Strategic Responses to Electricity Market Imbalances:

A Case Study of Öresundskraft's Financial and Environmental Optimization

by
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Contents

List of Figures

Sammanfattning

Under 2021 stod kraftvärmeverk för 9 % av elproduktionen i Sverige. Men svenska kraftvärmeverk planerar sin produktion beroende på behovet i fjärrvärmesystemet. När det sker oväntade händelser som påverkar produktionen är det värmebehovet som prioriteras i första hand. Detta gör att produktionen av elektricitet och hanteringen av obalanser gentemot elhandeln blir sekundär. Syftet med denna masteruppsats är att undersöka hur olika handlingsalternativ för att hantera obalanser gentemot dagen före marknaden påverkar Öresundskraft. Det som jämförs är de kostnader och intäkter som är kopplade till produktionen av värme och el, samt mängden koldioxidekvivalenter de olika alternativen innebär. Detta för att belysa vikten av handel på elmarknaden om det uppstår oväntade situationer som leder till obalanser.

Två olika scenarier undersöks; plötslig förlust av produktionsanläggning och prognosfel. I båda scenarierna studeras flera olika handlingssätt. De olika handlingsätten leder till olika kostnader, inkomster och mängd koldioxidekvivalenter. Det undersöks även hur resultaten hade påverkats om ett batteri på 20 MW och 20 MWh hade varit tillgängligt i systemet. Genom att dessa utvärderas och jämförs, vill vi visa skillnaderna det kan göra för ett företag om de är aktiva på elmarknaderna. Modellering och optimering utförs i Energy Optima, vilket är en programvara för ekonomisk driftoptimering av energisystem, som framförallt används inom fjärrvärmebranschen. Optimeringarna utförs på historisk data från 2022 och 2023.

Resultaten visar att det i de flesta fallen är ekonomiskt fördelaktigt att vara aktiv på intradagmarknaden. I vissa fall så var det lika fördelaktigt att låta obalansen gå till balansmarknaden, detta då priserna på de båda marknaderna var ungefär samma. Skillnaden är att balansmarknaden är en mer osäker marknad, som kan liknas med gambling, vilket gör att det inte är önskvärt att planera för att hamna där utan agera på intradagmarknaden om det är möjligt. De visade även att ett batteri på 20 MW och 20 MWh inte hade en stor inverkan vid oväntat bortfall av produktionsenhet, men det finns andra möjliga användningsområden för ett batteri av den storleken såsom stödtjänster. Även när man tittar på utsläpp av koldioxidekvivalenter är det fördelaktigt att vara aktiv på elmarknaderna, då det leder till mindre utsläpp än att till exempel motköra med andra enheter. Den övergripande slutsatsen från masteruppsatsen är att det mest pålitliga och fördelaktiga, både ekonomiskt och miljömässigt, handlingsalternativet är att vara aktiv på intradagmarknaden.

Abstract

In 2021, combined heat and power plants accounted for 9 % of the electricity production in Sweden. However, Swedish combined heat and power plants plan their production based on the demands of the district heating network. In instances of unforeseen disruptions affecting production, priority is given to meeting heating demand. Consequently, electricity generation and the management of imbalances towards the electricity market become secondary. The purpose of this master's thesis is to investigate how different actions to manage imbalance compared to the day-ahead market affect Öresundskraft. The study compares the costs and revenues associated with the production of heat and electricity, as well as the amount of carbon dioxide equivalents that the different alternatives entail. This to highlight the importance of trading on the electricity market if unexpected situations leading to imbalances occur.

Two different scenarios are analyzed; sudden loss of production facility and forecast error. Within each scenario, multiple strategies are evaluated, resulting in varying costs, revenues and carbon dioxide emissions. Furthermore, the study explores the potential effects of integrating a 20 MW and 20 MWh battery into the system. Utilizing historical data from 2022 and 2023, modelling and optimization are conducted using Energy Optima. Energy Optima is a software which optimizes production plans based on economic viability.

The results indicate that, in most instances, active participation on the intraday market proves economical advantageous. In some cases, it was equally advantageous to let the imbalance go to the balancing market, as the prices on both markets were approximately the same. Nevertheless, the balancing market is a more uncertain market, akin gambling, making it undesirable to plan to trade there instead of acting on the intraday market if possible. Moreover, the analysis reveals that the introduction of a 20 MW and 20 MWh battery has a negligible impact on addressing unforeseen production unit losses, although alternative applications such as ancillary services may be viable. Even from an environmental perspective, it is advantageous to be active on the electricity markets, compared to other analyzed strategies, since it leads to less emissions of carbon dioxide equivalents. In summary, the study concludes that active involvement on the intraday market is the most reliable and advantageous approach, both economically and environmentally.

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Last but not least, we want to thank each other for great collaboration.

Chapter 1

1. Introduction

This chapter consists of an introduction to the thesis. First, a short background to the problems that will be investigated is presented. Then, a short description of Öresundskraft, which is the company that owns and operates the powerplants that will be used in the optimizations. The purpose and research questions are presented to formulate what the goal of the thesis is and what will be investigated. In the last sections, the delimitations are described, which are set to simplify and streamline the optimizations.

1.1. Background

The Swedish energy market is facing a significant transformation and to those inter-connected challenges. The need to phase out fossil fuels means that the amount of weather-dependent energy sources, such as wind and solar, will increase. This leads to an increased need for predictable electricity production. In 2021, combined heat and power plants, CHP plants, corresponded to approximately 9 % of the total electricity production in Sweden. It is also a big part of the European energy system. In the same year, CHP plants corresponded to around 20 % of the total electricity production in Europe. CHP plants can be fueled by any form of flammable fuel. In Europe, it is still fossil fuels that is the primary source of fuel, but in Sweden around 90 % of the fuels are renewable or recycled, such as waste or pellets. Since CHP plants can use waste as fuel, Sweden has, from an international comparison and perspective, a low percentage of waste that ends up in landfills (1).

CHP plants in Sweden are planning their production depending on the need in the district heating system. This means that the demand for district heat also controls the electricity production. When the heat production is high, the electricity production is also generally high. In a CHP plant, this is the case until the demand for district heat is too large. To be able to produce enough heat to meet the high demand, the electricity production is reduced to make room for more heat production. This is usually done by redirecting the steam flowing through the steam turbine facility directly to the condenser, allowing for a larger portion of heat produced (2).

The electricity market in Sweden consists of four different markets. Today, most of the electricity is sold on the day ahead market, which closes the day before the actual delivery hour. There must always be balance between production and consumption of electricity (3). The reason for this is that the frequency on the Swedish electricity grid needs to be kept stable at 50 Hz and the frequency is affected in case of imbalance between production and consumption (4). To achieve this there are two more markets after the day ahead market. These are the intraday- and balancing markets. They are open closer to the delivery hour and gives the electricity producers an opportunity to trade to balance if they either produce more or less than they sold on the day ahead market. It is a way to maintain the balance between production and consumption (5).

CHP plants are considered a predictable energy source, but sudden unexpected changes can happen even with a CHP plant. Sudden loss of production or changes in the weather, which might influence the need for heating, are two common reasons that affect the production. CHP plants have a primary responsibility towards the heating market- meaning that the heat that has been promised needs to be delivered to the customers. At the same time, they have a secondary balance responsibility towards the electricity market. This means that they must produce the same amount of electricity as they promised to sell on the day ahead market. If they cannot do this because of unexpected changes in the production, they either need to solve it by trading on the intraday market or they will have to trade on the real-time balancing market, which often leads to high costs. If the CHP plant is a part of a bigger system with several plants and/or other components, they can try to change their production on the other plants to try to compensate for the loss and therefore minimize their need to act on the intraday- or balancing market. These different courses of action mean various incomes and costs for the company which will be further analyzed in this report (6).

1.2. Case study - Öresundskraft

During this study, the focus will be on two CHP plants that are connected to the same district heating network, both owned by Öresundskraft. Öresundskraft is an energy company that produces and sells both electricity and district heating and cooling. They are a part of a big district heating system in Skåne called Evita. Evita is a collaboration between the three biggest district heating producers in the north-west of Skåne; Öresundskraft, Kraftringen and Landskrona Energi. It connects Helsingborg, Landskrona and Lunds district heating networks and heat production components (7). The plants that are specifically assessed in this study are Filbornaverket and Västhamnsverket. Both plants are described in Chapter 3.

1.3. Purpose and Research questions

The purpose of this study is to investigate how different courses of action to handle imbalances towards the day ahead market affects Öresundskraft. Primarily, two aspects will be investigated - the costs and incomes that are connected to the operation according to the different alternatives, and the corresponding amount of carbon dioxide equivalents these emits. This study is relevant for combined heat and power producers since loss of production and forecast errors are factors that will always be present. The aim is to highlight the importance of trading on the electricity market if unexpected situations occur that lead to imbalances. Of course, the need to act on the electricity market is different depending on the amount of electricity that is produced and sold. But, by doing this work we wish to contribute with knowledge about the economic and environmental impacts it can have for the company if they are trading on the intraday market, since this is not something every combined heat and power producer is.

Two different scenarios will be investigated; sudden loss of facility and forecast error. In both scenarios different courses of action will be studied. These actions will lead to different incomes, costs, and amount of carbon dioxide equivalents, and by evaluating and comparing these, we want to show the difference it can make for a company if they are active on the electricity markets. In addition to this, a battery will be connected to the plants to investigate the possibilities of connecting a battery to minimize financial losses.

The thesis is based on three research questions, all presented below.

- How can Öresundskraft act on the electricity market to minimize financial losses in the event of unexpected losses of facility or forecast errors?

- How could an existing battery on the premises be beneficial during the unexpected errors mentioned in the previous question?

- Which of these courses of action leads to the least amount of carbon dioxide equivalents, and thereby minimize the environmental impact?

1.4. Delimitations

The delimitations of the study is listed below.

- The plants that are investigated in the study are part of a larger actual district heating network called Evita (7). To limit the complexity of the optimizations and to reduce the optimization times, the connections between the aforementioned plants and the rest of the system were cut. This will be described in more detail in Chapter 4.2.

- In the beginning of every optimization, we let the optimizer choose the starting level of the components.

- One of the analyzed courses of action for the studied scenarios was to utilize a battery on the premises. However, in reality there is no battery connected to any of the mentioned plants, and costs and an investment analysis for the battery is not included in the report. The consequences of this are further discussed in subchapter 7.5 regarding the battery storage.

- The location of the battery in the study basis differs slightly from what is possible in real life. As of now, the battery is simultaneously placed at both Filbornaverket and Västhamnsverket at the same time. The decision to do it this way was to balance the workflow and avoid unnecessary work that would have taken much longer. This is further discussed in subchapter 7.2 regarding the battery storage.

- One thing that is quite hard to avoid in simulation cases like these is, since we are working on historical cases, the optimizer will know beforehand when the loss of production will occur and potentially adjust its production slightly to prepare for this. We tried to make it as close to reality as possible by implementing code to be able to lock production in the beginning of optimizations.

1.5. Division of Work

Both authors have been included in all parts of the thesis. Jakob was mostly involved in writing Chapter 2 and Tove was most involved in Chapter 3. The dates and weeks that were optimized around were split into two groups and each author was responsible for a group. Both were involved in modelling in Energy Optima and equally involved in the rest of the chapters, namely Chapter 1,5,6,7 and 8.

1.6. Disposition

Chapter 1: Introduction - the subject is presented along with the research questions and delimitations.

Chapter 2: The Swedish energy market - a description of the energy market in Sweden.

Chapter 3: Combined Heat and Power plant - explains how combined heat and power plants work and their role on the energy markets.

Chapter 4: Methodology - explains how the modeling and optimizing in Energy Optima was made, together with the data gathering.

Chapter 5: Results on sudden loss of facility - shows all the results from optimizations on sudden loss of facility.

Chapter 6: Results on forecast error - shows all the results from optimizations on forecast errors.

Chapter 7: Discussion - provides a discussion and analysis regarding the results.

Chapter 8: Conclusion - presents the conclusions of the thesis along with answers to the research questions and recommendations for future work.

Chapter 2

2. The Swedish Energy Market

In this chapter, the Swedish electricity market is described to get a deeper understanding of how it works. The different markets and when they are active is explained followed by a section on balance responsibility and the balance responsibility party for Öresundskraft.

2.1. Overview

The electricity market consists of different types of markets up until the delivery hour, see Figure 2.1. First comes the forward market. The purpose of this market is that the electricity producers and buyers can secure future income and costs within the Forward Market. It can open as early as ten years before the delivery hour. Most of the financial trading for the Nordic electricity market happens on Nasdaq Commodities. Here, other things like emission rights are also traded. Next, is the day ahead market. Here, most of the produced electricity is traded. When the day ahead market closes, the intraday market opens. The purpose of the intraday market is for the electricity producers and consumers to be able to trade to achieve balance. Here, bidders can buy or sell electricity, depending on what their needs are to be balanced in the market. The balance responsibility towards the energy market will be described later in this report. The intraday market closes an hour before the delivery hour and thereafter, the trading happens on the real-time balancing market. On this market, all trading is done by the Swedish Transmission System Operator, Svenska Kraftnät, which buys and activates ancillary services to keep the frequency steady at 50 Hz, with a range from 49.9 Hz to 50.1 Hz (8).

In 2015, a new set of regulations took effect that made it possible for electricity exchange companies to trade electricity in Europe. To be able to run day ahead and intraday electricity markets in the EU, a company first needs to be a NEMO (Nominated Electricity Market Operator). NordPool is an example of a NEMO and almost all the electricity traded in the Nordics are traded on NordPool spot market (9). The countries included in this market are Sweden, Finland, Norway, Denmark, Estonia, Latvia, Lithuania, Belgium, France, The Netherlands, Luxemburg, Germany, Austria, Poland, and Great Britain. The electricity prices of the day ahead, intraday, and balancing markets included in this report will be from the Volue Insight website (10).

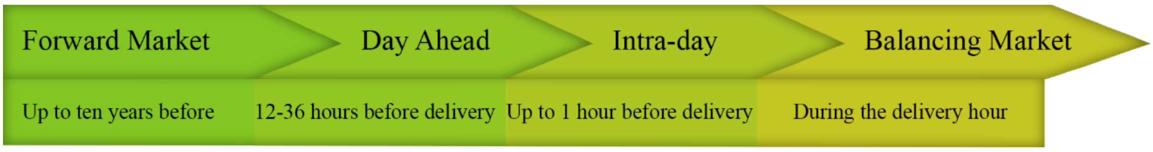

Figure 2.1: The electricity market and how long before the delivery hour the various markets open.

2.2. Day Ahead Market

Most of the electricity in the Nord Pool area (11) is sold on the day ahead market. The market is a wholesale market where electricity-intensive industries and retailers buy electricity directly from the producers. 89 % (372 TWh) of all the electricity production in the Nord Pool area in 2020 was sold on the day ahead market. This shows the market's great importance to the electricity market in its whole. On Nord Pool's day ahead market, 15 countries across 21 bidding zones, trade electricity with over 2000 orders placed by more than 300 buyers and sellers per day. Every day at 10:00 CET, all available capacities in the grid and on interconnections are published. More than 300 buyers and sellers have until 12:00 CET to submit their bids to Nord Pool for the specific delivery hours the following day (12). The bids specify quantity, price and which bidding zone it is for. All bids received hour for hour are summed up and a supply curve is created, in the same way a demand curve is created by adding all bids for the same hour (13).

The price on the day ahead market is set based on how much it costs to produce the last kilowatt hour needed to meet the demand. In Figure 2.2, the basis for the pricing fixture is illustrated. On the y-axis, the marginal costs are shown. The marginal costs in electricity production are, for example, fuel costs and production taxes and they differ between the different types of production. As can be seen in the figure, wind power and hydropower have low marginal costs, unlike coal- and oil-based electricity generation which have higher costs. This results in prioritization of the lowest marginal cost generation technologies, but the price is set by the most expensive production needed to meet the current demand. In the case of a low demand, fossil-fueled electricity production is not needed (14).

