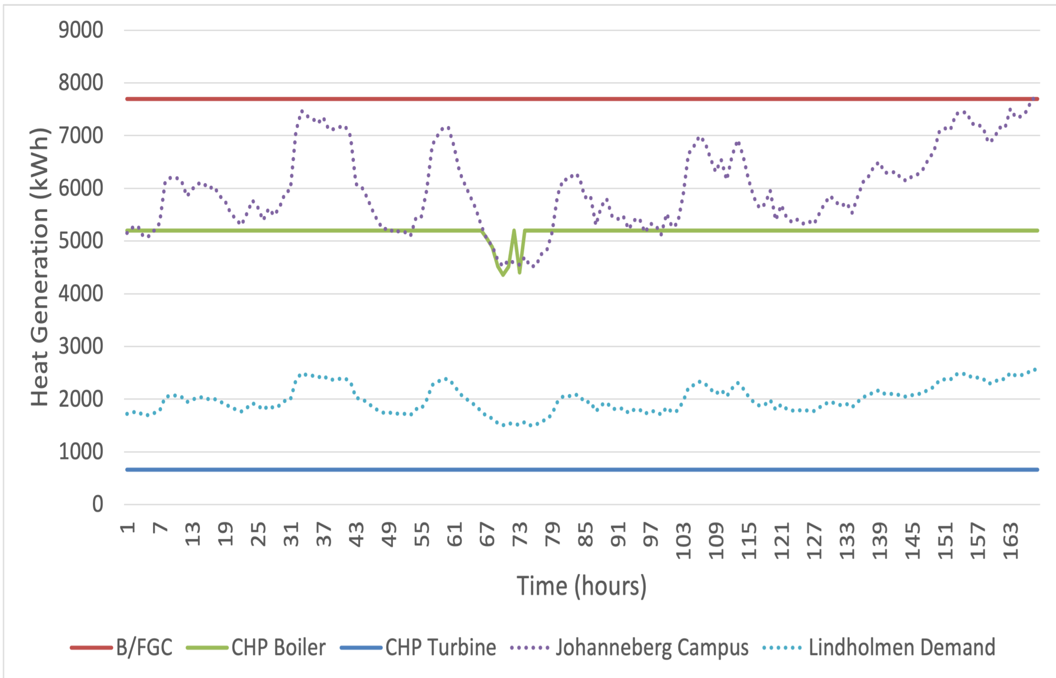
(a) Demand vs. Supply Bids



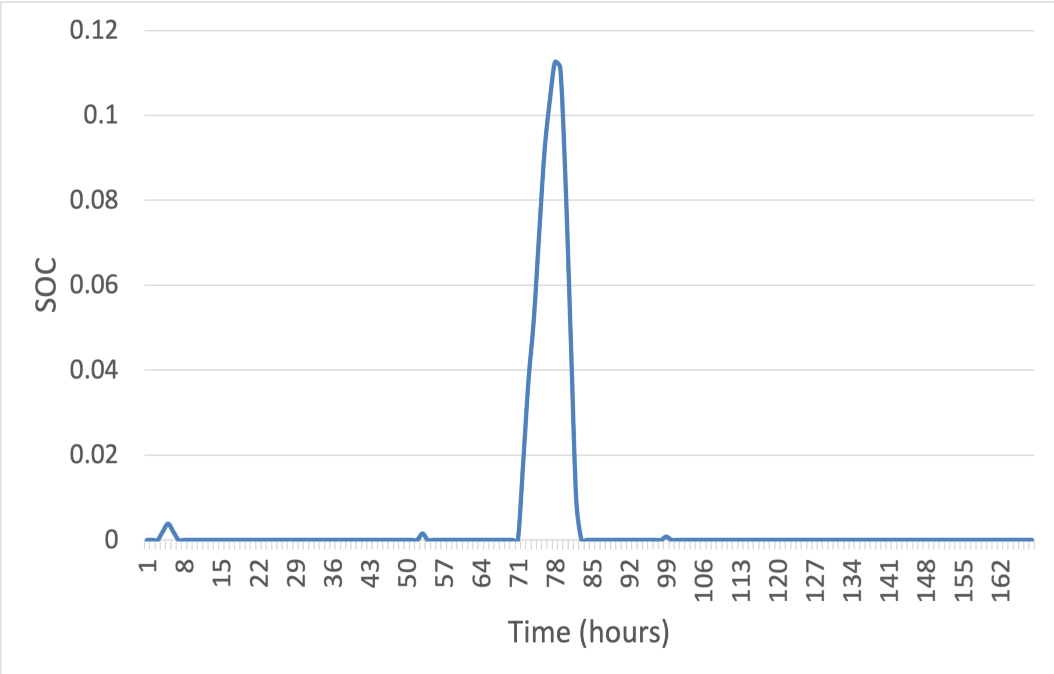
(b) Supply Bids

Figure 4.1: January Electricity Bids

Unlike electricity trading, the campus microgrid proved to have the capacity to meet its internal heat demand. As CHP heat production cannot be exported due to network constraints, the amount of heat generated from the CHP boiler was noted to be fairly consecutive, excluding the occasional valleys due to the decrease in local demand. On the contrary, heat production from the B/FGC unit can be exported, and thus, is willing to bid at maximum capacity and make a profit during the cold season, as heat price is expected to be high. It was noted that the TES unit would charge during periods where internal demand drops below the capacity of the CHP unit, and thus, agent 2 would use the CHP boiler to store heat for future usage when demand increases yet again. By doing this, all production from the B/FGC can be exported to the external DHN, thus maximizing profits.



(a) Demand vs. Supply Bids



(b) SOC of TES

Figure 4.2: January Heating Bids

Solving the market clearing optimization portion of the simulation results in a list of accepted bids, and the respective energy market price, per hour. The cleared bid valuations and subsequent market prices, per hour, during the investigated week in January, can be found in Figures 4.3 and 4.4, for electricity and heat, respectively. Demand bids from Johanneberg campus were excluded, as they were set at relatively high valuations.

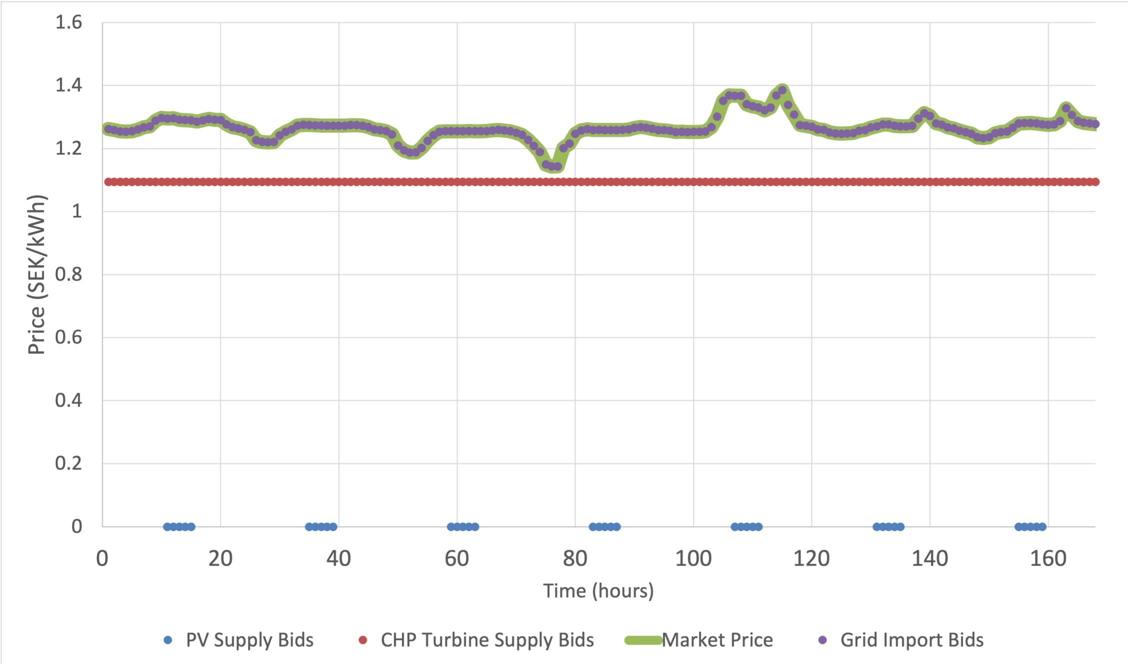


Figure 4.3: January Electricity Market Clearing

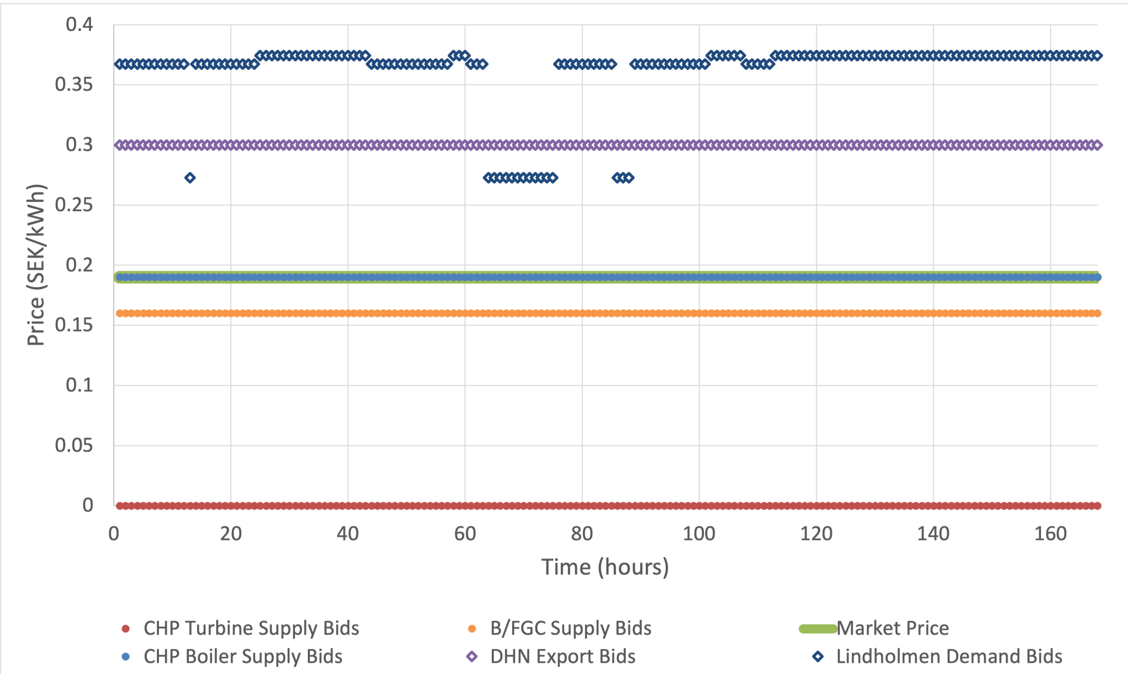


Figure 4.4: January Heat Market Clearing

As seen by Figure 4.3, it is clear that the price within the local energy market is identical to that of the external electricity grid. This is a result of the invariable necessity of importing electricity to meet demand. As a result, consumers will not

benefit from a reduced electricity cost standpoint, however, actors will gain unitary benefits, which will be later discussed in further detail. Considering agents within the LEM are not able to meet demand internally, electricity is never exported to the external grid or Lindholmen campus.
Internal generating units were noted to be much more effective in meeting both Johanneberg and Lindholmen campus heat demand, as seen by Figure 4.4, as consumers are able to purchase heat at a reduced cost in comparison to the DHN. The cost of heat within the LEM in January was steadily equal to CHP boiler's marginal costs of production - considering it is the most expensive cleared generation unit. Heat produced from the CHP unit is always utilized to meet internal demand, due to network constraints, allowing production from the B/FGC to be utilized to meet any remaining internal demand, followed by meeting all Lindholmen campus heating demand, and then exporting to the DHN - as revenue of selling to Lindholmen campus exceeds selling to DHN. Exporting to the external district heat network will always result in a revenue during the winter season, thus, the B/FGC consistently operates at capacity and exports remaining heat. Therefore, heat is never imported from the DHN during the winter season. The heat pumps are never used, as the cost ratio of purchasing electricity to selling heat was never deemed to be profitable. An illustration of the cleared bid quantities can be found in Appendix 1. A brief summary of the LEM results obtained from the January simulation can be found in Table 4.1, below.

Table 4.1: January Results

Electricity	Heat
CHP turbine operates at capacity	CHP boiler operates at capacity
All PV bids cleared	B/FGC unit operates at capacity
Never sold to Lindholmen	Always sold to Lindholmen
Demand never met internally	Demand always met internally
Always importing	Never importing
Never exporting	Always exporting
$HP_{w_{1,2}}$ never utilized	$HP_{w_{1,2}}$ never utilized

The term unitary benefit typically refers to the amount of money saved/gained by the cleared demand/supply participants, respectively, upon comparing the market price with the player's valuation bid. To illustrate, a depiction of market clearing for electricity at hour 37, and the associated unitary benefits of the suppliers and consumers, can be seen in Figure 4.5 and Tables 4.2 and 4.3, respectively. The unitary benefit of Johanneberg campus is simply classified as infinitive in reference to its large valuation bid price.

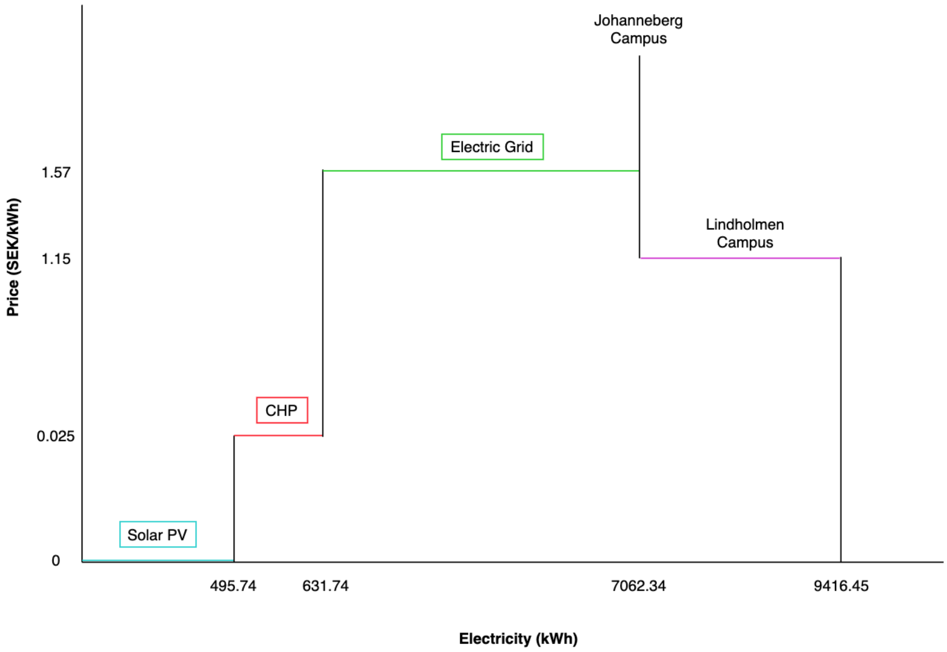


Figure 4.5: January Electricity Market Clearing

Table 4.2: Electricity Supplier Unitary Benefit at Hour 37

Supplier	Unitary benefit (SEK/kWh)
Solar PV	1.27
CHP	0.18
Grid Import	0.00

Table 4.3: Electricity Consumer Unitary Benefit at Hour 37

Demand	Unitary benefit (SEK/kWh)
Johanneberg Campus	∞
Lindholmen Campus	*rejected*
HP_{w1}	*rejected*
HP_{w2}	*rejected*
Grid Export	*rejected*

In respect local energy generation, electricity sold by solar PV secures the highest revenue due to its zero marginal cost, followed by CHP production. The remaining electricity is purchased from the external grid to meet demand. Other than Johanneberg campus, no other consumer participates in energy trading at this hour.
The market clearing and unitary benefits for heat at hour 37 can be seen in Figure 4.6 and Tables 4.4 and 4.5, below.

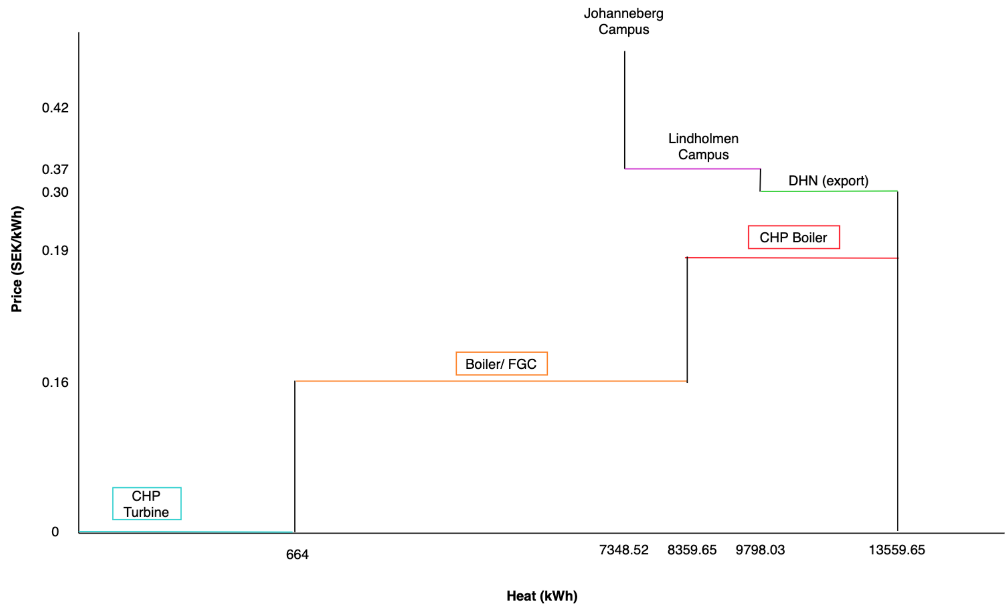


Figure 4.6: January Heat Market Clearing

Table 4.4: Heat Supplier Unitary Benefit at Hour 37

Supplier	Unitary benefit (SEK/kWh)
HP_{w1}	*rejected*
HP_{w2}	*rejected*
CHP Turbine	0.19
CHP Boiler	0.00
Boiler & FGC	0.03
DHN Import	*rejected*

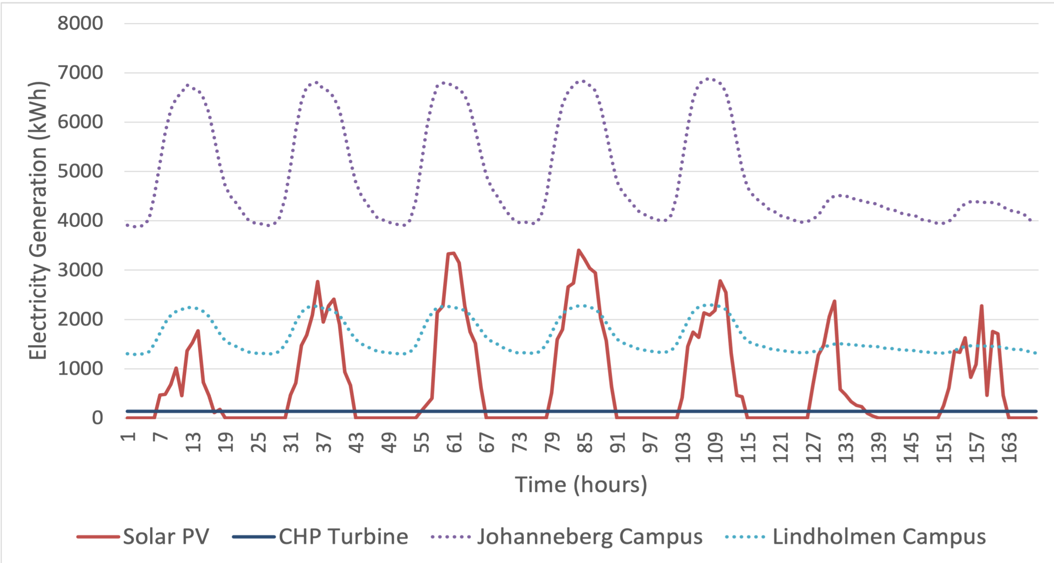
Table 4.5: Heat Consumer Unitary Benefit at Hour 37

Demand	Unitary benefit (SEK/kWh)
Johanneberg Campus	∞
Lindholmen Campus	0.18
DHN Export	0.11

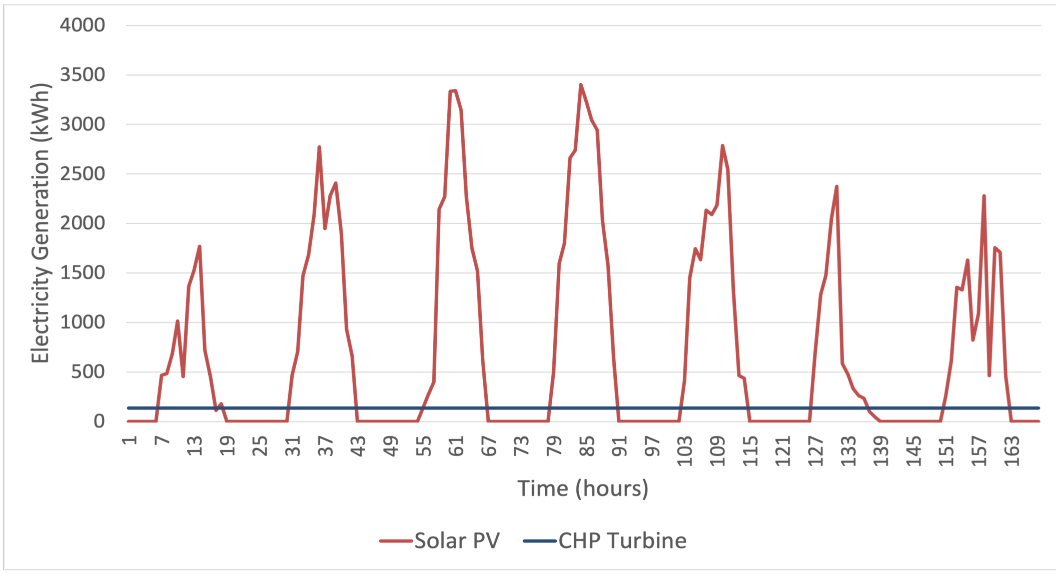
Aforementioned, in the winter season, the B/FGC operates at maximum capacity and it generates energy to meet remaining internal heat demand, all Lindholmen campus heat demand, and export the remaining heat to the external grid. Heat produced by the CHP boiler was identified to be most expensive, at a price of 0.19 SEK/kWh, thus, setting the market clearing price. Consequently, the boiler portion of the CHP obtains a unitary benefit of 0 SEK/kWh. Given that the CHP boiler is the most expensive cleared heat generating unit, the market price always clears at its marginal cost of operation during the week of January. As a result, the CHP boiler never generates a profit. Heat from the CHP turbine and B/FGC unit was able to be sold for a profit due to its comparably low marginal cost of production.

4.1.2 April - Spring Season

As the temperature becomes warmer, and the days become longer, energy demand and PV production decreases and increases, respectively. Despite this, and bidding at maximum CHP turbine production, the LEM nonetheless cannot meet electrical demands within the internal grid, as seen by the electricity bid quantities vs. demand in Figure 4.7. BES units remain offline for similar reasons noted during the January evaluation.



(a) Demand vs. Supply Bids

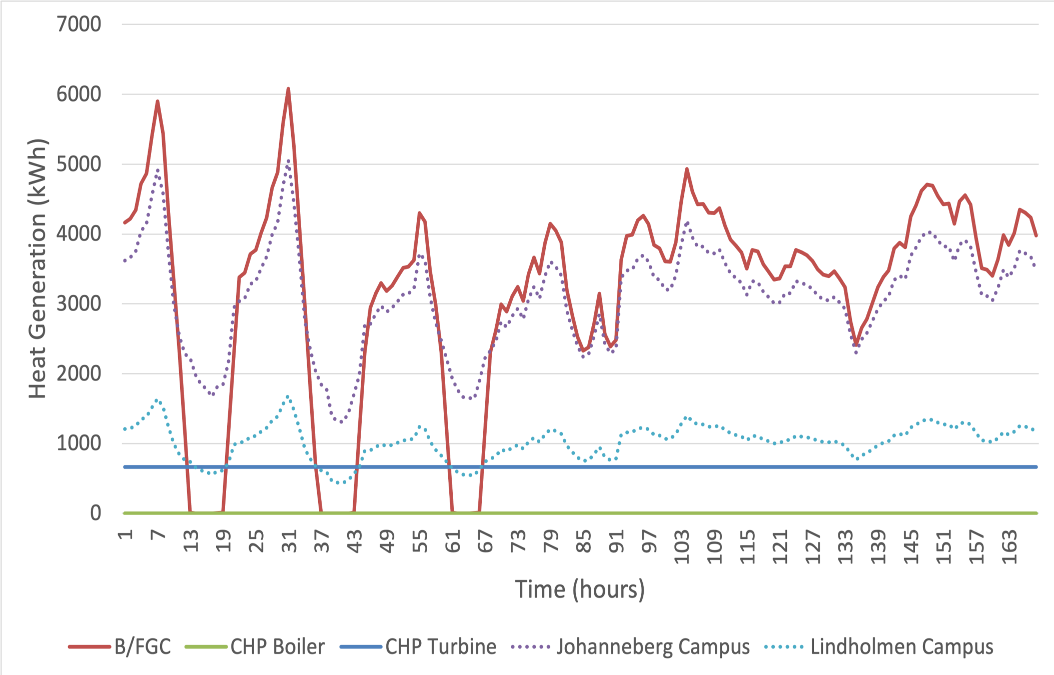


(b) Supply Bids

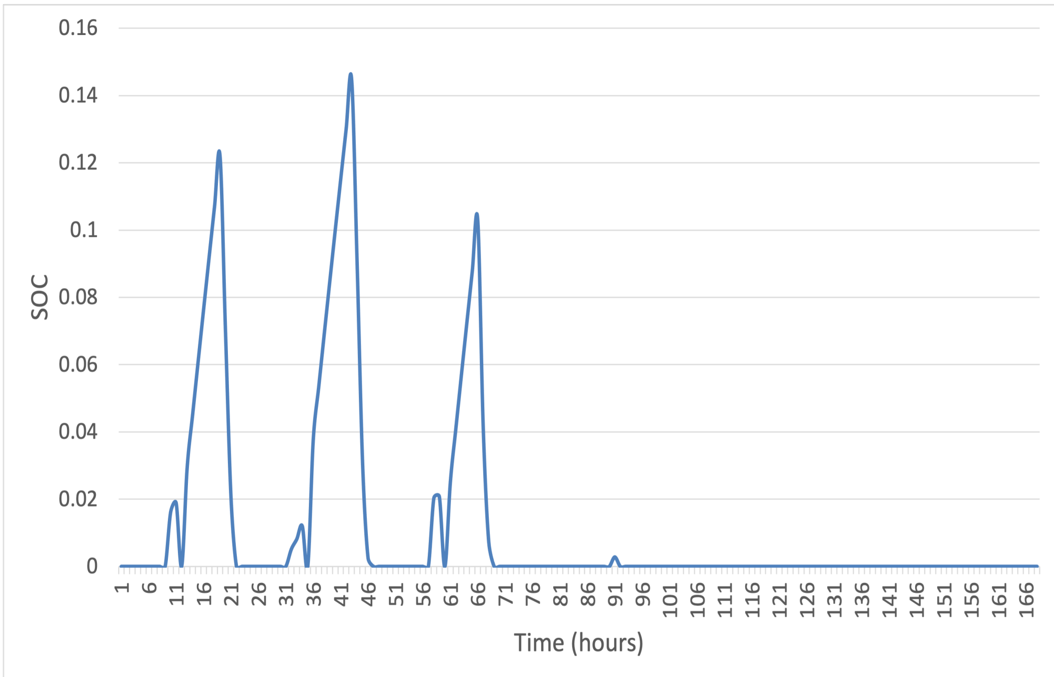
Figure 4.7: April Electricity Bids

Figure 4.8 presents the heat bid quantities and demand. Once again, heat pump bid quantities are neglected.
In comparison to January results, the market clearing price of heat within the LEM

is noted to slightly more dynamic. Hours when demand is low, the cost of purchasing heat from the external grid is likewise low, thus, no heat carrier supply bids are placed, as it would be non-profitable and it would be cheaper to import. Heat recovered from the CHP turbine during these hours are stored in the TES units for future use. Alternatively, when the price within the external grid increases, operating internal units become profitable and are utilized once again. As can be noted by Figure 4.8, the B/FGC unit has the potential to meet all of Johanneberg campus, and most of Lindholmen campus demand, and does so when not importing from the external grid. During hours when the B/FGC unit must begin ramping up/down, due to ramping constraints, energy from the TES unit is utilized, and the remaining heat is purchased from the external DHN. As it is non-profitable to export heat during the month of April, the LEM never does so. Additionally, heat is never set directly to the grid from the CHP boiler due to its high cost of production in relation to demand and external prices.



