Master's thesis

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

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Comparison of internal and external balancing in the intraday markets for a power producer located in NO3

Master's thesis in Electric Power Engineering
Supervisor: Gro Klaeboe

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Abstract

This master thesis investigates the potential related to a coordinated intraday bidding approach and handling of imbalances for a producer with a portfolio of intermittent and flexible production units in a pay-as-bid intraday market. The study is motivated by findings in recent literature that have found a potential profit from clearing imbalances with a coordinated intraday bidding approach.

An intraday bidding model with a rolling horizon approach for each stage of the intraday market are developed. A power producer with a portfolio of intermittent and flexible production units uses the bid model to maximize revenues from intraday trading while clearing imbalances. The intraday modelling uses the real-time order book in each stage. The model is built as a deterministic optimization problem that has to be solved for each stage of the rolling horizon. A base-case scenario with plant-wise imbalance clearing are obtained and compared against a case with coordinated intraday bidding approach.

A case study is performed for a power producer located in the price area NO3 with a portfolio of reservoir and run-of-river hydropower. The result is transferable to other portfolios including wind power. There are found a profit from shifting to a coordinated intraday bidding approach for the period modelled. The reasons for a better result with a coordinated approach is found to be reduced initial intraday transmission capacities for the period and the fact that the deterministic model will give a best-case result. A better representation of the marginal cost of production for the reservoir hydropower plant has been identified as an important improvement to make the results more reliable.

Sammendrag

Denne oppgaven undersøker potensialet knyttet til koordinert intradagshandel og hvordan en produsent med en portefølje bestående av fleksible og momentane produksjonsenheter kan bruke intradagsmarkedet til å håndtere ubalanser. Studien er motivert av nylige oppdagelser i litteraturen, som viser at det er mulig å generere meravkastning ved å koordinere intradagshandelen.

En bud modell med rullerende tidshorisont for hver time av intradagsmarkedet er blitt utviklet. En kraftprodusent med en portefølje bestående av fleksible og momentane produksjonsenheter bruker bud modellen for å maksimere inntektene fra intradagsmarkedet samtidig som ubalanser blir håndtert. Bud modellen bruker den ekte intradags-ordreboken i hver time av intradagsmarkedet. Modellen er bygd som et deterministisk optimeringsproblem som må bli løst for hver time av den rullerende tidshorisonten. Et base-case scenario der hver enhet dekker sin egen ubalanse er etablert og sammenlignet med et scenario der ubalansene blir håndtert på portefølje basis.

Et studie er utført på en kraftprodusent i prisområdet NO3 med en portefølje bestående av vannkraft og elvekraft. Resultatet er overførbart til andre produksjonsenheter som feks. vindkraft. Resultatet viser en meravkastning ved å skifte til koordinert intradagshandel for perioden som er blitt testet. Hovedgrunnen til et bedre resultat med koordinert intradagshandel er funnet til å kunne komme fra intradags-flaskehalser i overføringsnettet til og fra prisområdet NO3, og det faktum at den deterministiske modellen vil gi et best-case resultat. For å gjøre resultatet enda mer realistisk burde marginalkostnaden for produksjonen til vannkraftverket bli representert bedre i modellen.

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Chapter 1

Introduction

In the last years there has been an increased share of renewable energy production all over Europe. Mainly driven by the increased focus on reducing CO2-emissions, international climate-agreements like the Paris agreement which states that the temperature should not increase more than two degrees Celsius has forced the participating countries to reduce emissions. This is one of the main drivers for the increasing share of renewable power production sources installed in the European power system. The increased share comes mainly from installments of wind power generating capacity in the European power system. Unlike Norwegian's large share of flexible reservoir hydropower, wind power is an intermittent production source. The day-ahead commitments relies on wind forecasts and the post-day-ahead markets are used for ensuring that the commitments equals the actual production. The difference in actual production and day-ahead commitments are further in this thesis referred to as imbalance.

This thesis will investigate how a power producer in the price area NO3 with a portfolio of reservoir hydro and intermittent production sources can handle these imbalances in the most profitable way. The revenue from trading these imbalances in the intraday market and the revenue from using existing production sources to cover these imbalances are investigated. The analysis conducts of studying independent days to obtain the revenue from handling imbalances internally, and also a simulation over a longer time horizon to see the long-term gains from a common portfolio intraday coordination. The case study is performed in the price area NO3, which lately has experienced a large increase in installed power generating capacity, mainly wind power capacity installments [1].

The increased share of intermittent renewable energy sources means that producers are to a larger extent managing combined portfolios of flexible and intermittent production sources. The most common production units for the area NO3 are wind- and reservoir hydropower [2]. For a power producer in NO3 with a portfolio including both flexible and intermittent production sources it is interesting to evaluate the value of internal coordination/balancing of the portfolio when bidding in the intraday market. Internal balancing can be applied when there is a missmatch between the forecast or the actual production, and the day-ahead commitment. In a wind power plant, there could be more wind than anticipated at the time of day-ahead market closure, creating a production surplus that has to be corrected in the post-day-ahead markets. In this case the producer will have an economic incentive to sell the missmatch in real-time markets. The opposite case, is when the day-ahead commitments are larger than the actual production, creating a deficit. The producer is responsible for the balance, and in this case have three options to deal with the deficit. Either to buy excessive power in the intraday market, let the deficit be handled by the TSO in the balancing markets or use other power plants in the portfolio to cover the deficit.

In this thesis the value of intraday bidding coordination for a power producer with a run-of-river hydropower plant and a reservoir hydropower plant is investigated. The results obtained for the portfolio of run-of-river hydropower and reservoir hydropower are transferable to other portfolios with intermittent renewable energy production sources like wind power.