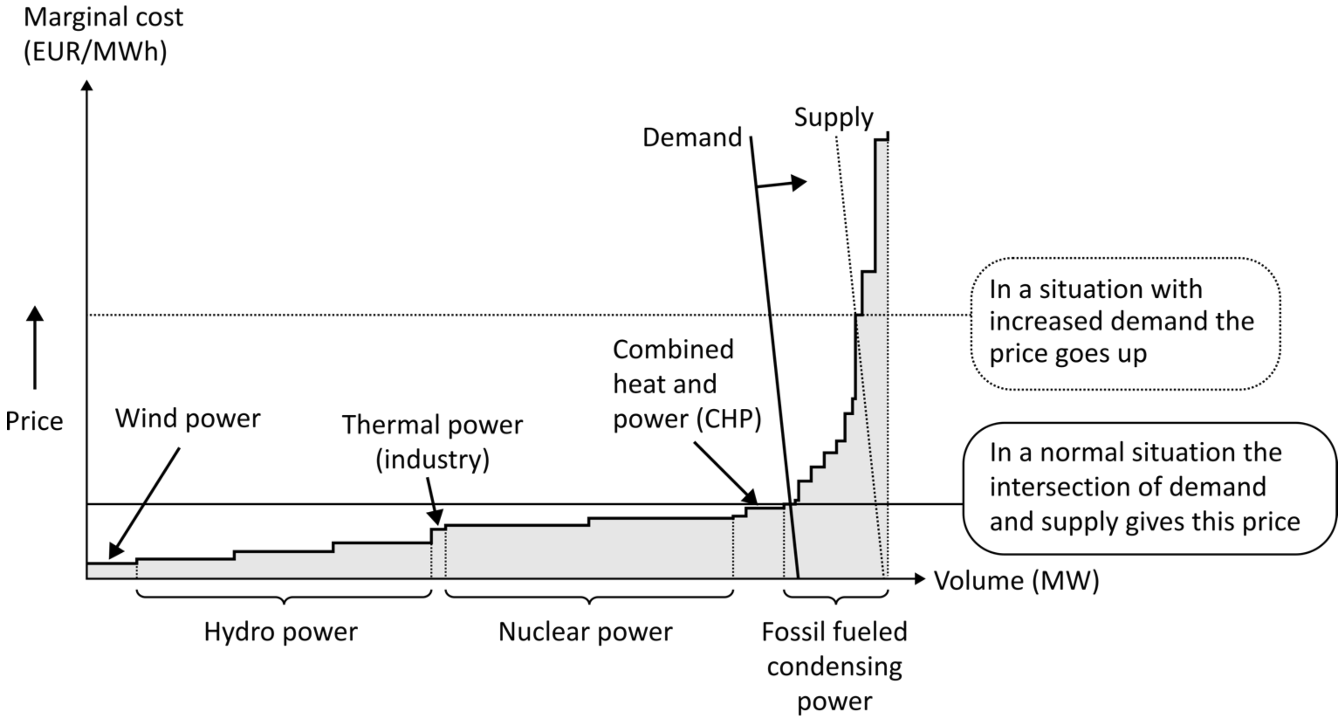

Figure 2.2: Pricing electricity on the day ahead market, based on (14).

2.3. Intraday Market

The intraday market is open from when the day ahead market closes until one hour before the delivery time. It has become increasingly important in line with the increasing share of renewable energy sources in the power system. The reason for this is that with a larger share of renewables, such as wind and solar, the forecasts of the production will be harder to predict.

As an electricity supplier you must always be in balance with the electricity market. In other words, you need to produce as much electricity as you have stated you would on the day ahead market. If you cannot produce the stated amount, you can trade on the intraday market.

There are different reasons to trade on the intraday market. Some examples are changes in the weather forecast, sudden loss of production units and changes in the demand. As mentioned earlier, some of the energy sources are dependent on weather. This means that the actual production is unknown until the delivery hour. Until then you must rely on forecasts. Sometimes these forecasts differ from the day ahead market which leads to a need to sell or buy electricity to be balanced. Additionally, a loss of production unit or changes in the demand might also lead to a need to trade on the intraday market (6).

2.3.1. Single Intraday Coupling

Single Intraday Coupling (SIDC) is a part of the intraday market, providing overview of how the intraday market operates geographically. It is a system that allows for a single cross-zonal intraday market in the EU. In 2022, the expansion of the system included the addition of Slovakia and Greece to the existing 23 countries. Sweden has been a part of this system since June 2018. The existence of this system makes it easier for the market participants to allow for the unexpected changes in production that will be studied in this report. It also promotes competition on the market and increases the liquidity (15).

2.4. Real-time Balancing Market

Svenska Kraftnät is the Swedish Technical Support Organization, TSO. Their most important task is to maintain the balance between the production and consumption of electricity. Simply, this implies that they ensure that electricity produced and consumed align every second. This is done to maintain the frequency at 50 Hz in the electrical grid. If there are disturbances in the balance, the changes in frequency can damage technical equipment. To be able to do this, Svenska Kraftnät utilizes ancillary services. These are contracts with producers to be able to provide different types of support to the electrical grid. After the delivery hour, Svenska Kraftnät calculates the balancing costs during the delivery hour. Since the balancing responsibility parties are obligated to keep this balance, they must pay for potential deviations. Thereafter, Svenska Kraftnät then verifies that the ancillary services that were needed for that delivery hour were activated, and that they provided what was promised. Thereafter, the ancillary service provider gets paid for it (16).

Since 2021, the Swedish TSO introduced an imbalance fee that electricity producers must pay if their electricity production is not balanced with what they have promised. This fee applies to the electricity producer if they act on the real-time balancing market and was introduced to create an incentive to always be as balanced as possible. The money from this fee is supposed to cover the costs caused by the imbalance (17).

2.5. Balance responsibility

As mentioned before, the electricity producer has a responsibility to be balanced with the electricity market. This is called a Balance Responsibility Party, BRP. If a balance-responsible producer is not in balance they must, as mentioned above, pay an imbalance fee to cover the cost for the TSO to restore balance. To be a BRP means that you must trade with the goal of continuously balancing the supply and withdrawal of electricity in the power grid (18).

2.5.1. Modity Energy Trading AB

While it may seem like Öresundskraft as a company would be a BRP and handle the responsibility themselves, this is not the case. Öresundskraft has transferred the responsibility to a company named Modity Energy Trading. Modity is an energy trading company which offers services to energy producers and industries to make the trading easier and to allow the producers to focus on their core business. The company is equally owned by Öresundskraft and Kraftringen and manages energy trades, and thereby portfolio management and balance responsibility for both electricity and gas. Öresundskraft must continue to aim towards producing as much energy as consumed by their customers, with the only difference being that Modity handles the balance responsibility and the energy trading, since that is their core business. It is important to point out that the money that is used to cover the costs of production losses, which lead to imbalances in production and eventually to imbalance fees, still comes from Öresundskraft, even though they have transferred the balance responsibility (19).

2.6. Ancillary Services

As aforementioned, ancillary services are a part of the Swedish energy system. They are relevant for the real-time balancing market and are either automatically or manually activated by the Swedish TSO, Svenska Kraftnät. The purpose of the ancillary services is to balance and manage any upcoming disturbances in the power system (20). There are different ancillary services that differ from each other depending on the bid sizes, activation times and whether it is up-regulation or down-regulation

Below is a table summarizing the different ancillary services in Sweden along with the minimum bid sizes, volume requirements, endurance times and the activation intervals.

Table 2.1 Summary of the ancillary services, based on (21).

Group	Remedial action	Frequency containment reserves			Frequency restoration reserves	
Type	**FFR**	**FCR-D UP**	**FCR-D DOWN**	**FCR-N**	**aFFr**	**mFRR**
Min bid size	0.1 MW	0.1 MW	0.1 MW	0.1 MW	1 MW	1 MW
Volume req. for SE	100 MW	567 MW	547 MW	235 MW	111 MW	300 MW
Endurance	30 or 5 s	20 min	20 min	1 h	1 h	1 h
Activation frequency	*	49.9 Hz - 49.5 Hz	50.1 Hz - 50.5 Hz	49.9 Hz -50.1 Hz	If deviates from 50 Hz	Manual, by TSO

**Automatic activation for changes in frequency when there are low levels of rotational energy in the system*

FFR – Fast Frequency Reserve
This reserve handles fast and deep frequency deviations that can occur in the case of low levels of inertia in the Nordic power system.

FCR-N – Frequency Containment Reserve – Normal
This reserve is an automatically activated reserve that activates to stabilize the frequency deviations that occur from small changes in consumption or production.

FCR-D up – Upward Frequency Containment Reserve – Disturbance
This is an automatic ancillary service that stabilizes the frequency in the event of a disturbance, limited to upward regulation.

FCR-D down – Downward Frequency Containment Reserve – Disturbance
This is an automatic ancillary service that stabilizes the frequency in the event of a disturbance, limited to downward regulation.

aFRR – Automatic Frequency Restoration Reserve
This is an automatically activated ancillary service that aims to restore the frequency to 50 Hz if the system frequency deviates from it.

mFRR – Manual Frequency Restoration Reserve
This ancillary service is apart from the others, activated manually by the swedish TSO. It aims to relieve the automatic ancillary services to restore the frequency to 50 Hz.

Chapter 3

3. Combined Heat and Power plant

In this chapter, combined heat and power plants will be described, including how they work and what their role is in the Swedish electricity- and heating market. It is also described in more depth which fuels can be used and the possibilities of having energy storage connected to the plant.

3.1. Overview

Combined Heat and Power plant, CHP, is sometimes also called cogeneration plant. This kind of power plant is producing two or more forms of energy. These types of energy are often thermal and mechanical. The thermal energy is used to transfer heat into a district heating network and the mechanical energy, often from a steam turbine, drives mechanical equipment such as a generator to produce electricity. An advantage of CHP-plants compared to a stand-alone power plant is that the total efficiency is higher. The reason for this is that the CHP-plant recycles some of the heat that would otherwise be lost in the process. Some examples of where heat losses may occur in are cooling systems and in exhaust gases. In a CHP plant these potential losses are instead recovered and later used in, for example, heating systems such as district heating. The efficiency of a CHP-plant is usually around 90 %. This is higher than the efficiency in many stand-alone power plants, which can be around 30-40 % (22)

A large CHP plant is more complicated than what will be described below, however, the basics are the same. By simultaneously generating thermal and electrical energy, not only does the plant have high efficiency, but there are also other benefits such as a decrease in emissions and pollutants (22).

3.2. Basic layout

Most CHP plants are based on steam turbines. In these plants, water is typically used as a transfer fluid. The water is heated by the combustion in the boiler and turns into overheated pressurized steam, which is transferred to the turbine. The heated steam flows through the turbine which is connected to a generator. Thereafter, the generator converts the kinetic energy in the turbine into electrical energy and therefore producing electricity which is transferred into the power grid. The rest of the energy from the fuel is directed to the condenser where the heat is recovered and can be used in the district heating network. In the condenser, the water in the district heating network is heated to the required temperature and then supplied to the customers on the district heating network with pumps. The heated steam is condensed into water and then fed back to the water circulation of the power plant, which results in a water balance that is nearly equally distributed (23). It is also possible to turn the turbines off and direct the steam straight into the condenser, bypassing the steam turbines completely. This means that more heat can be transferred into the district heating network with the same amount of fuel and can be useful when the heating demand is high. A schematic view of a CHP plant can be seen in Figure 3.1 below.

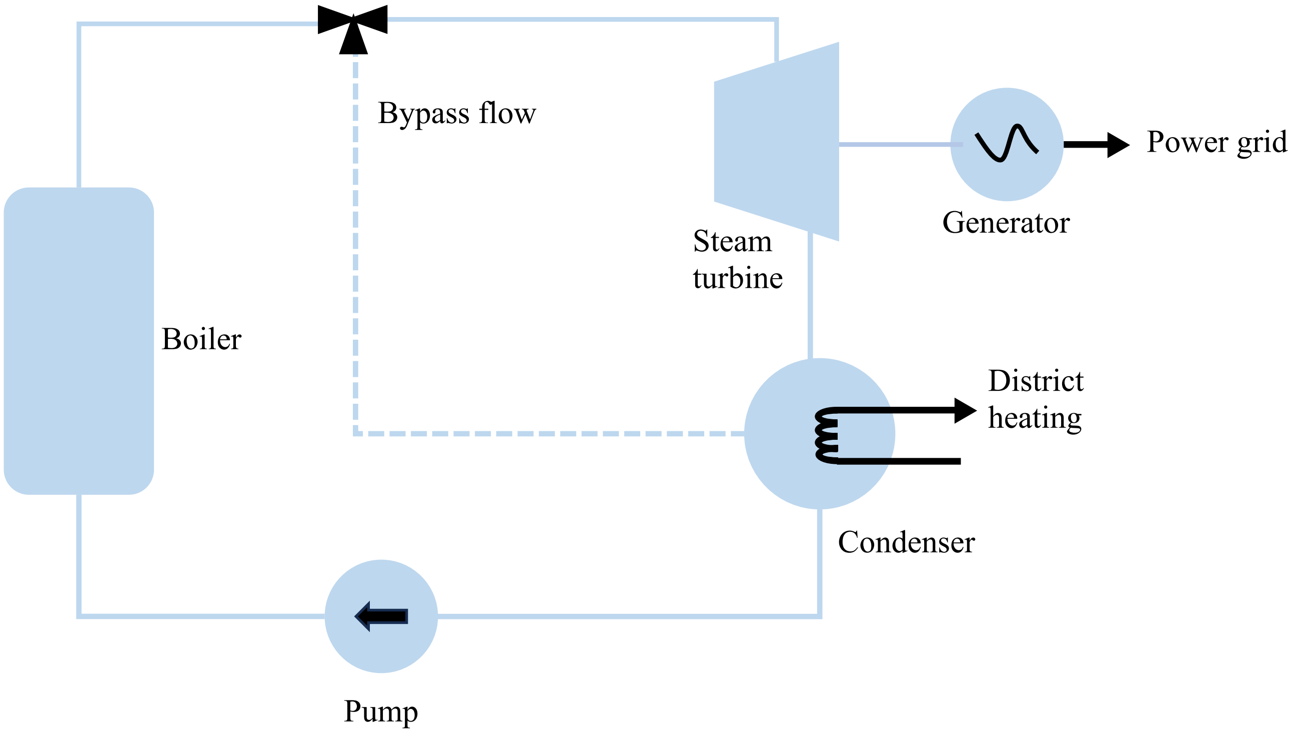

Figure 3.1: Schematic view of a cogeneration plant.

3.3. Fuels

A big advantage of CHP plants based on steam turbines lies in their versatility, as they can be fueled by a diverse range of sources, including gas, oil, wood pellets and waste (23). In Sweden, 90 % of the fuels utilized in CHP plants are renewable or recycled. Biofuel, particularly residues from forests like branches and stumps, is the most common renewable fuel source in Sweden (1). The reason why a variety of different fuels can be used is that the cycle with the turbines is closed and the combustion itself takes place outside of the closed cycle. This means that the turbines do not get exposed to unclean biproducts from the combustion which might lead to corrosion and/or erosion (23).

A notable aspect is that waste can be used as a fuel source, a process known as energy recovery. The waste that is used as fuel would otherwise go to landfills (1). The plants in Sweden do not only burn their own domestic waste, but they also import waste from other countries. According to a report from Svenska Miljöinstitutet, Sweden imported around 2.7 million tons of waste in 2014, where more than 80 % was used in energy recovery. Burning waste has both advantages and disadvantages. An economic advantage is that the energy producing companies get paid to use the waste as fuel in their CHP plants. They get paid for receiving and burning both the domestic waste from Sweden and the imported waste (24).On the other hand, one disadvantage is that there are higher demands on the purification of the flue gas while using waste as fuel (23).

3.4. Storage possibilities

It is possible to integrate various types of storage systems into a CHP plant to enhance its efficiency and flexibility. One such example is the use of batteries, which can be connected to store electricity during periods of low prices, or even negative pricing, and sell it during peak price periods. The periods with low, or even negative prices occur when there is an electricity production surplus. This is elaborated on in Chapter 3.4.2. Another alternative is thermal storage which is a comparatively less expensive option compared to batteries (25). Thermal storage is further described below in Chapter 3.4.1.

3.4.1. Thermal Storage

There are many advantages with thermal storage connected to a CHP plant. For example, the storage can be charged when the prices and demand are low, often during night-time. It can then be discharged when one or both are higher, which might lead to more income and a more flexible production. It is also easier to recover industrial excess heat since it can be stored and used when needed (26). Thermal storage can also make the plant more flexible in the ratio between electricity and heat production. The fact that CHP-plants have more than one energy type produced already makes it flexible. It is flexible both in the aspect that it can be decided when and how much thermal respectively electrical energy should be produced, and that the production can be optimized with the help of the thermal storage. By having production flexibility, the electricity production can be increased when the prices are high and decreased when they are low. But, by adding thermal storage, this flexibility is increased (27).

An example of thermal storage is Low Thermal Storage, LTS, which is the most common storage type connected to CHP-plants in Sweden. A low thermal storage is usually a water tank, also called an accumulator. The temperature of the water is high enough to be used in a district heating network, but often too low to produce electricity. So, the stored energy can only be used towards district heating (25). Even if the stored energy cannot be used to produce electricity, it can still reduce the control that the district heating demand has on the electricity production. By using an accumulator, the electricity production can continue even when the heating demand is high, but it also enables electricity production when the heating demand is low. On these occasions, there would probably not be any electricity production since the heating demand is low, but by storing the heat in the accumulator, the CHP plant can run and produce electricity (2).

Another kind of thermal storage is High Temperature Storage, HTS. Since the temperature is high, 500°C or higher, the stored energy can be used both towards heating production and to produce electricity by using a Rankine-cycle. HTS is more expensive than LTS and the medium that stores the energy in HTS cannot be water since the temperature is too high. Instead, materials such as molten salts, concrete and rocks are used to store the energy (23).

3.4.2. Batteries

To have a big electric battery on the production site is also an alternative. It is more a compliment than an alternative. As mentioned above, having a battery could be beneficial when the electricity sell prices are low. In the typical scenario without a battery, if the thermal storage is sufficiently filled and the district heating load is at a normal to low level, the plant would generally produce a significant amount of electricity. If they produce more than they have contracted to sell on the day ahead market, they can either sell in on the intraday market or let it go to the balancing market. This might cause problems since the prices are unpredictable. It might be beneficial, but it might also lead to high expenses. To avoid this the company can adjust their burning, which costs a lot of money, or dump heat through a cooling tower. This is where the batteries theoretically would be beneficial. Instead of adjusting the burner or dumping the heat, the excess heat can be redirected into the steam turbine to produce more electricity. Portions of this energy could then, instead of going to the grid, go into the batteries and can be stored for later use (29).