(a) Demand vs. Supply Bids



(b) SOC of TES

Figure 4.8: April Heating Bids

Thus, during the week of April, the market clearing for electricity is once again set at the cost of importing from the external grid, whilst the market clearing price for heat is seen to fluctuate between import costs, or the cost of B/FGC production, as can be seen in Figures 4.9 and 4.10. Heat is only sold to Lindholmen campus when the market clears at the B/FGC unit bid valuation. An illustration of the cleared bid quantities can be found in Appendix 1.

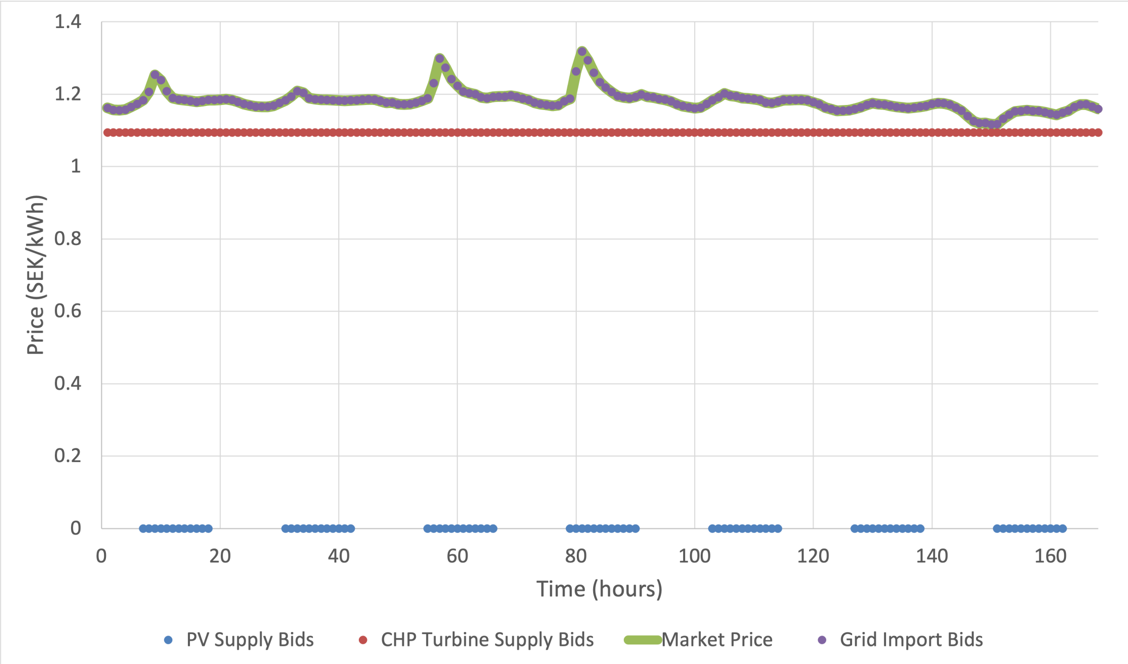


Figure 4.9: April Electricity Market Clearing

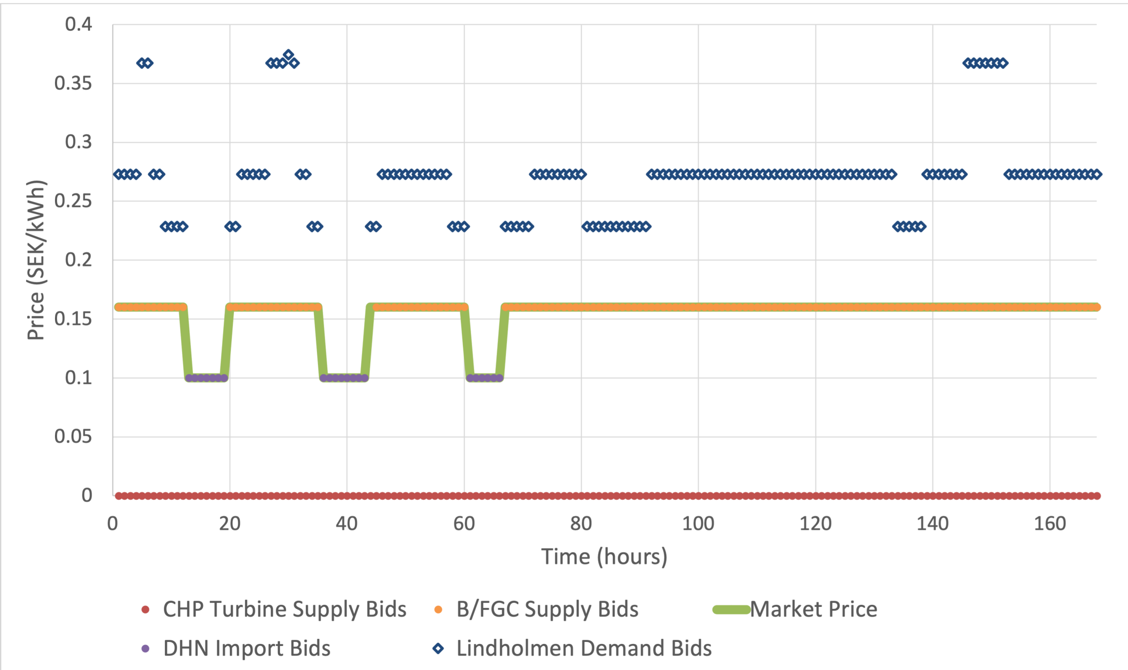


Figure 4.10: April Heat Market Clearing

A brief summary of the LEM results obtained from the April simulation can be found in Table 4.6, below.

Table 4.6: April Results

Electricity	Heat
CHP turbine operates at capacity	CHP boiler never operates
All PV bids cleared	B/FGC operates at capacity
Never sold to Lindholmen	Sold to Lindholmen if profitable
Demand never met internally	Demand met internally when profitable
Constantly importing	Importing when profitable/required
Never exporting	Never exporting
$HP_{w1,2}$ never utilized	$HP_{w1,2}$ never utilized

For ease of comparability, hour 37 is examined once again. An illustration of the market clearing for electricity can be seen in Figure 4.11, followed by a presentation of the associated unitary benefits of the suppliers and consumers, in Tables 4.7 and 4.8.

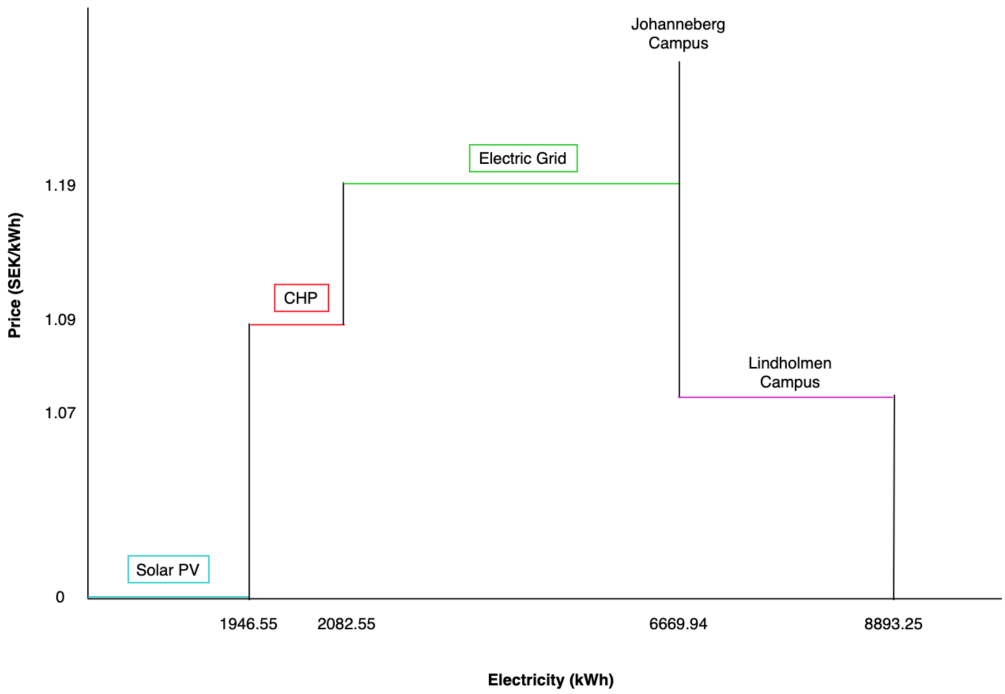


Figure 4.11: April Electricity Market Clearing

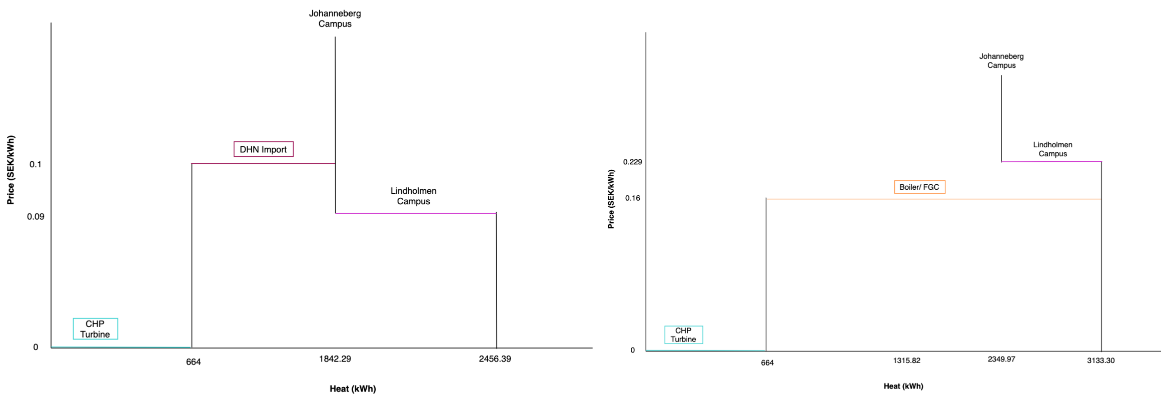
Table 4.7: Electricity Supplier Unitary Benefit at Hour 37

Supplier	Unitary benefit (SEK/MWh)
Solar PV	1.19
CHP	0.090
Grid Import	0.00

Table 4.8: Electricity Consumer Unitary Benefit at Hour 37

Demand	Unitary benefit (SEK/MWh)
Johanneberg Campus	∞
Lindholmen Campus	*rejected*
HP_{w1}	*rejected*
HP_{w2}	*rejected*
Grid Export	*rejected*

Aforementioned, the market clearing for electricity follows a similar pattern to results seen in January. Electricity generated by solar PV is dispatched first, thus obtaining the highest unitary benefit, followed by maximum CHP electricity production. Electricity is imported to meet the remaining demand, thus always setting the market price, at no unitary benefit.
Trading for heat at hour 37, demonstrates a situation where heat demand was met by importing from the district heat network, shown in Figure 4.12(a). However, only two hours prior, an instance where both Johanneberg and most of Lindholmen demand was met by the B/FGC can be seen, in Figure 4.12(b).



(a) Hour 37 **(b)** Hour 35

Figure 4.12: April Heat Market Clearing

The unitary benefits for heat trading at hour 37 can be seen in Tables 4.9 and 4.10. Tables 4.11 and 4.12 display the benefits at hour 35.

Table 4.9: Heat Supplier Unitary Benefit at Hour 37

Supplier	Unitary benefit (SEK/MWh)
HP_{w1}	*rejected*
HP_{w2}	*rejected*
CHP Turbine	0.1
CHP Boiler	*rejected*
Boiler & FGC	*rejected*
DHN Import	0.00

Table 4.10: Heat Consumer Unitary Benefit at Hour 37

Demand	Unitary benefit (SEK/MWh)
Johanneberg Campus	∞
Lindholmen Campus	*rejected*
DHN Export	*rejected*

Table 4.11: Heat Supplier Unitary Benefit at Hour 35

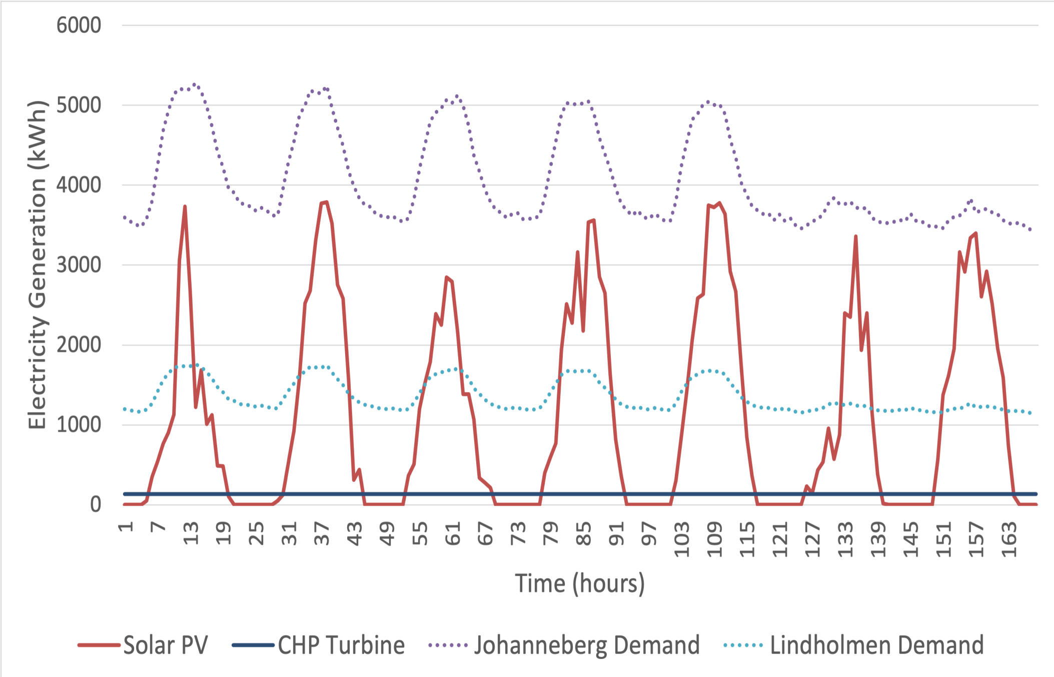
Supplier	Unitary benefit (SEK/MWh)
HP_{w1}	*rejected*
HP_{w2}	*rejected*
CHP Turbine	0.16
CHP Boiler	*rejected*
Boiler & FGC	0.00
DHN Import	*rejected*

Table 4.12: Heat Consumer Unitary Benefit at Hour 35

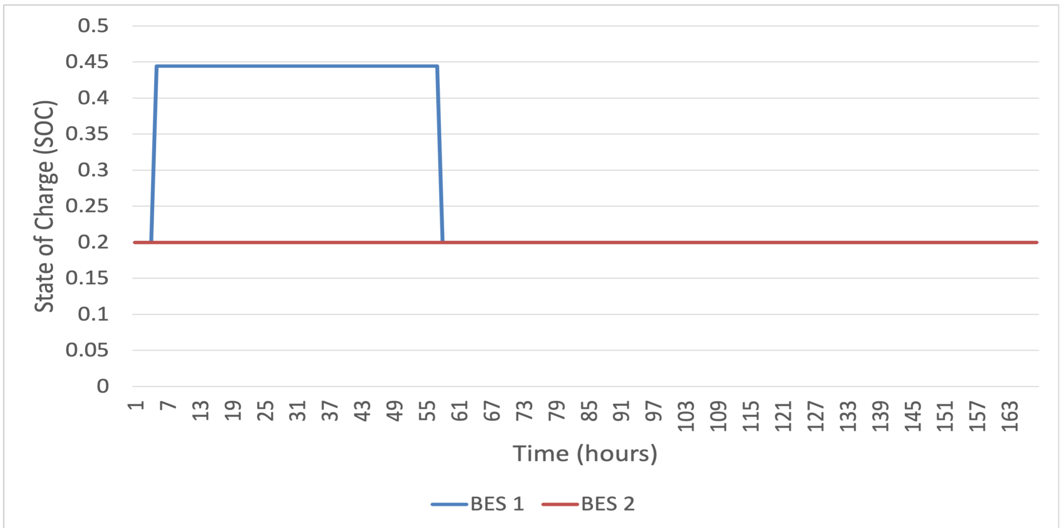
Demand	Unitary benefit (SEK/MWh)
Johanneberg Campus	∞
Lindholmen Campus	0.07
DHN Export	*rejected*

4.1.3 July - Summer Season

As expected, the trend follows literature such that solar PV production increases, and energy demand decreases, as the model shifts towards the summer season. Nevertheless, electricity demand could not be met by internal generation. Electricity prices are lowest in the beginning of the week, thus, one of the BES units charges when solar PV starts generating (hour 5), and discharges at peak cost (hour 58). Aforementioned, storage usage behaviour is anticipated to be more dynamic when considering a longer time frame. As the electricity system lacks price fluctuation within the week investigated, electricity generated via solar PV is commonly sold to the market directly. In addition, the CHP turbine does not bid or generate at maximum electrical production. This is a result of the dependency set between the two energy carriers. A visual representation of the electrical bid quantities can be seen in Figure 4.13.



(a) Demand vs. Supply Bids

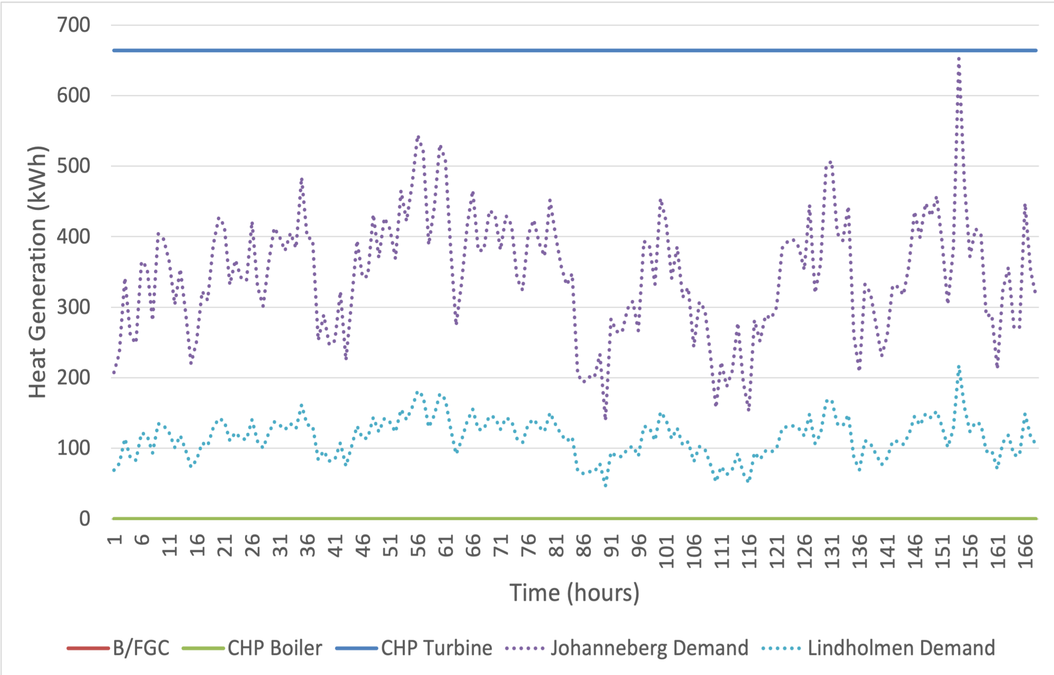


(b) SOC of BES

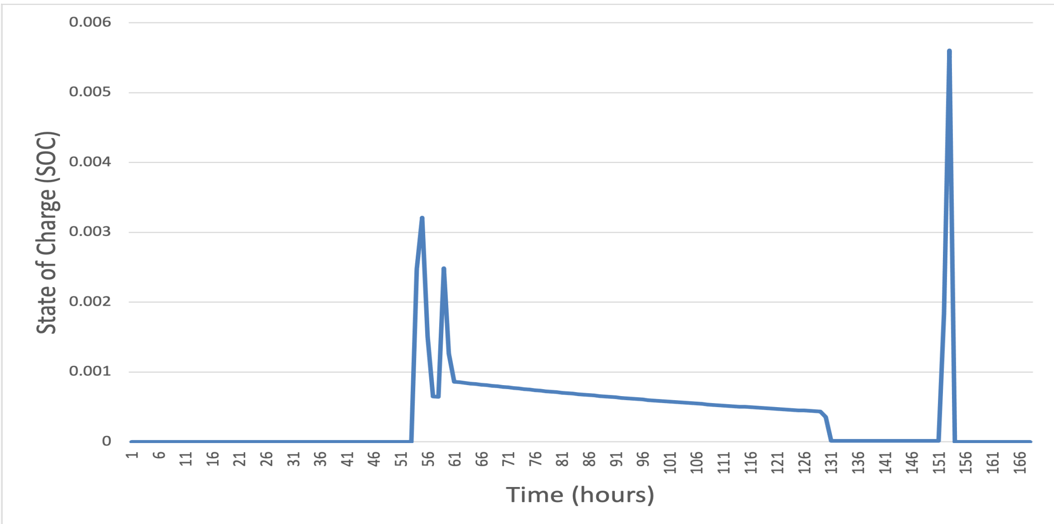
Figure 4.13: July Electricity Bids

Heat demand is naturally extremely low in July, thus, agent 2 only bids the heat recovered from the CHP turbine, as it exceeds internal heat demand, as seen in Figure 4.13(a),below.
When the market is cleared, CHP turbine bids are accepted in a manner such that electricity generation is dependent on how much heat will be accepted. The quantity of heat recovered should be equivalent to the demand required by Johanneberg and Lindholmen campus, considering CHP turbine heat has a bid valuation of 0 SEK/kWh, in relation to the consistent importing price of 0.1 SEK/kWh from the external DHN. Hours when prices to import electricity are high, the CHP turbine

will be cleared to produce more, and the excess heat is stored in the TES unit. This heat will thus be utilized to meet heat demand peaks. Granted that heat demand can be fully met in this manner, other heat generating units remain offline throughout the duration of the week investigated.



(a) July Heating Bids



(b) SOC of TES

Figure 4.14: July Electricity Bids

As a result, energy trading within the LEM during the summer season will invariably establish a market price equivalent to the external grid for electricity, and 0 SEK/kWh for heat, as shown in Figures 4.15 and 4.16. An illustration of all cleared bid quantities for the week of July, can be found in Appendix 1.

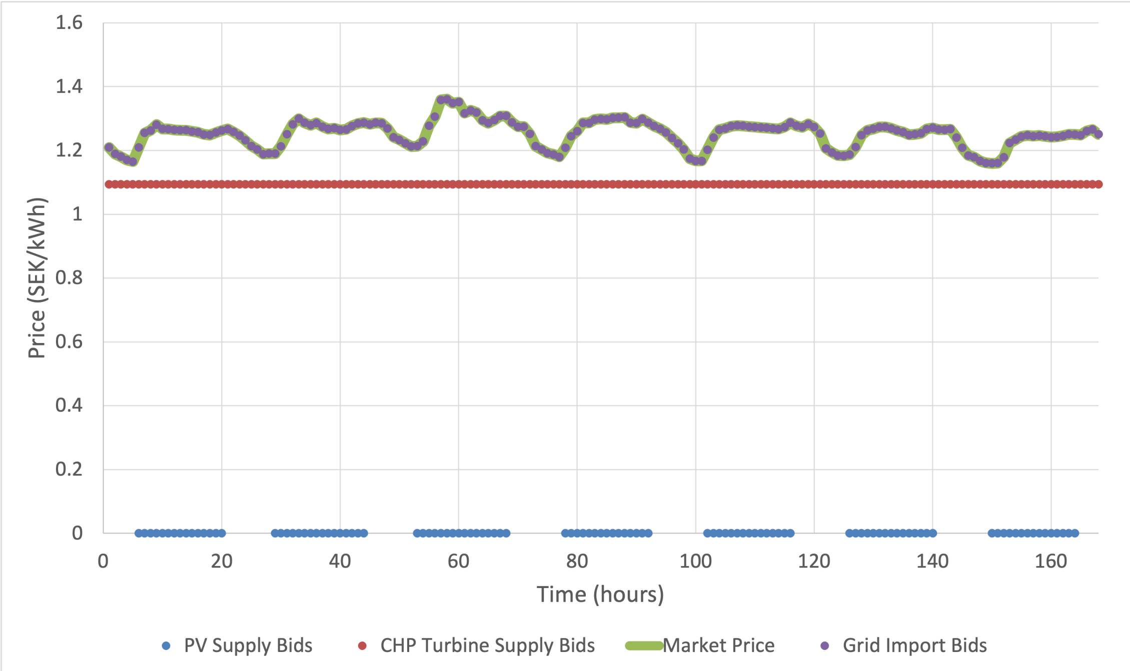


Figure 4.15: July Electricity Market Clearing

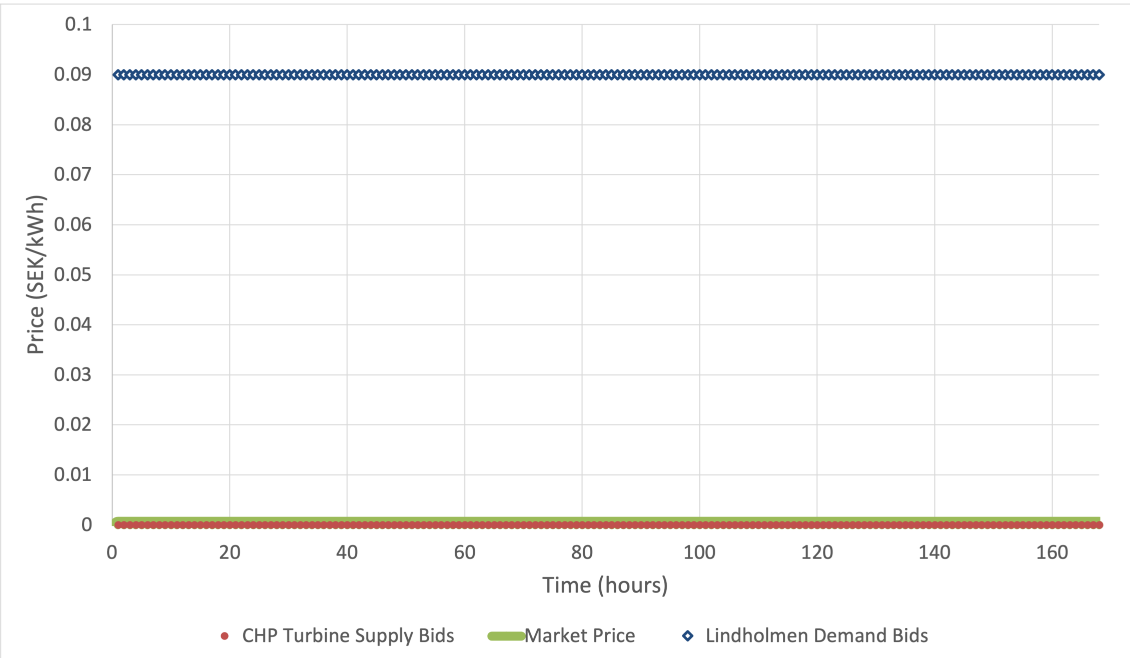


Figure 4.16: July Heat Market Clearing

A brief summary of the LEM results obtained from the July simulation can be found in Table 4.13, below.

Table 4.13: July Results

Electricity	Heat
CHP turbine cleared quantity varies	CHP boiler never operates
All PV bids cleared	B/FGC never operates
Never exporting	Never exporting
Never sold to Lindholmen	Always sold to Lindholmen
Demand never met internally	Constantly meets internal demand
Constantly importing	Never importing
HP_{w_s} never utilized	HP_{w_s} never utilized

A display of the above mentioned results can be seen once again in hour 37. Recovered heat from the CHP turbine was sufficient in meeting the demand for Johanneberg and Lindholmen campus, thus, no unitary benefit was obtained within the LEM for trading heat.