Days with congested initial intraday transmission capacities to and from NO3 is of special interest for this thesis. The hypotheses is that days with congested transmission capacity will result in fewer participants to trade with in the intraday market. Fewer participants means fewer limit orders, and less volume depth for bid and ask prices. With lower volume depth of the bid and ask prices, less volume can be traded before the market price is affected. This means that the spread between bid and ask prices will increase due to the lower liquidity in the intraday market. This is further explained and tested in chapter 5 and section 5.2.1.

To find the value of internal intraday coordination and internal balancing, a hydropower production model and an intraday bidding model are build in the programming language python. The model is build as a deterministic optimization model and is tested for a power producer located in the price area NO3. The model will use historical day-ahead commitments, and the historic intraday order book for placing bids. For each day the model uses a rolling horizon framework for each hour of the intraday market, and every bid will be placed in the real-time order book. The contribution from this thesis is to evaluate if a power producer should use internal intraday coordination or only rely on the markets when clearing imbalances.

Section 2 gives the background of the Nordic power markets and the background for hydropower modelling. Section 3 gives an overview of previous research in the field, while section 4 presents the mathematical model and the case study this model is tested for. In section 5 the revenue from internal balancing are compared with trading the imbalances at market for selected days with limited transmission capacity. Section 6 presents the results, and in section 7 the conclusion from this research are presented.

Chapter 2

Background

In this section the relevant theory of power markets and hydropower production will be covered.

2.1 Power Market

2.1.1 The day-ahead market

The Nordic power market are organized as follow: day-ahead market, intraday market and balancing market. In the day-ahead market, producers and consumers/wholesalers can submit their bids for production/-consumption for the next day. It is a physical market, and there is a closed auction. The market is cleared by the market operator. All the bids has to be given before the market closes at 12:00 CET the day before delivery, and are delivered to the market operator simultaneously. The market operator will then clear the market and obtain a system price, based on marginal cost. Due to transmission constraints the market is divided into different areas. The market is designed to maximize social welfare. [3][4].

The day-ahead market, often referred to as the "spot market", is the market where most of the volume are bought and sold. At 10:00 CET the available capacities on interconnectors are published, participants in the day-ahead market can submit their bids for delivery next day until market-closure time at 12:00 CET. Orders are cleared at 12:42 CET or later, and the system price will be the equilibrium price between supply and demand. All units will get the same price, and the less expensive units are utilized first ensuring the maximization of social welfare. Orders to the Nordpool Day-ahead market are matched with the Single Day-Ahead Coupling (SDAC), through the Euphemia algorithm. The SDAC creates a single cross-zonal day-ahead market for European members of SDAC. The main objective is to increase the overall efficiency by increasing the competition, liquidity and utilize the production units in a more efficient manner [5]. The participants will get the result of which orders that are accepted after the clearing of the market, and for the accepted orders given a legally binding contract to produce/consume the given energy. The market operator Nord Pool accepts different order types: single orders, block orders, exclusive group orders and flexi orders. Some of the orders can include complex requirements that has to be fulfilled, like e.g. requirement for a minimum revenue [3][4].

2.1.2 The intraday market

At 14:00 CET the intraday market opens. This is two hours after the closure of the day-ahead market and now every market participant know the system and area prices, the transmission constraints and eventually their commitments from the day-ahead market that has to be fulfilled. The nordic intraday market is called Elbas, and Nordpool has been the market operator historically. This is a continuous market and it is possible to trade energy around the clock every day until one hour before actual delivery. This market enables closer to real-time trading, where imbalances from the day-ahead commitments can be adjusted. Like the day-ahead market this is also a physical market. The intraday market is based on a double auction mechanism and is a pay-as-bid market. This means that market participants can chose price and volume for their submitted buy or sell orders. These orders are continuously matched with other orders in the order book, if they're not matched immediately, the orders will be stored in the order book and evaluated against future orders. The contract for intraday and day-ahead market are hourly contracts. Also in this market, Nord Pool offers a wide variety of order types, like limit orders,iceberg orders, fill-or-kill orders, immediate-or-cancel-orders and block orders for consecutive production hours [4][6]. The other Nordic Intraday market, EPEX spot, which was launched in May 2020 has similar order types as Nord Pools Elbas market [7].

The Nordic intraday market is also connected to Europe through the Single Intraday Coupling (SIDC). Large parts of Europe are part of the Single Intraday Coupling and the objective is the same as the objective for the Single Day-Ahead Coupling (SDAC). Currently there are 22 European countries that are members of the SIDC, including all of the nordic countries that are in the Elbas market. A third wave of new member countries are expected in Q3 2021. XBID is the tehcnical solution for the SIDC [8][9]. The SIDC was lauched in 2018, initially with 14 countries including the Nordic and Central Europe. It was further expanded to 22 countries in 2019. The initiative gives a common order book for the intraday market, and will show orders from different areas and power exchanges as long as there are transmission and ramping capacity. The Transmission System Operator (TSO) normally publishes the transmission capacities when the intraday market opens, and continuously updates the available capacity as the market develops. For some borders there are separate auctions for transmission capacities. The Nordic Intraday market opens at 14:00 CET and in the first hours one can trade in the Nordic, Baltic and Polish market, at 18:00 CET the German intraday market opens, at 21:00 CET the market in Netherlands opens, and after 22:00 trading with the remaning countries can start [10].