The stored energy in the batteries could later be used for various purposes. One example could be in the case of sudden price changes on the intraday market. Having fast accessible energy that is ready to be directed into the grid is beneficial because it would then, theoretically, be possible to provide ancillary services to generate more money. Another example would be in the case of sudden loss of production. In this case, the electricity production suddenly stops or is lowered. In the case without the batteries, this would imply that the producer would preferably need to buy the lost electricity instantly on either the intraday or the balancing market. Either of these would incur costs, sometimes a considerable amount. If a battery exists instead, it would be possible to immediately cover up for some of the lost electricity production to meet the promised amount that was bid the day prior on the day ahead market. This, of course, depends on the battery size and the specifications of the battery.

The type of batteries that are used in battery storages are mostly Lithium-ion batteries. One example of a battery storage that was supposed to be operational by Q1 in 2024 in Stockholm is Stockholm Exergi and Polar Capacity’s project of building large scale battery storages in the Stockholm area. The project consists of building a total of 100 MW battery storage in the Stockholm area. The first step in this project was to build a 20 MW storage in Haninge, Stockholm. There, they were going to use lithium batteries to store the energy. This is the same kind of batteries that can be found in most electric vehicle battery packs (30). The battery storage facility that is going to be analyzed and studied for this report is a 20 MW battery storage facility connected to Öresundskraft’s electrical grid in Helsingborg. This battery storage will potentially be able to help with imbalances and lack of production within the electricity markets (31).

3.5. Combined Heat and Power Plants in Sweden

There are approximately 170 CHP plants in Sweden today. In 2021 they produced a total of 15.4 TWh of electricity and 26.5 TWh of heat, which corresponds to around 9 % of the total electricity production and 47 % of the heat production that year. This demonstrates the importance of CHP plants in the heating- and electricity markets in Sweden (32).

3.5.1. Öresundskraft

Öresundskraft owns and operates two CHP plants that are relevant for this report, both located in Helsingborg. One uses waste as fuel (Filbornaverket) and the other one uses biofuels (Västhamnsverket). Öresundskraft started as early as 1859 and has continuously expanded and developed until what it is today (33).

3.5.2. Filbornaverket

Filbornaverket, located in the northeast parts of Helsingborg, is a waste incinerated CHP plant. It has a nominal power of 18 MW of electricity and 72 MW of district heat. It uses 100 % of the available energy in the waste and it has a highly efficient flue gas purification which takes the plant's emissions levels to far under the governmental requirements (34).

3.5.3. Västhamnsverket

Västhamnsverket, located in the harbor of Helsingborg, is a biofuel incinerated CHP plant with a nominal power of 69 MW electricity and 138 MW district heat. The plant was built back in 1983 and was originally fueled with oil. Initially, it got rebuilt to be fueled by coal first and then again to be fueled by biofuels only. Since 2006 the only type of fuel in Västhamnsverket is biofuels (34). Since 1990 they have managed to reduce the emissions by 90 % with the rebuilds and change of fuels. At Västhamnsverket there is also a heat pump which can supply the grid with 30 MW district heat and 10 MW district cooling. It does this by utilizing the sewage water and the energy therein. With the help of the heat pump, the temperature is raised to the level at which it can be transferred to the district heating network. Since heat is extracted from the sewage water, the temperature drops by six degrees and can then be used to lower the temperature in the district cooling system (35).

Chapter 4

4. Methodology

The following chapter presents the method of the work. First, historical data was gathered to be used in the optimizations to make them as realistic as possible. After collecting the data, two different scenarios, sudden loss of facility and forecast error, and four different courses of action were modelled in Energy Optima 3.

4.1. Data gathering

The majority of the data required for the optimizations was supplied by Energy Opticon and Öresundskraft, and it was already in Energy Optima 3. This included historical data such as actual values from the district heating load, which were utilized in the optimization process. Before the modelling could begin, it was necessary to identify when there was an error. By using historical data from scenarios that have occurred, more realistic results were expected. Öresundskraft provided us with days during 2022 and 2023 when unexpected facility losses had occurred or when there had been a significant difference between forecast and actual district heating demand. Once the relevante days were identified, historical electricity prices were gathered from a website called VolueInsight. (10). It is a website that, among other things, provides hourly data on actual average prices for various markets such as intraday, day ahead, regulation up and regulation down.

However, a challenge was encountered with the intraday market, where only one price was available. In Energy Opima 3 it is preferable to always have a lower sell price than the buying price to prevent the optimizer from purchasing the maximum allowed electricity and immediately selling it for profit, which is an unrealistic scenario. To address this, a selling price was created by multiplying the actual historical price for each hour by a factor of 0.66. This method mirrors Öresundskraft’s approach when estimating the value on the intraday sell market. A comparison of their selling and buying price on the intraday market was conducted to determine the factor they use. Although Öresundskraft’s prices were available, collecting all prices from the same database was preferred to ensure comparability of the results.

Prices collected from the website were in EURO/MWh, but in Energy Optima the price in SEK/MWh is preferrable. The website for the European Central Bank was used to find the exchange rate for our specific dates, allowinf the conversion of prices to the right unit, SEK/MWh (36).

4.2. Modelling

All the modelling was done using Energy Optima 3, an optimization software that is provided by Energy Opticon. It solves mixed integer linear optimization problems, primarily from a cost perspective. The area of usage is mainly optimization of district heating and electricity production.

Evita is the name of a district heating grid with many different plants and connections. To perform the optimizations, a copy of the whole system, where all the various production plants and connections were included, was provided. Since Evita is a very large and complicated system, the specific plants of interest was isolated by delimiting the connecting desired segment and the rest of the system. This was achieved by restricting the connections between Helsingborg and Landskrona.

The delimited system that was used consisted of two CHP plants with different fuels, waste respectively pellets, and a heat plant that runs on bio oils. The heat plant only runs when there is no other way to meet the heat demand, since it is expensive and runs on bio oils. There is also a heat pump which runs on electricity and is used when the production is not enough to meet the heat demand. The heat pump is prioritized over the heat plant. Instead of just cutting the connection with Landskrona, it was limited and set to a specific value, which could not be changed even if the production in Helsingborg was inconveniently lowered. The specific value was the historical value for that specific hour. This means that when the production is forced to be lowered in Helsingborg, the only components that can be used to solve the problem, in addition to act on the electricity market, is the different production plants in Helsingborg, which are mentioned above.

The modelling and design task revolved around creating the two scenarios and analyzing various courses of action. The method that was used is described in a simple way in Figure 4.1 below. The first step was to identify, by looking at historical data, when there had been an error. Thereafter, the electricity prices were collected prior to running an optimization without the error and at last another optimization with the error. All of this will be described in detail below.

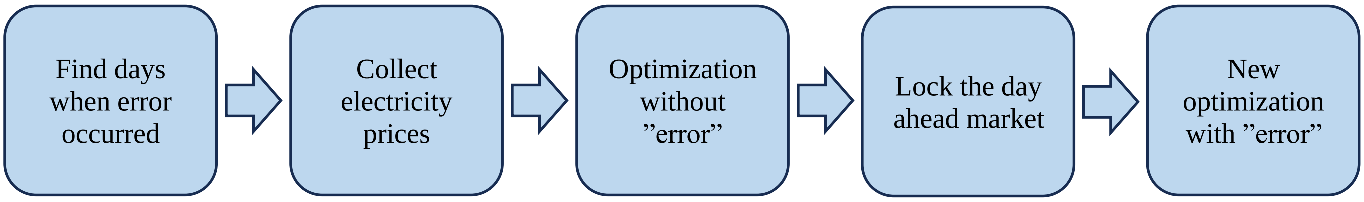

Figure 4.1: Simplified description of the method.

4.3. Modelling the scenarios

The two different scenarios that were investigated were sudden loss of production and forecast error. The difference between these two scenarios is that in the case of sudden loss of production, some production unit/s stop working, either because they break or due to other maintenance related reason. This first case causes problems in terms of planning how much electricity to sell because they are mostly unplanned for and the downtime is not always easy to predict. The other case that was investigated was the forecast error case. A forecast error is when the actual district heating load differs from the predicted forecast. This can be caused by sudden weather changes or changes in heating usage by the customers. This can then lead to the production plant having to produce more heat than previously needed and therefore must sacrifice some electricity production, which can then create an imbalance towards the electricity market.

4.3.1. Sudden Loss of Facility

First, an optimization was done where the availability that causes the sudden loss of facility was deleted. Besides this, the intraday- and balancing markets were closed so that the only market that was open was the day ahead market. This approach was necessary to determine the optimized quantity for the day ahead market, if the production loss would not occur. At 10:00 the day before the delivery hour, Öresundskraft needs to place their bids for the day ahead market. If the loss of production is before this, they can change their bids for the next day to match their new production plan. However, if the production loss is after 10:00, they cannot change their bids for this day or the next and will have to do one of the actions below. As a result of this, it was essential to lock the quantity that is sold and bought on the day ahead market during the time it could not be changed due to rules on the market itself. If the loss occurred before 10:00, the quantity on both day ahead markets was locked from the start of the optimization until 00:00 the day after the loss. If the loss occurred after 10:00, it was locked from the start of the optimization until 00:00 two days after the loss of production, see Figure 4.2 and Figure 4.3. In the figures, the locked trading on the day ahead market is inside the dashed square. To be able to lock the decided trading on the day ahead market, four forecasts were created, maximum and minimum for both buying and selling. After optimizing without loss of production, the bought quantity for each hour was copied into both the maximum and minimum forecast for buying on the day ahead market. The same was done for the hourly sold electricity. These forecasts are then used later during the optimization of loss of production facility.

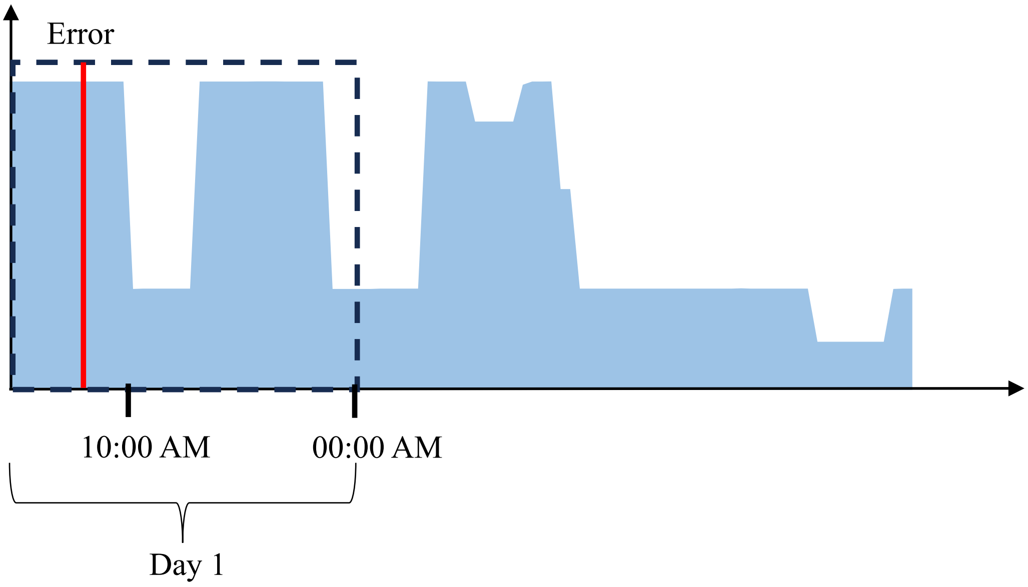

Figure 4.2: Explanation on how the day ahead market is locked when the loss of facility occurs before 10:00.

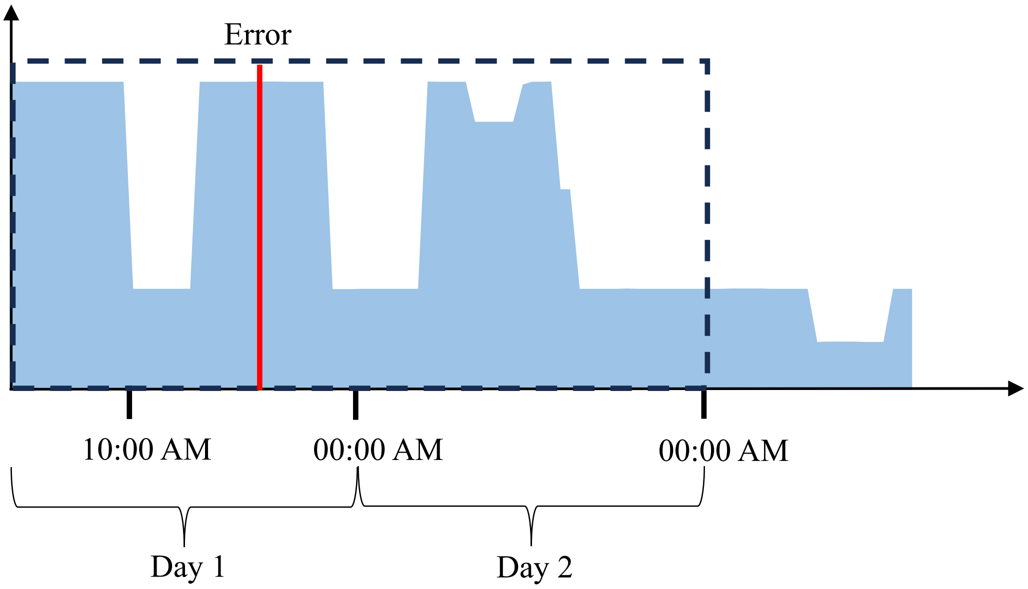

Figure 4.3: Explanation on how the day ahead market is locked when the loss of facility occurs after 10:00.

After this, a new optimization was made. Here the unavailability was brought back and in the basic mode, all the actions were opened- intraday, balancing market and counter production. To recreate the different courses of actions, various cases were modelled. All which are described in Chapter 4.4

4.3.2. Forecast Error

Since the weather and temperatures outside are difficult to predict, forecast errors may occur. A forecast error is defined as either an over- or an under estimation of the hourly district heating load. Other things that can affect the district heating load and create forecast errors are customers’ heating usage or faults elsewhere in the district heating grid.

To model this scenario, a summary of the predicted district heating loads on a weekly basis for 2023 and compared them to the actual load. The five weeks with the largest discrepancies between forecast and actual load, either positive or negative, were then selected, and their forecasts were downloaded. These forecasts contained multiple values on all days except the first. On day one, a forecast can be made for all the following days of the week. On day two, a forecast can be made for all the following days except for day one which is now in the past. This continues until seven days has passed and on the last day of the week, there exists seven different predictions of the district heating load. The latest prediction for each day was then summed up into a single forecast for the week. An optimization was then made with that forecast to lock the amount of electricity predicted to be sold and bought on the day ahead market for the whole week. Another optimization was made where the district heating forecast was replaced with the actual load via a line of code. The different courses of action, further described below in Chapter 4.4, were then tested with this optimization.

4.4. Modelling the courses of action

The possible actions were built with special programming which is used by Energy Optima to modify the software and make it behave in ways that are outside the normal functions. By writing code, it is possible to override what is set up in the program and make changes to individual optimizations. Some optimizations can be seen as special cases and therefore needed to be modified with the special programming. This was essential for a faster and more comprehensive workflow. It also allows different optimizations to be executed at the same time with different settings.

4.4.1. Intraday Trading

The intraday case was modelled by opening the intraday in special programming and simultaneously closing the balancing market. The optimizer often had to be limited to buy or sell on the intraday market before the unavailability started. The optimizer was allowed to buy and sell on the intraday market during the unavailability to compensate for the lost electricity production. By doing this, data on how much it bought and sold, and at which cost, during the unavailability was achieved. This data could then be compared to the other courses of action.

The intraday case was done in two different ways. The first was intraday + counter production, which is presented above. The other way was only intraday trading. To be able to do this, the electricity production from the available plant was limited so that it could only produce the same amount of electricity as it did when there was no error. In other words, counter production was not possible.

To take away the possibility of counter production, two new forecasts were created. Electricity out from Filbornaverket and electricity out from Västhamnsverket. These variables were studied by taking the values from the optimization without the loss of facility or with forecast error and using these values in the new forecasts forcing the plants to run in this way. At the hours where it was not wished to lock the plants, -1 was used, which means that the plant could run in a way that was most profitable, without needing to take previous optimizations into consideration. The electricity production was then limited with special programming.

4.4.2. Counter Production

To recreate the counter production case, both the intraday- and balancing market were closed with special programming. This means that the only option to cover up for the loss of electricity production was to produce more electricity with the other plant. This did not always work, as in some cases the plant that was available was either already running on maximum capacity, or the electricity production that was lost was larger than the available plant can increase with. In these cases, the intraday market was opened, but the price was set to 100 000 SEK/MWh, which is an unreasonably high value. This value is roughly 100 times larger than what the prices usually are. By doing this, Energy Optima used counter production as much as possible, and when the maximum capacity was reached, the rest of the electricity was bought on the intraday market. When the results from these optimizations were calculated, the high prices for the intraday market were changed to the real lower prices.

4.4.3. Balancing market

This course of action shall reflect that one chooses to do nothing. In other words, neither trade on the intraday market or try to produce more with the other plant to cover up for the lower electricity production and unbalance towards the electricity market. Instead, one must trade on the balancing market. In some cases, the price on the balancing market is equivalent to prices on the intraday- or day ahead market. Other times, the prices are very high which leads to high costs for the energy producing company. The balancing market is very unpredictable and in addition to this, there is also an imbalance fee of 1.15 euro/MWh, so it should be avoided to trade here if possible. Sometimes this is not possible as there can be a shortage of electricity to buy on the intraday market and/or it is not possible to produce more with the available plant.