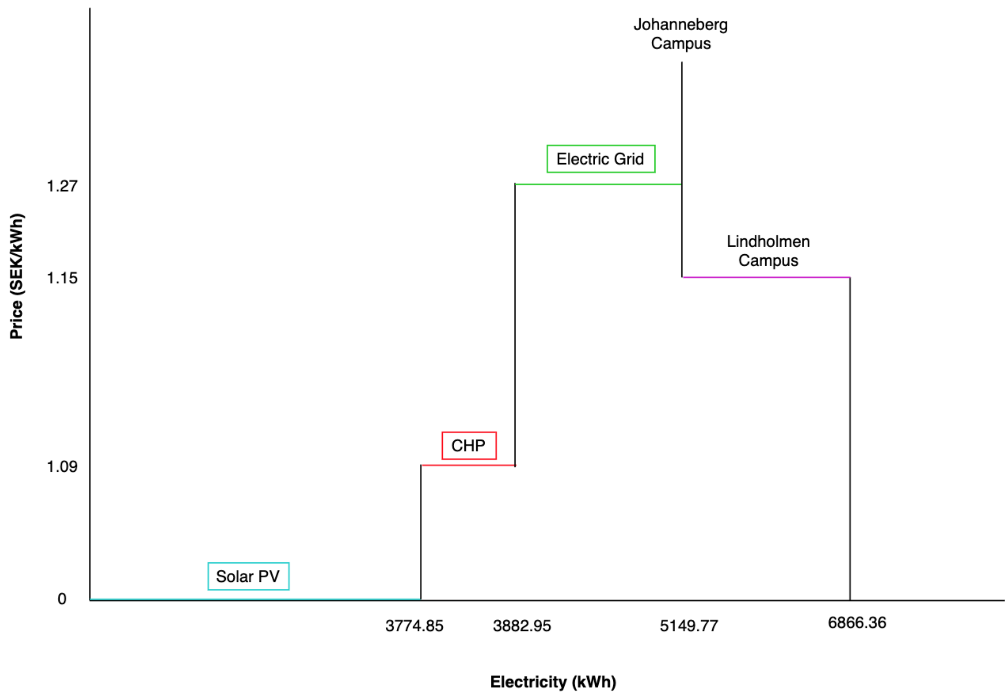


Figure 4.17: July Electricity Market Clearing

Table 4.14: Electricity Supplier Unitary Benefit at Hour 37

Supplier	Unitary benefit (SEK/MWh)
Solar PV	1.27
CHP	0.18
Grid Import	0.00

Table 4.15: Electricity Consumer Unitary Benefit at Hour 37

Demand	Unitary benefit (SEK/MWh)
Johanneberg Campus	∞
Lindholmen Campus	*rejected*
HP_s	*rejected*
Grid Export	*rejected*

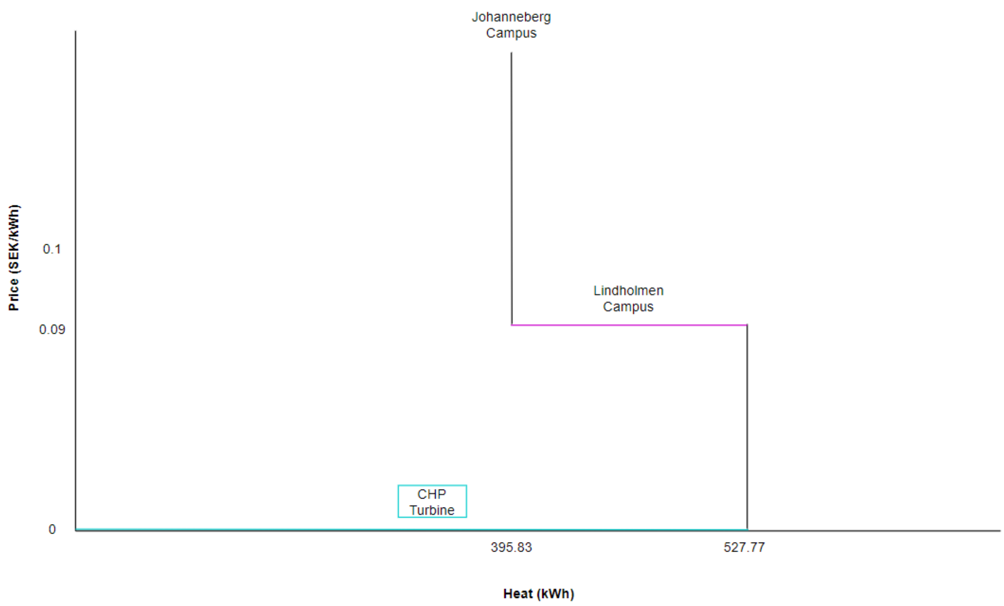


Figure 4.18: July Heat Market Clearing

Table 4.16: Heat Supplier Unitary Benefit at Hour 37

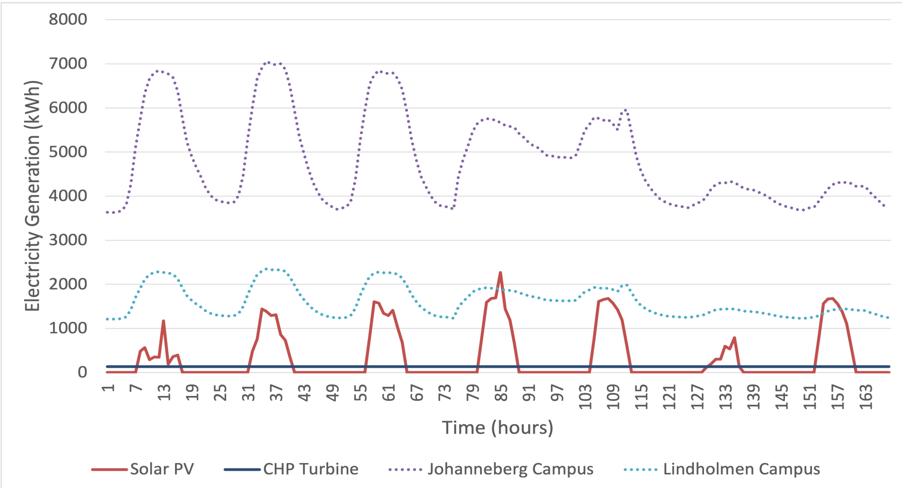
Supplier	Unitary benefit (SEK/MWh)
HP_s	*rejected*
CHP Turbine	0.00
CHP Boiler	*rejected*
Boiler & FGC	*rejected*
DHN Import	*rejected*

Table 4.17: Heat Consumer Unitary Benefit at Hour 37

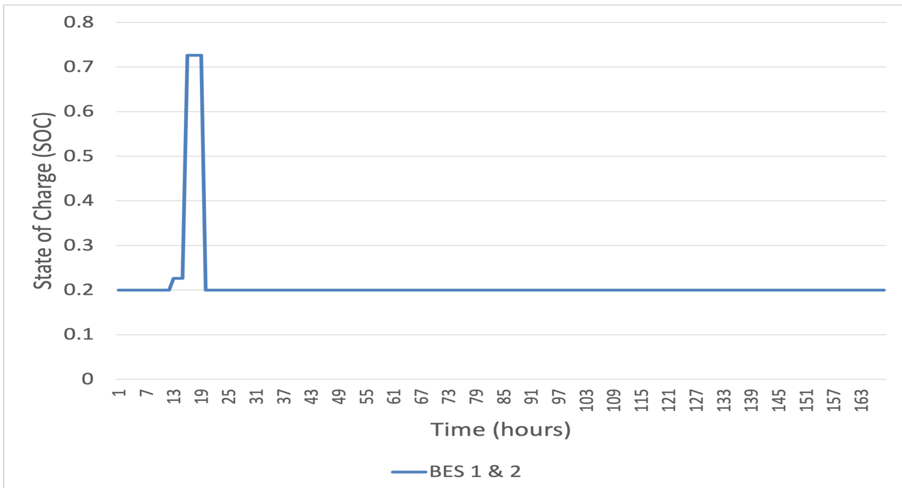
Demand	Unitary benefit (SEK/MWh)
Johanneberg Campus	∞
Lindholmen Campus	0.09
DHN Export	*rejected*

4.1.4 October - Fall Season

Shifting towards the fall season, results obtained are seen to closely follow the trend seen in the winter season, with the major discrepancy being the lack of usage of the CHP boiler. The CHP turbine continues to maintain a profit by running at full capacity, however, the main source of heat generation is obtained from the B/FGC unit, due to its lower production costs. Both the CHP boiler and B/FGC units were utilized in January as heat was being exported for a profit, however, exporting heat in October is unprofitable, thus, the CHP boiler does not participate and the B/FGC unit generates heat to meet internal demand. Both BES units are noted to charge during the two lowest electricity price hours, where solar PV is also generating energy (hours 13 and 17), and discharging at peak price (hour 20). Naturally, the lack of revenue in heat trading and the direct utilization of recovered CHP turbine heat, prevents any application of the TES unit during this period. Electricity and heat bid quantities throughout the week can be seen in Figures 4.19 and 4.20.



(a) Demand vs. Supply Bids



(b) SOC of BES

Figure 4.19: October Electricity Bids

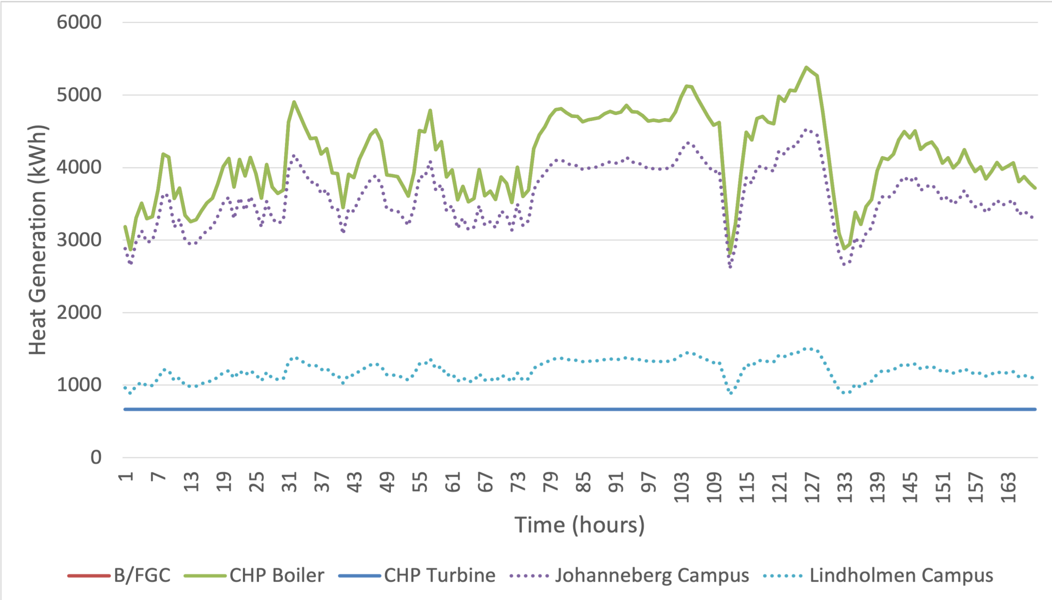


Figure 4.20: October Heating Bids

As a result, energy trading within the LEM during the fall season will invariably retail at prices equivalent to the external electricity grid, and the B/FGC unit's marginal cost of production, for electricity and heat trading, respectively. An illustration of the cleared energy market prices and bid valuations, at each hour of the week, can be seen in Figures 4.21 and 4.22. An illustration of all cleared bid quantities for the week of Oct, can be found in Appendix 1.

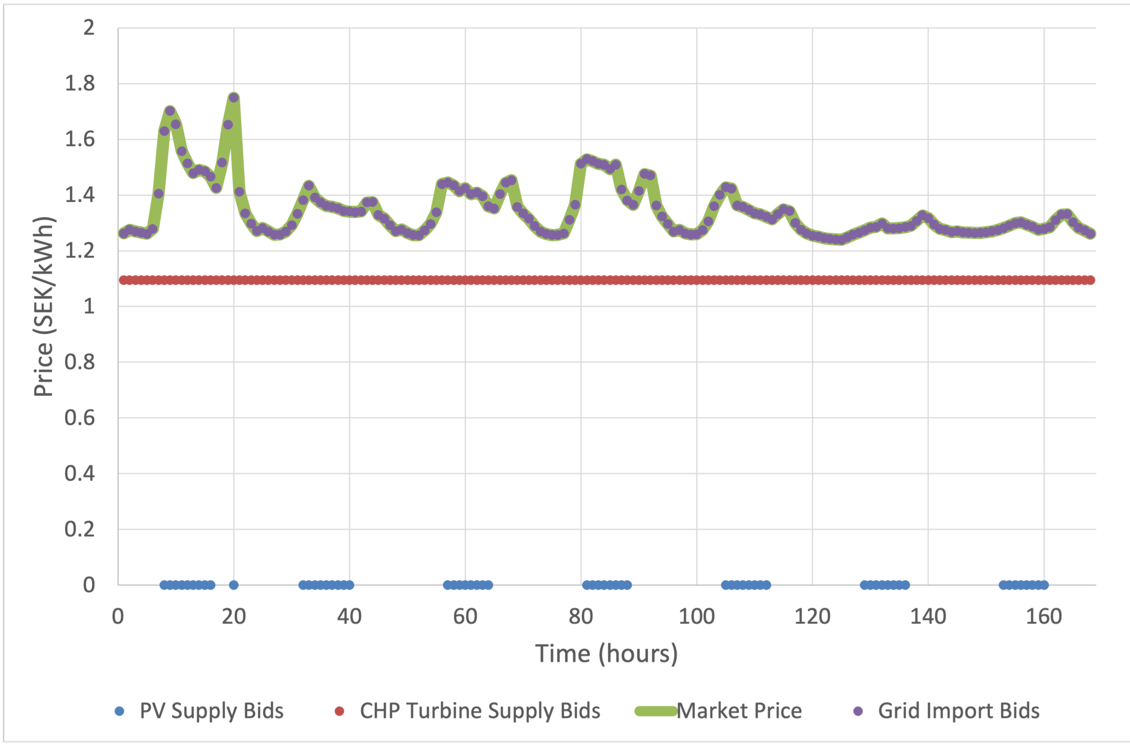


Figure 4.21: Oct Electricity Market Clearing

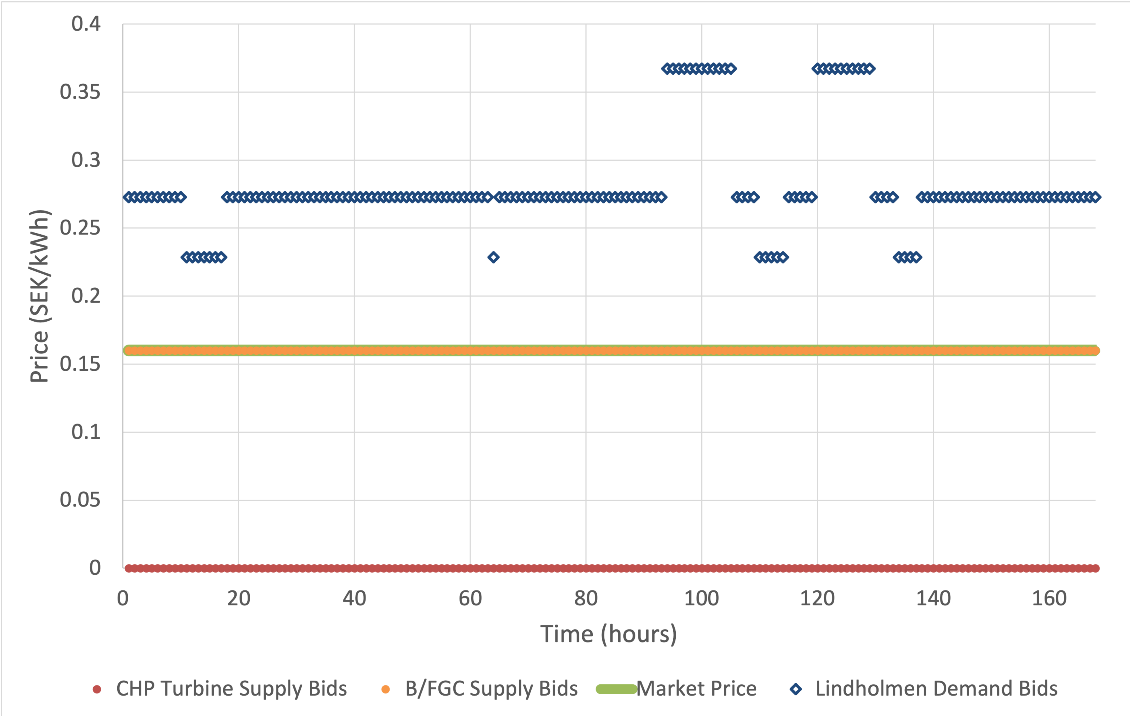


Figure 4.22: Oct Heat Market Clearing

A brief summary of the LEM results obtained from the week of October, can be found in Table 4.18, below.

Table 4.18: October Results

Electricity	Heat
CHP turbine operates at capacity	CHP boiler never operates
All PV bids cleared	B/FGC always operates
Constantly importing	Never importing
Never sold to Lindholmen	Always sold to Lindholmen
Demand never met internally	Demand always met internally
Never exporting	Never exporting
No HP demand cleared	No HP production cleared

A display of the above mentioned results can be seen once again for hour 37. All hours are noted to follow the same trend in regards to which bids are cleared, for both electricity and heat trading.

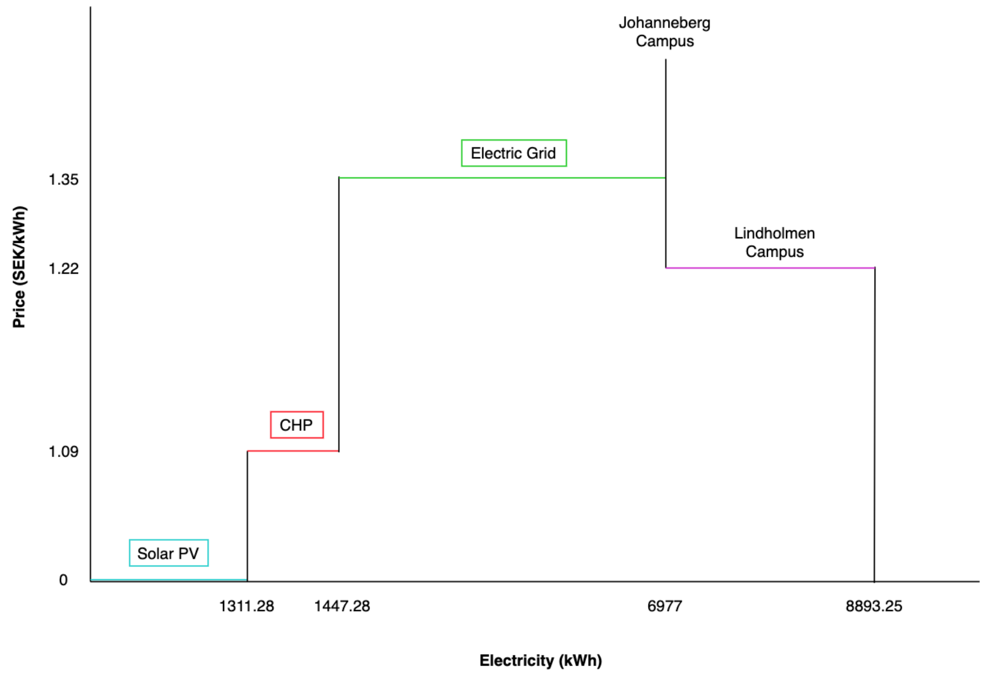


Figure 4.23: October Electricity Market Clearing

Table 4.19: Electricity Supplier Unitary Benefit at Hour 37

Supplier	Unitary benefit (SEK/MWh)
Solar PV	1.36
CHP	0.26
Grid Import	0.00

Table 4.20: Electricity Consumer Unitary Benefit at Hour 37

Demand	Unitary benefit (SEK/MWh)
Johanneberg Campus	∞
Lindholmen Campus	*rejected*
HP_s	*rejected*
Grid Export	*rejected*

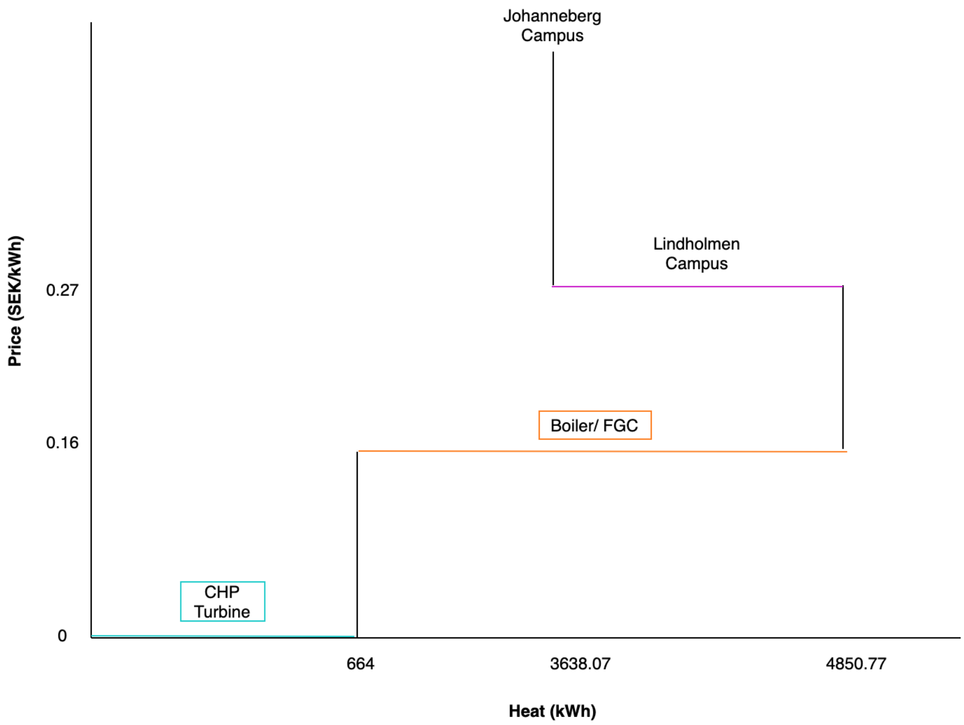


Figure 4.24: October Heat Market Clearing

Table 4.21: Heat Supplier Unitary Benefit at Hour 37

Supplier	Unitary benefit (SEK/MWh)
HP_s	*rejected*
CHP Turbine	0.16
CHP Boiler	*rejected*
Boiler & FGC	0.00
DHN Import	*rejected*

Table 4.22: Heat Consumer Unitary Benefit at Hour 37

Demand	Unitary benefit (SEK/MWh)
Johanneberg Campus	∞
Lindholmen Campus	0.11
DHN Export	*rejected*

4.1.5 Summary

Overall, the significant impacts meteorological parameters have on the energy sector and how a local energy market operates were analyzed. When simulating the LEM model under base case parameters, the market clearing price for electricity was always determined to be equivalent to that of the external price, as demand was never able to be met internally, regardless of the season. As a result, actors participating

in trading electricity obtain unitary benefits, however, consumers gained no distinguishable price savings from buying internally rather than externally.
Conversely, LEM benefits were identified when trading heat, as the LEM clearing price was mainly equivalent to the marginal costs of internal production, with the sole exception of selective hours in April where prices for importing heat drops below internal generation costs at certain hours. Although dispatching based on marginal costs aids in keeping energy costs low, and acts as an incentive towards RES integration, base case results prove that concerns may arise when one generating unit continuously induces the market price, for they secure no benefits for an extended period of time and thus actors may lose inventive to produce energy or to invest in updating their technologies. This will be further discussed in Chapter 5.

Unlike other technologies situated within the campus microgrid, none of the heat pumps were utilized throughout the base case. This is a result of the ratio of energy prices between electricity and heat averaging at approximately 6, while the COPs average at around 3. A heat pump will only purchase electricity when the price is low in comparison to the profit obtained from producing and selling heat. Such a scenario will occur when external electricity prices are low, or there is sufficient supply from variable solar PV. However, as proven in all four weeks assessed, such a situation is unlikely with the assessed generation technologies. Thus, when simulating the base case, it is not economically beneficial for the heat pump to run at any hour. Lower electricity prices could be achieved by sufficiently installing additional PV panels and obtaining high irradiance. Such a case will be evaluated in the next section. However, it is important to note that heat demand is high during the winter season, and low in summer; where in a solar dominated energy system, electricity price is lower in the summer than winter, establishing a mismatch between heat demand and electricity price. Therefore, it is foreseeable that production from heat pump will be minor.
A comparison of the average market clearing price between the external networks and local energy market, for electricity and heat, can be seen in Figures 4.23 and 4.24, respectively.

Table 4.23: Average Electricity Market Clearing Price Comparison (SEK/kWh)

	External	Base Case
January	1.27	1.27
April	1.18	1.18
July	1.25	1.25
October	1.34	1.34
Average	1.26	1.26

Table 4.24: Average Heat Market Clearing Price Comparison (SEK/kWh)

	External	Base Case
January	0.40	0.19
April	0.28	0.15
July	0.1	0.00
October	0.31	0.16
Average	0.27	0.13

4.2 Scenario 1: Increased Solar PV and CHP Capacity

Upon implementation of the Optimized Capacity Modeling code, an increased investment of 5294.39 kWh for solar PV and 5509.33 for the CHP boiler and turbine was calculated to be optimum. The reference model was thus re-simulated under the new capacities, and compared with findings obtained from the base case. The main discrepancies between the two scenarios will be discussed in this section.

4.2.1 January - Winter Season

When analyzing results obtained during the week of January, other than the heightened quantities of bidding, the main discrepancy found pertained to the CHP unit. For 9 hours within the week, the CHP boiler does not produce due to the lower demand quantity, which can be met by the B/FGC unit and recovered heat from the turbine. Moreover, the TES unit was utilized less, due to the higher capacities, no longer needing to save energy in advance, as seen in 4.26. As a result, the heat market still clears at the bid valuation of the CHP boiler, excluding the hours that it is offline, and thus the B/FGC then sets the clearing price. Market clearing price for electricity is still equal to the external grid price, as hours of sunshine are low during the winter season. All cleared bid quantities and respective market prices for the investigated week of January can be found in Figures 4.25 and 4.27, for electricity and heat, respectively. Table 4.25 and 4.26 presents a summarized comparison with the base case, for electricity and heat, respectively.