2.1.3 The balancing market

The balancing market is the third physical market. The intraday and day ahead market creates a balance between supply and demand, but events that disturbs this balance can occur in the hour of production. The TSO uses the balancing market for upward and downward regulation to create an instantaneous balance between supply and demand at 50Hz. Both consumption and production resources can be offered in this market. A power producer will submit their ramping capacity in the market, and if imbalances occur the TSO will buy this ramping capacity. The most cost-efficient alternatives will be used first. The closure time of the market is 45 minutes before the operating hour and the market is called "real-time market". The commodity traded in this market are energy and the only buyer is the TSO. To participate in the balancing market, a generator needs to have a certain amount of ramping capacity upward and downward in a short time interval. The TSO is responsible for the balance in the system, and will buy the needed capacity in the market [4].

The balancing market are divided into primary reserves (FCR), secondary reserves (FRR-A) and tertiary reserves (FRR-M). The primary and secondary reserves are activated automatically, while the tertiary reserves needs to be activated manually by the TSO. The primary and secondary reserves are spinning generator reserves, which handles momentary imbalances. The tertiary reserves are used to release the secondary reserves [11].

Participants can register their bids to the TSO until 21:30 the day before the operating hours. The participant can correct these bids or register new bids until 45 minutes before the operating hour. The reserves that are bid to the balancing market needs an activation time of maximum 15 minutes, this is to ensure safety of delivery [11]. In figure 2.1, the different closure times for the different Nordic power markets are illustrated.

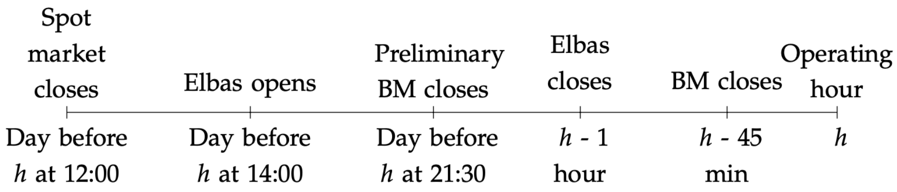


Figure 2.1: Timeline for closure times for the different markets in the Nordic power market.

The Nordic balancing market has historically used a two-price clearing system. From 1 November 2021 there is expected a shift from a two-price clearing system to an one-price clearing system [12][13]. Previously, the participants would still get prices according to an one-price system as long as they informed the TSO about their imbalance minimum 45 minutes before the operating hour. The difference between the two systems are illustrated in table 2.1. In a two price system there should never be profitable to have an imbalance, but in an one-price system the participant could actually make a profit with an unsettled imbalance.

The Nordic TSOs by regulation sets the balancing market price higher than the day-ahead price when the system is regulated upwards, and lower than the day-ahead price when regulated downwards. An imbalance contributing in the regulated direction of the system will get the balancing market price instead of the day-ahead price in an one-price clearing system. If the system is regulated upwards and the producer has an imbalance contributing in the same direction, he would get paid according to the balancing market price which by regulation are higher than the day-ahead price he would have obtained in a two-price clearing system. The same principle applies to downward regulation, but here the producer would pay the balancing market price if the imbalance contributes in the same direction as the system instead of paying the day-ahead price which by regulation is higher than the balancing market for downward regulation [14].

Even if it could be profitable in some scenarios to let the TSOs clear the imbalances in an one-price clearing system, this is a gray area to speculate in. The TSOs states that every producer is responsible for planning the production in balance and responsible for their own imbalances. If a market participant continuously has an imbalance from the original production plan, the TSOs can in a worst-case scenario impose restrictions against this participant.

The requirements for planning in balance is receiving increased attention, and new requirements can limit the freedom of producers deviating from the production plan [15]. Other measures the TSOs can use for reducing speculations in the balancing market is to introduce imbalance fees, making it more expensive to let the TSO handle the imbalance. Currently the Nordic TSOs (without Energinet) has agreed to harmonise the imbalance fee level in the balancing markets at 1,15EUR/MWh with the go-live of the one price clearing system 1 November 2021 [13].

	One-price clearing system		Two-price clearing system	
	Production deficit	Production surplus	Production deficit	Production surplus
Upward regulation	Pay BM-price	Get BM-price	Pay BM-price	Get day-ahead price
Downward regulation	Pay BM-price	Get BM-price	Pay day-ahead price	Get BM-price

Table 2.1: Imbalance pricing according to one- and two-price system in the Nordic balancing market.

This thesis would not include the balancing market, but this is important theory for the reader to be able to understand the alternatives a producer has for clearing imbalances. The shift in clearing system for the balancing market can potentially change the approach to the the balancing market among producers. Future work could include the modelling of the balancing market, to evaluate the revenues from clearing the imbalances here versus in a pay-as-bid intraday market.

2.1.4 The financial power market

In addition to the physical markets there is also a financial power market. The physical markets are traded at Nordpool, while the financial power market are traded at the Nasdaq OMX exchange or by bilateral contracts. This market is purely financial and there is no physical power exchange between the participants. This market is used for risk management and speculation [4]. This thesis will not include the financial power markets.

2.2 Hydropower

Hydropower uses the mechanical energy of falling water to generate power. The potential energy of water can be stored in reservoirs with dams that holds the water back. This makes the reservoirs work like an enormous battery. Hydropower is one of the most cost-efficient alternative to generate power. The main methods of hydropower generation is reservoir hydropower, run-of-river hydropower and pumped-storage hydropower, according to [16]. This thesis will focus on both of the first methods. The first method utilizes dams and reservoirs, and are able to store the potential energy of water. The second method is to use run-of-river hydropower. In this case there are either very small intake reservoirs or no reservoir at all. The plant uses the natural flow of water to generate power. This means that in periods with less water flowing in the river, the power plant will also generate less power. While for reservoir hydropower the water can be stored depending on the capacity in the reservoir and saved for later usage. This makes it possible to save water in low-price periods and utilize it in high-price periods. This is an obvious advantage that reservoir hydropower has over run-of-river hydropower. The disadvantage with reservoir hydropower compared to run-of-river hydropower is a large capex investment, and the dams and reservoirs uses a lot of areal and cascades river-systems which can have an impact on the Eco-system [16][17].