The recreation of this was done by closing the intraday market with special programming and limiting the electricity production from the available plant, meaning counter production wasn't possible. This was done in the same way as for the intraday case described in Chapter 4.4.1.

4.4.4. Utilization of a Battery

The utilization of a battery in connection with the electricity production had to be modelled in the software. Since no electrical batteries exist in the software, this problem had to be navigated by modelling a thermal storage with two user-defined units connected to it, one at the inlet of the storage and one at the outlet of the storage. The user defined units that were used in connection to the thermal storage are not real, but rather fictional units designed to make our thermal storage act as a battery. The inlet unit converts electricity coming from the electricity production and converts it into district heat with the same amount of energy. At the outlet the same is done, but reversed. Thermal energy is converted into electrical energy that can be directed into the electricity grid.

4.5. Optimizing on costs

All the optimizations have the same time step - one hour. They either start at 10:00 the day before or the same day as the sudden loss of production and run the following five days. If the error occur is before 10:00 the optimization is started the day before, and if it appears after 10:00 it is started the same day. This was done because the production plan for the day ahead market needs to be handed in by 12:00 for the following day. If the production unit is unavailable for longer than the five-day optimization period, the optimization period is extended by the necessary number of days.

The optimizations on forecast error differed slightly. These optimizations started at 10:00 on Monday and lasted for the duration of the week.

Three views were created in Optima. In the first one, only the day ahead market, specifically how much is bought and sold was looked at. In the second view, all the electricity that was bought and sold in all the markets, day ahead-, intraday- and real-time balancing market was looked at. In addition to this, the electricity consumption by the boiler and the electricity production was shown. In this view two graphs were created, one for the sold and consumed electricity, and one for the bought and produced. The last view showed different costs and incomes. It showed the costs for operation, fuel and bought electricity on all markets, and the income from sold electricity on all markets. These were made so that it would be easier to compare the different cases and courses of action.

After the optimizations, many different results was achieved and it was chosen to focus on the costs and incomes. The costs that were looked at were fuel, operations and bought electricity on the day ahead- intraday- and balancing markets. The incomes that was looked at were income from sold electricity on the three markets mentioned above. Since only the electricity market in our report was analyzed, the income from the heating market was not taken into consideration. The costs and incomes were exported to excel where a result, total cost minus total income, was calculated and different graphs were generated. The results from the different optimizations were compared to the optimization where loss of production or forecast error was deleted. The comparison was made by calculating the price-increase as a percentage for all the different actions, so that it would be easy to compare them and see which one was the most financially favorable.

4.6. Optimizing on CO2 equivalents

Carbon dioxide equivalents are used to describe and compare the climate impact from different greenhouse gases. A gas expressed in carbon dioxide equivalents describes how much carbon dioxide would have to be released to have the same environmental impact. It is calculated by multiplying the gas’s GWP, Global Warming Potential, with the tons of the gas (32). Another word for GWP is greenhouse effect. It is a measurement of the radiative forcing effects for a greenhouse gas. There are both direct and indirect impacts. The direct impacts are when the gas itself acts as a greenhouse gas and the indirect impacts arises from chemical processes where the original gas generates other greenhouse gases (33).

To be able to optimize on carbon dioxide equivalents more data was needed. Firstly it was researched how much the different fuels used in the plants emit, or what their carbon dioxide equivalents were per MWh fuel. The fuels researched were pellets (0.378 tons CO2/MWh fuel) and waste (0.172 tons CO2/MWh fuel). Both were collected from a document provided by Naturvårdsverket, which can be downloaded from their website (35).

To optimize on carbon dioxide equivalents an external energy supply was created and connected to a sink that was named “CO2 sink”. This was not enough to be able to calculate the CO2 equivalents, further code was needed. As previously mentioned, data was collected for the fuels in tons of CO2 per MWh fuel, this was then put into a formula which multiplies the factors previously presented with the calculated fuel usage from the optimizer. The formula summarizes this and puts it in a variable named “CO2” which can then be read hourly and summarized for every optimization.

Since this report also includes electricity bought on the electricity markets, the formula had to be extended to include this. The data for this was retrieved from a website called Electricity maps, from which an excel file containing the data needed was downloaded (36). On Electricity maps, both historical and live data on how many grams of CO2 equivalents emitted during electricity production in different countries can be found. In some countries it is also split up between the different zones. It was chosen to not only take the data from zone four, which is the zone that the CHP plants that was modeled on was located, but for the entirety of Sweden. The reason for this is that a large amount of electricity is transferred between the zones depending on where the demand and production are. Therefore, it was considered more realistic to take the data corresponding to whole of Sweden. The data was collected hourly for 2022 and 2023, and contained hourly grams of CO2 equivalents per kWh which was recalculated to tons CO2 per MWh to fit the format of the formula. Related to the electricity markets, the same hourly emission factor for the different markets was assumed. This means that all the hourly values, previously mentioned, were applied regardless of whether electricity was bought from the day ahead, intraday, or real time balancing market. Since the software generates the amount of electricity bought in MW, this could then be multiplied with the factor for each hour and added to the total CO2 value.

It was thought to be interesting to explore whether the optimizer would adopt a different approach to the problem if minimizing CO2 emissions were prioritized, instead of costs. To achieve this, the total flow running through the previously created external energy supply in the topology was given a price per MWh, allowing for this value to be varied. A high value means that if a lot of CO2 is released, the price will be high and the optimizer will try to avoid this. Conversely, a low price suggests that CO2 emissions are of lesser concern to the optimizer, potentially resulting in higher emissions compared to scenarios with a higher price.

In the optimizations, the objective was to determine which course of action would result in the lowest amount of CO2 equivalents, utilizing the data described above. To accomplish this, a high value to the external energy supply was applied, emphasizing the reduction of CO2 emissions in our optimization process.

Chapter 5

5. Results on Sudden loss of facility

In the following chapter the results from optimization on sudden loss of facility will be presented. The outcomes from the optimizations around each loss of facility will be shown in graphs. Sudden loss of facility has been optimized in three different ways: optimizing on costs, optimizing on costs with a battery and optimizing on CO2. These results will be presented in detail below.

5.1. Optimizing on costs

The outcomes from the optimizations are presented as percentages. The initial scenario for each date, wherein no sudden loss of facility occurs, serves as the baseline case. Subsequently, the results obtained from the remaining optimizations on that particular date are presented by comparing them with the baseline case, showing the increase in the result, costs minus income, as a percentage. The results are then presented in a graph with the purpose to provide a simple overview of the outcomes from each date.

The results include the costs for both the production, operation, and fuel costs, of electricity and district heating. This differs from the income, where only sales revenue from the electricity market and income for burning waste, is considered. One of the plants, Filbornaverket, uses waste as fuel which leads to income instead of cost. Therefore, the costs consistently outweigh the income in all optimizations. However, it is important to note that in reality, there is additional revenue generated from the heating market, which renders the overall operation profitable. But this revenue is the same for all optimizations on the same date since the heat demand and price for heating is unchanged. Therefore, including this in the result wouldn’t have changed it.

The results from each date are presented in the graphs below. On each of these dates, there has been a sudden loss of facility, at either Filbornaverket or Västhamnsverket. Despite this loss, ensuring sufficient heat production to meet the heat demand remains crucial, alongside fulfilling prior commitments made on the day ahead market. Each column in the graph illustrates the outcomes derived from an optimization with specific settings, each representing different courses of action, as described in the methodology outlined in Chapter 4.

In Figure 5.1 below, the results from optimizations on date 1 are depicted. During this period, there was a loss of Filbornaverket, requiring adjustments to the production plans to compensate for the loss of both heat and electricity production. With Filbornaverket unavailable, the only operational production units are Västhamnsverket and the heat pump. The figure illustrates that “counter production” is the most expensive alternative and that intraday + counter production and intraday are equally profitable.

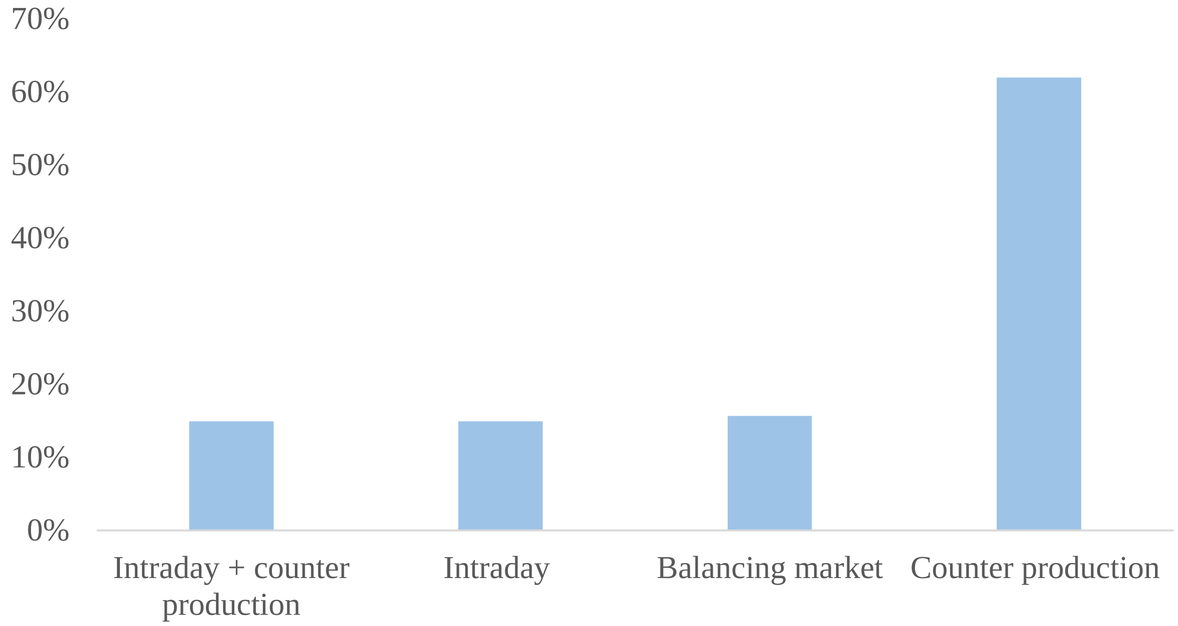

Figure 5.1: Optimizations around date 1.

In Figure 5.2, the percentage increase in the results from various optimizations when a loss of Filbornaverket is illustrated. It is evident that the most profitable course of action is intraday + counter production, while the least profitable is balancing market.

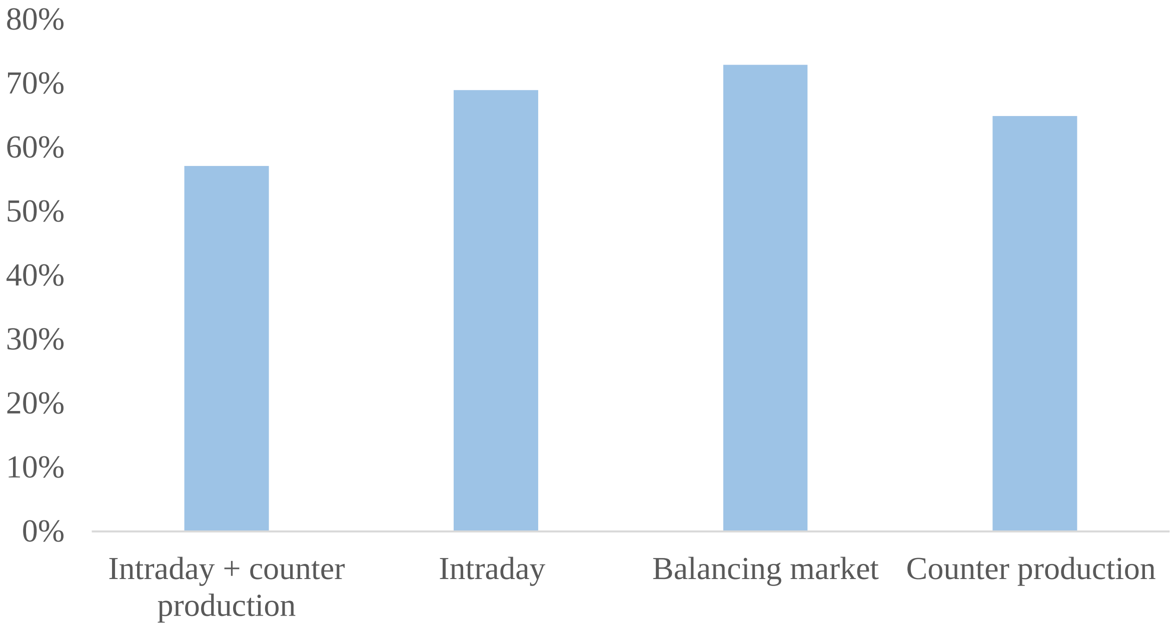

Figure 5.2: Optimizations around date 2.

Below is an illustration of the results from a sudden loss of Filbornaverket, Figure 5.3. In the figure, it is shown that the most profitable course of action is intraday + counter production along with counter production.

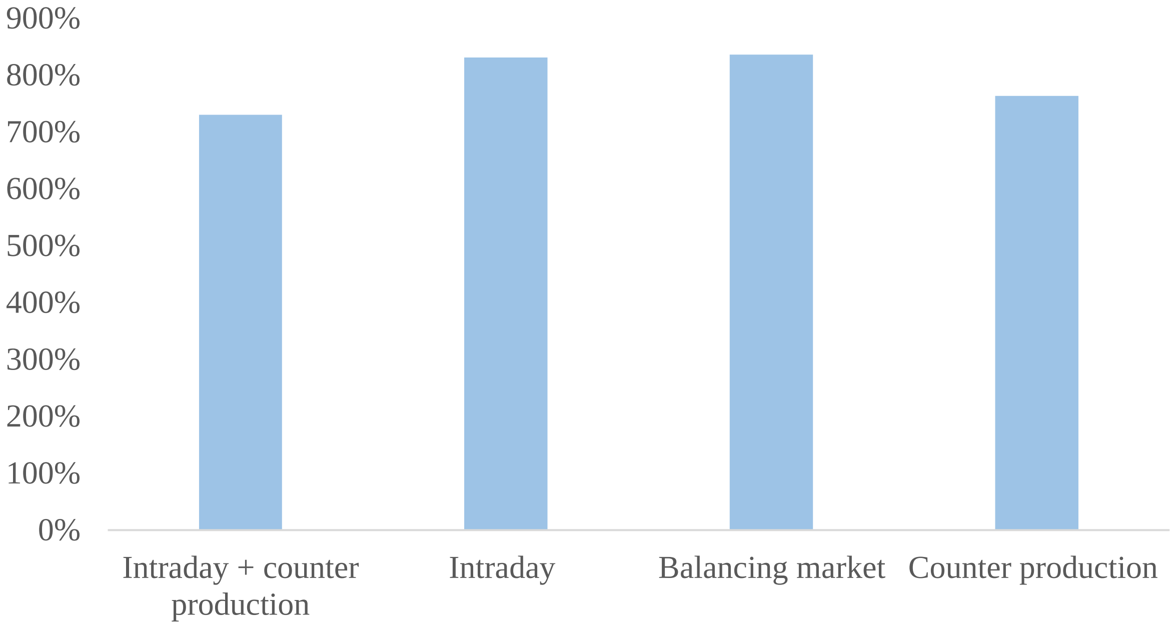

Figure 5.3: Optimizations around date 3.

Figure 5.4 depicts the percentage increase in the result from various optimizations in the event of a loss of Filbornaverket. In this case, the most profitable option is intraday + counter production, while balancing market is the least profitable.

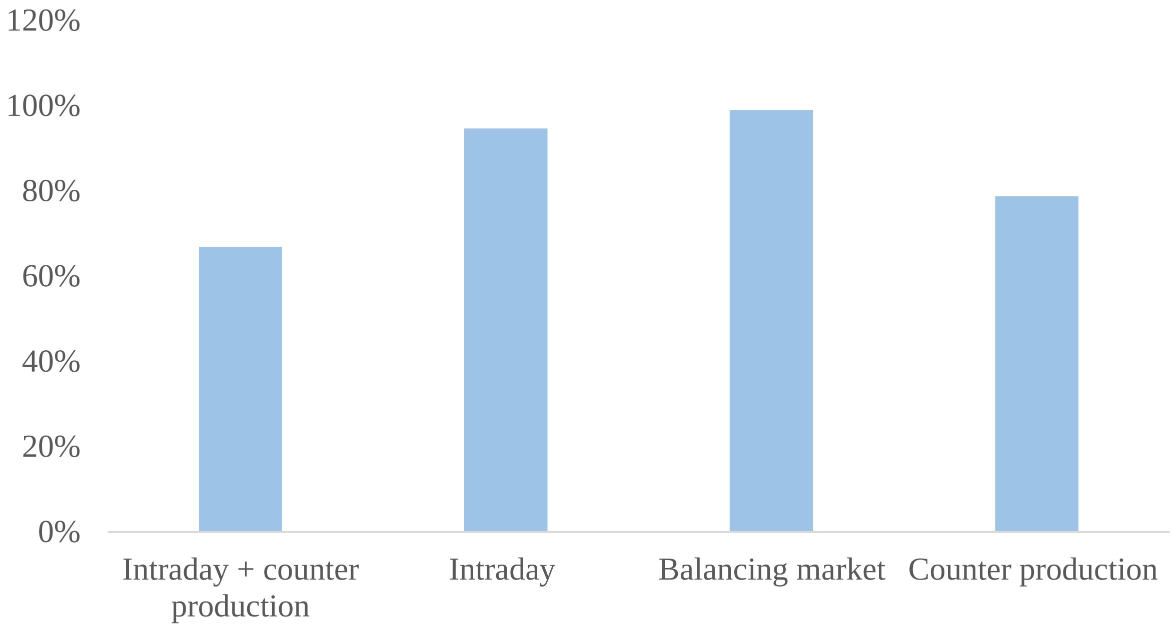

Figure 5.4: Optimizations around date 4.