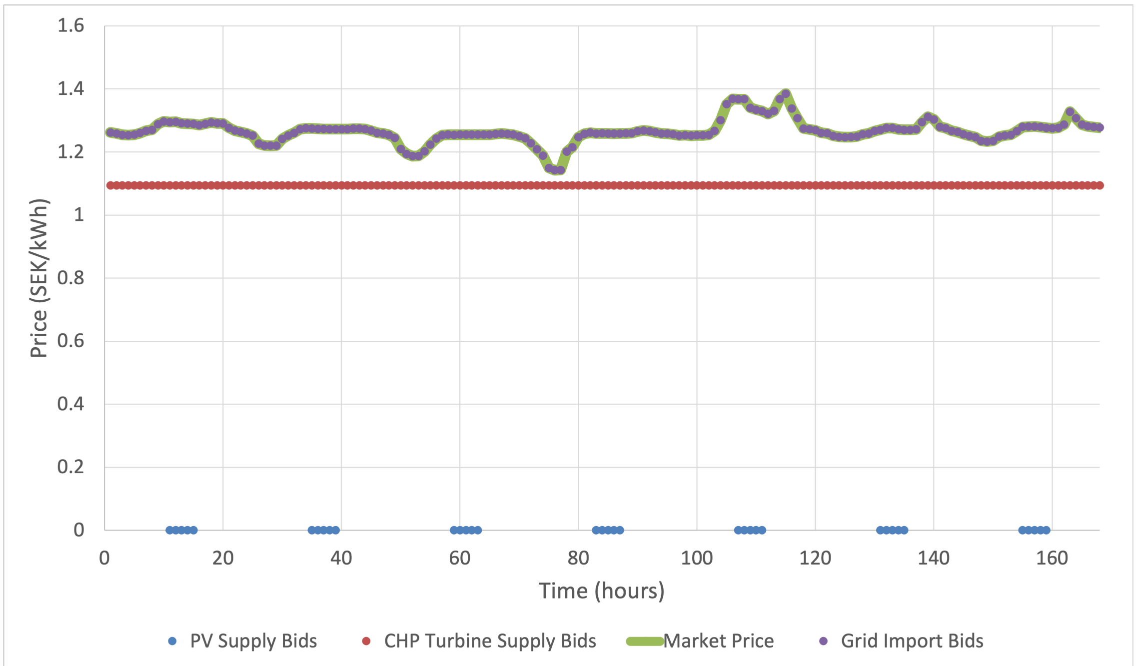


Figure 4.25: January Electricity Market Clearing

Table 4.25: January Results for Electricity Trading

Base Case Scenario	Optimized Investments Scenario
BES not utilized	BES not utilized
CHP turbine constantly utilized	CHP turbine constantly utilized
Always import	Always import
Never export	Never export
Never sold to Lindholmen	Never sold to Lindholmen
$HP_{w1,2}$ never utilized	$HP_{w1,2}$ never utilized

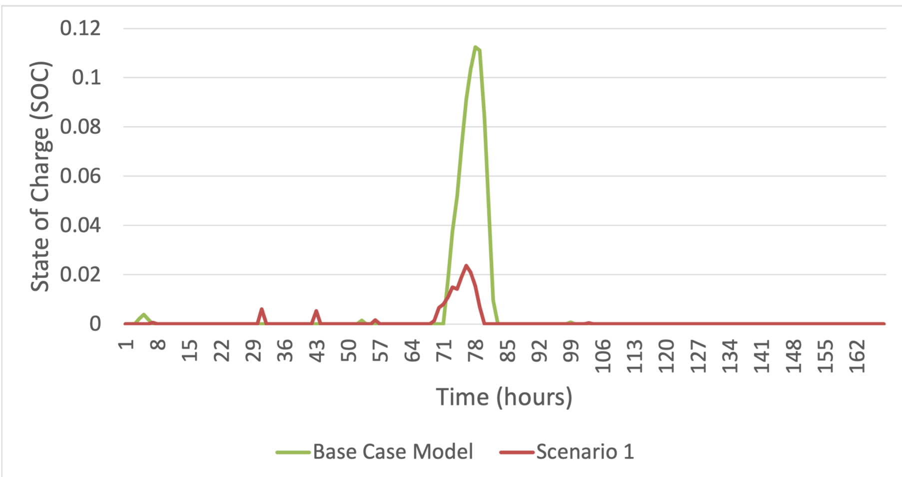


Figure 4.26: January TES Utilization Comparison

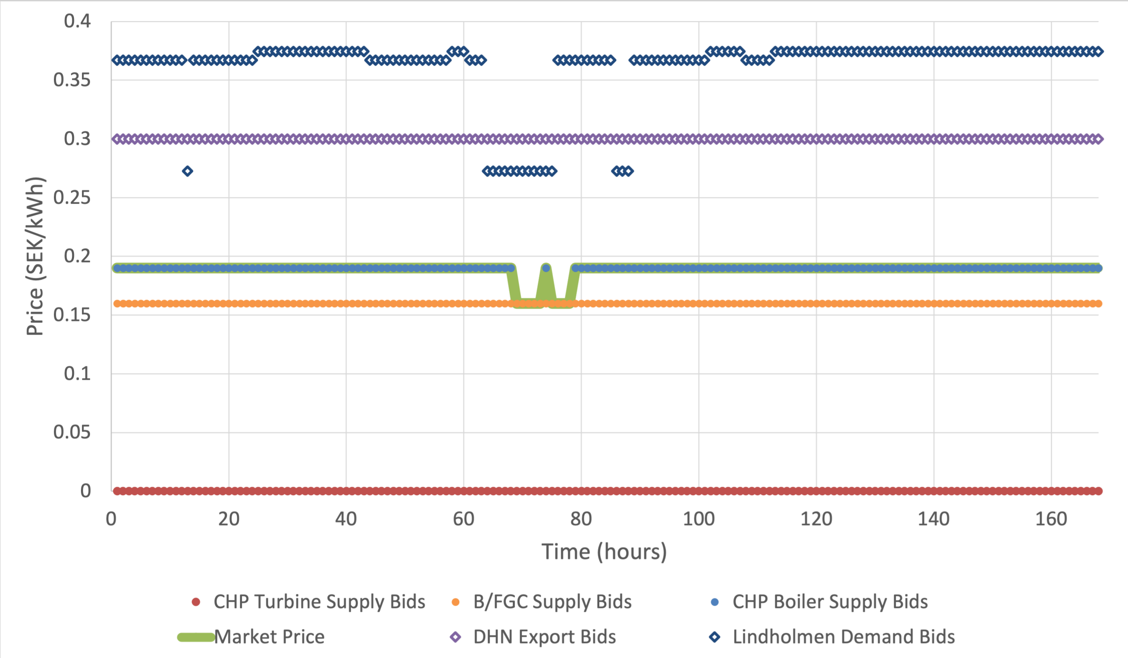


Figure 4.27: January Heat Market Clearing

Table 4.26: January Results for Heat Trading

Base Case Scenario	Optimized Investments Scenario
TES utilized occasionally	TES utilized occasionally
CHP boiler constantly utilized	CHP boiler frequently utilized
CHP turbine constantly utilized	CHP turbine constantly utilized
B/FGC constantly utilized	B/FGC constantly utilized
Never import	Never import
Always export	Always export
Always sell to Lindholmen	Always sell to Lindholmen
$HP_{w_{1,2}}$ never utilized	$HP_{w_{1,2}}$ never utilized

An illustration of all cleared bid quantities can be found in Appendix 2.

4.2.2 April - Spring Season

When trading electricity, the main discrepancy found during the week of April was the reduced quantity of electricity imported from the grid. With an increase in hours of sunlight and enhanced electrical production, electricity demand was able to be met internally within a handful of hours throughout the week. During said hours, excess electricity production was sold to Lindholmen campus. Thus, the market clearing price of electricity, although mainly equivalent to the external grid price, is occasionally set to the marginal cost of production from the CHP turbine. The CHP turbine no longer runs consistently at maximum capacity, but as needed. An illustration of the cleared electrical bid quantities and respective market prices can be found in Figure 4.28. Table 4.27 presents a summarized comparison with the base case.

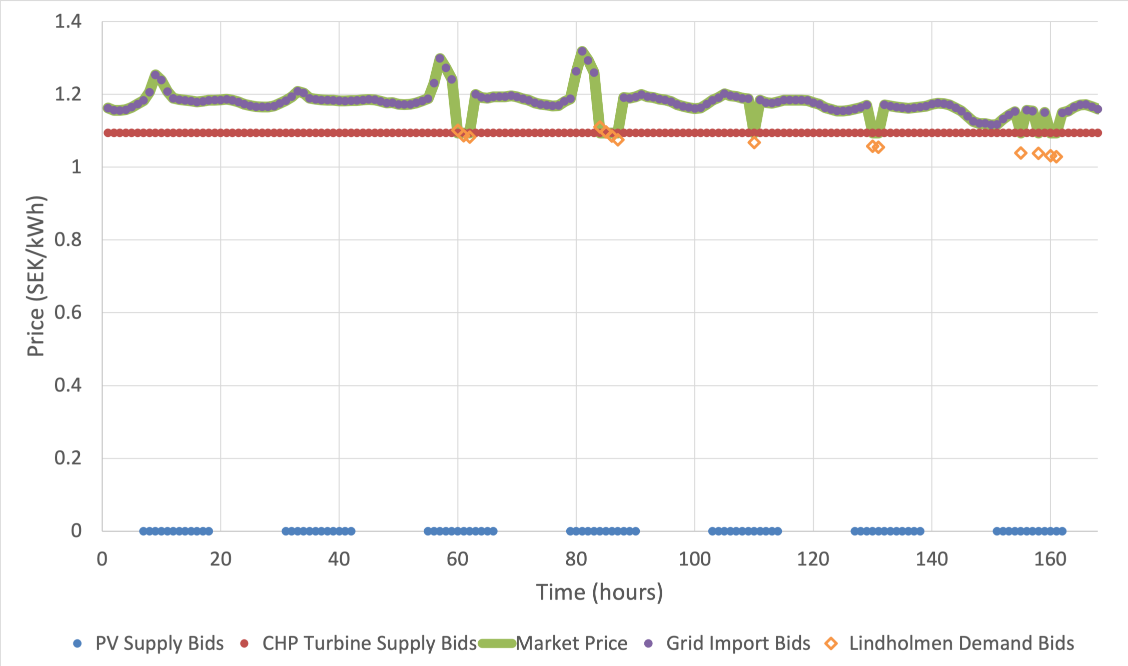


Figure 4.28: April Electricity Market Clearing

Table 4.27: April Results for Electricity Trading

Base Case Scenario	Optimized Investments Scenario
BES not utilized	BES not utilized
CHP turbine operates at capacity	CHP turbine output subject to dependency
CHP turbine always cleared	CHP turbine always cleared
Always import	Import not always required
Never export	Never export
Never sold to Lindholmen	Occasionally sold to Lindholmen
$HP_{w_{1,2}}$ never utilized	$HP_{w_{1,2}}$ never utilized

When analyzing the trading of heat, similar to the results obtained in January, heat was once again never directly obtained from the CHP boiler. As heat demand decreased, the quantity of heat recovered from the CHP turbine, in addition to discharge from the TES unit, was found to be sufficient in meeting internal demand, and most of Lindholmen campus demand - excluding 6 select hours, where the B/FGC unit was cleared to meet remaining unmet demand. Heat was imported from the DHN at 3 consecutive hours as heat recovered from the CHP turbine did not meet all demand, and the cost to import dropped below the cost of internal production. Nevertheless, heat importation occurred less regularly than what was noted in the base case model. As a result, the market clearing price for trading heat fluctuated between the bid validations of the CHP turbine, occasionally B/FGC unit, and uncommonly cost of importation.

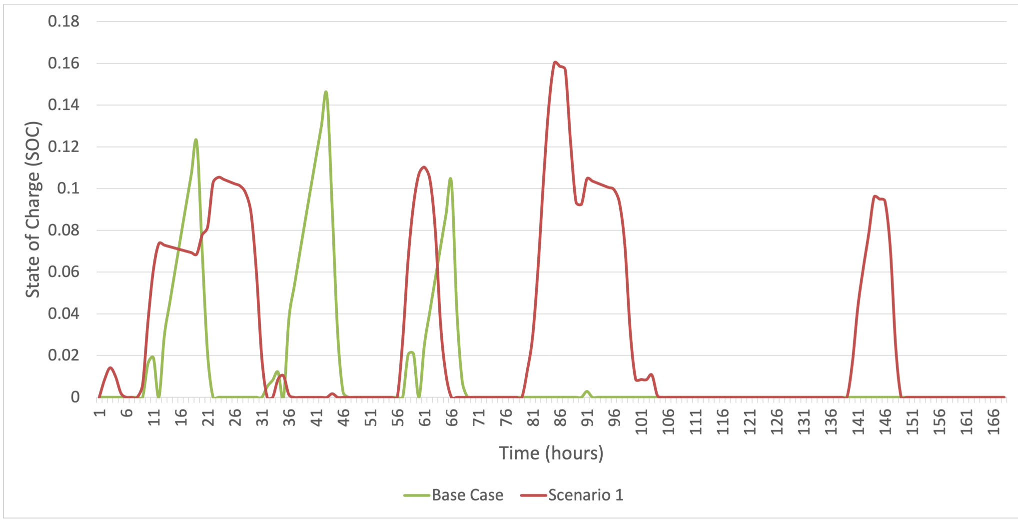


Figure 4.29: April TES Utilization Comparison

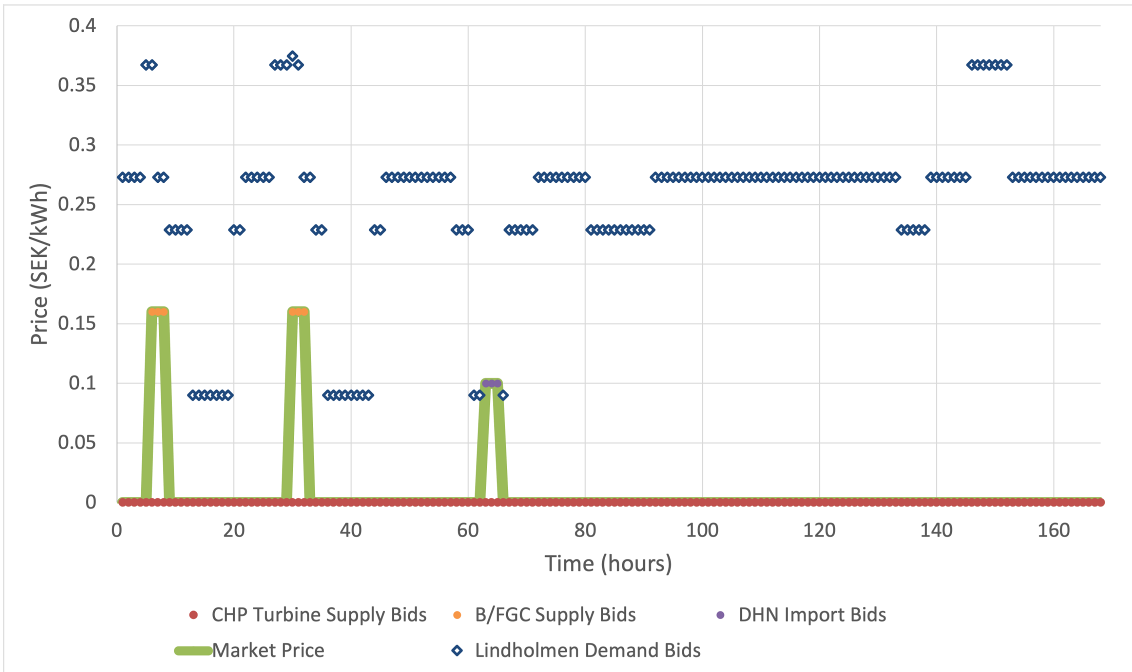


Figure 4.30: April Heat Market Clearing

Table 4.28: April Results for Heat Trading

Base Case Scenario	Optimized Investments Scenario
TES utilized occasionally	TES utilized frequently
CHP boiler never utilized	CHP boiler never utilized
CHP turbine ran at capacity	CHP turbine output subject to dependency
B/FGC utilized often	B/FGC occasionally utilized
Import occasionally	Occasionally import
Never export	Never export
Often sold to Lindholmen	Often sold to Lindholmen
$HP_{w_{1,2}}$ never utilized	$HP_{w_{1,2}}$ never utilized

An illustration of all cleared bid quantities can be found in Appendix 2.

4.2.3 July - Summer Season

Hours of daylight considerably increases during the summer season, resulting in high solar PV production and importing less quantities of electricity. Due to the increased capacity, the internal network is able to meet additional hours of electrical demand without aid from the external grid. During said hours, excess electricity is produced and stored in the BES units and/or sold to Lindholmen campus, resulting is more frequent usage of the BES units, as seen in Figure 4.31. At specific hours, production from solar PV exclusively was able to meet internal demand, Lindholmen campus demand, and exporting remaining energy for a profit. HP_s was utilized for heat production occasionally during said hours, due to the extremely low cost of electricity. As a result, the local market price for electricity fluctuates between the bid valuations of solar PV, CHP turbine, and the external grid, as seen below.

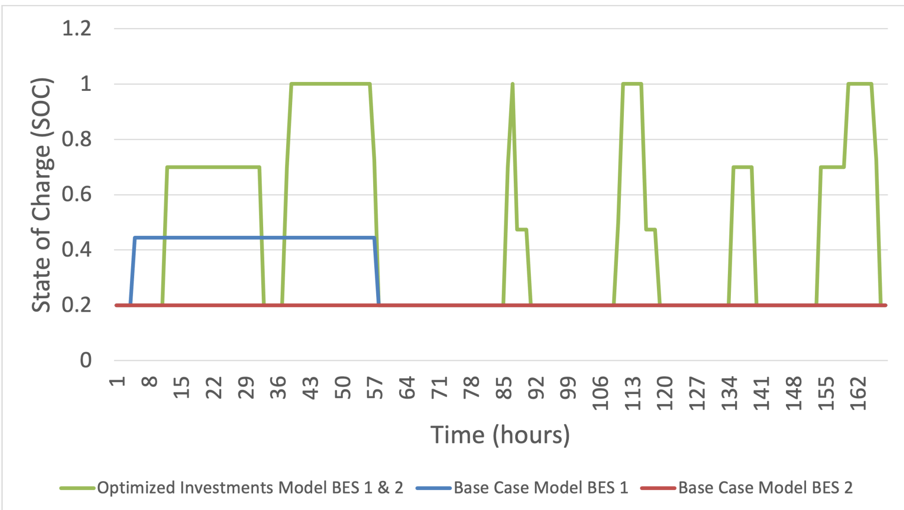


Figure 4.31: July BES Utilization Comparison

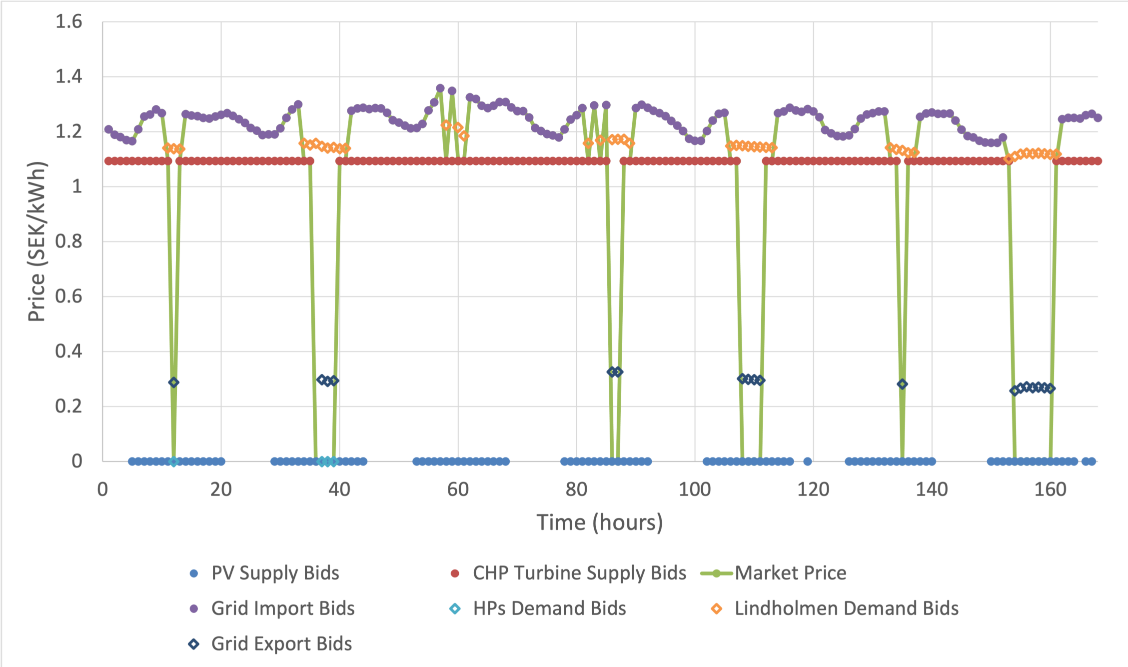


Figure 4.32: July Electricity Market Clearing

Table 4.29: July Results for Electricity Trading

Base Case Scenario	Optimized Investments Scenario
BES occasionally utilized	BES frequently utilized
CHP turbine output subject to dependency	CHP turbine output subject to dependency
CHP turbine always utilized	CHP turbine occasionally not utilized
Always import	Import not always required
Never export	Occasionally export
Never sold to Lindholmen	Occasionally sold to Lindholmen
HP_s never utilized	HP_s rarely utilized

July heat trading demonstrated that as the weather became warmer and heat demand decreased, heat recovered from the CHP turbine was sufficient to meet internal and most of Lindholmen demand. Due to the solar PV's ability to meet a larger quantity of demand, electricity generation from the CHP turbine has fallen. Thus, at specific hours, heat recovery from the turbine was noted to be insufficient in meeting internal demand due to the dependency with the electricity market, and as a result, heat was imported from the external DHN for at a low cost. The HP_s ran for four hours, whilst CHP production was low, two of which were able to meet internal demand without the need to import heat. As expected, no heat was sold to Lindholmen campus during low CHP production hours, and the TES was not utilized. As a result, the local market clearing price for heat trading was often set at the CHP turbine and HP valuation of 0 SEK/kWh, however, occasionally was equivalent to the imported heat price of 0.1 SEK/kWh.

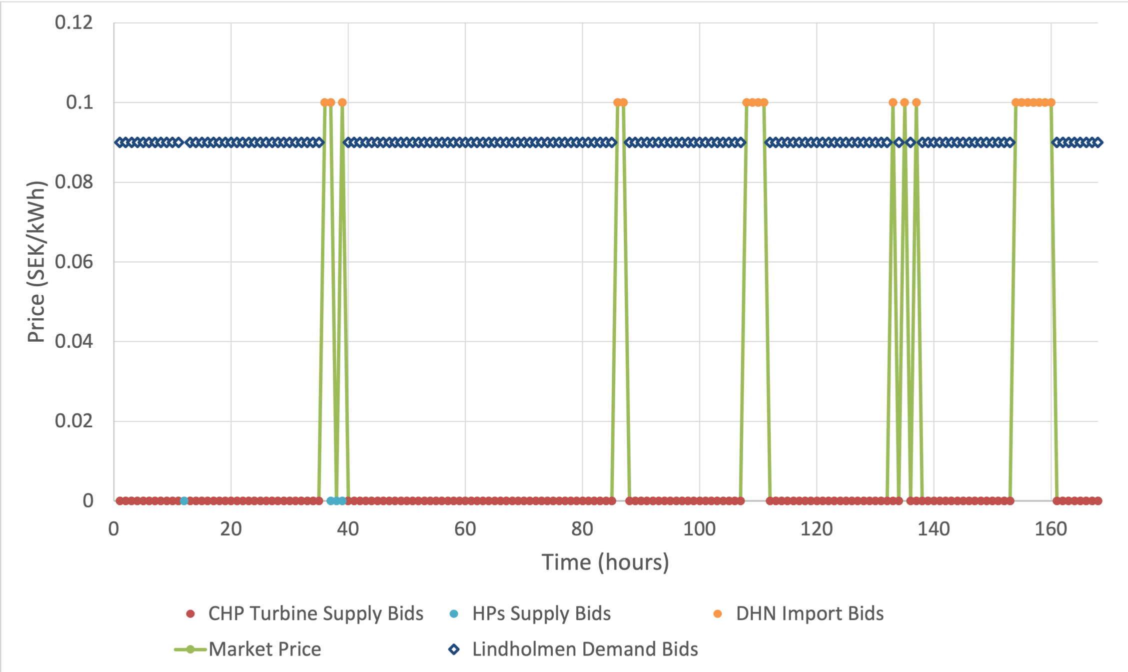


Figure 4.33: July Heat Market Clearing

Table 4.30: July Results for Heat Trading

Base Case Scenario	Optimized Investments Scenario
TES frequently utilized	TES never utilized
CHP boiler never utilized	CHP boiler never utilized
CHP turbine output subject to dependency	CHP turbine output subject to dependency
B/FGC never utilized	B/FGC never utilized
Never import	Import occasionally
Never export	Never export
Always sold to Lindholmen	Often sold to Lindholmen
HP_s never utilized	HP_s rarely utilized

An illustration of all cleared bid quantities can be found in Appendix 2.

4.2.4 October - Fall Season

In regards to trading electricity, the sole discrepancy within the week of October, in relation to the base case, is that the CHP turbine no longer runs regularly at full capacity, but now adheres to the constraints set by the AND-dependency, amidst its larger production capabilities. Additionally, electricity production from the CHP turbine is high enough that importing from the external grid was not required at 5 distinct hours.

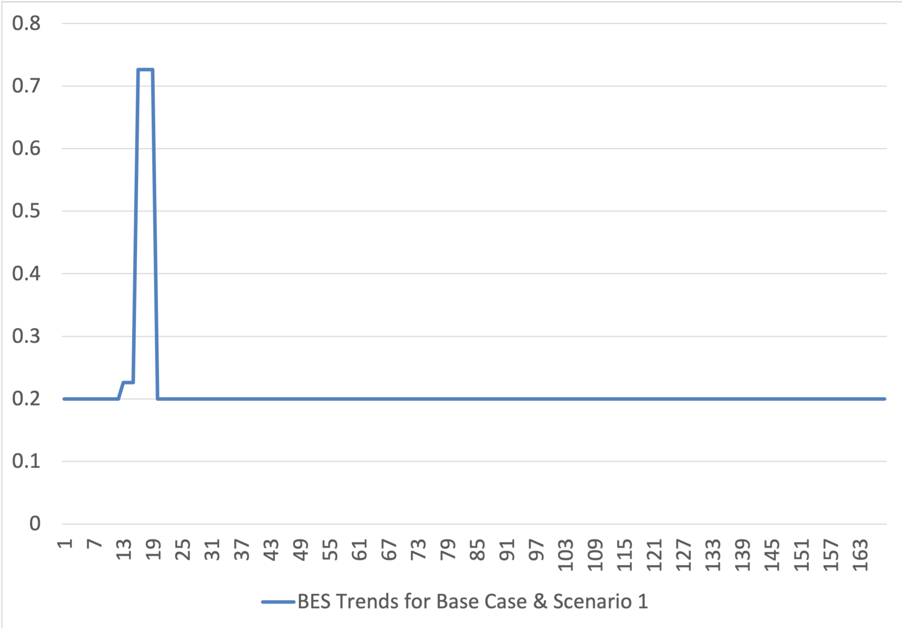


Figure 4.34: October BES Utilization Comparison

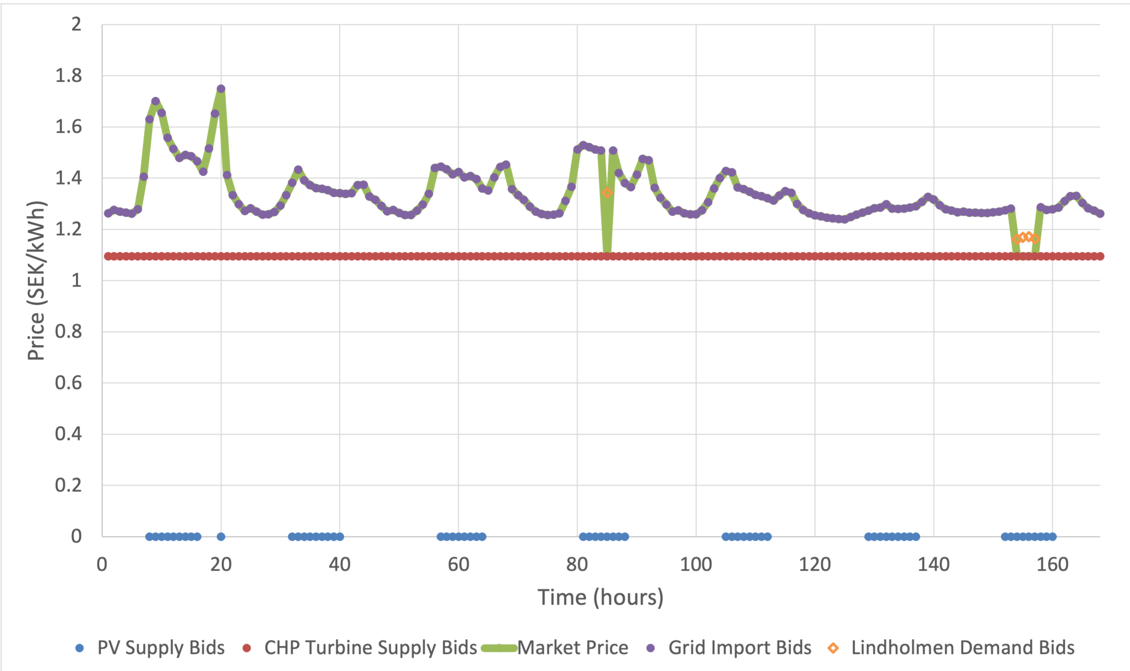


Figure 4.35: Oct Electricity Market Clearing

Table 4.31: Oct Results for Electricity Trading

Base Case Scenario	Optimized Investments Scenario
BES occasionally utilized	BES occasionally utilized
CHP turbine ran at capacity	CHP turbine output subject to dependency
CHP turbine always cleared	CHP turbine always cleared
Always import	Import rarely not required
Never export	Never export
Never sold to Lindholmen	Rarely sold to Lindholmen
HP_s never utilized	HP_s never utilized

In the base case, Johanneberg and Lindholmen heat demand is always met via production from both the B/FGC and heat recovered from the CHP turbine. Upon evaluating the effect of increased capacities in October, it was found the the B/FGC unit was no longer needed, and recovered heat from the CHP turbine itself, with effective implementation of the TES unit, was sufficient in meeting Johanneberg and Lindholmen campus demands.