Reservoir hydropower has a high grade of flexibility and can ramp the production up/down in a short time horizon. These characteristics fill out the intermittent characteristics of renewable energy sources like solar and wind, which only generates power when the weather conditions are right. One example of how these units can cooperate to utilize their strengths is in a windful period. In this period wind power can cover the load, and reservoir hydropower can store the water, and in periods with less wind, reservoir hydropower can utilize this water to cover the demand in the system.

Equation 2.1 shows that the power output from a hydropower plant is given by the discharge q $[m^3/s]$, the plants net head level H(q) [m], and the plants efficiency $\eta(q)$ [18]. The head level can be described as the height difference between water in upstream and downstream reservoirs.

$$P = 1/10^6 * q * \gamma * g * H(q) * \eta(q) \tag{2.1}$$

The equation 2.1 shows that both the net head H and the efficiency η depends on the discharge q. This is due to different discharge levels affects the head losses in the tunnels, penstock and pressure shafts. Thus making both the net head H and the efficiency η a curve of the discharge. $1/10^6$ is a constant for converting the generated power to MW, γ is the water density and g is the gravitational constant. The relationship between the discharge and the power output p is a non-linear relationship [18] This is due to that both the efficiency of the plant and the head level of the plant depends on the discharge q. A normal simplification in the field of hydropower modelling is to disregard the head variation or approximate it by piece-wise linear-functions. By doing this simplification the relationship between the output power p, and the discharge q, becomes linear. This makes the model less computational heavy [19]. Catalão *et al.* [20] have found that for large reservoirs the head level can be neglected.

For a run-of-river hydropower plant the flow of the river will determine the discharge. Since there are no or very little storing possibilities, all the water that is bypassed the plant will be lost, and the potential income for the producer will also be lost. While the generator and turbine for a reservoir hydropower plant typical has a efficiency of approx. 90%, the generator and turbine for a run-of-river plant is usually designed for producing over a wide span of discharge. Therefore the efficiency is typically lower than for a reservoir hydro turbine and generator, but the span from minimum production to maximum production is typically much higher. This is important due to the cyclical nature of rivers and inflow. Some periods are dry, and others can be very wet due to melting or/and heavy rainfall. To be able to utilize all the water at a wide span of discharge, the generator and turbine has to be designed to cope with this [17][21].

The operational cost of hydropower plants are usually very low, and often disregarded in scheduling problem. For reservoir hydropower the water has an opportunity cost, called water value. This is due to the possibility to store water for later usage. A run-of-river hydropower plant doesn't have this opportunity cost since there are no storage capacity, and will typical utilize all the water it can, since water not used immediately will be a lost income. The reservoirs can only store a certain amount of water, making the water value a function of reservoir level, inflow and future market prices [19].

The hydropower producer can use the day-ahead and intraday market to sell energy. They can also bid ramping capacity to the TSO for usage in the balancing market.

Chapter 3

Related literature

In this section relevant literature for internal balancing will be presented. The section will cover literature related to internal balancing and intraday modelling. The literature will cover reservoir hydropower and wind power as the modelling and bidding of wind power can be transferred to a run-of-river hydropower producer.

3.1 Intraday modelling

Reservoir hydropower producers has historically used the one-price cleared day-ahead market, and has a tradition for bidding marginal cost. Therefore there are less coverage of intraday modelling in the literature compared to day-ahead modelling for hydropower producers. Engmark and Sandven [22], Bovim and Naess [23] and Akersveen and Graabak [24] models the intraday market after closure of the day-ahead market. Engmark and Sandven [22] use a rolling horizon approach in the intraday market, while Akersveen and Graabak [24] uses a scenario tree for modelling the intraday market and Bovim and Naess [23] reduce the problem size by reducing the stages and products. This thesis also models the intraday market after the day-ahead closure and uses a rolling horizon approach through the time steps of the intraday market. But the model in this thesis is deterministic and tries to quantify the value of internal balancing, therefore the rest of the literature are focused on internal balancing.

3.2 Internal balancing

In this section we will give an overview of other research done on handling imbalances in a combined portfolio of reservoir hydropower and other intermittent renewable power generating sources. Internal balancing in the intraday market is not so well covered in the literature, this can be due to the fact that this is a typical remote area problem, where the transmission capacities are weak, and the intraday market liquidity are low.

The topic of coordinated wind and hydro power bidding in post spot markets have been addressed in several papers. Korpas *et al.* [25] investigates how Norwegian hydro power can be used for balancing wind power in Europe from a system perspective. Fleten *et al.* [26] addresses the same problem from a portfolio perspective. Riddervold *et al.* [15] and Matevosyan *et al.* [27] addresses the problem of bidding wind- and hydro power in the day-ahead markets, and settling the imbalances in the post-spot markets.

Riddervold *et al.* [15] establishes the definition of imbalance cost, and use it to investigate the potential profit of shifting from a plant based schedule to a common load requirement for hydropower and wind in the same price area. They perform a case study for a power producer with both reservoir hydro and wind power assets, and tests their process for one day where there are both imbalances in hydro- and wind power. They don't try to quantify the long term effects of coordination, as this thesis has tried to quantify for a period during winter 2020.