Figure 5.5 depicts the percentage increase in the result from various optimizations in the event of a loss of Filbornaverket. In this case, the most profitable option is intraday + counter production and intraday.

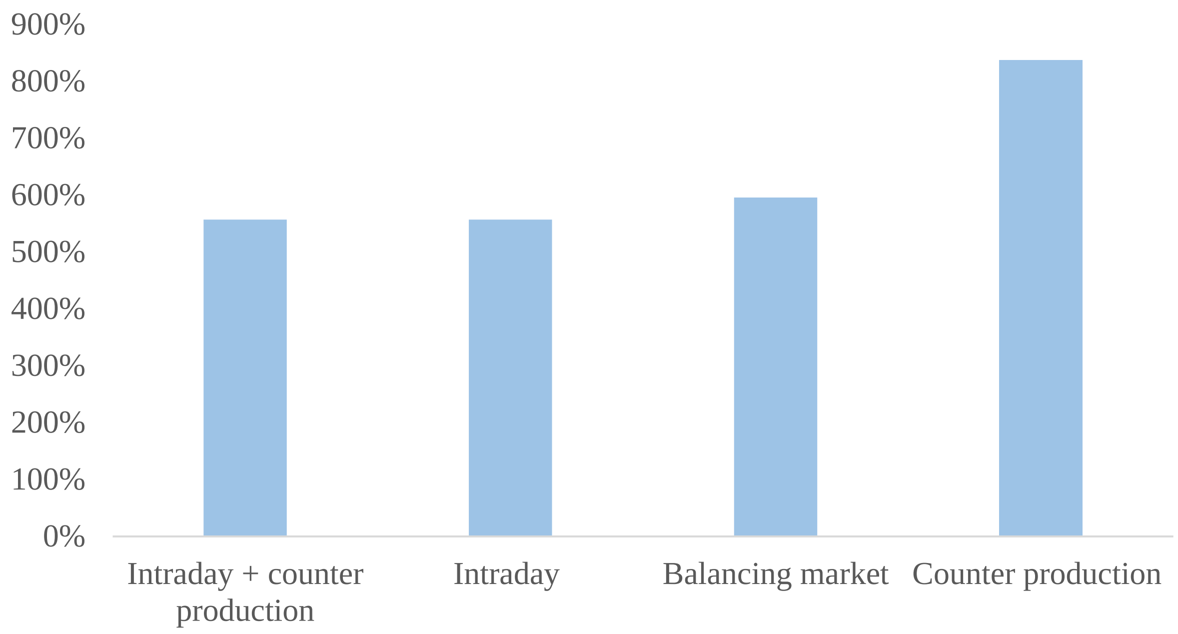

Figure 5.5: Optimizations around date 5.

In Figure 5.6, the results from four optimizations during a loss of Filbornaverket is presented. In this case, the most profitable course of action is intraday + counter production and counter production.

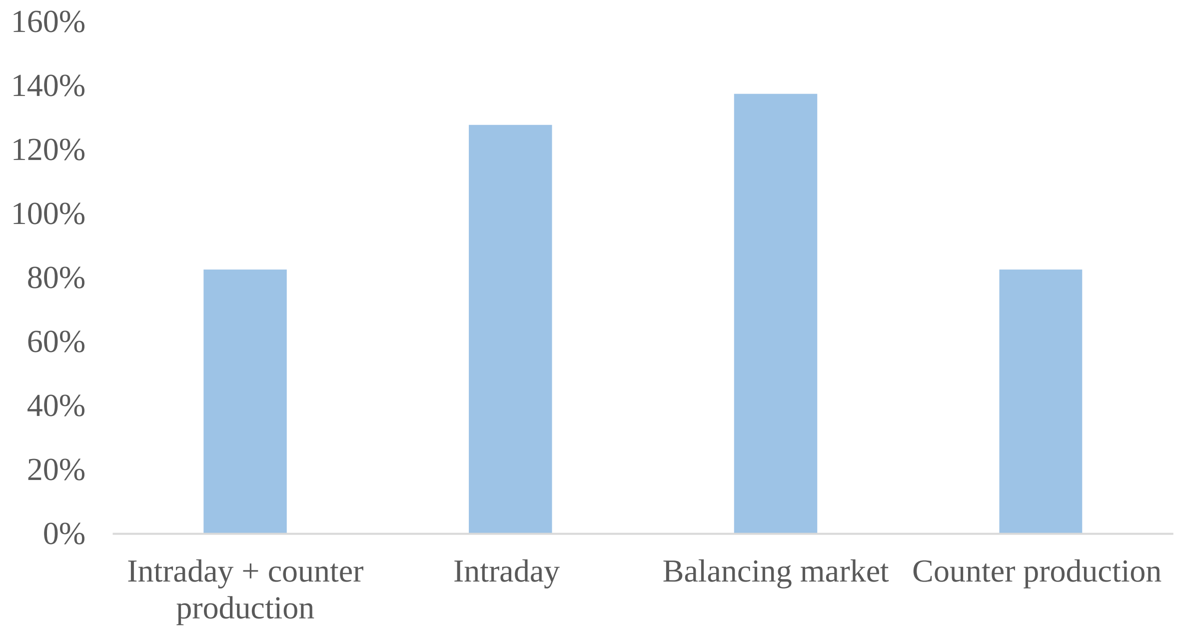

Figure 5.6: Optimizations around date 6.

Figure 5.7 below illustrates the results from four optimizations conducted during a loss of Filbornaverket. It is evident that counter production is the least profitable option and that the rest of the optimizations have approximately the same results.

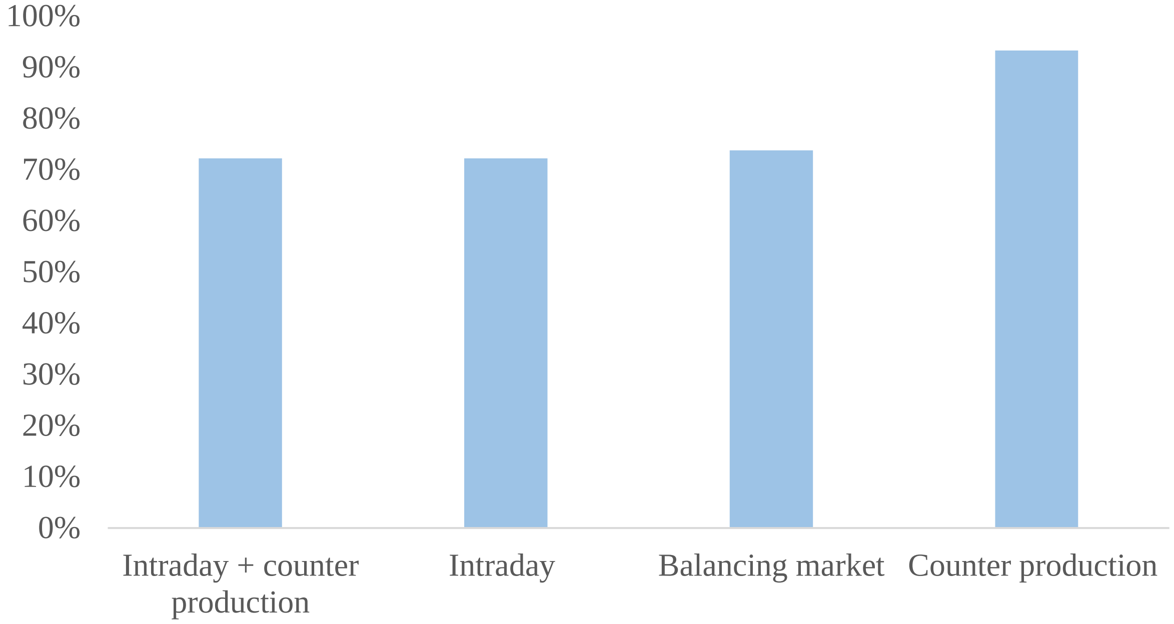

Figure 5.7: Optimizations around date 7.

Figure 5.8 below illustrates the results from four optimizations conducted during a loss of Västhamnsverket. It is evident that the balancing market is the least profitable option and that the rest of the optimizations have approximately the same results.

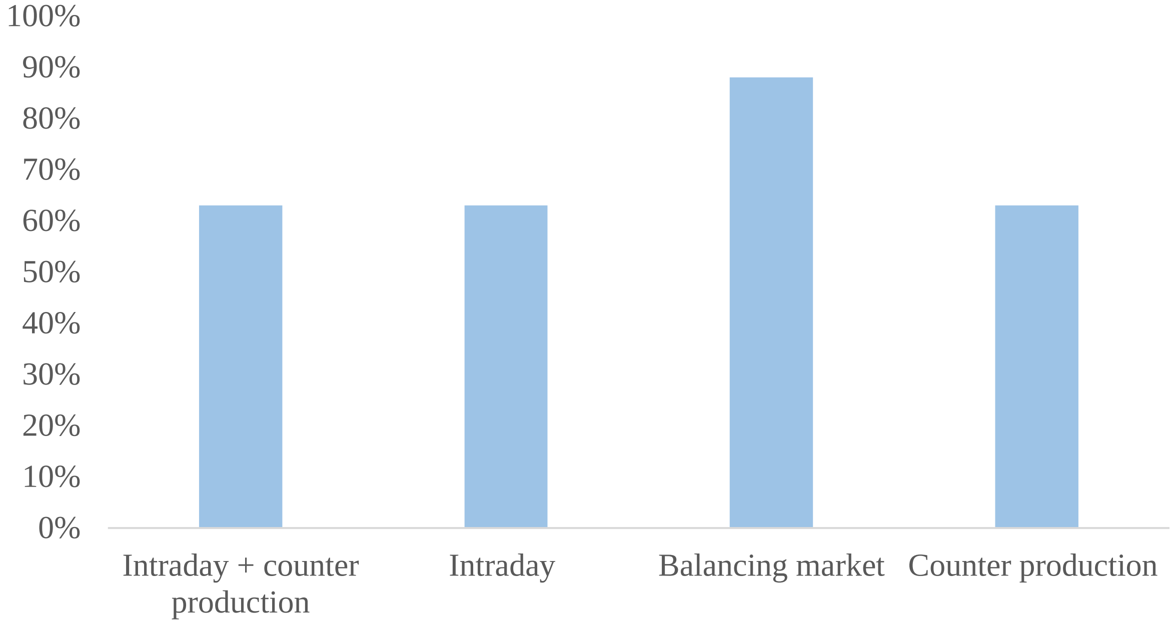

Figure 5.8: Optimizations around date 8.

A summary of the graphs above can be found in Table 5.1. This table outlines the most profitable course of action based on our optimizations. As indicated in the table, the most financially advantageous strategies are either intraday or intraday + counter production.

Table 5.1 Summary over the most profitable course of action on all dates.

Date	**Most profitable course of action**
1	intraday + counter production and intraday
2	intraday + counter production
3	intraday + counter production
4	intraday + counter production
5	intraday + counter production and intraday
6	intraday + counter production and counter production
7	intraday + counter production and intraday
8	intraday + counter production, intraday and counter production

5.2. Optimizing on costs with a battery

In the following results, a 20 MW battery was connected to the plants and could be used to mitigate losses in the event of a loss of production.

When optimizing with the battery, it was assumed that the battery was connected to the plant that was unaffected by the outage. Its usage was limited solely to the outage period and not before or after. For clarity, the scenarios with and without the battery was compared in the same graph. Like the optimizations without battery, those with the battery is compared to the baseline without an outage. Therefore, both optimization scenarios for each action have been compared against the same baseline case and subsequently compared to each other in the graphs below.

Figure 5.9 below illustrates the results of eight optimizations in the event of a failure of Filbronaverket. The blue bars represent the optimizations without the battery, while the green bars represent the optimizations with the battery.

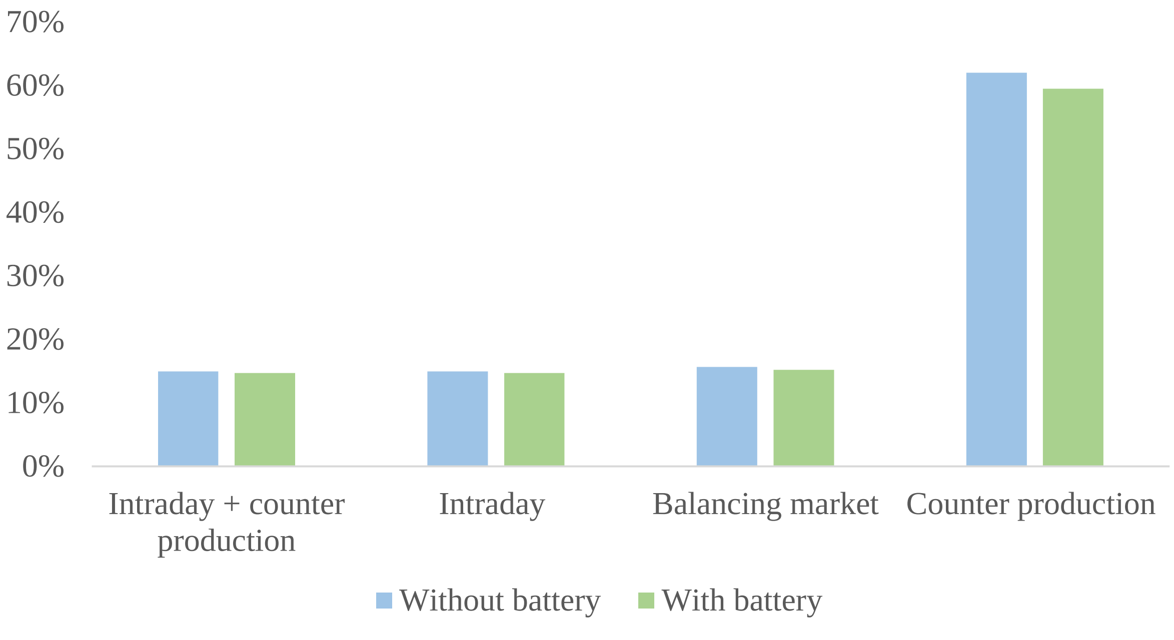

Figure 5.9: Optimizations around date 1. Both with and without the battery.

Figure 5.10 below illustrates optimizations during a failure of Filbornaverket.

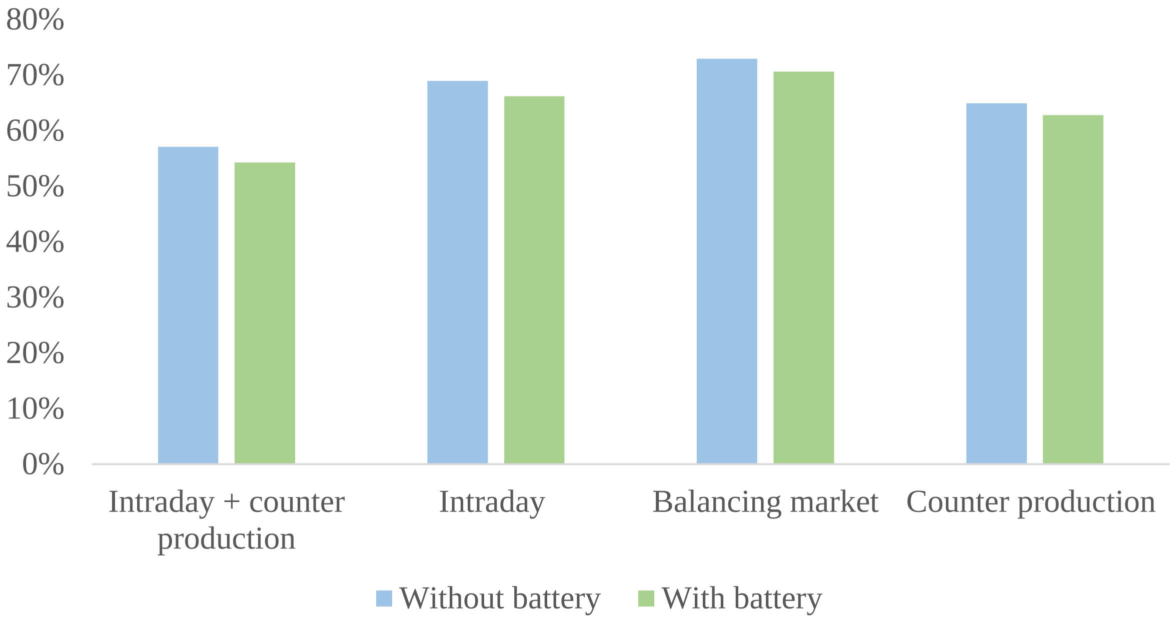

Figure 5.10: Optimizations around date 2. Both with and without the battery.

In Figure 5.11 below, optimizations during in outage of Filbornaverket are shown.