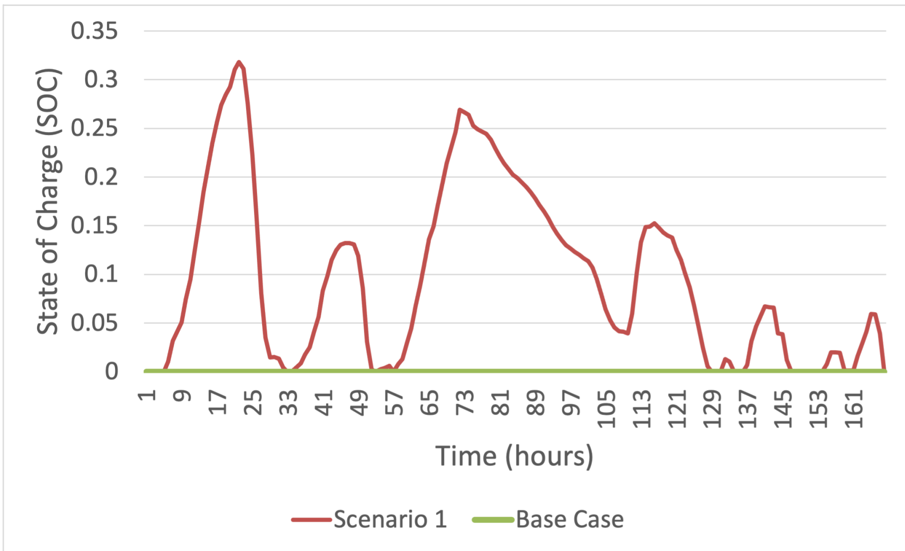


Figure 4.36: October TES Utilization Comparison

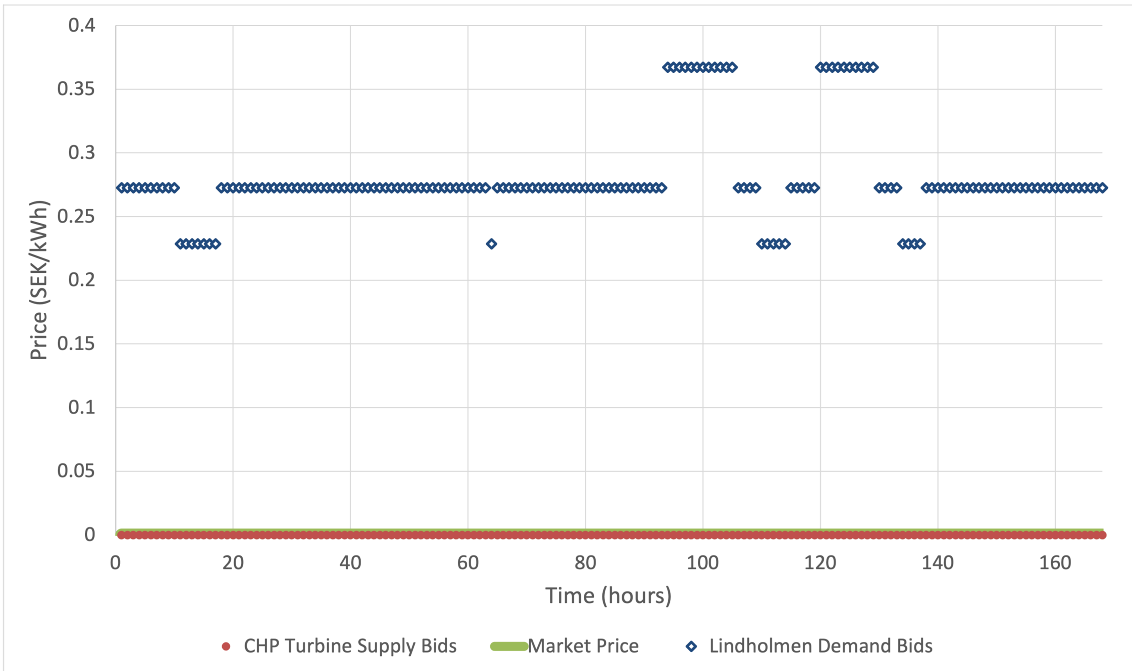


Figure 4.37: Oct Heat Market Clearing

Table 4.32: Oct Results for Heat Trading

Base Case Scenario	Optimized Investments Scenario
TES never utilized	TES frequently utilized
CHP boiler never utilized	CHP boiler never utilized
CHP turbine ran at capacity	CHP turbine output subject to dependency
B/FGC always utilized	B/FGC never utilized
Never import	Never import
Never export	Never export
Always sold to Lindholmen	Always sold to Lindholmen
HP_s never utilized	HP_s never utilized

An illustration of all cleared bid quantities can be found in Appendix 2.

4.2.5 Summary

Overall, the main objective of increasing investments in the Solar PV and CHP units was to advance internal electricity production, whilst ensuring an annualized profit. The resulting increased investment of 5294.39 kWh for solar PV and 5509.33 for the CHP boiler and turbine was not large enough to enable the campus microgrid to have the option of going off grid, as it is significantly dependent on the external grid for electricity. The increase, however, did considerably elevate internal electricity production. As a result, the local retail value of electricity did drop below external costs at specific time periods.
The capacity increase of the chosen technologies had subsequently resulted in a more

prominent impact when trading heat. In view of the larger quantity of heat recovered from the CHP turbine, the CHP unit no longer sent heat directly from the boiler to the grid, due to its larger bid valuation, which would not be accepted upon market clearing. Thus, heat produced within the CHP boiler was always used to operate the turbine. This has additionally lead to the lack of use of the B/FGC unit, which only operates during the winter season, and slightly in the spring. Inevitably, the local retail value of heat dropped to 0 SEK/kWh for considerable amount of hours during the weeks of April, July, and all of October. A comparison of the average market clearing price for both electricity and heat can be seen in Figures 4.33 and 4.34, respectively.

Table 4.33: Average Electricity Market Clearing Price Comparison (SEK/kWh)

	External	Base Case	Scenario 1
January	1.27	1.27	1.27
April	1.18	1.18	1.17
July	1.25	1.25	1.08
October	1.34	1.34	1.34
Average	1.26	1.26	1.22

Table 4.34: Average Heat Market Clearing Price Comparison (SEK/kWh)

	External	Base Case	Scenario 1
January	0.40	0.19	0.24
April	0.28	0.15	0.01
July	0.1	0.00	0.01
October	0.31	0.16	0.00
Average	0.27	0.13	0.07

4.3 Scenario 2: Price Fluctuation

When investigating the effects of fluctuating external energy prices on the LEM, energy storage devices play a key role in ensuring cost stability. In order to properly investigate the effects of exaggerated external price fluctuations, the optimized investment capacities obtained from Section 4.2 will be utilized. This is done in consideration of the inability of the base case to meet internal electricity demand, and thus, no major alterations would be noted. The main discrepancies between the different scenarios evaluated will be discussed in this section.

4.3.1 January - Winter Season

In response to the highly dynamic prices within the external market, agent 1 charges the BES units during hours of PV production when external grid prices are relatively low, and discharges the electricity when prices are high, attaining a heightened revenue, as can be seen in Figure 4.38. This contradicts agent 1's lack of BES operation in the base case and scenario 1, as the price fluctuations were not deemed dynamic enough for the battery to be profitable. Moreover, high external prices generally occurred during the daytime, when the sun is shining, thus, PV generation was sold directly.

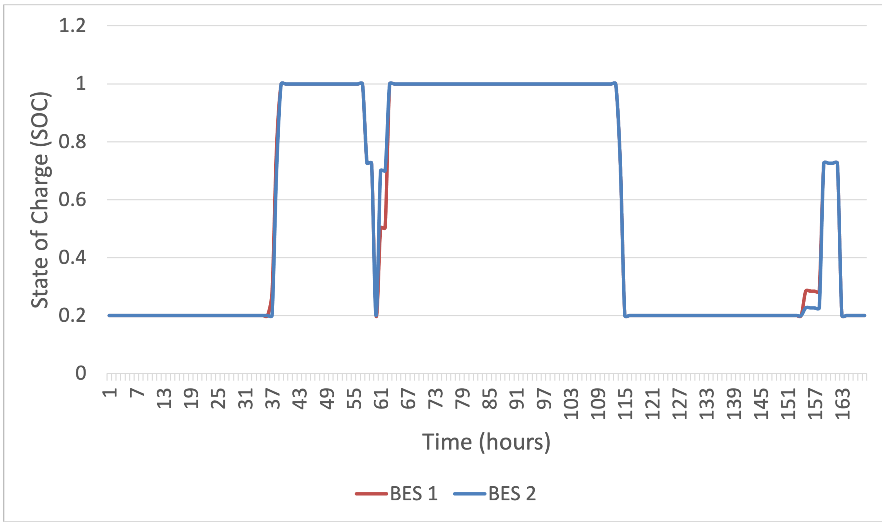


Figure 4.38: January BES State of Charge

Similarly to scenario 1, the CHP turbine produces at or near maximum capacity, maximizing revenue from both electricity and heat trading. TES usage thus does not alter, as seen in Figure 4.39.

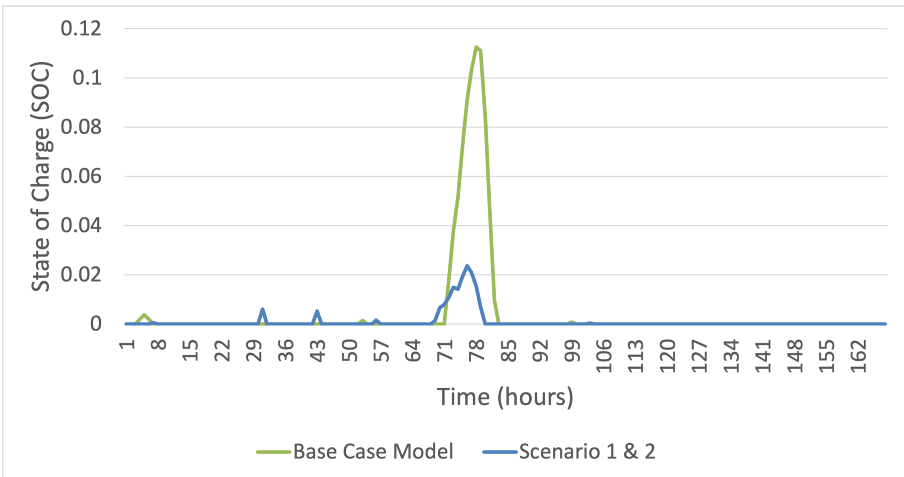


Figure 4.39: January TES Utilization Comparison

Overall, it was concluded that importing electricity is always required during the week of of January, for all the scenarios investigated. Therefore, the local energy market electricity clearing price is always equal to external grid costs. An illustration of all cleared bid quantities can be found in Appendix 3.

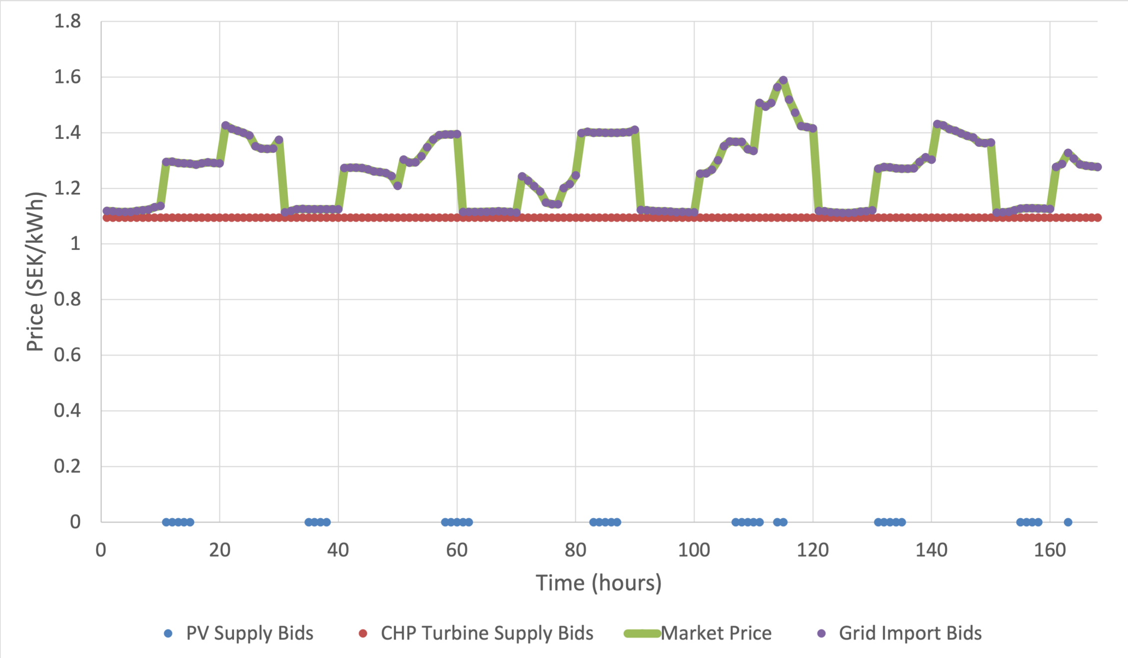


Figure 4.40: January Electricity Market Clearing

4.3.2 April - Spring Season

Similar to January, the BES units were utilized, charging when the electricity prices are low, and discharging when prices are high, as seen in Figure 4.41. This contradicts previous scenarios, where the BES units were never used. The BES units were utilized more frequently in the spring, than in the winter season, as a result of longer periods of daylight.

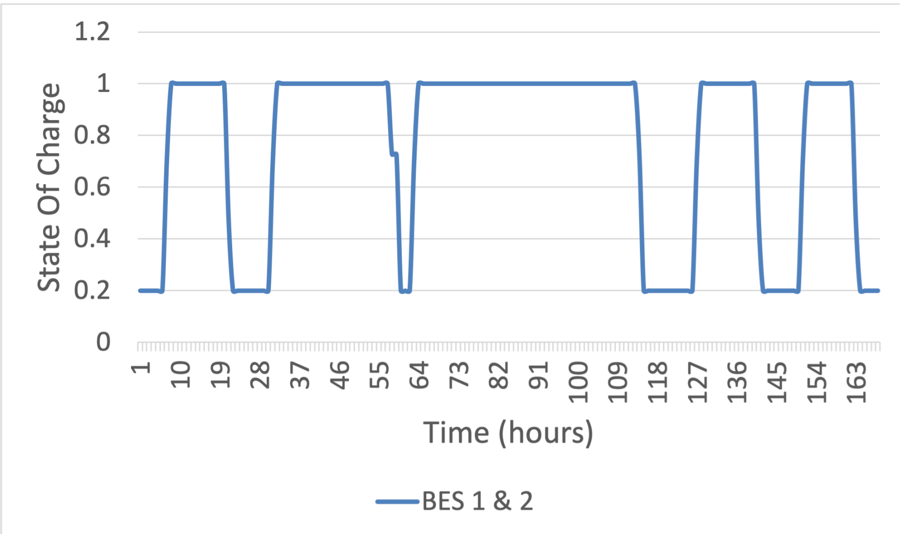


Figure 4.41: April BES State of Charge

Upon examining the market clearing price of electricity, it was noted that CHP electricity production bids are almost always cleared, in addition to import bids, despite external grid prices dropping below production costs. This is done in order to maximize overall social welfare, in view of the benefits obtained from participating in heat trading and given the minor consumer losses, stationed within a magnitude of 10^{-2} SEK/kWh. Only 3 nonconsecutive hours were noted to not clear the CHP turbine bids, but only import from the external grid at a lower cost, considering that discharge from the TES unit was able to meet both Johanneberg and Lindholmen demand, at those hours. TES charging occurs when external electric prices peak, thus, agent 2 increases CHP turbine production to maximize profits within the electricity trading sector, and charge the excess heat. In conclusion, the local market price for electricity would fluctuate between the external grid price and CHP turbine marginal production costs. An illustration of all cleared bid quantities can be found in Appendix 3.

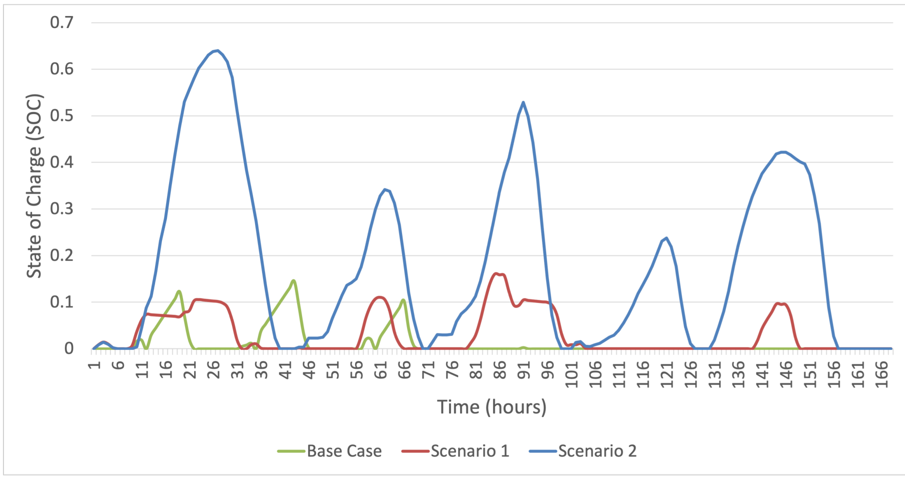


Figure 4.42: April TES Utilization Comparison

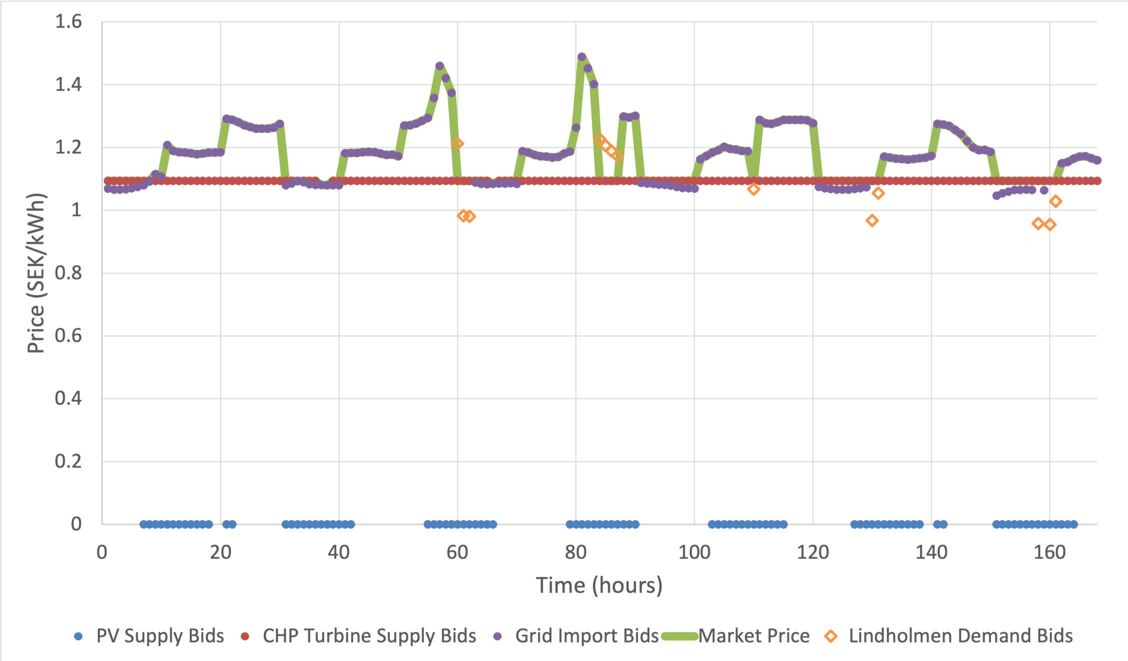


Figure 4.43: April Electricity Market Clearing

4.3.3 July - Summer Season

As predicted, the BES units are cycled more frequently when external grid prices fluctuate, and due to the CHP unit's bid dependency, more excess heat is stored for future use when production must be increased to maximize profits when electricity prices are high.
Similar to findings observed in April, agent 2 will not reduce CHP electricity production when external grid prices drop below production costs, and the local energy market clears this production in order to maximize total social welfare when considering revenues obtained from trading heat. As before, consumer losses were minor, within a magnitude of 10^{-2} SEK/kWh. HP_s was operated at 5 separate hours when local electricity price was cleared at Solar PV's bid valuation. During 4 of those hours, the heat pump met all internal heat demand, while the last hour needed aid from importing heat from the external DHN. In conclusion, the cost of electricity within the local energy market fluctuated between the marginal costs of solar PV, marginal costs of the CHP turbine, and the cost of importing from the external grid.

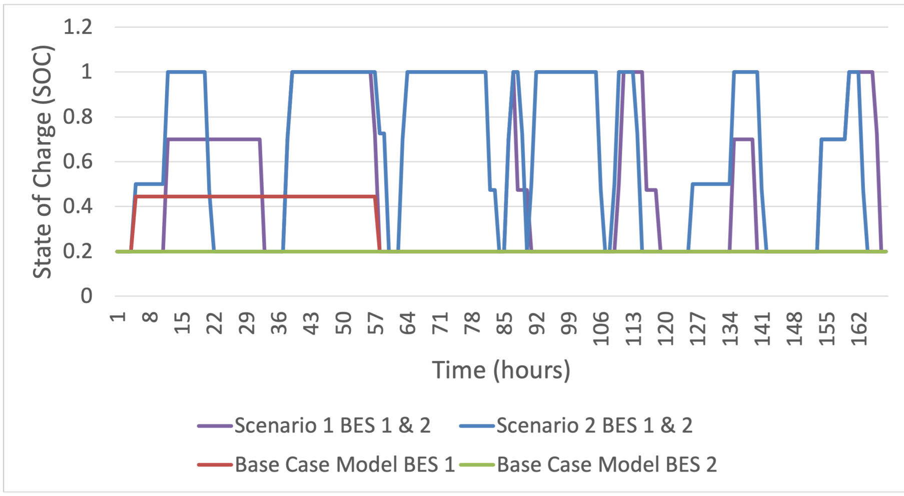


Figure 4.44: July BES State of Charge

Figure 4.45: July Electricity Market Clearing

An illustration of all cleared bid quantities can be found in Appendix 3.

4.3.4 October - Fall Season

In both of the previous models, the BES units were seen to charge at two separate accounts, before discharging once, resulting in one cycle during the entire investigated week within October. Due to the external grid's fluctuating prices, the BES units were utilized at a greater extent and cycled numerously - charging when prices are low, and discharging when prices peak, as seen in Figure 4.46.

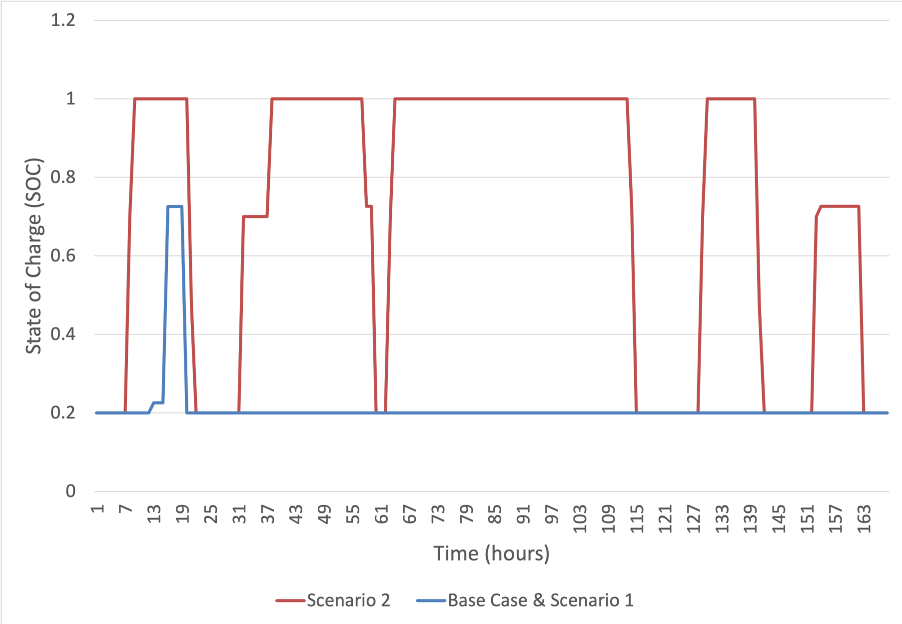


Figure 4.46: Oct BES State of Charge

In comparison to the lack of usage of the TES unit in the base case model, and somewhat regular usage in the optimized investments model, usage of the unit was much more frequent when external electricity prices are dynamic.

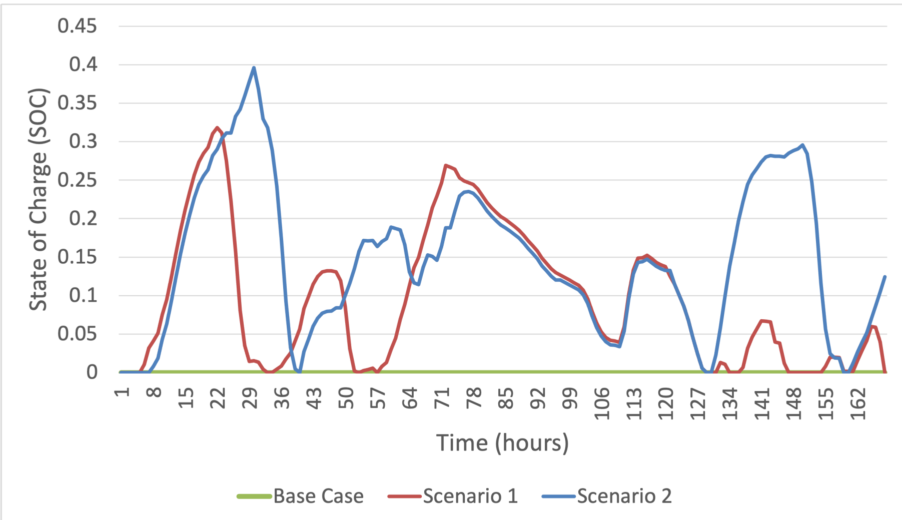


Figure 4.47: Oct TES State of Charge

Considering demand was only able to be met internally for 4 of the 168 hours evaluated in October, the local energy market price for electricity is equivalent to the external grid, apart from the 4 aforementioned hours, where electricity is sold at the CHP turbine marginal production costs. Despite the fluctuating prices of electricity within the external grid, costs did not drop below the marginal cost of production of the CHP turbine.

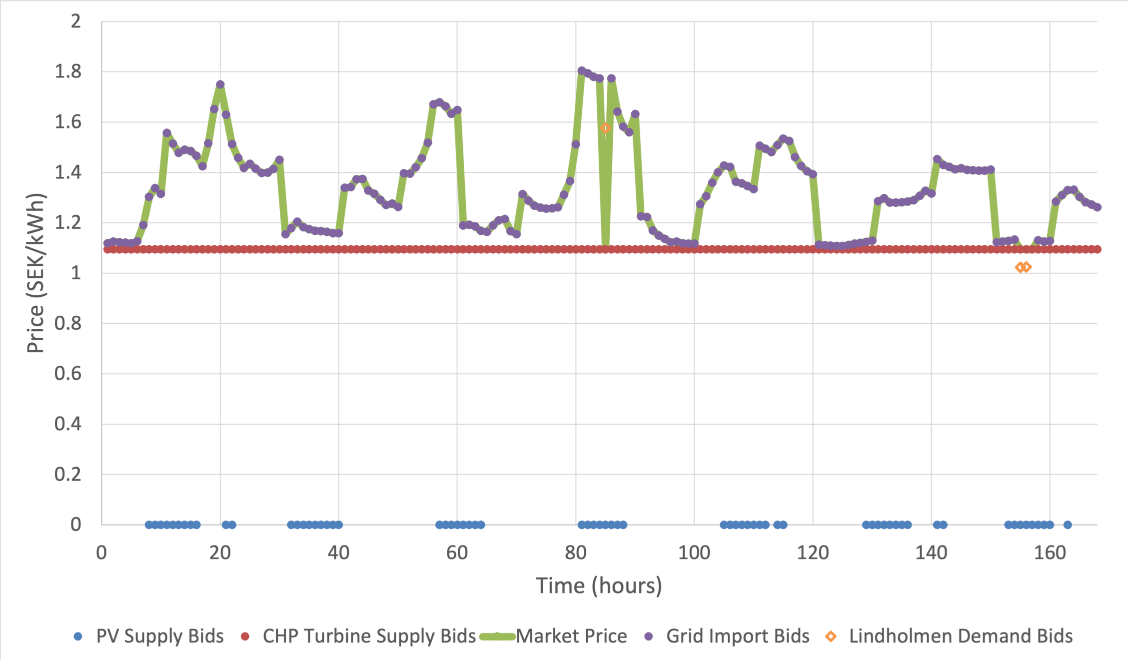


Figure 4.48: Oct Electricity Market Clearing

An illustration of all cleared bid quantities can be found in Appendix 3.

4.3.5 Summary

In all the weeks evaluated, storage units proved to provide local energy stability, reliability, and economic feasibility, when external grid prices undergo peaks and valleys. The BES units aided in storing cheap energy for future trading, resulting in increased revenue. The TES unit operated similarly, whilst also reducing revenue losses that would have otherwise occurred due to curtailment when heat generation from the CHP turbine exceeded demand, making the low emission energy investments more profitable. Moreover, if there were no network constraints and the CHP unit could export to the external DHN, the unit would be more likely to displace external high emission technologies.

5
Discussion

The need to decarbonize the energy grid, and exploit the falling costs of renewable technologies and technological advances, has demonstrated opportunities for a systemic change in how energy is generated and traded. Large integration of modern technologies, such as intermittent RES, prosumers and electrical vehicles (EVs), requires grid advancements that enable bidirectional power flow, and mitigating major congestion problems in already heavily loaded grids. Upgrading the current grid would require a substantial amount of money and time. A prevalent topic of research to solve this issue explores smarter, more flexible, local energy systems. This study investigated the feasibility of developing a virtual local energy market at Chalmers Univeristy of Technology, where local agents can sell low-carbon energy and make money by being flexible with how they generate and utilize energy.
The investigation proved to be advantageous in multiple aspects. The integration of currently available energy systems to provide a synergistic supply of electricity and heat ensured efficient use of renewable energy, as society progresses towards economic decarbonization. Although electricity production was frequently deemed insufficient in meeting internal campus demand throughout the study, if production capacities could be enhanced in a cost-effective manner, it is evident that the anticipated benefits of energy reliability, stability and quality would be observed within electricity trading, much like that noted with the local trading of heat. In addition to mitigating anthropogenic climate impacts and promoting clean energy, the local market reduced internal energy costs. Moreover, by generating energy internally, dependency on external systems and transmission technology was limited. As well as serving internal demands, the LEM also benefited external systems by easing the strain on the grid and DHN during periods of peak demand, and acted as additional operators. This was observed most clearly when larger price fluctuations in external markets were were simulated (scenario 2), in addition to the consistent exporting of heat during the winter season in all three scenarios. In scenario 2, when electricity prices became volatile externally, the local energy market was able to provide internal price stability through the efficient management of energy supply. Fundamentally, energy price stability preserves a consumer's purchasing power and an agents confidence in participating in an energy market. Mitigating periods of high energy price volatility avoids complications regarding economic decision-making and the hindrance of economic growth.