Riddervold *et al.* [15] establishes five steps for the model. The first step is associated with day-ahead market bidding for the wind power plant based on wind forecasts. The imbalance cost for wind are also calculated here. In step two the hydropower producer sells production to the day-ahead market based on optimisation with predicted inflow and prices. After the day-ahead market is cleared, the hydropower producer re-optimizes the production with obtained day-ahead commitments and prices, and updated inflow forecast to obtain a new optimal production plan. In step 4 the intraday markets are open, and the hydropower producer will obtain a new re-optimization with actual inflow and intraday-prices to find the new production. In the same step the imbalance cost for hydropower are calculated and defined as the base case. In the last step, the commitments from both hydro- and wind power are added as a common commitment, and wind power are added as an additional production source. The imbalance cost for the last step are obtained and compared with the base-case imbalance to find the value of internal balancing. The paper finds a reduced imbalance cost for a power producer with a portfolio of both hydro- and wind power by internal balancing in a pay-as-bid intraday market.

Obersteiner *et al.* [28] and Riddervold *et al.* [15] establishes a two-price clearing system for clearing of imbalances in a pay-as-bid intraday market. This thesis use the same definition of imbalance cost to calculate the cost of imbalance. While they also introduce the "cost of imperfect forecast", for calculating the imbalance cost for both the day-ahead and the intraday market, this thesis uses a definition that solely relies on intraday bid-ask prices. Riddervold *et al.* [15] predict prices for the day-ahead market and uses a "synthetically" intraday order book to obtain the intraday bid-ask spread. The bid-ask spread is simply defined as a fixed margin of $+-15\%$ of the day-ahead price, with a correction factor of $+-1\%$ for each MW of imbalance. Obersteiner *et al.* [28] use historic day-ahead and imbalance prices, and actual and forecasted wind power production to explain difference in wind power imbalance cost for various case studies.

Angarita and Usaola [29] studies how wind power producers can reduce the imbalance cost due to imperfect forecast by combine a bidding strategy with a hydropower producer in the day-ahead markets. This thesis studies how a run-of-river hydropower producer can reduce the imbalance cost by combine a bidding strategy with a hydropower producer in the intraday market.

The paper Matevosyan *et al.* [27] performs a case study of a hydropower producer and wind power producer connected to a weak grid in Northern Sweden. The producers will seek to use wind power when the conditions are right for wind power production, while the hydropower utility decreases the production if there is expected transmission congestion. The coordination strategy is divided into two parts, where the first is base case hydro power planning for the day-ahead market without consideration of wind power. The second part is re-planning of the hydro power production for the day-ahead market and the balancing market considering wind power production. The first part of the planning algorithm is bidding in the day-ahead markets under uncertain prices based on historical data. The second parts relates to managing imbalances in a balancing market with uncertain prices. The optimization problem is defined as a two-stage stochastic program with recourse. The paper finds a positive result with coordination between wind- and hydropower for both producers.

Chapter 4

Problem formulation

In this section the mathematical model and the bid model will be presented. The nomenclature and framework for the model is first described, before the bid model and hydropower model are described. Then the differences between the model for internal coordination of intraday bids and the model for separate intraday trading are presented. At last the case study and the period modelled will be described.

4.1 Overview

The intraday bidding model uses historical day-ahead commitments for both plants. It is assumed that none of the plants has market impact, and will act as price takers in the intraday market. These assumptions are standard, and the focus can be concentrated on the thesis objective.

The bid model uses a rolling horizon approach through the time steps of the actual day. In the first ten hours, there is only bidding available on production hours for the next day. After midnight, the production starts, so the previous hour are removed for each time step of the rolling horizon. Since the model will bid in the real-time order book for each stage of the rolling horizon, a time when the model sees the order book must be defined. This is called snapshot, and is chosen to be at minute 55 for each stage/hour of the rolling horizon. After each time step the model has to update prices, water level, orders and other factors regarding the production and order book. Updating the factors regarding the production and order book after each time step is important, so the model doesn't take the same orders, or commit itself to more production than the power plants can deliver. Accepted orders are removed from the order book. When an order is accepted this affects the commitments of the plant and thus will affect the next stages of the rolling horizon framework.

To see the actual value of internal balancing, a fully deterministic approach is done. This means that order books, inflow, water value and spot commitments are based on historical data. A perfect insight into the order books, means that the most profitable trades will be taken. It is not realistic to obtain the same results when taking uncertainty into account. This is still a relevant approach since it shows the full potential of internal- coordination and balancing. The paper Riddervold *et al.* [15] mentions that further research could quantify the effect of internal coordination in the intraday market by modelling over a longer time frame with historical intraday prices. This model tries to quantify a best-case scenario for internal intraday coordination over a long time horizon. The deterministic approach simplifies the validation and testing of the model, as the results obtained can be compared against historic data. Another advantage with only using real-life data is that the result shows the real-life potential.

For each stage of the rolling horizon the model has to solve a deterministic optimization problem. The model simulates one day at a time, and will have perfect insight into the order book at each time step.

4.2 Mathematical model

4.2.1 Nomenclature

Sets and indices

$t \in \{0, 31\}$ - time steps in the intraday market. Time step 0 represents the first hour of trading (14:00-15:00) the day before production. Time step 8 represents the trading hour 22:00-23:00, which is the trading hour for product 00:00-01:00. 00:00-01:00 is the first hour of production. The last time step for bidding is time step 31, which represents the the last bid hour (21:00-22:00) for the product 23:00-00:00

o - order index

m - the index for market/time/products/production hours

$M = \{max(t\text{-}8, 0), 23\}$ - products that are open at time step t

$M^{startup} = \{max(t\text{-}7, 0), 23{+}1\}$ - start up coupling for time step t

$M^{status} = \{max(t\text{-}7, 0)\text{-}1, 23{+}1\}$ - production status at time step t