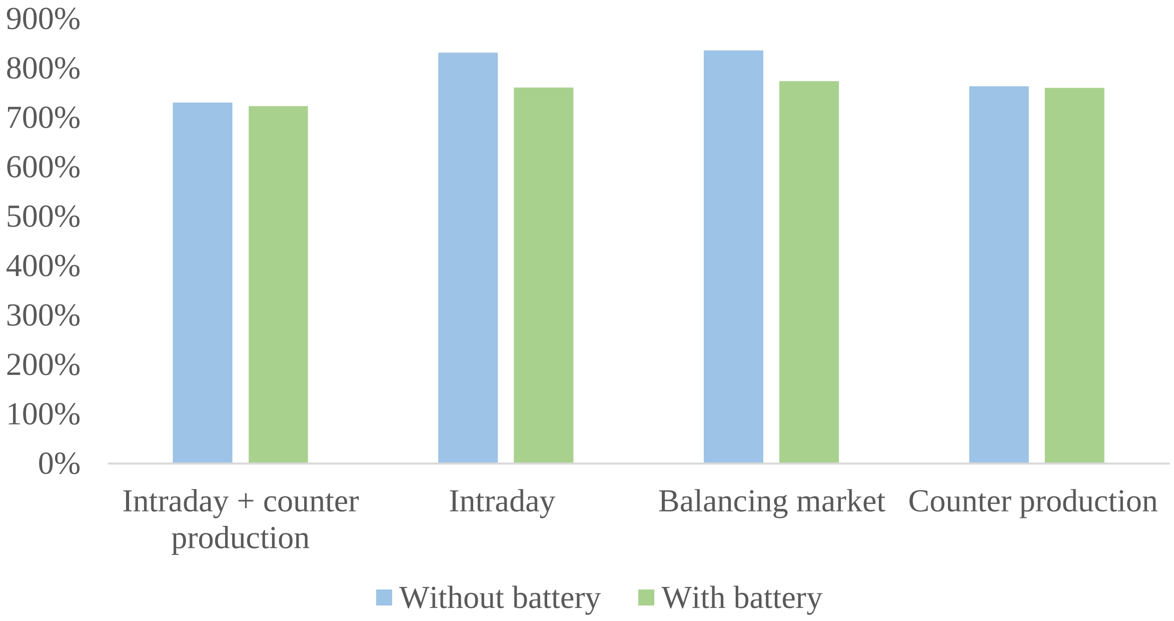

Figure 5.11: Optimizations around date 3. Both with and without the battery.

Figure 5.12 below illustrates optimizations during an outage of Filbornaverket.

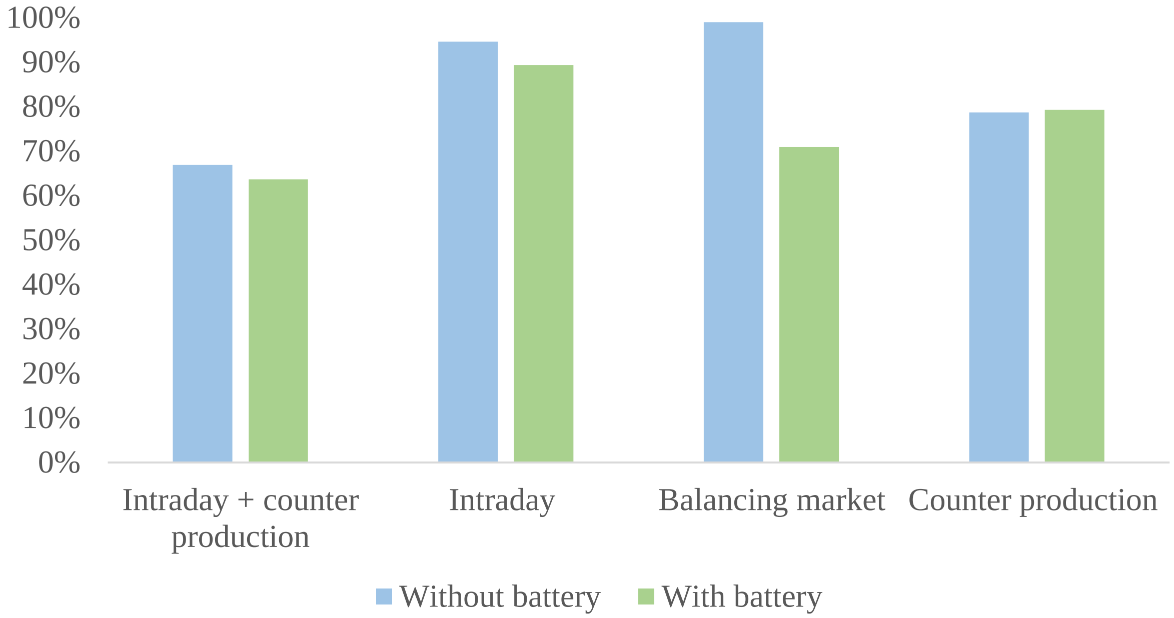

Figure 5.12: Optimizations around date 4. Both with and without the battery.

Figure 5.13 below illustrates optimizations during a failure of Filbornaverket.

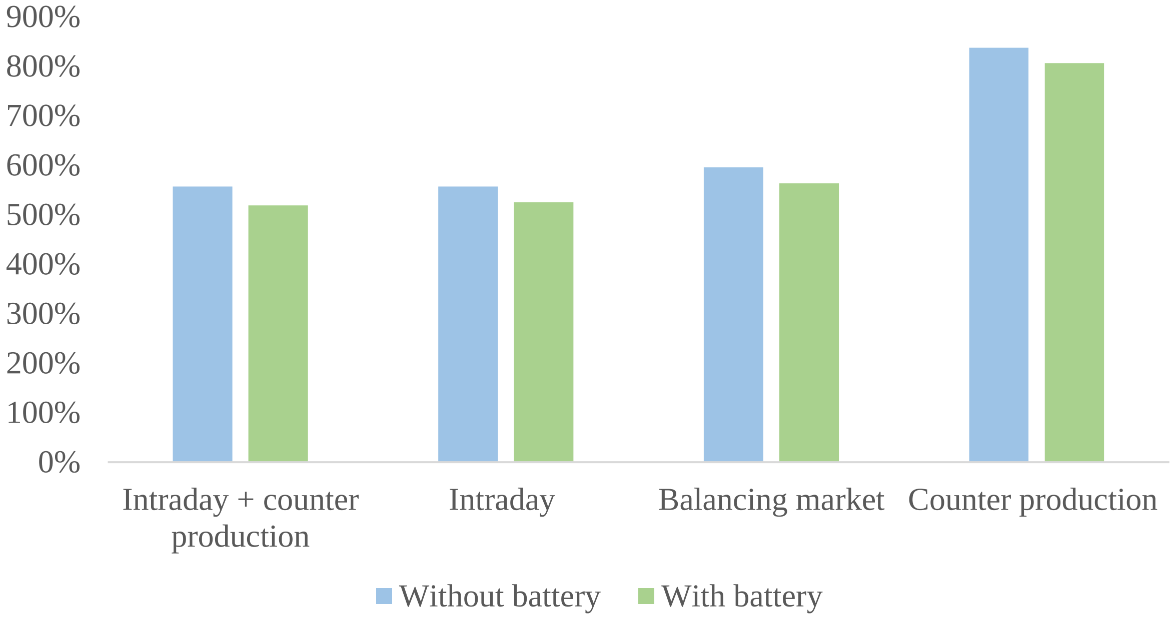

Figure 5.13: Optimizations around date 5. Both with and without the battery.

Figure 5.14 below illustrates optimizations during an outage of Filbornaverket.

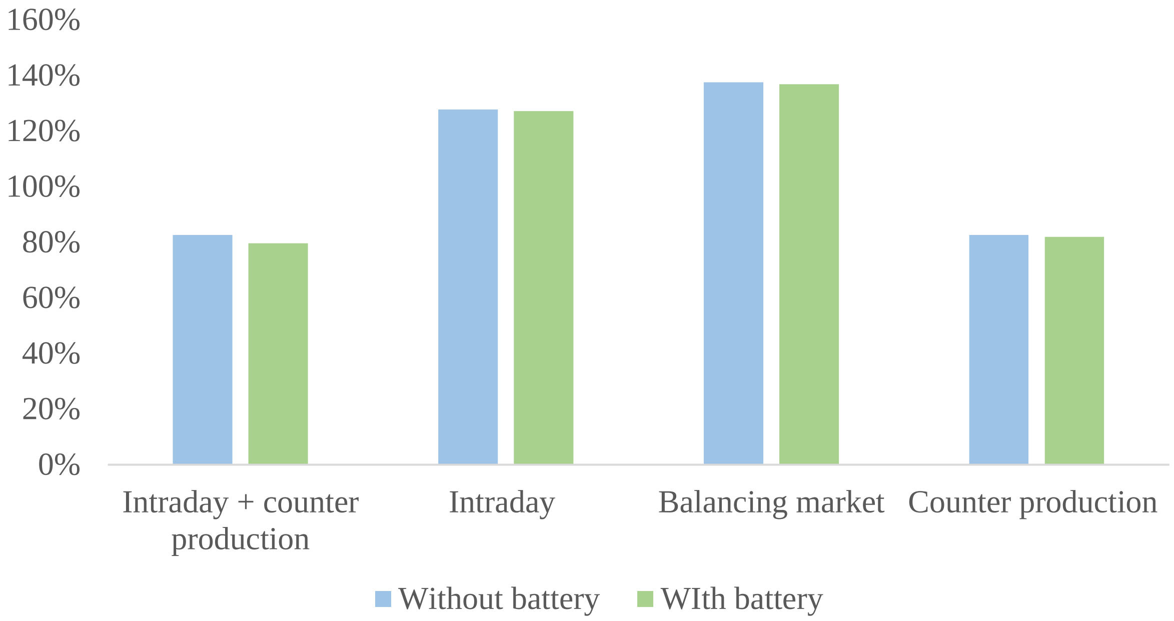

Figure 5.14: Optimizations around date 6. Both with and without the battery.

Figure 5.15 below illustrates optimizations during an outage of Filbornaverket.

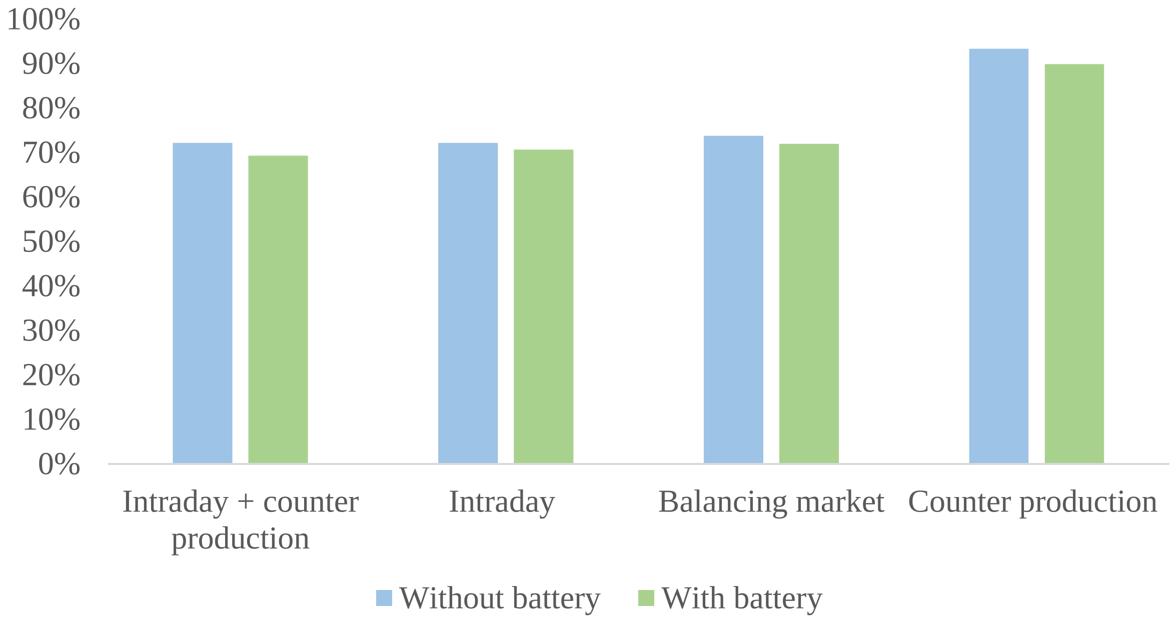

Figure 5.15: Optimizations around date 7. Both with and without the battery.

Figure 5.16 below illustrates optimizations during an outage of Västhamnsverket.

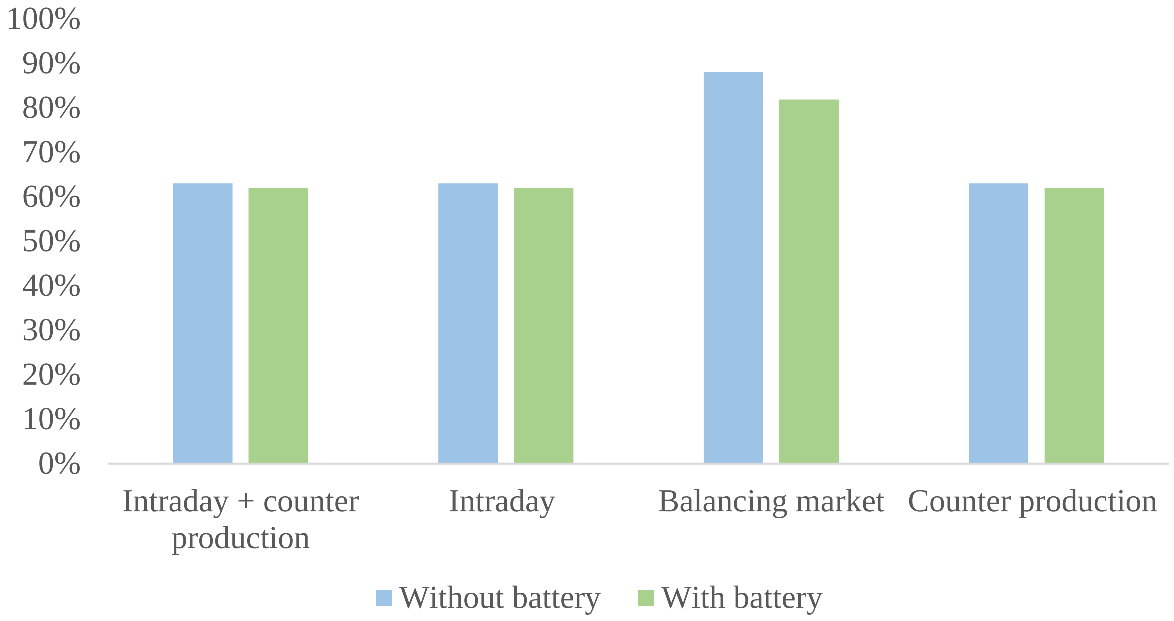

Figure 5.16: Optimizations around date 8. Both with and without the battery.

5.3. Optimizing on CO2 Emissions

Table 5. below presents a summary of all dates for which optimization had been conducted on CO2 equivalents. All the optimizations showed that intraday led to the least amount of released CO2 equivalents in total. As a result, intraday was chosen to be the baseline case and all the other courses of action were presented in relation to this. The alternative that released the second most CO2 equivalents was put into Table 5. in the third column. In the fourth column the increase in percentage from the intraday alternative to the second-best alternative is presented. These optimizations were all made from the perspective of minimizing CO2 equivalent emissions.

Table 5.2 Summary over the course of action that corresponds to the least amount of CO2 equivalents emissions.

Date	**Baseline case**	**Second best alternative**	**Increase in percent compared to the Base line case**
1	intraday	intraday + counter production	+0 %
2	intraday	intraday + counter production	+3.9 %
3	intraday	intraday + counter production	+24.8 %
4	intraday	intraday + counter production	+1.6 %
5	intraday	counter production	+27.2 %
6	intraday	intraday + counter production	+19.3 %
7	intraday	intraday + counter production	+21.2 %
8	intraday	counter production	+0.8 %

Chapter 6

6. Results on Forecast Error

In this chapter, the results from the forecast error case will be presented.

Optimizations was performed on the five weeks with the highest absolute forecast error in 2023. The base line case was based on the forecast that turned out to be incorrect. Thereafter, three optimizations with different courses of action were performed with the actual district heating demands. The optimizations with the actual demand were compared with the base line case to obtain the difference in costs in percentage. All the results are presented below in graphs, along with a summary in Table.

In some cases, the results are negative. The reason for this is that money was saved during optimizations with the actual demand compared to optimizations with the forecast error.

This part of the project was only optimized on money and not on CO2 emissions. The results that were obtained from the CO2 chapter was sufficient to draw conclusions for our investigation.

In figure 6.1, the results from optimizations during week A are presented. It is clear that it is profitable to be active on the electricity markets compared to counter production.