Despite the many benefits observed within the study, a number of technical challenges were also encountered. A main challenge observed within the 3 models investigated arises when the local retail value of energy drops to 0 SEK/kWh for an

extended period of time. Although this is favorable from an emissions and consumer stand point, such that cleaner and low-cost production technologies are able to satisfy a larger quantity of demand, the drop in players participating in the market hinders desired competition. In addition, when a market is over penetrated with cheap energy, the cost of investing in updated technology, as old systems approach their end-of-life, becomes too high in relation to the lack of returned profit. This results in additional loss of participants, and lack of incentives to invest in new innovative technology.
Although increasing the capacity of the BES unit was found to be prohibitively expensive in scenario 1, with increasing technological advancements leading to cost reductions, potential investments could allow actors to become more tactful in their bidding strategies. For example, assume actor 1 is capable of providing sufficient solar PV generation and possesses a suitable amount of storage. The agent's capability of storing and load shifting would advance the agent's bidding strategy. These complementary technologies would store energy during periods of low demand, when market prices would otherwise be near zero, and sell it during high demand hours when prices become more lucrative. As a result, this would raise otherwise very low electricity prices, when solar PV alone would otherwise be sufficient in meeting demand, whilst also decreasing pressure during high demand hours. An example of this can be seen in Figure 5.1. This strategy reduces price volatility in addition to improving electric reliability and resilience to unprecedented events. It also aids in offsetting the seasonal mismatch between energy demand and PV production in northern Europe.

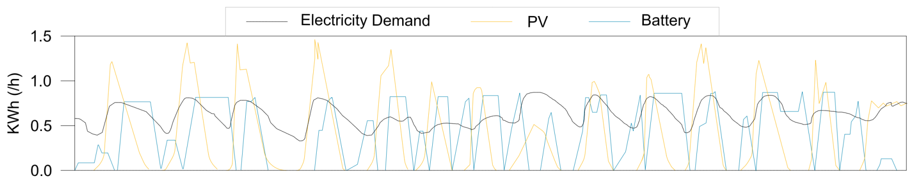


Figure 5.1: Ideal Solar PV Generation. *Adapted from [56]*

The capacity of the TES unit was found to be sufficient in the modeled scenarios. However, if thermal storage units that can hold heat for long durations were utilized, electricity can be purchased in the summer when prices are cheap, and used to produce heat via the heat pumps, which is then stored for winter use. Moreover, by eliminating network constraints and allowing the export of CHP produced heat to the external DHN, actor 2 would be able to increase their revenue during the colder months.

In addition to the already low number of participants modelled, the lack of heat pump utilization has resulted in agent 2 dominating the heat market, hence, mitigating competition within the heat sector. Having a limited number of participants enables too much market influence in the hands of a few, which is inconsistent with the conditions of a perfect competitive market. In order to alleviate these concerns, it should not be too complicated and risky for new actors to join and participate in the LEM, such as neighbouring prosumers or other LEMs. This will aid in rising

competition and encouraging further innovation towards efficient and economical energy generation. Prosumers could also be added internally by investing in roof top solar on campus buildings, allowing actor 4 (Johanneberg campus buildings) to generate and use/sell their own energy, easing dependency on the external grid. Actor 4 could also become a prosumer by investing in storage units. When there is too much energy generation, consumers could be incentivized to use or store the energy for later. If there is too much demand and not enough generation, consumers can save money by using less, or even make money by selling the energy they do not need back to the market. Moreover, by expanding the market and increasing the number of actors involved, the actor that sets the market price for an extended period of time (thus not securing unitary benefits) will shift more frequently and it increases the chance that price discovery results in a more efficient solution.
With big data analytics and IoT technologies, all the buying and selling between market participants could eventually occur automatically using smart systems, keeping things smart and simple. This concept is typically known as a smart grid system. The European Union defines a smart grid as an electricity network that can cost-effectively integrate the behaviour and actions of all users connected to it, including generators, consumers, and prosumers, in order to ensure an economically efficient, sustainable power system with low losses, high levels of supply quality, security, and safety [57]. A smart grid's energy network allows for the two-way flow of electricity and data, as well as the detection, reaction, and prevention of changes in use and other concerns, using digital communications technology. Smart grids are self-healing and allow power users to have an active role in the system.[58]. Updating today's aging infrastructure and the local market with smart technology will allow utilities to interact with customers more effectively when assisting in managing power demands and the distributed energy resources.

Lastly, one of the biggest challenges in this study was allotted to the price relationship between the LEM and external networks. The financial motivation of the local energy market is generally determined based on these linkages. A generating agent would not willingly trade on a market that acquires them less revenue, such that a consumer would not deliberately purchase energy at a higher cost. Some advantages of the LEM is the reduced energy costs due to lack of transmission fees and lowered energy losses, in addition to energy management via storage technology. However, the practicality of it all is highly dependent on the price relations.
In consideration of the fees both the LEM and external networks would have to pay to import energy from each other, generating actors within the LEM generally prioritized meeting Johanneberg campus demand. However, a scenario may arise where internal generators would acquire a larger profit by participating within the external market rather than selling internally. Additionally, an instance could occur, similar to what was observed in scenario 2, where there had been selective hours that the retail value of electricity within the LEM slightly exceeded the value of importing from the external grid. This was due to the fact that clearing CHP electricity production maximized the total social welfare of the LEM, in view of the unit's dependency with heat trading. These events may lead to major challenges that go beyond the scope of this study, but should be further investigated. It is also

advised to acquire more about the impacts of other bidding strategies, or the implementation of economical or administrative policy instruments, such as subsidies, taxes or regulations, to prioritize energy trading within the LEM, prior to exporting.

A potential major addition to the LEM that should not be overlooked is EV charging. Given the uncertainties surrounding both vehicle adoption rates and the future evolution of the transportation sector in terms of the mix of mobility types and charging infrastructure solutions, forecasting the impact of PEVs on distribution networks is a tough challenge [59]. Nevertheless, it is undeniable that the electrification of transportation has played a critical role in expanding structural change in current transport and energy systems and the adoption of charging infrastructure within local energy markets is expected. The transition has the potential of increasing electricity demand and energy management capabilities within the LEM. EV charging could be conducted smartly, via the implementation of approaches such as smart charging, which enables the grid to alter the charging power based on internal production and availability, and yielding prices signals that promote charging to occur outside of peak demand times. However, it is important to consider whether the increasing energy demands will be met with increased revenues for the utility, and how this will impact pricing. Demand management measures will play a critical role in this, along with network policies [60] [61] [62].

6

Conclusion and Future work

6.1 Conclusion

With the growing amounts of distributed energy resources, and introduction to new and growing demands (e.g. electrical vehicles, centralization, ect.), energy system transformations are being spurred into many economies worldwide. This study addresses this problem by investigating the highly discussed potential solution of local energy markets. In order to do so, an optimization-based market clearing design was simulated for a hypothetical local energy market within Chalmers University of Technology. The reference model was designed based on current campus investments, and is connected to external electricity grid and district heat networks. Two alternate scenarios were also investigated, where solar PV and CHP unit capacities were increased, and LEM flexibility and response to price volatility within the external electricity grid were analyzed. Every scenario was simulated for one week of the four seasons, and compared based on the quantity of energy offered by the generating actors and final market clearing price, each hour. The model was designed to trade energy and heat as separate commodities, but in an interconnected and simultaneous manner using bid-dependencies. The computed simulation ensured that market players were able to make thoughtful bid decisions to maximize their potential profits, and market clearing operated to maximize total social welfare.

Results confirmed that constructing a common marketplace with multiple energy carriers potentially leads to synergies and increases efficiencies of utilized resources. The simulated market was found to be beneficial in integrating variable renewable energy systems and aided in the mitigation of power shortages and price volatility as local participants act as additional generators. Transmission and distribution losses, and costs, were reduced due to local generation and consumption. Local energy markets proved to offer grid stability, and has the potential to increase awareness and engagement of end-users with the integration of prosumers [48]. The system would also be capable of reducing peak loads and overall CO_2 emissions. Despite not seeing benefits seen in regards to reduced electricity prices in the base case, as internal generation did not satisfy demand, heat costs were cut by up to 52% in the winter and 100% in the summer. When looking at the effects of expanding the solar PV and CHP units' capacity in the first sensitivity case scenario, no power price reductions were noticed in the winter, while costs dropped by up to 13% on average in the summer. In the winter and summer, heat prices reduced by an average of 53% and 100%, respectively. In the second sensitivity example, LEMs proved to be

reliable and provided cost stability when analyzing the influence of electricity price variations.
This said, the designed LEM was found to be highly dependent on the external electricity grid in order to meet internal needs. Moreover, a major challenge found in this study is the LEM's price relation to the external networks, which should be further investigated, but is beyond the scope of this study.

Although the real-life feasibility of constructing local energy markets is still under investigation, this study was able conclude that LEMs have significant benefits when tackling the challenges of the future energy market, such as the heightened integration of variable RES, the need for higher flexibility, and effective employment of energy storage technologies.

6.2 Future Work

This thesis aimed to develop a simplified market design for the purpose of transparency and understanding of market clearing results. In order to conduct a deeper analysis on the benefits and barriers of local energy markets, the following ideas could be researched:

Short-term vs. long-term: Reduced transmission fees is one of the main advantages of trading on a LEM as energy is generated and utilized within the same geographical location, thus transmission services are expendable. The current model investigates the short-term operation of a LEM, however, an analysis of long-term performance needs to be further investigated. The additional implementation of long-term storage units with sufficient capacities could be highly beneficial.

Demand Response: Further research should be conducted on load flexibility options permitting consumer engagement and/or computerized consumption adjustments in response to pricing signals. Computerized temperature adjustments in buildings, turning off certain lights, or avoided usage of energy intensive equipment during peak demand hours are common examples of demand response.

Bidding Strategies: There are various bidding techniques that could be implemented other that marginal pricing that have not been tested. Different bidding strategies and the affect on price relations between the LEM and external networks need further investigation.

Prosumers: Aforementioned, the integration of additional actors and prosumers into the LEM would be advantageous, and it would be fascinating to simulate such a process to learn more about the benefits and how the market would react. Prosumers can be portrayed by installing solar panels on the roofs of the buildings on campus, or providing consumers with storage units. Actors 1 and 2 can also adjust their bidding strategies to charge their storage units with imported energy when prices are cheap, rather than merely their production.

Price Relation Between Markets: As discussed in the previous section, the feasibility of a LEM is greatly dependent on the extent of its compatibility with existing wholesale markets and other frameworks that currently govern energy trading. The impact of various price relation events between the markets should be investigated, and strategies to mitigate potential challenges should be determined.

Forecasting: The model can be designed more realistically by implementing market mechanisms that handle forecast errors, such as intra-day trading.

Reset CHP Waste Heat Price: CHP waste heat price was set to zero for simplicity, however, it may be beneficial to explore other prices to mitigate the CHP unit becoming the marginal unit for extended hours when its capacity is increased.

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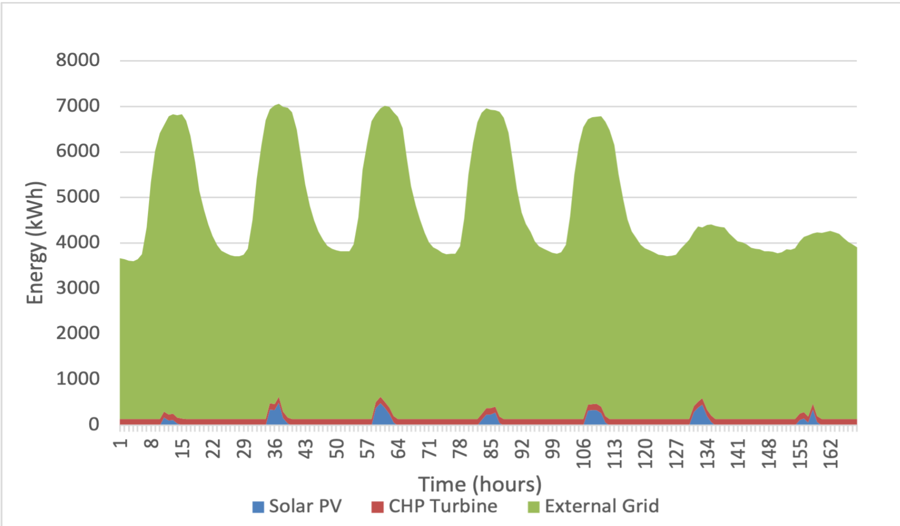
url

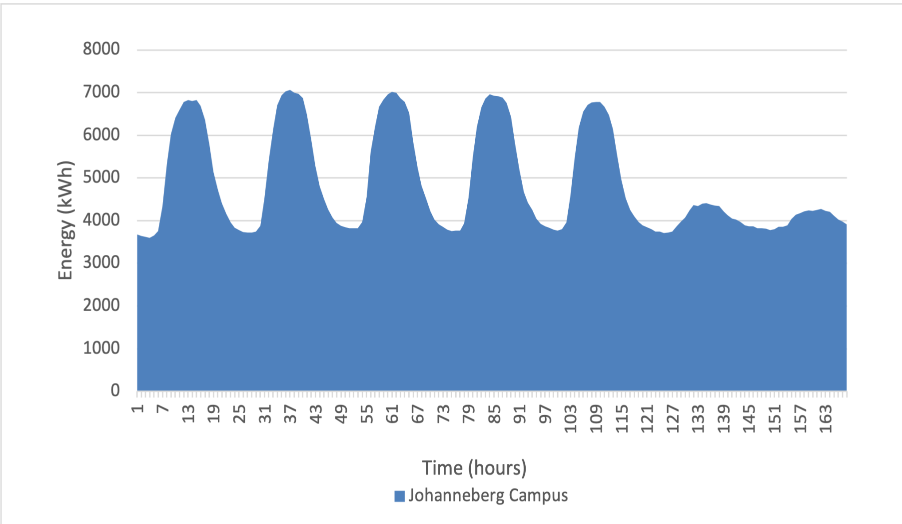
A

Appendix 1 - Base Case Cleared Quantities

January:

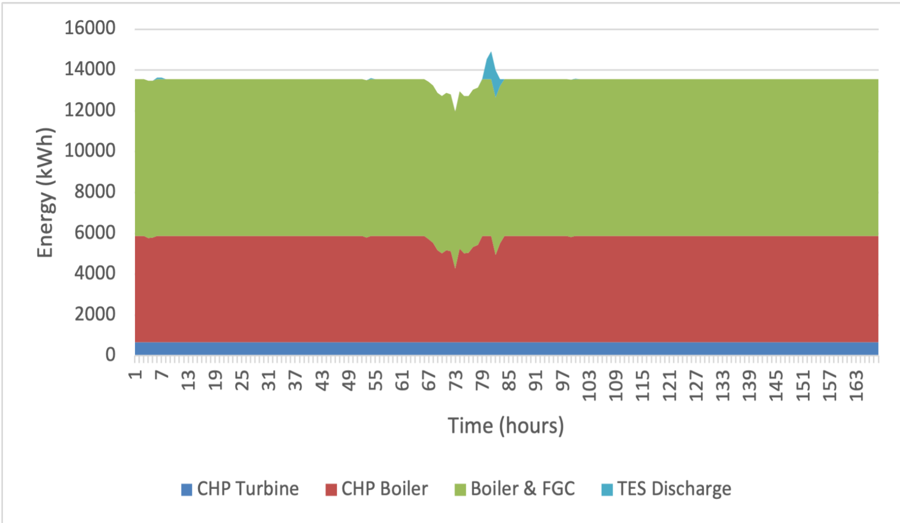


(a) Supply Quantity



(b) Demand Quantity

Figure A.1: January Electricity Cleared Bid Quantities



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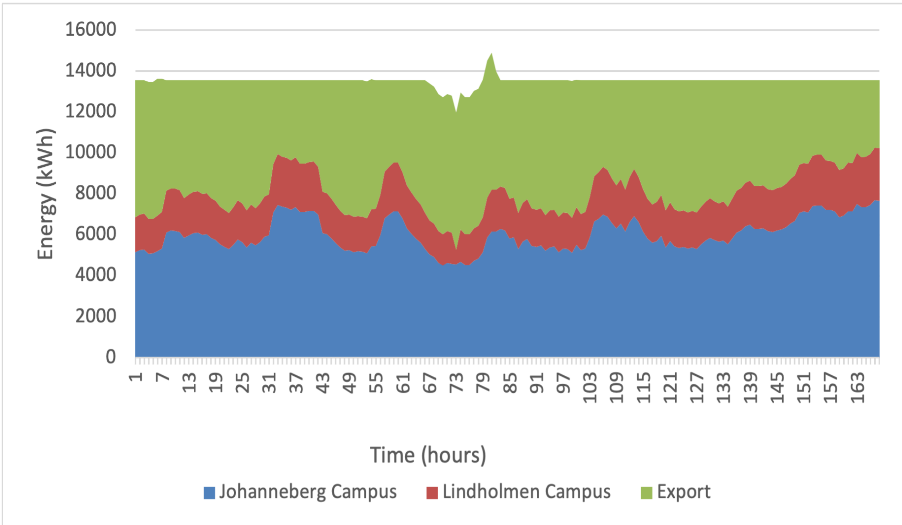
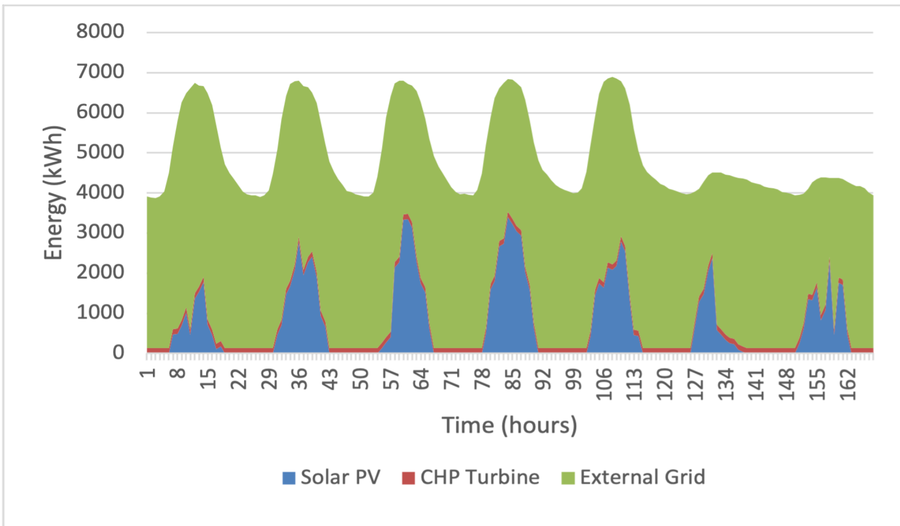


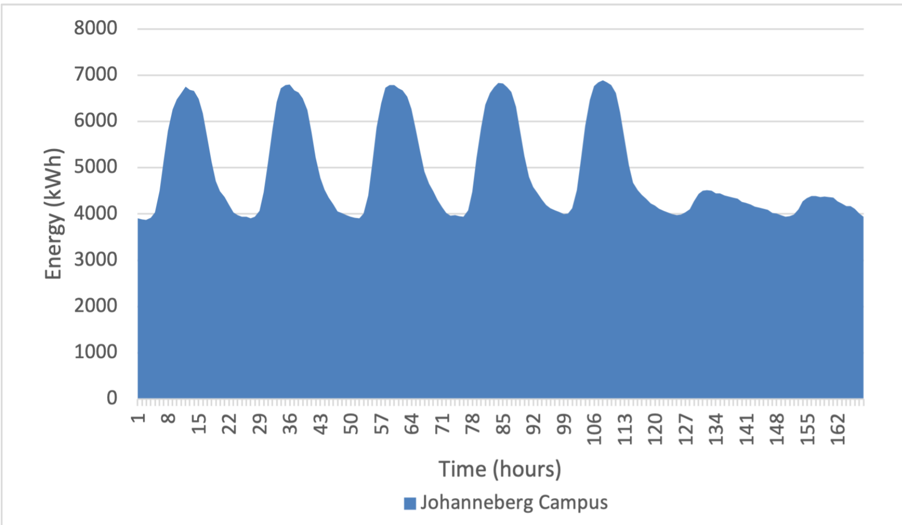
(b) Demand Quantity

Figure A.2: January Heat Cleared Bid Quantities

April:

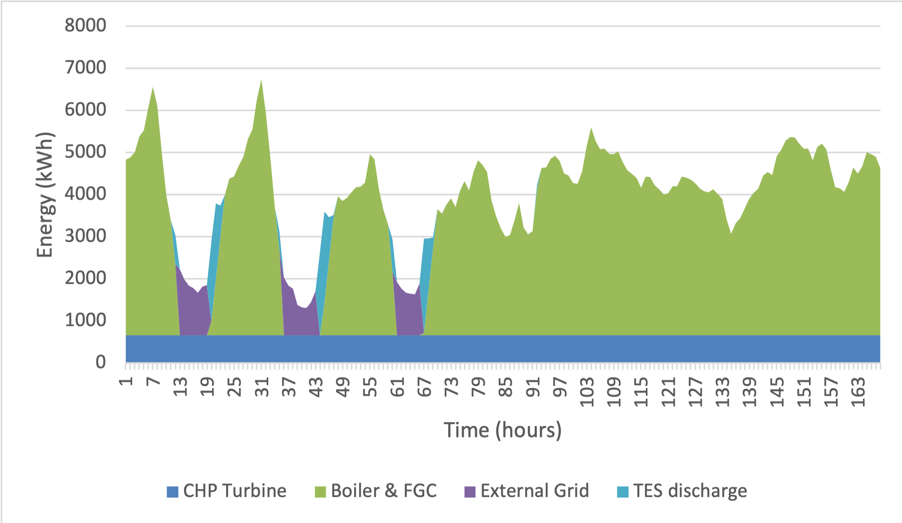


(a) Supply Quantity



(b) Demand Quantity

Figure A.3: April Electricity Cleared Bid Quantities



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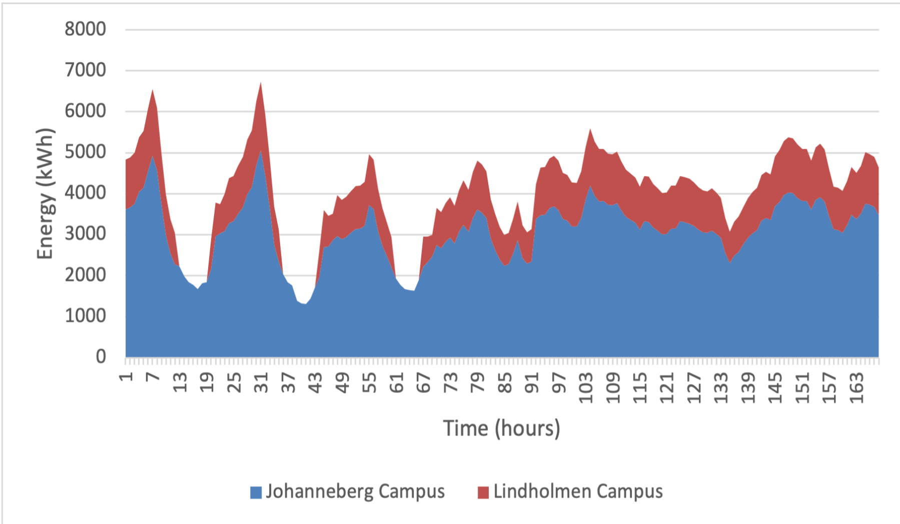
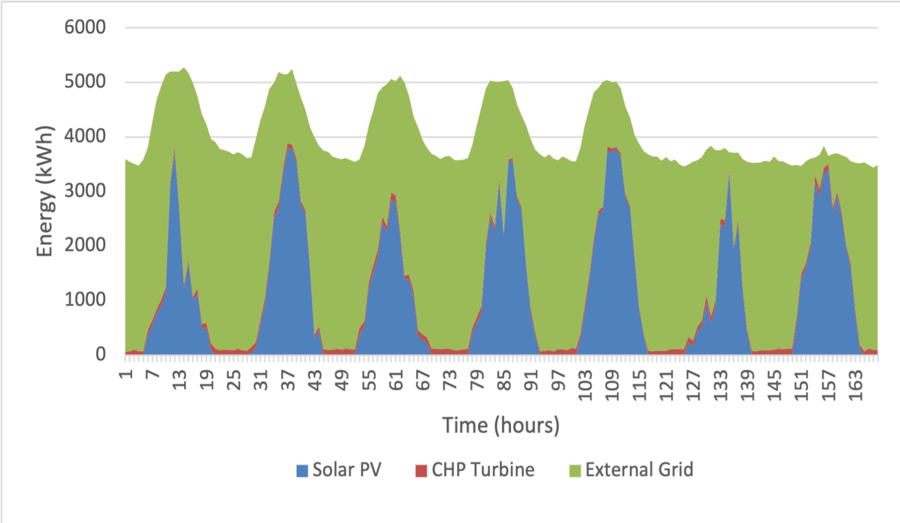


(b) Demand Quantity

Figure A.4: April Heat Cleared Bid Quantities

July:



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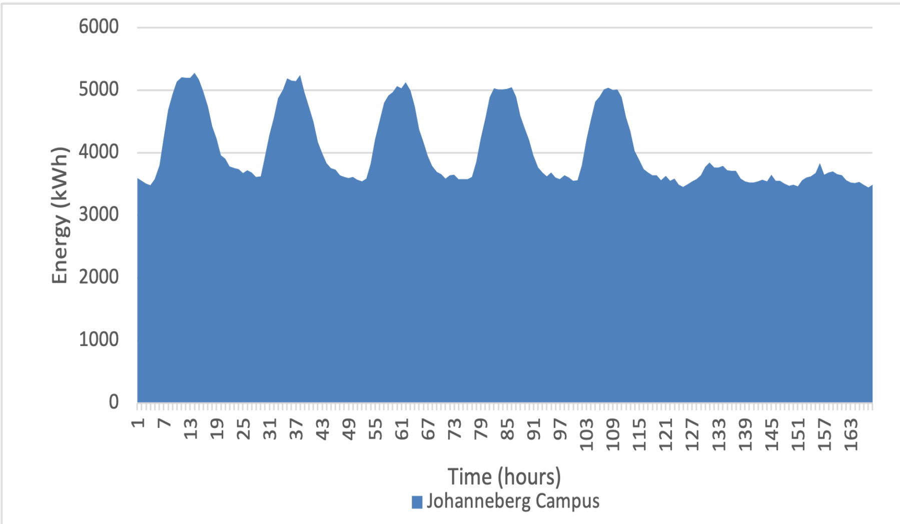

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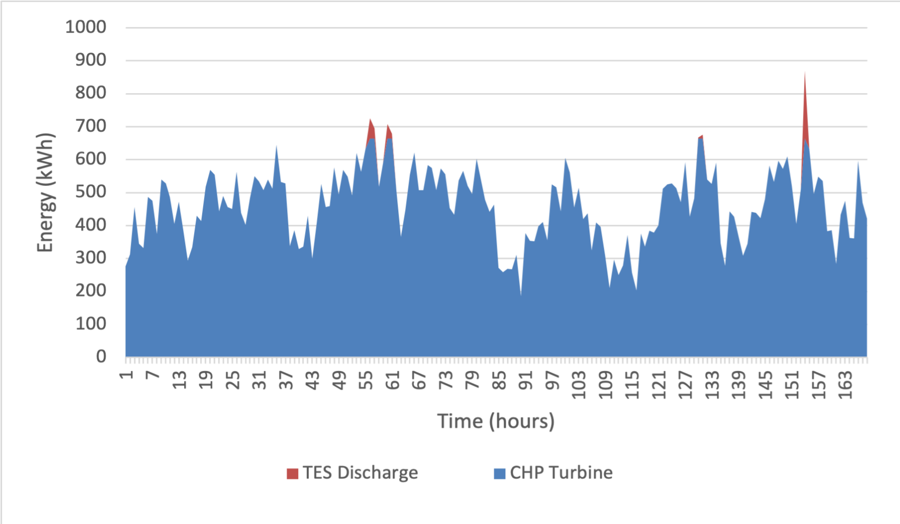
Figure A.5: July Electricity Cleared Bid Quantities