$M^{res} = \{max(t\text{-}7, 0)\text{-}1, 23\}$ - reservoir coupling at time step t

$j \in J$ - production-discharge segments

O_m^{buy} *and* O_m^{sell} - intraday buy and sell orders for product m

i - production unit i

Parameters

$Price_{mo}^{buy}, Price_{mo}^{buy}$ - intraday order book prices for product m

$V_{mo}^{buy}, V_{mo}^{sell}$ - maximum buy and sell volumes in order book

$V_m^{initial}$ - initial commitments for each product, includes day-ahead commitments and intraday commitments for previous time steps

ϵ_j - production-discharge efficiency for different segments

P^{min}, P^{max} - minimum and maximum production capacity

$P^{Commitment}$ - Total production for the run-of-river plant, includes the day-ahead commitments

$C^{startup}$ - cost for starting up plant [€]

$R^{initial}$ - initial reservoir volume

R^{min}, R^{max} - minimum and maximum reservoir volume

$U^{initial}, U^{last}$ - Production status for first and last hour of production, used for connecting the production between days

$Q_j^{segment,max}$ - maximum discharge for production-discharge segment j

Q^{min} - minimum discharge

F - $3600/10^6$, conversion factor between m^3/s and $Mm^3/hour$

L - length of each time step [hours]

I_m - inflow in each product/production hour

$Watervalue$ - constant for all time steps of the day

$Penalty$ - Penalty cost for scenarios where the commitments are larger than the production

Variables

p_m - production for each production hour m

r_m - reservoir volume for each production hour m

q_m - discharge for each production hour m

$q_m^{spillage}$ - spillage for each production hour m

$q_{mj}^{segment}$ - discharge for each production hour m and discharge segment j

$v_{mo}^{buy}, v_{mo}^{sell}$ - accepted volumes from order books

pen_m - penalty variable for situations where the model can't cover the commitments

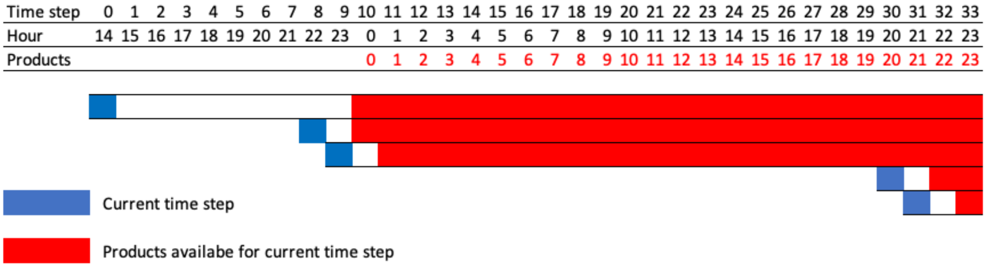
a_m - startup variable for each production hour m, binary variable

u_m - production status for each production hour m, binary variable. 1 for production, 0 if no production

4.2.2 Market modelling

The model uses historical day-ahead commitments and prices. The intraday market is modelled with a real order book in each stage of the rolling horizon. All orders are seen as individual orders, even if there is possibility for more complex orders, this is covered in chapter 2.1.2. For the reservoir hydropower plant orders are accepted as long as they are profitable compared to the marginal cost. For the run-of-river hydropower, orders are taken to settle the imbalance between day-ahead commitments and the actual production. The imbalance between actual production and day-ahead commitments acts as a constraint for the amount of orders the run of river hydro can accept, while the production capacity determines the amount of orders the reservoir hydro can accept.

Figure 4.1 shows the time-logic of the intraday market. It opens after the closure of the day-ahead market at 14:00 CET. All bids have to be placed at least one hour prior to the production hour. As the figure 4.1 indicates there are 31 time steps that are available for bidding in the intraday market. To bid in the last product the bid has to be placed before 22:00. There are in total 10 hours of bidding before the production starts at midnight. The rolling horizon has to update water levels, prices, commitments and other factors regarding production and bidding for each time-step.



Time step	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
Hour	14	15	16	17	18	19	20	21	22	23	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Products											0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23

Figure 4.1: Timeline for bidding in the intraday market.

The objective is to maximize the revenue from participating in the intraday market for unit i, while also covering the initial day-ahead commitments. The model simulates a total of 33 time steps, as shown if figure 4.1. For each bid hour the model sees the real time order book and has to choose which orders to accept in order to maximize the revenues from intraday trading.

$$max\ z = \sum_{i} \sum_{m \in M} \Big(\sum_{o \in O_m^{buy}} Price_{i,mo}^{buy} * v_{i,mo}^{buy} - \sum_{o \in O_m^{sell}} Price_{i,mo}^{sell} * v_{i,mo}^{sell} \Big) \tag{4.1}$$

$$+ Watervalue * r_M - \sum_{i} \sum_{m \in M^{startup}} C_i^{startup} * a_{i,m} \tag{4.2}$$

$$- \sum_{i} \sum_{m \in M} pen_{i,m} * Penalty \tag{4.3}$$

The first part of the objective 4.1 maximizes the profits from intraday trading for each time step for unit i. Since the reservoir hydro has a marginal cost of production, the objective 4.2 also has to maximize the water value for the end of each day, subtracting the costs related to start up of the plant for unit i to obtain the production cost. The production costs for the run-of-river hydropower relates to start up of the plant. This deterministic optimization problem will give an intraday commitment for unit i, that maximizes the intraday trading revenues and also maximizes the water value for the reservoir hydropower. The objective is the same for separate intraday trading and a common portfolio approach, the difference between separate and common approach is described in section 4.3.2. The total revenue is given by the revenue from intraday trading and the revenue from the volume sold and price obtained for each hour in the day-ahead market. Equation 4.3 is a special case for scenarios where the model can't fulfill the commitments and this penalty variable gives the model an opportunity to fulfill the commitments at a high cost. The high cost ensures that the model only uses the penalty variable when it is necessary.