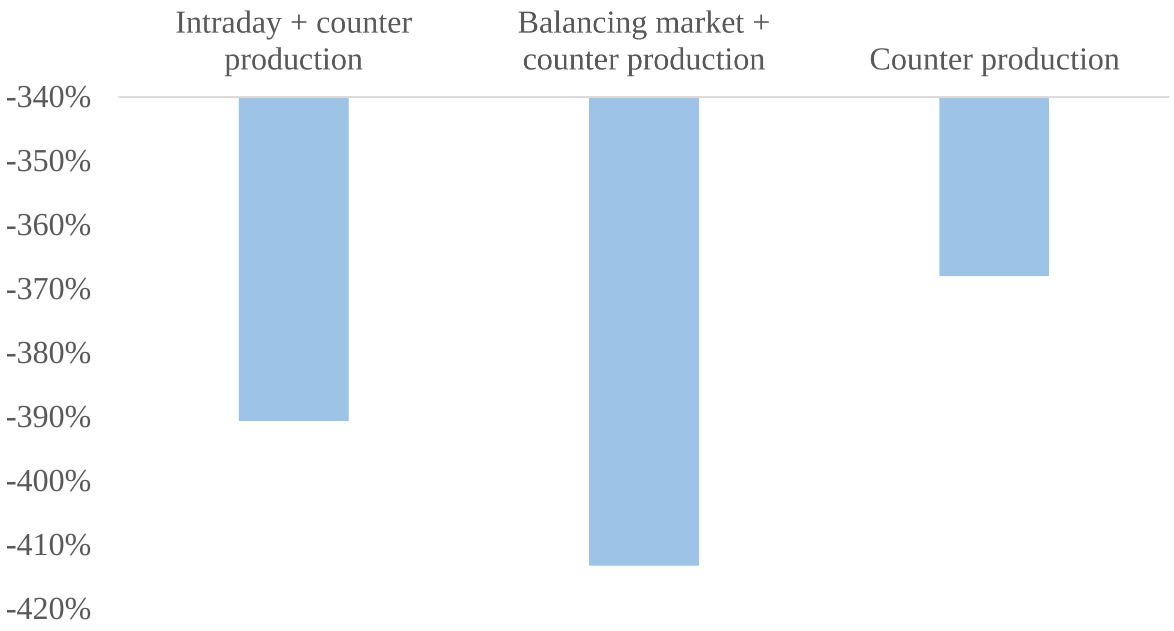

Figure 6.1: Optimizations on week A.

Figure 6.2 presents the results from optimizations during week B. The results are similar to the results from week A.

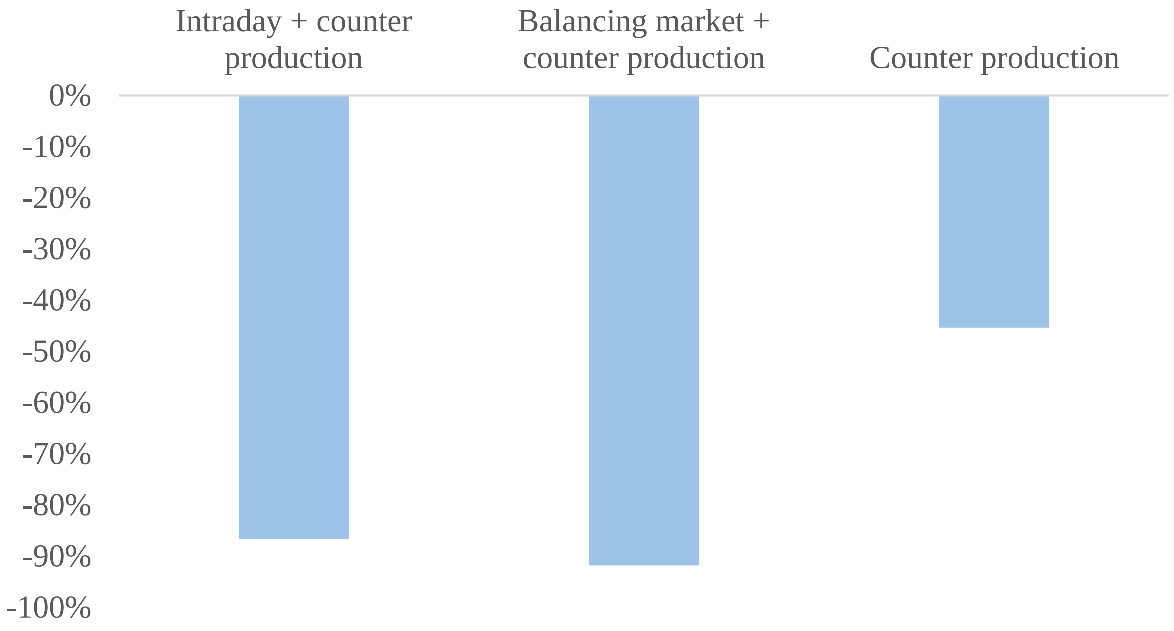

Figure 6.2: Optimizations on week B.

In figure 6.3, optimizations during week C are presented. Similar to the two previous weeks, it is most profitable to be active on the electricity markets.

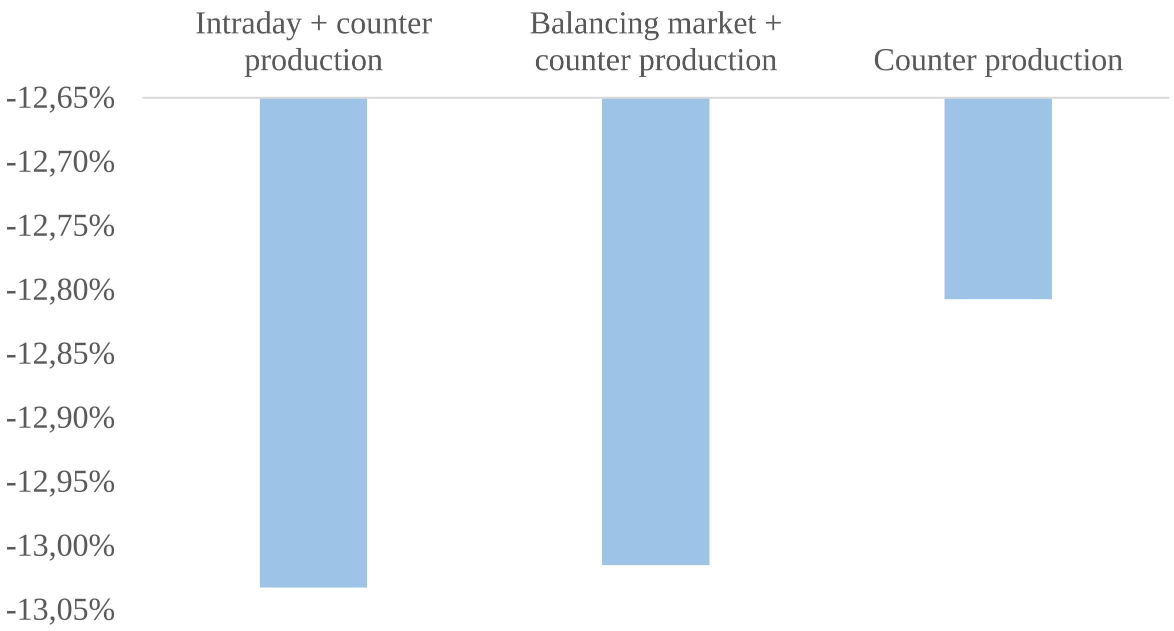

Figure 6.3: Optimizations on week C.

In figure 6.4, the results from optimizations during week D are presented. Unlike the previous weeks, the district heating load was higher than in the forecast. This lead to an increase of costs.

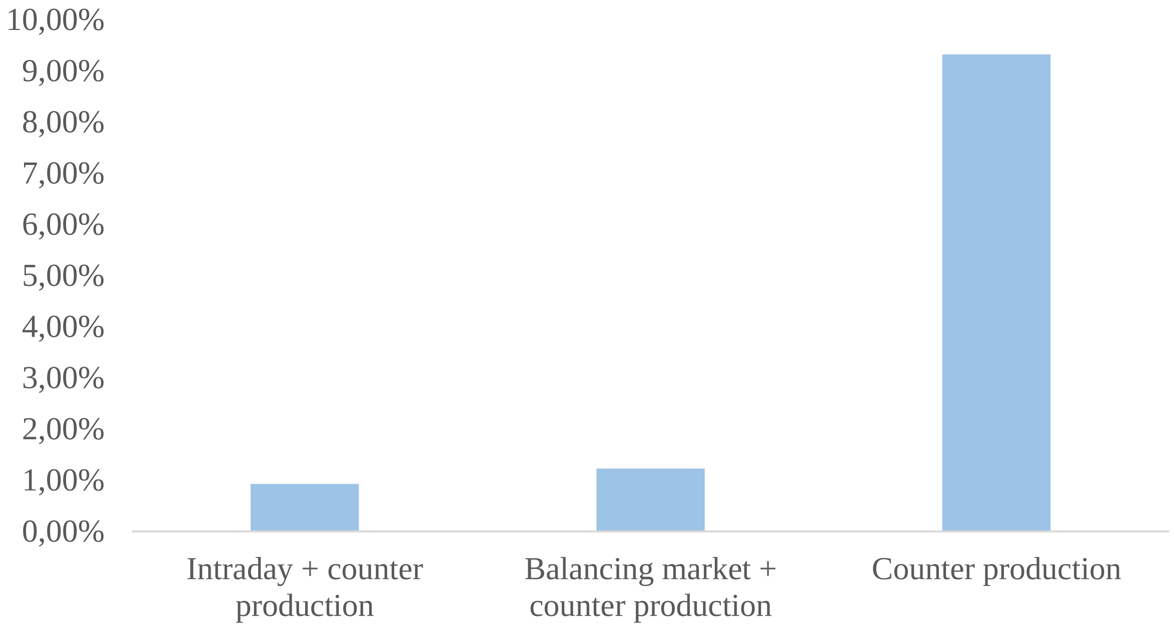

Figure 6.4: Optimizations on week D.

In figure 6.5, optimizations during week E are presented.

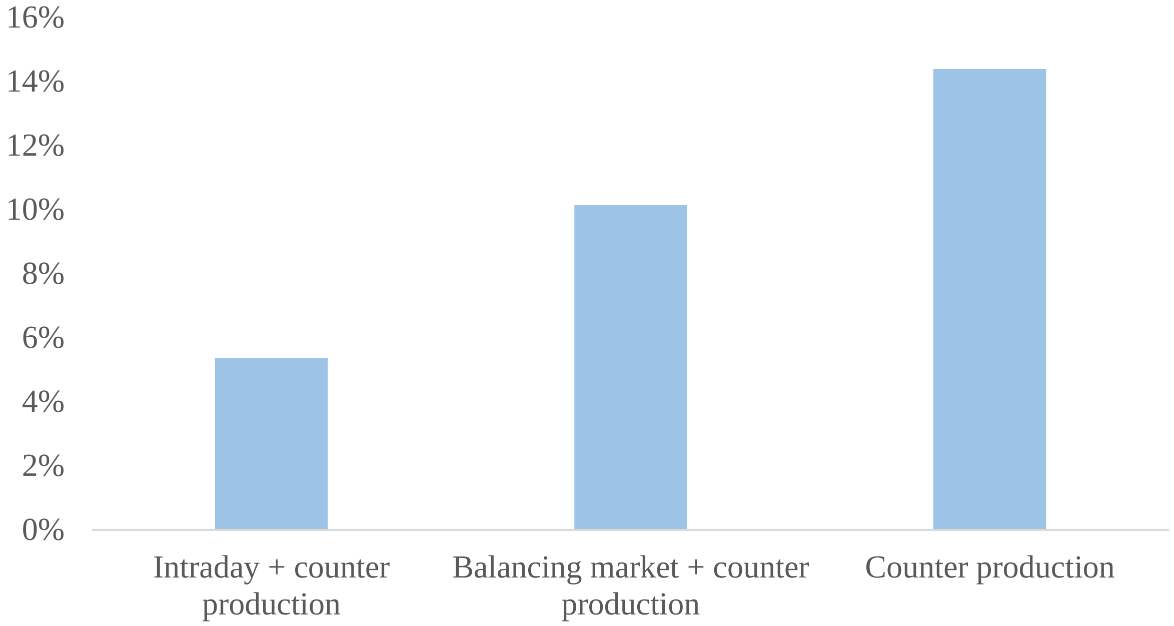

Figure 6.5: Optimizations on week E.

Table 6.1 Summary of the courses of action that corresponds to the least amount of costs when optimized on forecast errors.

Week	**Most profitable alternative**
A	balancing market + counter production
B	balancing market + counter production
C	intraday + counter production
D	intraday + counter production
E	intraday + counter production

Chapter 7

7. Discussion

In this chapter, the results from all the optimizations will be discussed. Additionally, the assumptions made during the work will be discussed.

Most of the results from the optimizations lead to the same conclusion, which is that by being active on the intraday market, it is possible to decrease the financial losses in case of an unexpected error. The different scenarios and courses of action will be discussed further below.

7.1. Sudden loss of facility

By looking at Table 5.1, it becomes evident that it is financially beneficial in all cases to engage actively on the intraday market. Additionally, in some scenarios, counter production is also advantageous if an opportunity arises and there is no requirement for a plant start-up. This will be further discussed in the subsequent sections.

In graphs Figure 5.1, Figure 5.5 and Figure 5.7 it is noticeable that intraday + counter production and intraday display the same percentage increase in costs. This can be explained by the fact that in the base line case, only Filbornaverket is in operation, while Västhamnsverket remains inactive. Therefore, to enable counter production, Västhamnsverket needs to be started, incurring high start-up costs. Both intraday + counter production and intraday options ultimately lead to trading solely on the intraday market. However, in a scenario where both plants are active in the base line case, there might be a distinction between intraday and intraday + counter production. The latter could potentially involve some counter production, resulting in less intraday trading.

Another aspect to consider, regarding whether intraday and intraday + counter production result in the same production plan, is the electricity prices on the intraday market. If the prices are favorable, there will likely be an increase in intraday trading. However, if the prices are not favorable, it might be more profitable to opt for counter production. Therefore, the decision between intraday and intraday + counter production hinges not only on the initial costs and potential start-up costs for plants, but also on the real time electricity prices.

Furthermore, in all the graphs, balancing market is either equal to or is greater than intraday. This is mainly because, in most cases, the prices on the balancing market are higher than the intraday market, making it less profitable. However, there are instances where this is not the case, as seen in figures Figure 5.1, Figure 5.3 and Figure 5.7. When the difference is small it might seem more convenient to opt for the balancing market instead of trading on the intraday market. However, there are important considerations to keep in mind. Firstly, even small differences can accumulate to significant financial impacts over time. Secondly, trading on the balancing market entails more uncertainty and risk, resembling gambling. When forced onto the balancing market, one must accept the available bids, which at times can be exceedingly high and result in large financial losses.

There is a penalty fee that must be paid if trading on the balancing market. However, this fee did not make a big difference in the calculations since it is only 1.150 euro/MWh. In contrast, the price on the balancing market is considerably higher. For instance, the average price on the balancing market is approximately 20 euro/MWh around date 1 and 70 euro/MWh around date 7 (10). This implies that the penalty fee is relatively small when compared to the electricity price, and therefore does not make a substantial difference. It is more like a symbolic fee that needs to be paid. For the fee to have a significant impact, it would need to be higher in comparison to the electricity price.

In some instances, there might not be enough electricity available for purchase on the intraday market to compensate for the lost production. In such situations there is likely to be high prices on the balancing market due to the existing shortage of electricity. Therefore, it remains profitable and less risky to purchase as much electricity as possible on the intraday market. The remaining amount, which is not available on the intraday market, must then be bought from the balancing market. This approach aims to minimize losses by ensuring that as much electricity is bought at, possibly, lower intraday market prices, with the remaining shortfall covered by purchasing on the potentially higher priced balancing market.

Looking at Figure 5.4, you can see that it differs compared to the other results, since “counter production” is more profitable than intraday. The reason for this lies in the fact that it is not feasible to push Västhamnsverket much further, as it is already operating at nearly maximum capacity in the base line case. However, it can still produce slightly more, allowing for some counter production. Since Västhamnsverket is already operational, there are no start-up costs involved. Another contributing factor could be the electricity prices during this period. Comparing the electricity prices around date 4 with those around date 3, shows that they are generally higher on date 4 (10). In some instances, they are up to 10 times higher. The combination of Västhamnsverket’s existing operational state, absence of start-up costs and higher electricity prices during this period likely explains why counter production is more cost-effective than intraday in this specific scenario.

In Figure 5.6, intraday + counter production and counter production has the same production plans, and therefore also the same results. In the base line case both Västhamnsverket and Filbornaverket are operational. Therefore, when Filbornaverket is lost, there is no start-up costs in order to use Västhamnsverket for counter production. In addition to this, the average price on the intraday market around date 6 is one of the highest compared to the average price during the other optimizations. If compared to one of the lowest average prices, it is around

790 % higher. This implies that intraday + counter production only led to counter production since this produced the lowest result. This also explains why intraday is more expensive than both intraday + counter production and counter production.

Most of the cases corresponded to a loss of Filbornaverket. However, there was one scenario where there was a loss of Västhamnsverket instead. In Figure 5.8, it is evident that intraday + counter production, intraday and counter production yields the same results. In the base line case, both Filbornaverket and Västhamnsverket are operational, and Filbornaverket is operating on maximum capacity. When Västhamnsverket was lost, counter production from Filbornaverket was not possible and since it was already operational, there were no start-up costs involved. This resulting in that both intraday + counter production and counter production meant only trading on the intraday market, leading to the same production plan and therefore also the same costs as for intraday. The balancing market option is more expensive, but it could have been even more expensive. After talking to Öresundskraft about this date, we learned that they were quick with acting on the intraday market which saved them money. The bids on the intraday market were not enough to cover for the lost production though, which meant that they ended up on the balancing market. This contributed with an increase of the prices on the balancing market. So, if they would not have traded on the intraday market, the balancing prices would probably have been even higher than they were in our case since we used the real historical prices.