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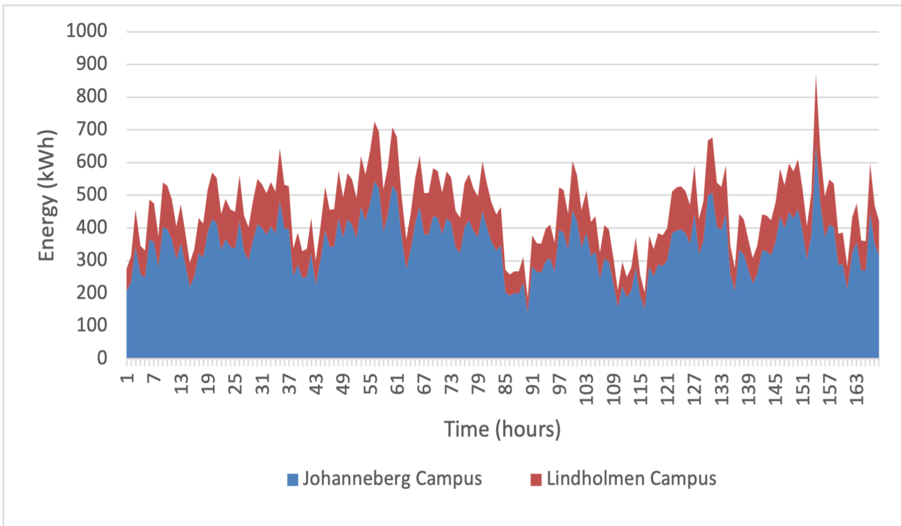
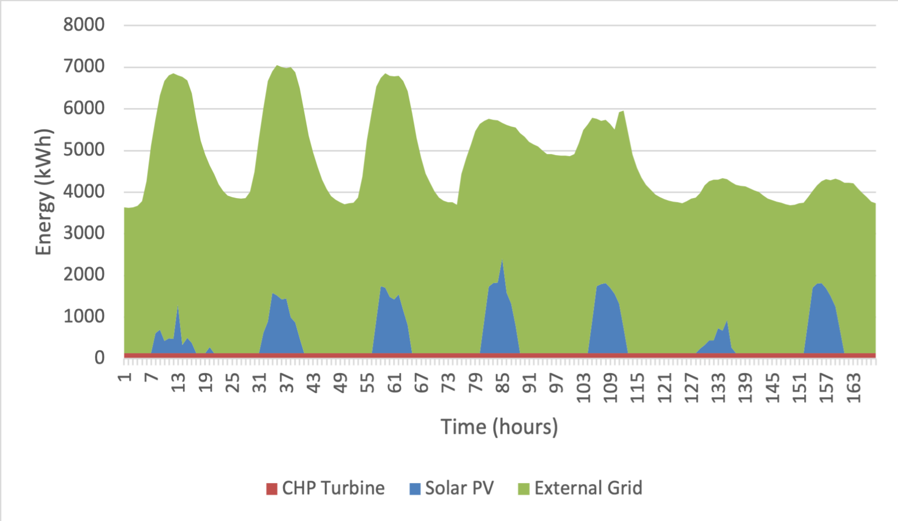


(b) Demand Quantity

Figure A.6: July Heat Cleared Bid Quantities

October:



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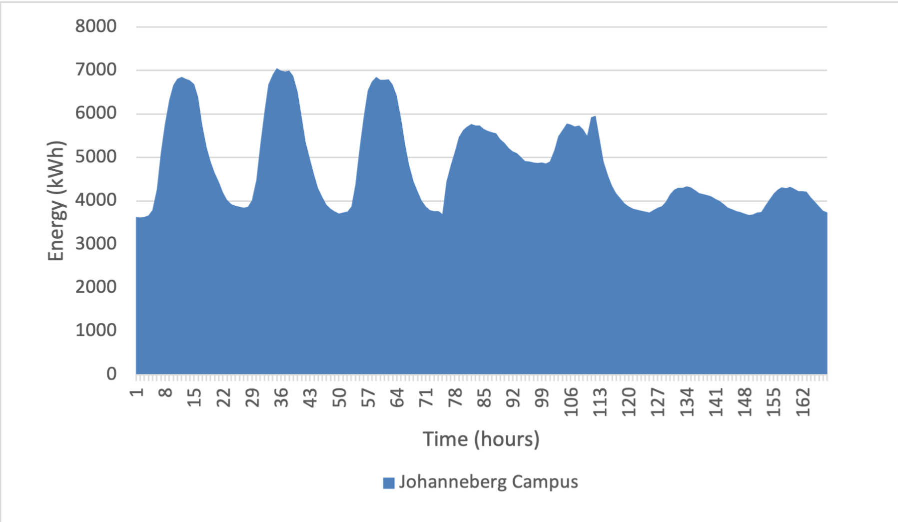
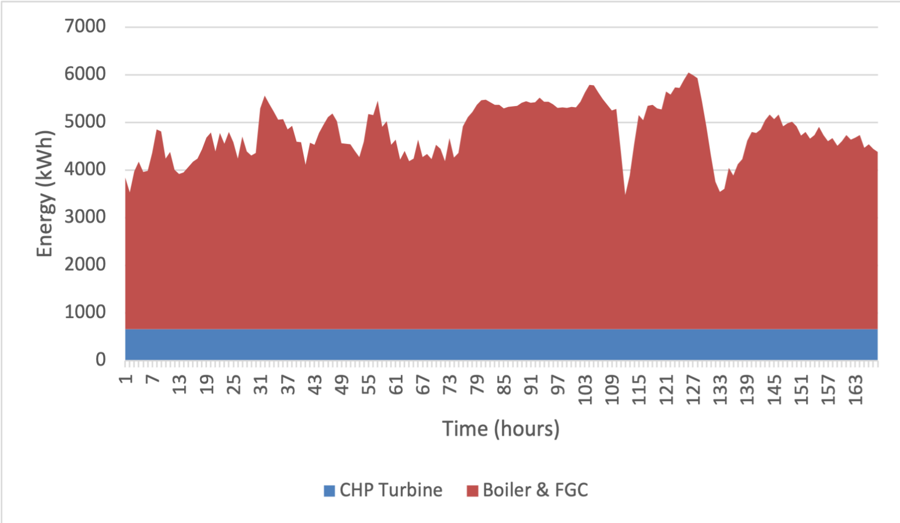


(b) Demand Quantity

Figure A.7: October Electricity Cleared Bid Quantities



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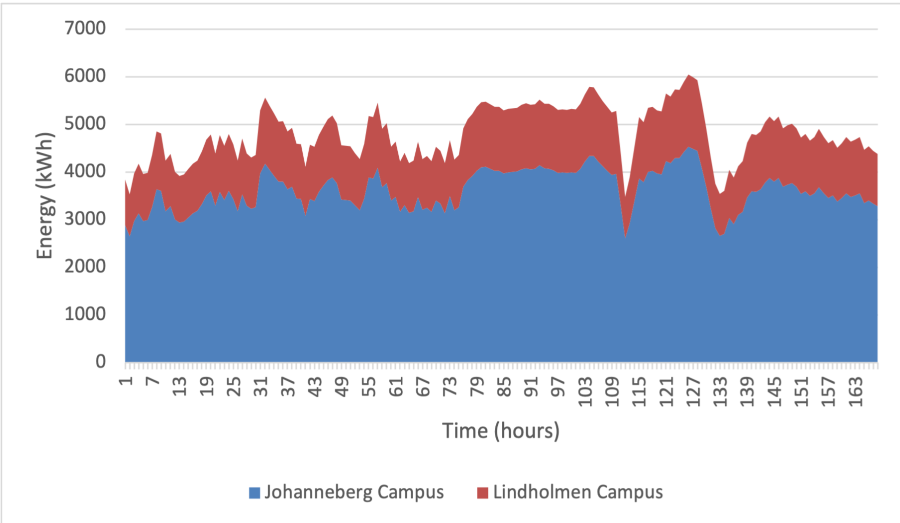


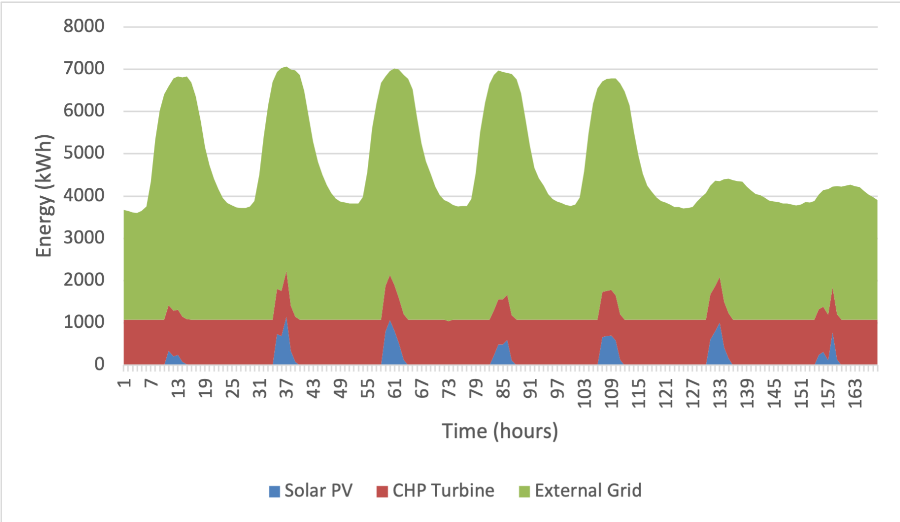
(b) Demand Quantity

Figure A.8: October Heat Cleared Bid Quantities

B

Appendix 2 - Scenario 1 Cleared Quantities

January:



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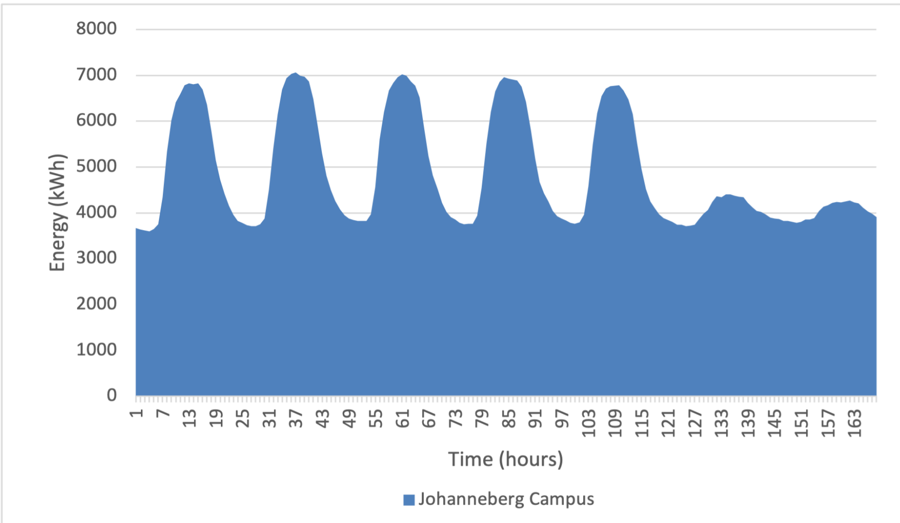
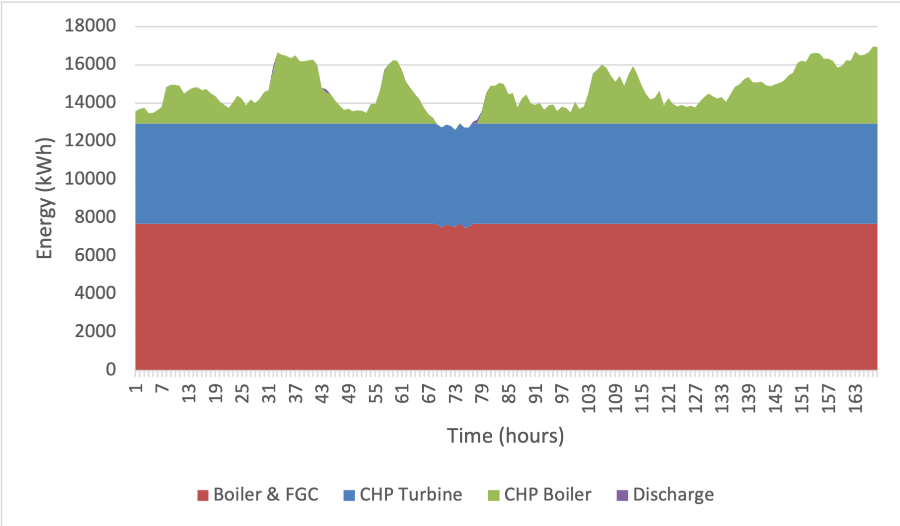
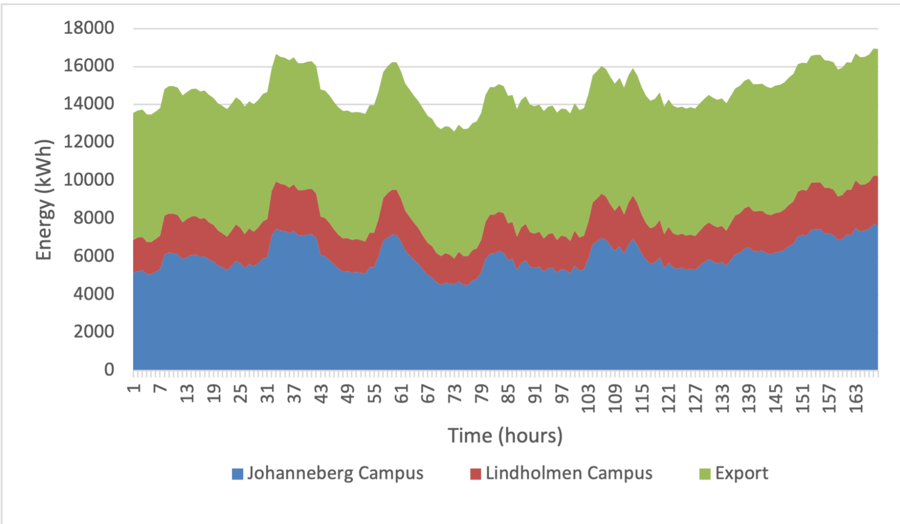


(b) Demand Quantity

Figure B.1: January Electricity Cleared Bid Quantities



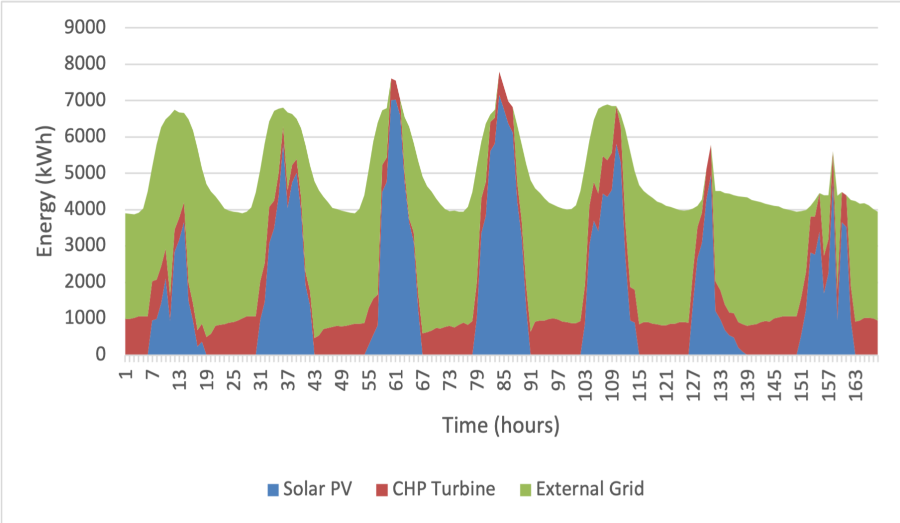
(a) Supply Quantity



(b) Demand Quantity

Figure B.2: January Heat Cleared Bid Quantities

April:



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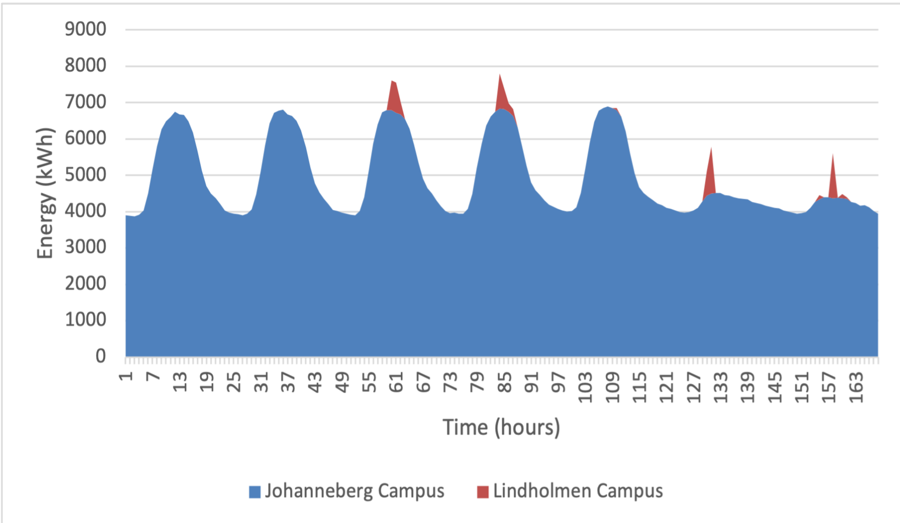

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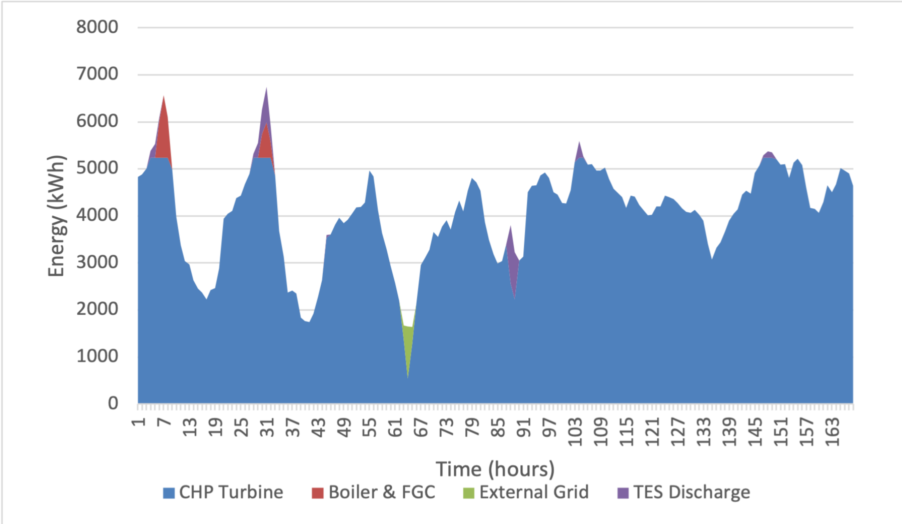

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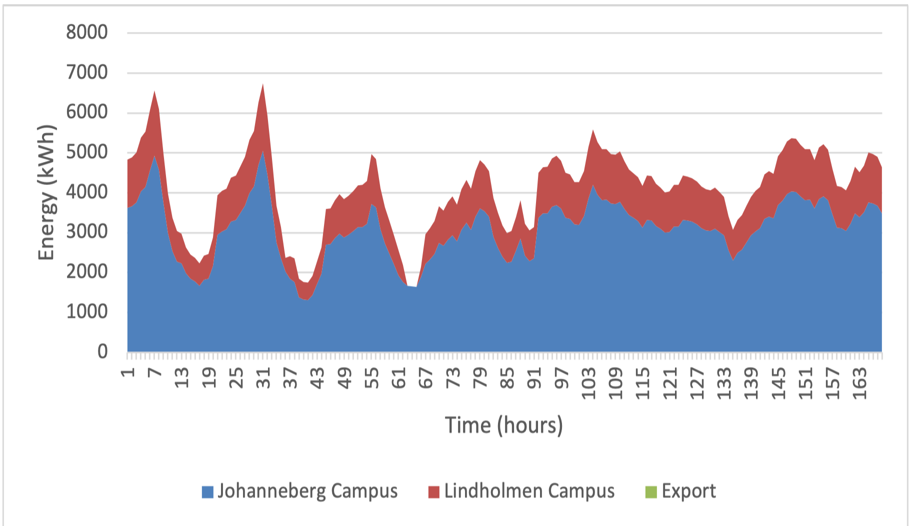
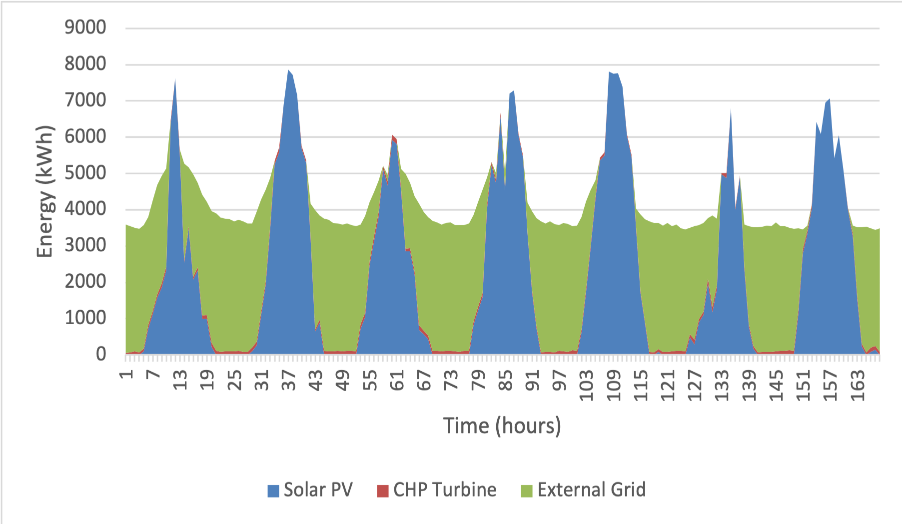


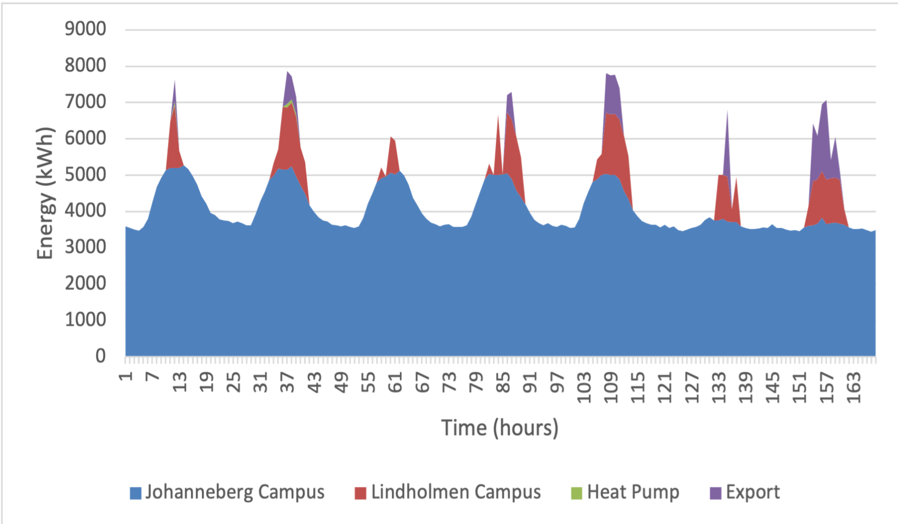
(b) Demand Quantity

Figure B.4: April Heat Cleared Bid Quantities

July:

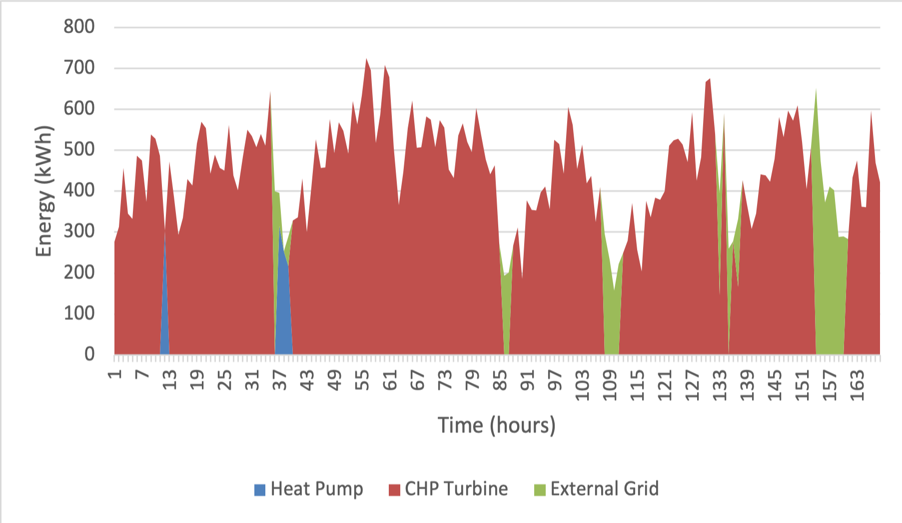


(a) Supply Quantity

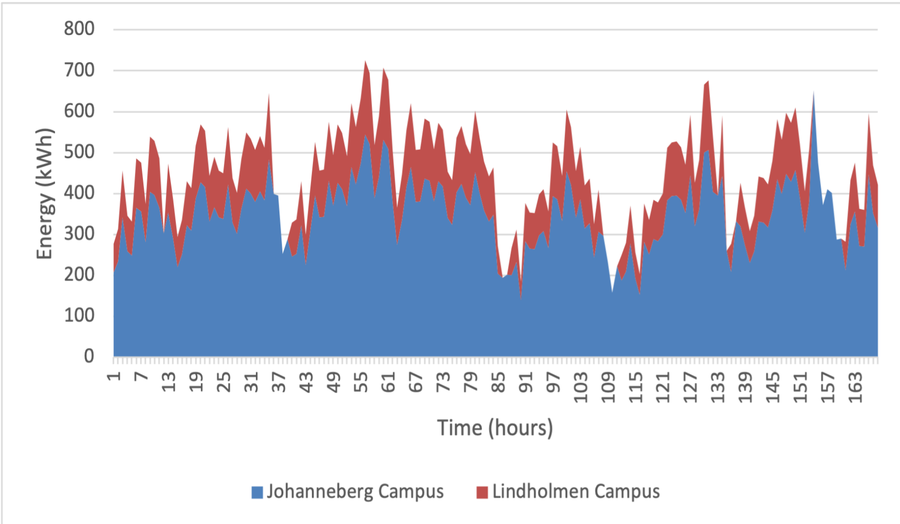


(b) Demand Quantity

Figure B.5: July Electricity Cleared Bid Quantities



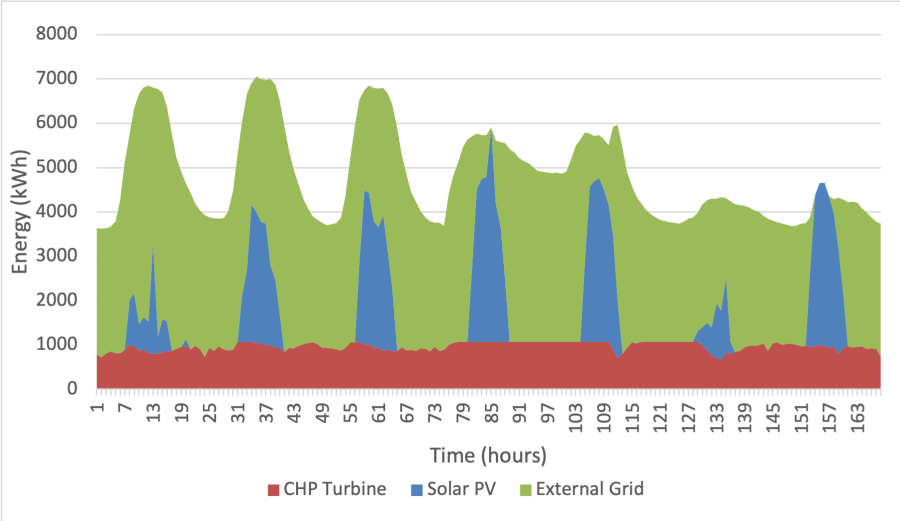
(a) Supply Quantity



(b) Demand Quantity

Figure B.6: July Heat Cleared Bid Quantities

October:



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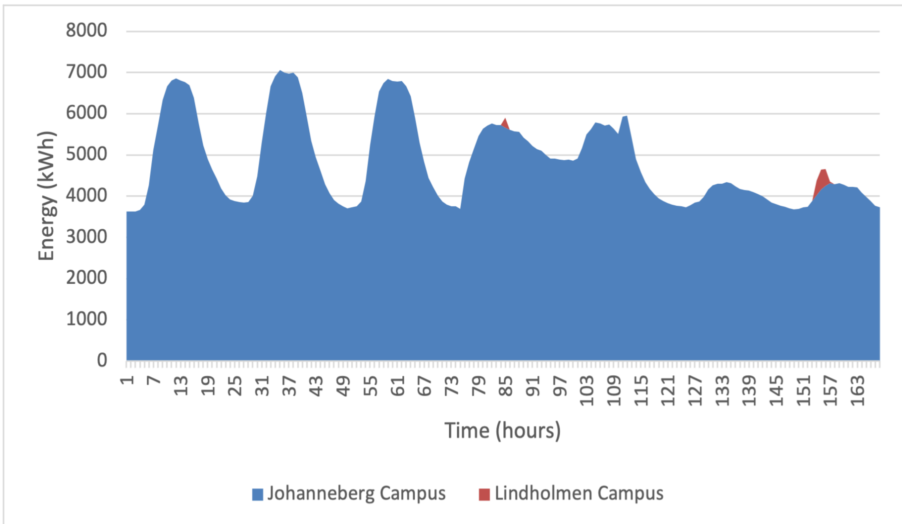
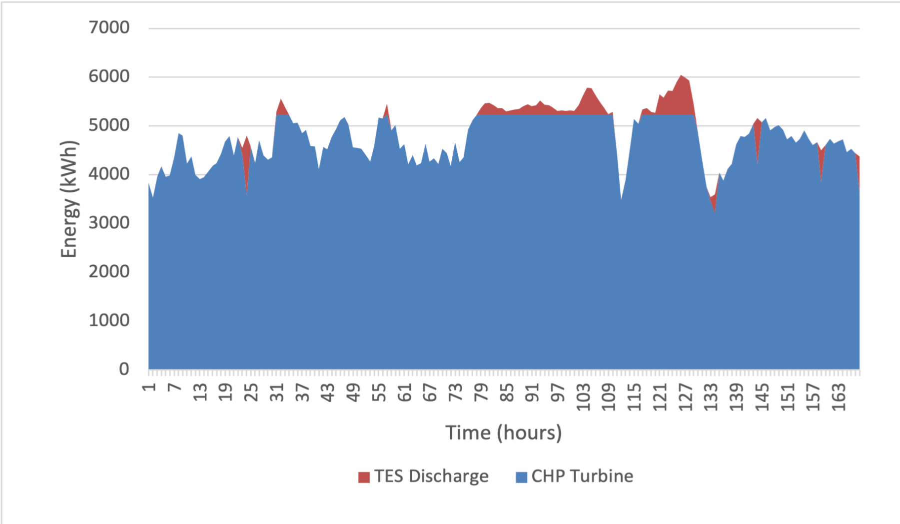


(b) Demand Quantity

Figure B.7: October Electricity Cleared Bid Quantities



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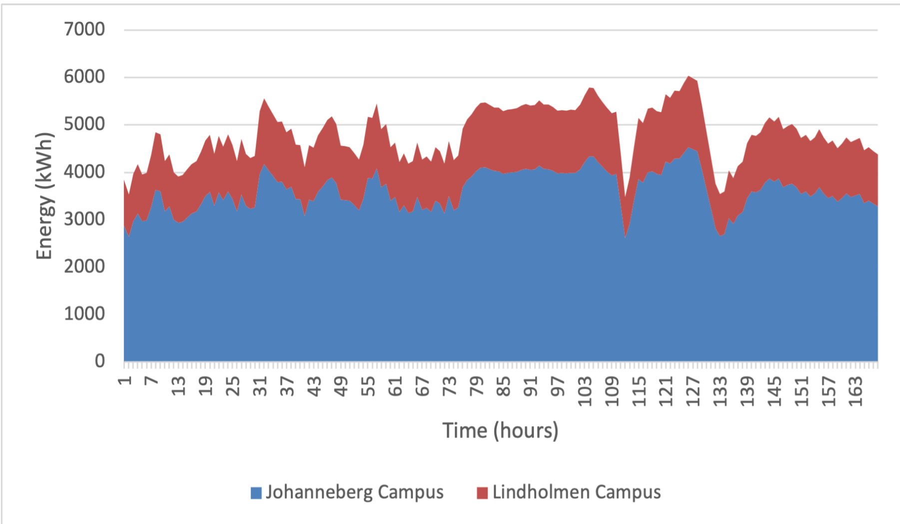
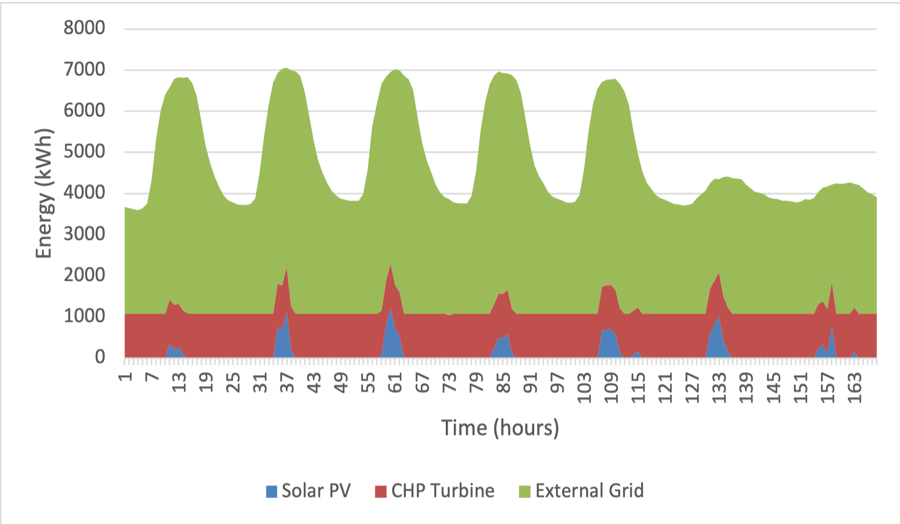


(b) Demand Quantity

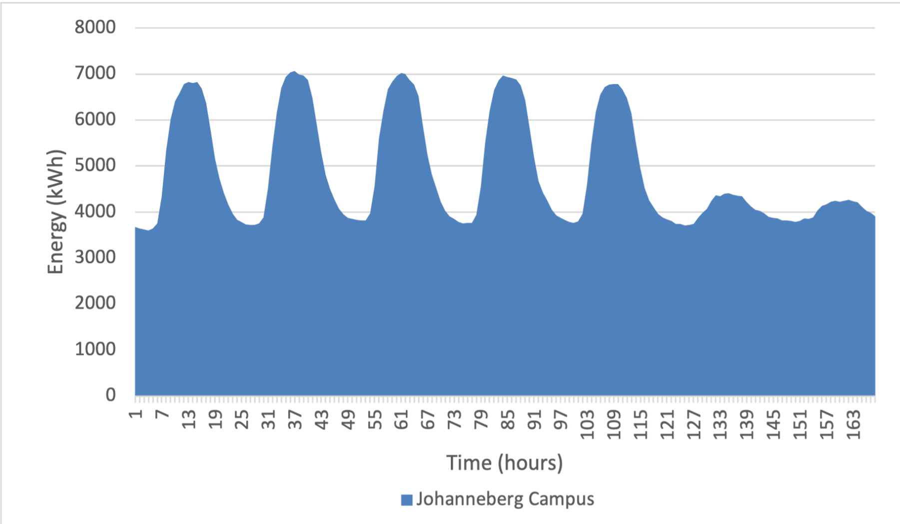
Figure B.8: October Heat Cleared Bid Quantities

C
Appendix 3 - Scenario 2 Cleared Quantities

January:

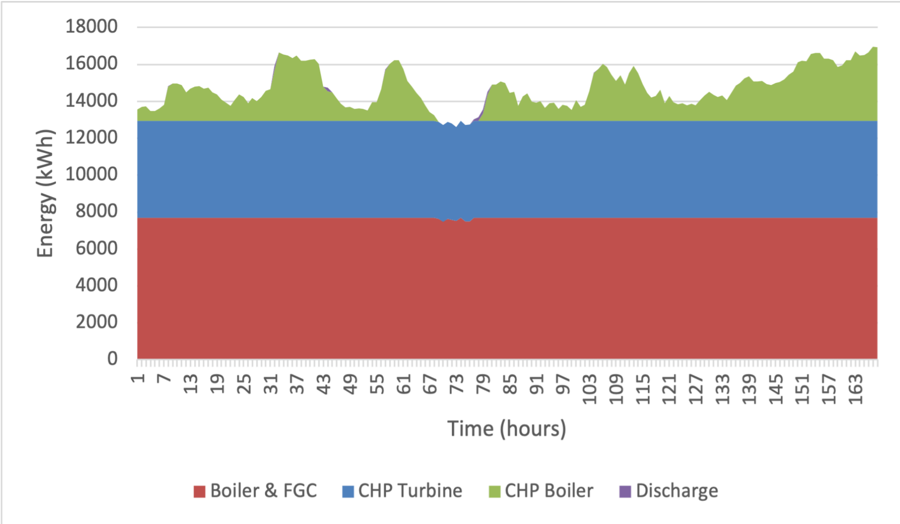


(a) Supply Quantity



(b) Demand Quantity

Figure C.1: January Electricity Cleared Bid Quantities



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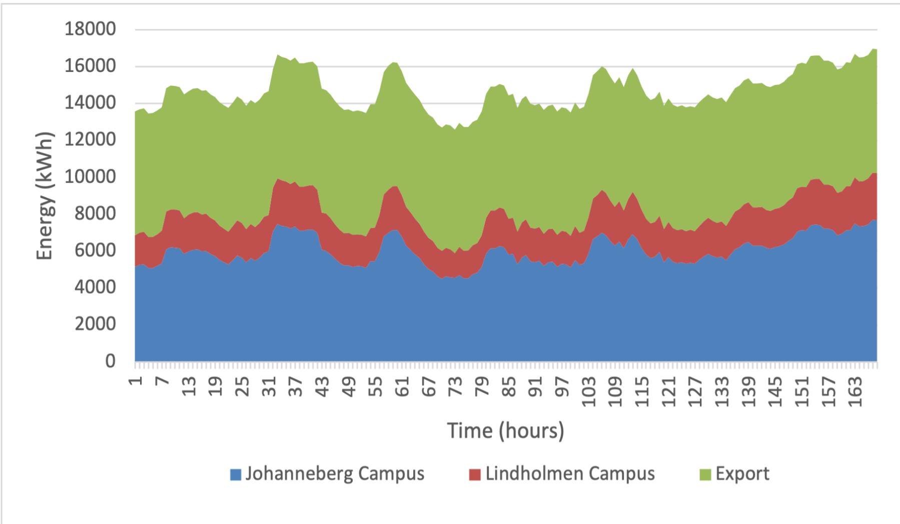
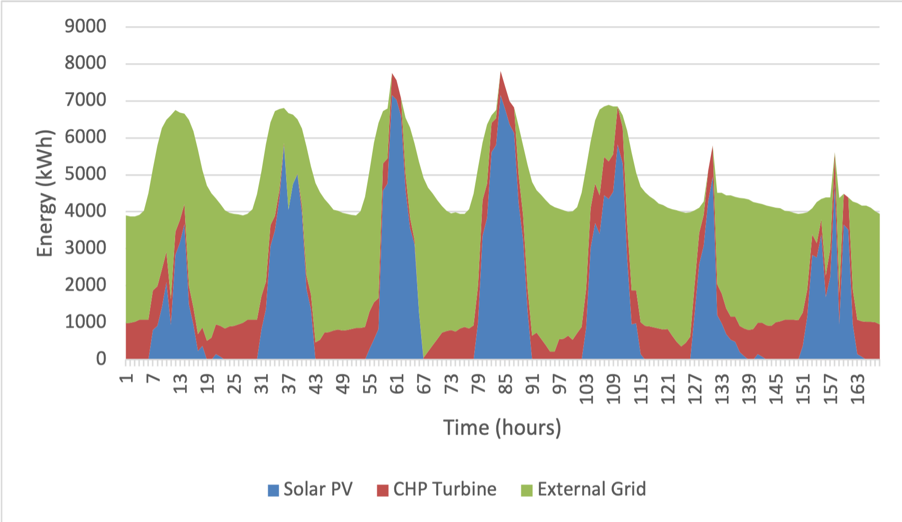


(b) Demand Quantity

Figure C.2: January Heat Cleared Bid Quantities

April:



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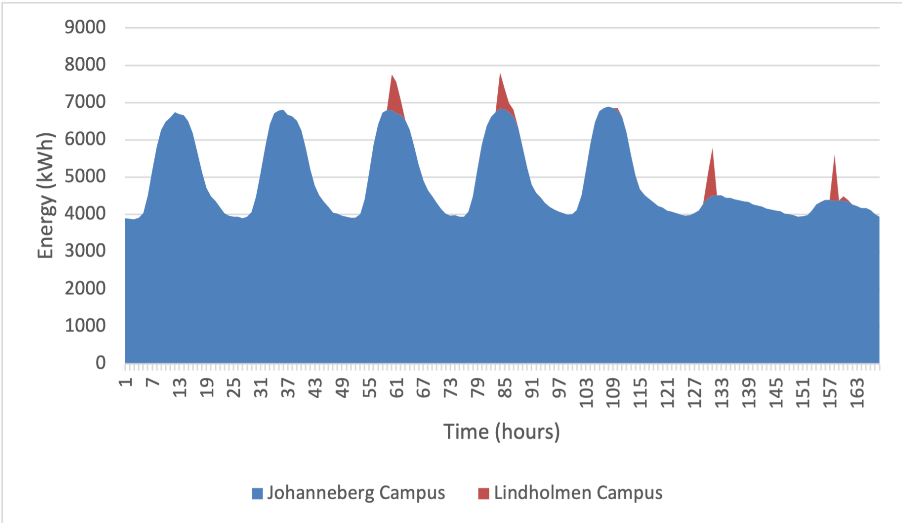
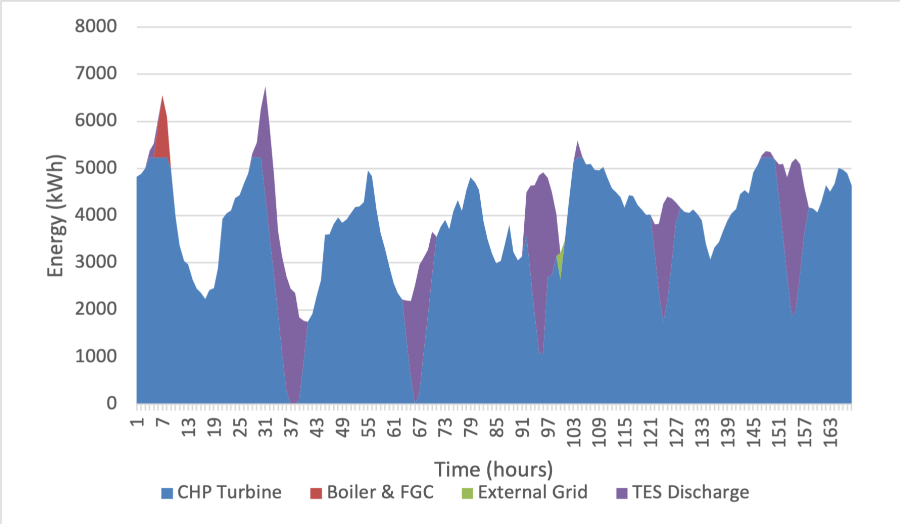
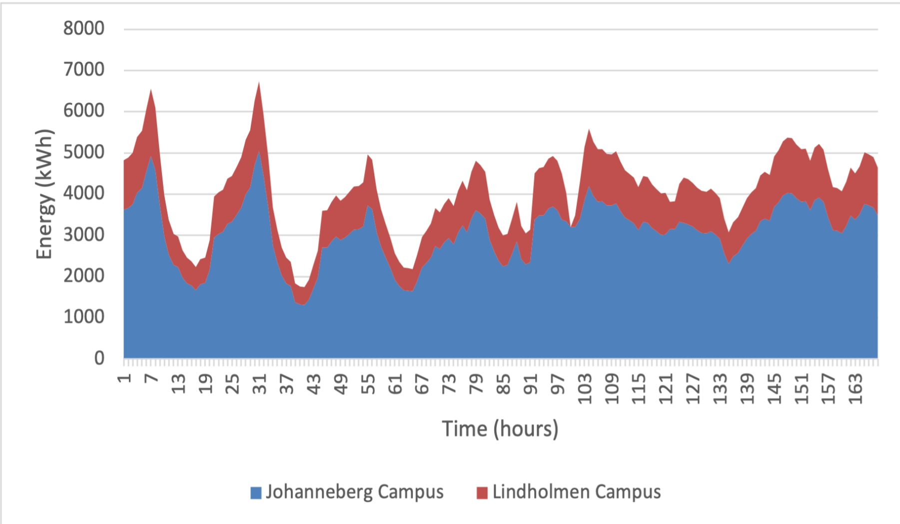


(b) Demand Quantity

Figure C.3: April Electricity Cleared Bid Quantities



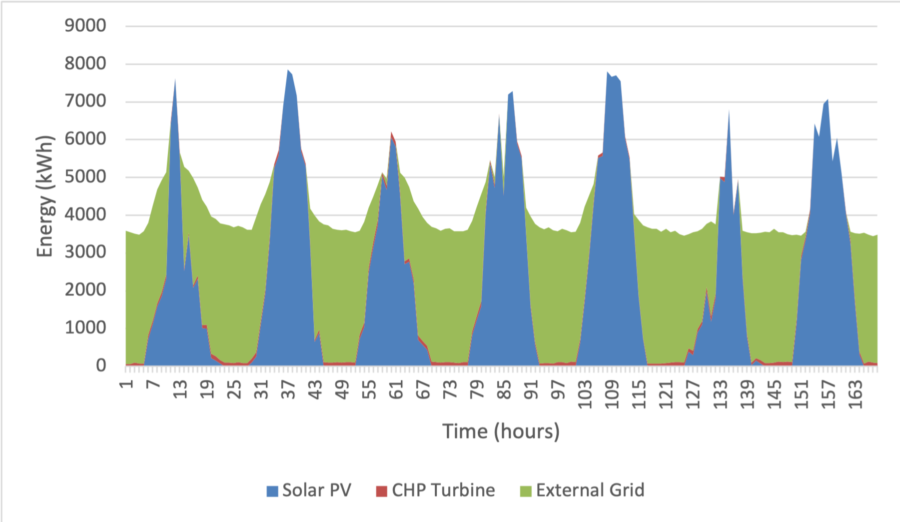
(a) Supply Quantity



(b) Demand Quantity

Figure C.4: April Heat Cleared Bid Quantities

July:



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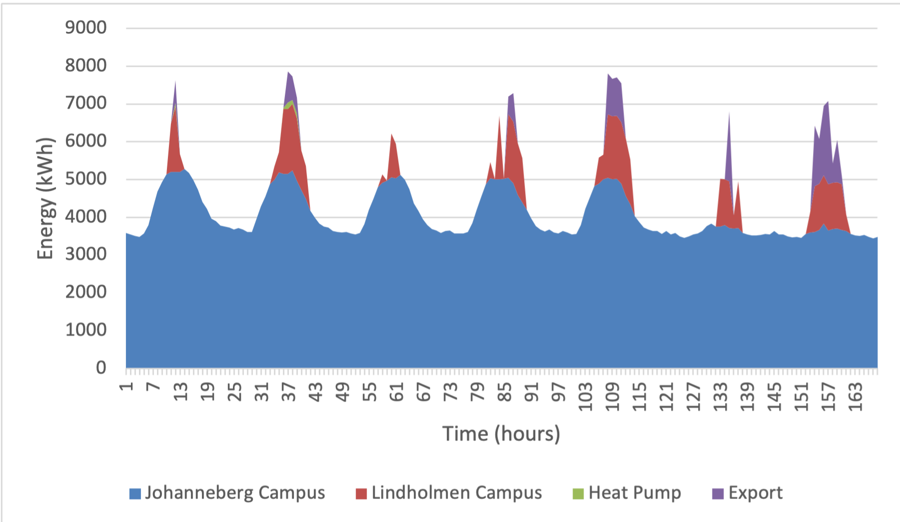

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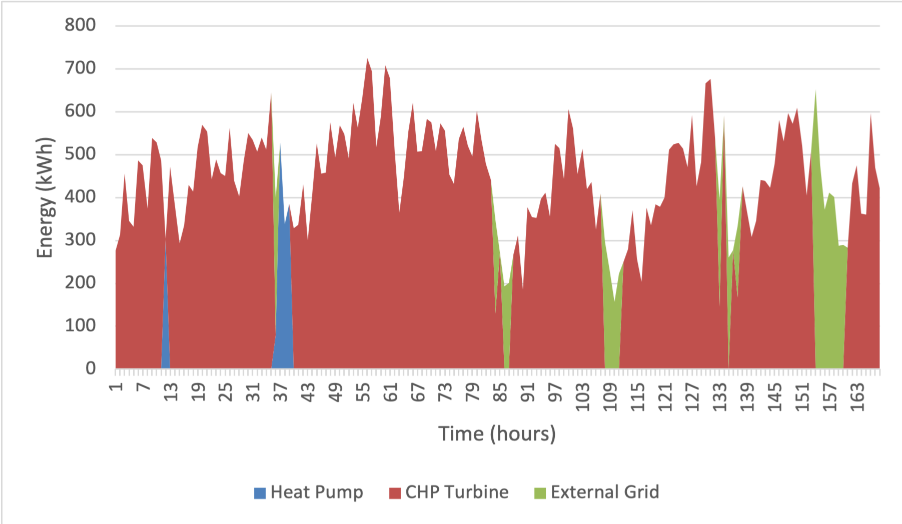
Figure C.5: July Electricity Cleared Bid Quantities



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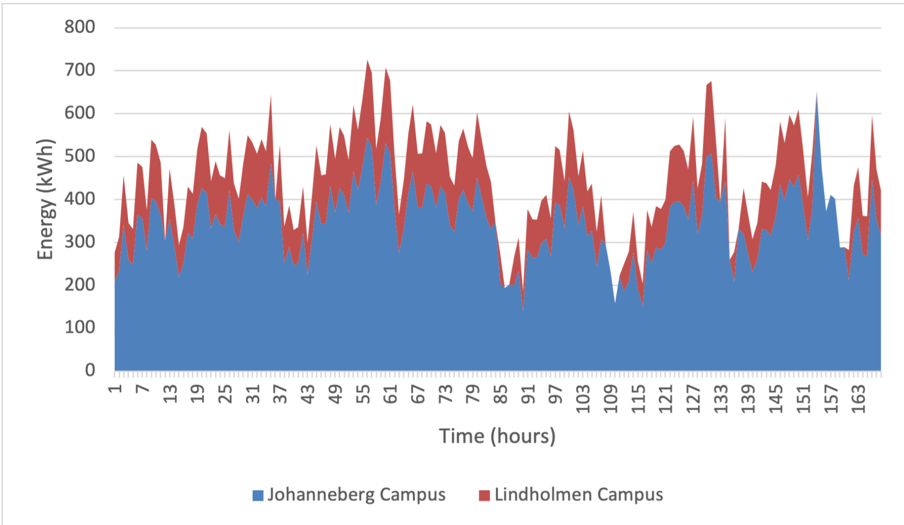
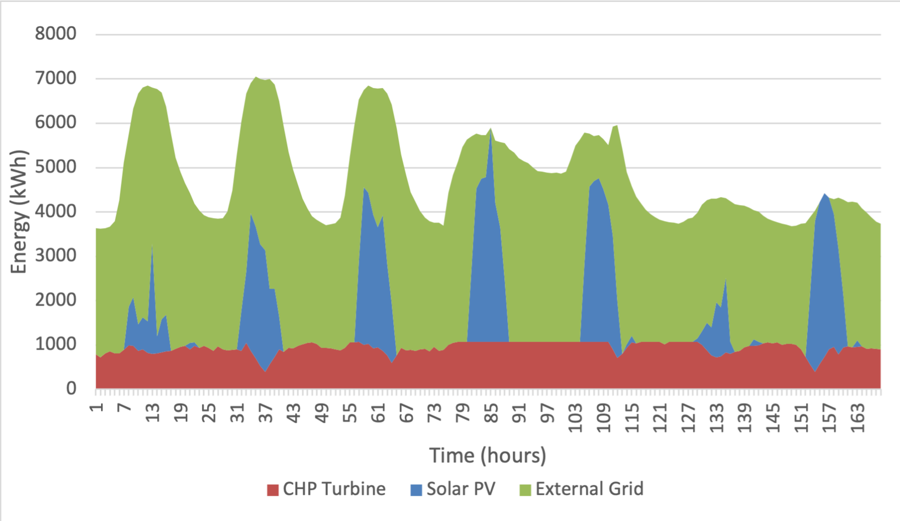


(b) Demand Quantity

Figure C.6: July Heat Cleared Bid Quantities

October:



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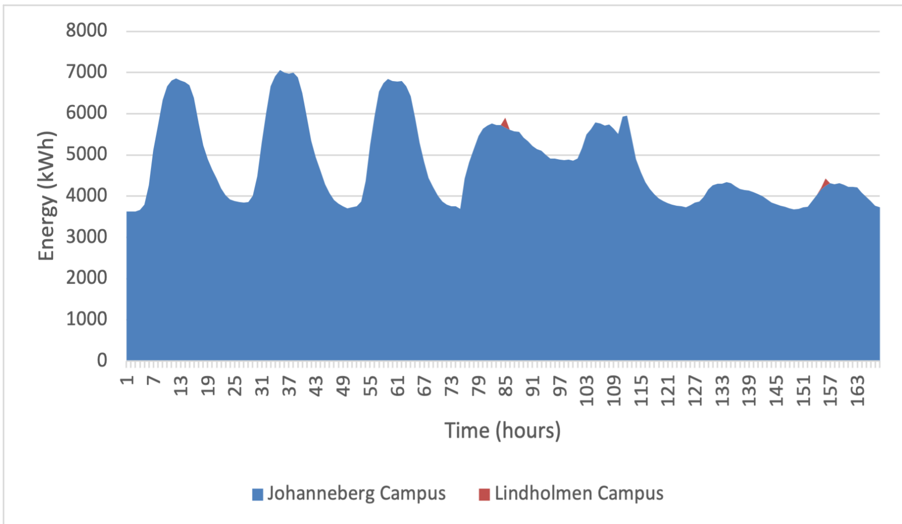
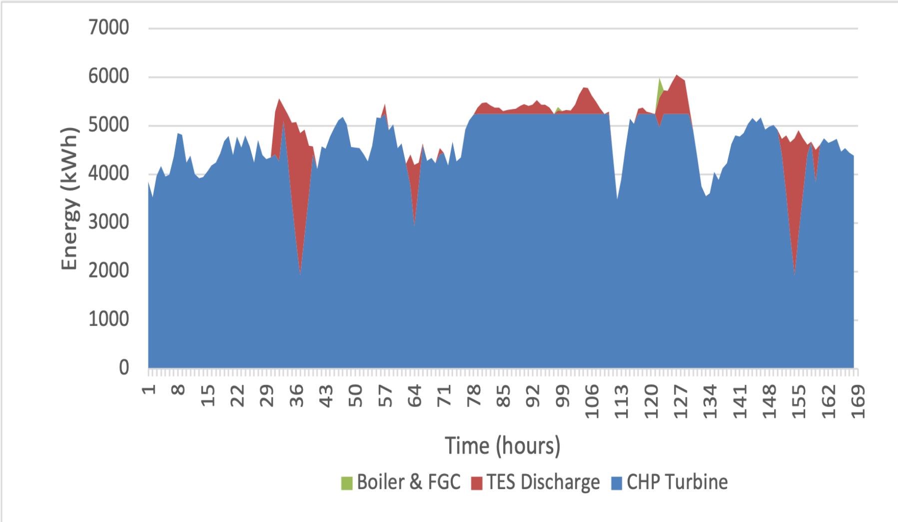


(b) Demand Quantity

Figure C.7: October Electricity Cleared Bid Quantities



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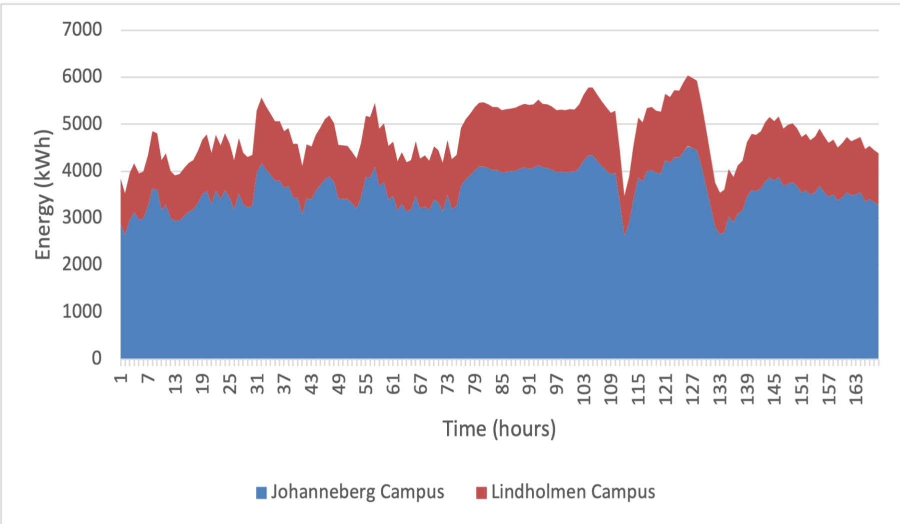

(b) Demand Quantity

Figure C.8: October Heat Cleared Bid Quantities

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