The maximum buy and sell volume for unit i, is constrained by the restrictions given in 4.4 and 4.5. The buy and sell volume in real-time order books is given by two variables that are constrained by the parameters V_{mo}^{buy} and V_{mo}^{sell}.

$$0 \leq v_{i,mo}^{buy} \leq V_{i,mo}^{buy} \qquad \forall\ i,\ m \in M,\ o \in O_m^{buy} \tag{4.4}$$

$$0 \leq v_{mo}^{sell} \leq V_{mo}^{sell} \qquad \forall\ i,\ m \in M,\ o \in O_m^{sell} \tag{4.5}$$

4.2.3 Hydro power modelling

This section covers the hydropower modelling. It consists of one reservoir hydropower plant and one run-of-river hydropower plant. The reservoir hydro has a reservoir, while there is no storage capacity for the run-of-river plant.

Historical day-ahead commitments are used for both plants. The reservoir hydropower plant uses reservoir level, inflow and water value to determine the amount of energy that are available to be traded in the intraday market. For the run-of-river plant both the day-ahead and total production are from historical data. This means that the volumes available for intraday trading is the difference between historical production and historical day-ahead commitments. Since the plant has no storing capacity, and zero marginal cost regarding production it is assumed that the production always equal the historical production. This is a major difference between reservoir hydropower and run-of-river hydropower, where reservoir hydropower have an alternative cost regarding the usage of water, since it can be stored. This is further covered in section 2.2.

The bid and hydropower model are connected through the restriction 4.6. This restrictions simply states that the production from the production unit i, has to equal the day-ahead commitments and the volume traded in the intraday market for unit i. The initial commitment is updated for each stage of the rolling horizon, so for each new bid hour the model knows the day-ahead commitment and the previous committed volume from the intraday market for unit i.

$$p_{i,m} = V_{i,m}^{initial} + \sum_{o \in O_m^{buy}} v_{i,mo}^{buy} - \sum_{o \in O_m^{sell}} v_{i,mo}^{sell} \tag{4.6}$$

For reservoir hydro the production-discharge curve is implemented as a convex piece-wise linear production-discharge curve. This is a normal simplification to obtain a linear relationship between head level, discharge and production. This is further described in section 2.2. The same production-discharge curve is used for all head levels. To obtain a more realistic model, different production-discharge curves for different head levels could be included in future research. The production-discharge segment curves is not included for the run-of-river hydro. Due to some challenges regarding the data and negligible storing possibilities the production-discharge-curves was not included. For the run-of-river hydropower the post day-ahead production volume is decided from the difference between the historical day-ahead commitments and the historical production. This is a deterministic approach, and further research could include inflow and production-discharge data for the run-of-river hydropower.

The production-discharge restrictions are shown in 4.7 and 4.8. The first restriction states that the production is the sum of the minimum discharge, the sum of the discharge segments and spillage if this occur. The discharge for a hydropower plant relies on the physical size of the intake and penstock. The variable for discharge is restricted by the parameter of maximum discharge as it can be seen in restriction 4.8. This means that when the plant reaches maximum discharge, there is not possible to increase the discharge to increase the production. If the reservoir is overflowing this is represented as $q^{spillage}$ in restriction 4.7. The discharge restrictions are only used for the reservoir hydropower plant since the production for the run-of-river plant is decided from historical data.

$$u_m * Q^{min} + \sum_{j \in J} q_{mj}^{segment} + q_m^{spillage} = q_m \qquad \forall\, m \in M \tag{4.7}$$

$$0 \leq q_{mj}^{segment} \leq Q_j^{segment,max} \qquad \forall\, m \in M \tag{4.8}$$

Restriction 4.9 connects the discharge and production. The production equals the sum of minimum production times the production status and the sum of the discharge segments times the efficiency for that segment. Restriction 4.10 sets the boundaries for lower and upper production capacity times the production status. Restriction 4.11 defines the production for the run-of-river hydropower plant. For this plant the production equals the historic production in each stage of the rolling horizon. A penalty variable is also included in the restriction 4.11, this is included to handle situations where the plant can't fulfill the day-ahead commitments and the intraday commitments. The restrictions 4.9 and 4.10 are valid for the reservoir hydropower plant, while restriction 4.11 is valid for the run-of-river hydro.

$$u_m * P^{min} + \sum_{j \in J} \epsilon_j * q_{mj}^{segment} = p_m \qquad \forall\ m \in M \tag{4.9}$$

$$P^{min} * u_m \leq p_m \leq P^{max} * u_m \qquad \forall\ m \in M \tag{4.10}$$

$$P^{Commitment} + pen_m = p_m \qquad \forall\ m \in M \tag{4.11}$$

Constraint 4.12 gives the reservoir balance. The reservoir volume for the last product, discharge and inflow determines the volume in each stage of the rolling horizon. Constraint 4.13 connects the reservoir balance with the reservoir volume before before the first product is open. The reservoir is constrained by a lower and upper volume in constraint 4.14. The inflow is based on historical values, but future work could include a stochastic inflow for both plants. The reservoir restrictions are only included for the reservoir hydropower plant.

$$r_m = r_{m-1} + F * L * (I_m - q_m) \qquad \forall\ m \in M^{res} \tag{4.12}$$

$$r_m = R^{initial} \qquad \forall\ m = max(t\text{-}8, 0) - 1 \tag{4.13}$$

$$R^{min} \leq r_m \leq R^{max} \qquad \forall\ m \in M \tag{4.14}$$

The reservoir volume is an important parameter for the marginal cost of production for the reservoir hydropower plant. Therefore the volume is accounted for in the objective function 4.2. The volume is multiplied with the water value to find the total value of the reservoir. The model uses a constant water value for the day, further research should include a dynamic water value. This will give a better representation of the marginal cost of production. Constant water value throughout the day is a valid simplification for large reservoirs [30]. The reservoir for this plant is small, and it is filled and drained several times a year.