It is notable that during the optimizations, there was prior knowledge of when the failure would occur and its duration. This enabled us to create individual operation plans and thus maximize the utilization of the unaffected assets beyond what would be feasible in reality. Consequently, in many cases, counter production was advantageous. It can, for example, be seen in Figure 5.2. However, in reality, it is not always possible to implement such precise plans and adjust the plant's production in real time. For counter production to be as profitable as possible, the plants need to adjust their production rapidly in real time. In reality, the plants have start-up and adjustment times to change the outputs. Adjusting the plants up and down introduces more wear and tear on machine parts and is something that should be avoided if possible.

After talking to Öresundskraft during the latter phase of the project, it become evident that counter production is less feasible than initially hypothesized. This confirms what was previously discussed about counter production above.

The key takeaway is that by being active on the intraday market, it is possible to substantially mitigate losses in the event of a facility outage. This strategic approach allows for a more flexible and cost-effective response to unexpected circumstances, ultimately leading to the improvement of financial outcomes.

7.2. Battery Storage

It was assumed that under normal operational conditions without any loss of production, the battery would either not be used or that it would be used for ancillary services. With this assumption we could optimize on using the battery to cover up for lost production when it occurred. Looking at the results we got, displayed in figures Figure 5.9 to Figure 5.16 it became evident that a battery of this size does not make a substantial difference in a system as large as the one we are working on. The battery in question is 20 MW, 20 MWh in size. This means that the battery could output a maximum of 20 MW for one hour. In all our optimizations it did just that, full load for one hour and then full charge at another time to be fully unloaded during another hour. The battery is only at 20 MW which, in comparison to the electricity production capacity of the plants available, is not that much. The results show that in most cases, less than one percent of costs could be saved compared to a case without a battery available.

During the work, it was assumed that there was no investment cost of the battery, i.e. that it already exists in the system. Therefore, we did not account for payback of the investment in our calculations of profitability, which makes the optimizations with the battery seem more profitable than it would be in a real case.

Another thing that makes our results with the battery better than they would be in a real case, is the way the battery was implemented. During our work, the battery was available at both Västhamnsverket and Filbornaverket at the same time. This decision was made to make the workflow smoother. We would otherwise have been forced to move the battery between the plants in the software, which would have been difficult since we were performing optimizations simultaneously on different dates in the same system. This would not have been possible in a real case; cables would have had to be dug between the plants and that would introduce losses and extra costs.

Since we used historical data when we optimized, the prices on the electricity markets were already known. This affected the cases we did with the battery in a way that the optimizer could buy electricity from the intraday- or balancing market when the price was lower and use the bought electricity by unloading the battery when the prices were higher. In a real case, the prices are not known beforehand.

Replicating this in real life is therefore not possible which leads to slightly better optimization result with the battery than what would have been in reality. Worth mentioning is that it might be possible to observe trends on the intraday market related to the hours of the day and act accordingly, but not replicate how the optimizer worked.

With all of this in mind, we concluded that a battery of this size would not be favorable to have and use for what we tested it for in Öresundskraft’s case. During our literature study we stumbled across some plans to build battery storages with capacities up to 100 MW. We think that a battery storage of this size could potentially be more favorable to cover for losses of production. Of course, this would mean high investment costs which is something that could be explored further in future work.

Furthermore, towards the end of this study, we recognized that in a real case, companies would likely not have the option to use the battery for both ancillary services and covering production losses simultaneously for a battery of that size. This raised the question of whether a larger battery could potentially be divided into two parts and utilized for both purposes. This question remains open for future research in this field. However, considering the size of the battery studied in our research, it is likely more advantageous to use it for ancillary services, as these typically require smaller volumes to participate compared to covering production losses, seen in Table 2.1, “min bid size”.

An example of an ancillary service that could work for Öresundkraft would be the mFRR service. This is because the minimum amount that can be bid is well below the size of the battery, and that the activation time is only 15 minutes which seems reasonable in this case (41).

Mälarenergi is a Swedish company that had plans in 2022 to participate in the ancillary service markets, specifically the mFRR service without a battery. They said that they have performed a pre-study that showed that having ancillary services available could help them gain millions of Swedish crowns. In the same article, it states that with a battery, it is possible to participate with the faster services such as aFFR and FCR-N for example (42). This is also what we hypothesize will be possible for Öresundskraft after completing this study.

7.3. CO2 Emissions

Given that all the electricity bought on the electricity market - whether it is on the intraday or the balancing market - is assumed to have the same environmental impact per kWh, it consequently has the same amount of carbon dioxide equivalent emissions in the optimizations. The option of being active on the electricity markets is usually the option that results in the least environmental impact considering the amount of CO2 equivalents, as seen in Table 5.. In the table, it is seen that on some dates, the result varies only a few percentage points, and in a few it varies much more. The reason for this is that on the dates where it is a small increase of CO2 emissions, the production plan of intraday and intraday + Counter production was almost the same. However, we argue that this provides additional reason to primarily engage on the intraday market. This is advantageous for the company’s financial interests in most cases, but it is also more beneficial for the environment when considering greenhouse gas emissions and their contribution to the greenhouse effect.

The optimizations were only done in three cases compared to loss of facility, where more cases were made. We only optimized on acting on the electricity markets, counter production, and a composition in between. This resulted in the three cases, intraday or balancing market, counter production only and electricity market (intraday) and counter production. As mentioned before, the option of being active on the electricity markets resulted in the least amount of CO2 emissions. An explanation to the counter production alternative having such high emissions can be that in most of the studied cases, Filbornaverket is the producing facility that suffers from loss of production. To compensate for the lost electricity production, the optimizer usually decided to start Västhamnsverket and produce electricity through that. The average emissions of CO2 equivalents from produced electricity in 2022 and 2023 was 0.025 tons CO2 / MWh. However, the data used to calculate the emissions of carbon dioxide equivalents from Västhamnsverket was 0.378 tons CO2 / MWh, which is 1500 % higher than for produced electricity. This explains why intraday implies less emissions of carbon dioxide equivalents.

One interesting result we got that differed from the rest of the results, but also backs up the previously mentioned consequence of using Västhamnsverket for counter production, is in the case where Västhamnsverket suffered from loss of production, see date 8 in Table 5.. Here, the CO2 emissions for intraday and counter production were almost the same. This case differs from the usual cases because Västhamnsverket is running high and also suffers from a loss of production. The data of ton CO2/MWh that was used for Västhamnsverket versus Filbornaverket is approximately twice as high. So, in conclusion, when counter production is used and it is Västhamnsverket that is making up for the lost production, the CO2 emissions suffer more than if it were the other way around. It is important to mention that this is a singular case and that this only happened once on our studied cases, but it is still worth discussing.

To obtain the CO2 equivalents for the electricity, we used Electricity maps. This is a website that compiles electricity data from the whole world. They present carbon dioxide intensity from more than 200 zones around the world. To collect all this data, they use many different sources. For example, they use government sources, such as energy ministries, government-affiliated sources, such as official statistical bureau, transmission or distribution system operators and utility companies, that generate or manage power directly. They estimate the data they cannot access. Because of this, the data might not always be one hundred precent correct. To ensure accuracy of the data, they consistently verify their data sources (40).

The data we collected from Electricity maps was essential to perform our desired optimizations. Since there is no other source that provides this information, we could not verify the data in any way. Due to Electricity maps' efforts to verify their data, we opted to utilize their data, despite not having alternative data to compare it to.

CHP plants have the capability to mitigate CO2 emissions during combustion through the installation of a carbon dioxide separation system, commonly known as CCS (Carbon Capture and Storage) system. These systems can often be integrated without changing the structure of the existing plant. Öresundskraft already has plans to build a CCS system at Filbornaverket with the aim of capturing a substantial portion of the CO2 emitted during combustion. It is projected that approximately 90 % of the CO2 present in the flue gases will be separated before release through the chimney. The separated CO2 can then either be stored or repurposed as a raw material, contributing to a significant reduction in greenhouse gas emissions from the plant's operations (43).

Most of our optimizations on sudden loss of facility, except for those done around date 8, involves a loss of Filbornaverket. Therefore, the installation of a CCS system at Filbornaverket would not have altered many of our results since the available plant for counter production was Västhamnsverket. So, for our results this would not have made a big difference, but in reality it will significally decrease Filbornaverket's emissions of carbon dioxide.

7.4. Forecast Error

The results from the forecast error optimizations vary slightly compared to the other cases we have considered. It is not possible to solely be active on the electricity market in these cases, one must also counter produce at the same time. The reason for this is that in the case of forecast errors, it is the district heating forecast that differs. To be able to fulfill this and change heat production, it is not possible to only be active in the electricity markets. Some kind of counter production is needed to be able to fulfill the heating demand. In our tests where the forecast error had a noticeable impact on the results, it was preferable to be active on the intraday market while simultaneously counter producing.

An interesting week to discuss is week A, B and C, in Table, where the forecast error resulted in the ability to produce more electricity than what was bid on the day ahead market. This might have been because all three weeks are in the beginning of summer, and it can be hard to predict the temperature and weather in these transitional seasons. In this case the forecast error was negative which led to a lower district heating demand than what was planned for. This meant that more steam could go through the steam turbines and produce more electricity.

According to our optimization, the most money that could be made here was with the counter production + balancing market alternative. We have a rough idea of what the reason behind this could be. The balancing market is an unstable and uncertain market, and the prices are generally higher there than on the intraday market. Since electricity is being sold rather than purchased, this results in a more profitable alternative.

However, it is important to keep in mind that the balancing market is inherently more uncertain and the prices on it may be significantly worse than on the intraday market. While it was advantageous in this week, it is not always guaranteed to be that way. Intraday trading is comparatively more secure and to end up on the balancing market is not something that should be planned for due to the uncertainty of the market.

When discussing forecast errors, it is also interesting to go to the root of the problem, the forecast itself. If we conducted this study few decades ago, chances are that the forecast errors would be much larger than they are today. A forecast relies on advanced technology, measurements, and mathematical models to predict weather, energy usage and much more to create a forecast that producers base their production on. If the methods for creating forecasts were better, the problem of forecast errors would possibly not exist. This is, of course, something that is out of most energy producers' hands and that advances as technology advances. It allows the opportunity for further investigation and the question of "What happens when the perfect forecast model exists?" arises.

Another notable aspect to mention is the increasing presence of weather dependent energy sources in the energy mix, such as wind- and solar power. This trend is driven by the need to phase out fossil fuels in the energy production. The transition towards these renewable sources highlights the growing importance of accurate forecast models to maintain the power system's balance and ensure that the frequency remains at 50 Hz.

7.5. Initial Conditions of the Optimizations

One of the delimitations mentioned in the first chapter was that in the beginning of every optimization, we let the optimizer choose the starting conditions of all the producing components in the model. By doing this the plants could be started in the beginning of the optimizations without any start-up costs. A reason for this is that since we optimized on historical data, the dates was connected to actual measured values, in other words, to what was actually done in reality during that time. But when we performed our optimizations, we wanted to investigate what they could have done differently and therefore we didn't want the actual historical production plan to decide the start value of the components.

Another reason to why we choose to do it this way was that initially, before we set this setting, we got various unrealistic expenses in the beginning of the optimizations, and it was difficult to control when the plants were allowed to run and how much they should produce. By using the setting mentioned above, we avoided these unrealistic additional costs.

7.6. Isolation of the district heating network

Another delimitation we made was to focus solely on an isolated part of a larger system, which is described in 4.2. This decision was made to simplify the optimization process and reduce duration times on the optimizations. However, Öresundskraft would have had other options available when an error occurred if the connections were not limited. Their district heating network is connected to other networks, forming a large system, and it is possible to transfer district heating between these networks to compensate for production losses. This, in turn, could have influenced Öresundskraft's actions on the electricity market, and the results from our optimizations.

One result that was affected by this delimitation was in the case where Öresundskraft lost Västhamnsverket on date 8. During this loss of production, our results and way of handling the lost production capacity differs a bit from what was done in reality, and what could be done if this delimitation was not implemented. Because of this implementation, we have no control over in which direction district heating is sent and cannot reverse the flow in the lines. On this date, it was a lot of district heat production that was lost, and the optimizer in our case “knew” that in advance, which led it to charge the accumulator tank more than what maybe would have been reasonable in reality. This led to our optimization being able to fulfill the district heating need, which is the number one priority. In reality, Öresundskraft chose to change the direction of the district heating to start importing instead of exporting district heating to Helsingborg. This is worth mentioning because if this delimitation did not exist, it would theoretically be possible to get slightly cheaper total costs of the optimizations since instead of producing more to fill the accumulator, we could reverse the lines in some cases.

Nevertheless, we believe that the results obtained not only provide insights into Öresundskraft’s potential actions, but also shed light on how other companies that own CHP plants could minimize losses in the event of unexpected disruptions. Given that Evita is a significant and unique collaboration among district heating networks, the results we obtained by isolating Helsingborg may prove to be more relevant for other companies.

Chapter 8

8. Conclusions and recommendations for future work

In this chapter, the research questions will be answered, and conclusions drawn from the results of the study will be presented. Additionally. A subchapter will be dedicated to exploring potential for future research in the area.

- *How can Öresundskraft act on the electricity market to minimize financial losses in the event of unexpected losses of facility or forecast error?*

In most cases on sudden loss of facility it was most profitable to be active on the electricity markets, especially on the intraday market. Counter production meant, in most cases, more costs and therefore it was less profitable. Sometimes trading on the intraday- and balancing market led to the same costs. However, the balancing market is more unreliable with more unstable prices than the intraday market, therefore it is not desirable to plan on trading there. intraday + counter production was either the same or more profitable than intraday. But, since it can be hard to plan for and make counter production profitable if the extent of the loss of facility is unknown, we consider it more profitable, to trade on the intraday market.

In case of forecast errors, it was not possible to only be active on the electricity markets. There was, in all performed optimizations, a need for counter production to fulfill the heating demand. But by being active and trading on the electricity markets it, is possible to not only save but to sometimes also make money if the forecast error led to a lower heat demand. As mentioned before, it is not desirable to plan for trading on the balancing market. Therefore, the option that was most profitable was trading on the intraday market in collaboration with counter production.

The overall conclusion is that the most profitable and reliable course of action for Öresundskraft, in case of an unexpected error, is trading on the intraday market. We believe that is also true for other companies that owns CHP plants.

- *How could an existing battery on the premises be beneficial during the unexpected errors mentioned in the previous question?*

Having a 20 MW, 20 MWh battery on the premises to help with unexpected errors showed to not be very beneficial in itself. Using it solely to compensate for lost production often proved to make minimal difference. The conclusion regarding this is that if a battery should be beneficial for this use, it needs to have a larger capacity than the battery we have studied. Otherwise, it could theoretically be used for ancillary services, which is something we have not tested, but hypothesize about with the support from the cited sources.

- *Which of these courses of action leads to the least amount of carbon dioxide equivalents?*

The conclusion regarding CO2 emissions is that it is almost always best to act on the electricity markets to reduce the CO2 emissions in case of loss of production or forecast errors. Since acting on the intraday market already has shown to be financially beneficial, the incitements for doing so only strengthens when also taking the CO2 emissions into account. Worth noting is that CCS's exist and can be added to existing plants to minimize the emissions. But we have to draw conclusions from what currently exists on the plants that we have studied.

8.1. Recommendations for future work

If this work is to be further expanded on, there are some areas that can be investigated further to create a more complete picture of all the available ways of handling losses of production or forecast errors.

As mentioned above regarding the battery, there are things that can be further investigated. The size of the battery is a factor that would be interesting to examine further. A bigger battery leads to larger investments and operation costs, but it might also lead to greater savings and incomes if used the right way. Somewhere, these two parameters will meet depending on the size of the battery and this is something that would be interesting to present visually and compare to what is being built in Sweden and around the world today.

As we also mentioned above in the previous chapter, it could be possible to divide a larger battery into two parts and utilize one part for ancillary services and one part for emergency backup in case of loss production occurs. Additional questions to be considered are: "Is it possible to always have one part of the battery for ancillary services?" and "Have the other part switch between ancillary services and emergency power?"

To extend this research, a distinct investigation focusing on ancillary services, as referenced in subchapter 7.2, could be undertaken. Exploring the potential integration of battery storage capable of delivering ancillary services into the system could lead to an increase in income for the company. Therefore, it could be a profitable investment for companies that owns CHP plants.

It would also specifically be of interest to Öresundkraft since the plans for a battery storage are already in place, but if ancillary services are profitable, it would potentially be possible to integrate small battery storages capable of providing ancillary services elsewhere in the system to provide an increase in income and stability to the system.

In the subchapter about forecast errors above, the root of the problem, the forecast, was discussed. One expansion that can be made to this work to account for the future of energy production is, to study and discuss what would happen if perfect forecasts exists and how that changes the energy producers’ ways of planning their production, and even if it can affect how future energy producing facilities are built, such as combined heat and power plants for example.

In subchapter 7.3 it is mentioned that Öresundskraft will install a CCS in the coming years. The carbon capture rate for this CCS is believed to be 90 %, meaning that 90 % of the biogenic and fossil CO2 emissions will be captured through this system. This is something that potentially could alter the results and potentially prioritize another course of action over the ones that were shown to be optimal in this study.

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