The restriction for production statuses are defined in 4.15, 4.16 and 4.17. These are used for monitoring the start and stops for unit i, and connecting the last hour of the previous day with the first hour of the following day. This ensures that the start-up between the days are connected even if the time horizon is only for one day at a time. It is important to include the start/stop costs for accounting for the wear of the turbine and generator.

The start-up costs are also defined in the objective function 4.2. The start-up costs are defined as 150EUR for the reservoir hydro and 75EUR for the run-of-river hydro.

$$a_{i,m} \geq u_{i,m} - u_{i,m-1} \qquad \forall\ i,\ m \in M_i^{startup} \tag{4.15}$$

$$u_{i,m} = U_i^{initial} \qquad \forall\ i,\ m = max(t\text{-}8, 0) - 1 \tag{4.16}$$

$$u_{i,m} = U_i^{last} \qquad \forall\ i,\ m = 23 + 1 \tag{4.17}$$

4.3 Models

This thesis objective is to find the value of internal coordination in the intraday market. To obtain this value the model are simulated for a given period, first a base-case scenario are obtained with plant-wise imbalance clearing in the intraday market. Then the base-case scenario are compared against the results from the same period with a common intraday participation. There are assumed that the run-of-river hydropower producer is risk neutral, and will bid the expected production to the day-ahead market.

4.3.1 Plant-wise imbalance clearing

Plant-wise imbalance clearing means that each plant acts independently in the intraday market. All volume are traded against the pay-as-bid order book. The plants has to cover their imbalances by making trades in the intraday market. If the run-of-river hydro plant has an imbalance between day-ahead commitments and actual production, this imbalance has to be bought or sold in the intraday market depending on the direction of the imbalance. The same occurs for reservoir hydro, if the marginal costs are higher than the price obtained, this imbalance should be settled in the intraday market in order to maximize the total revenue from the plant. The constraint for plant-wise imbalance clearing are presented in restriction 4.6. This is the base-case scenario that the revenue from common intraday participation are compared against.

4.3.2 Common intraday participation

The common intraday participation restriction is introduced in restriction 4.18. The constraint might seem similar to the constraint 4.6, but there are some important differences. Restriction 4.6 is a plant specific restriction, that states that the plant i, has to cover the total commitments. For restriction 4.18 the day-ahead commitments still has to be met by each plant, but the total intraday commitment has to be met in total. This means that the total intraday commitment is covered by the productions from both plants.

$$\sum_i p_{i,m} = V_{i,m}^{initial} + \sum_i \Big(\sum_{o \in O_m^{buy}} v_{i,mo}^{buy} - \sum_{o \in O_m^{sell}} v_{i,mo}^{sell} \Big) \tag{4.18}$$

4.4 Case study

In this thesis, the Mørre hydropower plant and the Usma hydropower plant has been modeled. The Mørre plant is connected to a reservoir, Storvatnet, while Usma is a run-of-river plant with negligible storing possibilities. Both of the plants are owned and operated by TrønderEnergi, and located in the price area NO3. Mørre has a maximum production capacity of 14MW, and minimum production of 6.5MW, while Usma has a maximum capacity of 9.9MW. Due to the variety in inflow for run-of-river plants, these plants are designed to be efficient over a wide range of discharge levels. Therefore this thesis assumes that the Usma plant has a minimum production of 0MW. While Usma has a negligible reservoir, the reservoir for the Mørre plant is filled and drained several times a year. The regulated water level are small for this reservoir, only at 4.7 meters, this equals a reservoir volume of 3.6 million cubic meters. Both of the plants consists of one generator and one turbine and the annual yearly production is 54GWh for Mørre and 30.5GWh for Usma [31][32].

The period modelled lasts from the start of February 2020 to 22 May 2020. 2020 was a special year in the Nordic power system for both producers and consumers, it was a very wet year with low average prices. The average day-ahead market price for price area NO3 in 2020 was 9,46 EUR/MWh, compared to 38,54 EUR/MWh in 2019 and 44,08 EUR/MWh in 2018 [33]. The wet winter of 2020 makes this period great for modelling the run-of-river hydro since the plant had production almost the entire period. The winter periods has historically been periods with little to no production for the Usma plant. The Norwegian regulatory agency NVE measures the reservoirs degree of filling for each week. Their statistics shows that for the period modelled the degree of reservoir filling is 55,4%, compared to 38,5% for the same period in 2019 and 28,9% for the same period in 2018 in the price area NO3 [34].

The model simulates a period with approximately 110 days. In this period there are 10 days where the model can buy products with negative prices in the intraday market. The model does not currently handle negative buy prices, so these days are removed. Negative buy prices in the intraday market are very unusual. Further research could simulate for longer periods to see the long-term effects of internal coordination in the intraday market.

The rolling horizon models one day at a time independently of the other days. To validate the model, each day starts with the historic reservoir level for Mørre. This means that if the reservoir volume from last day deviates from the historic reservoir level of next day, the previous production plan would not be valid in real-life. In further research the reservoir level input for the next day could be obtained from the previous production plan from the model for each day.

Chapter 5

Analysis of internal balancing

In this section the results of internal balancing for some selected days are analysed in detail. This section will also present an analysis for the transmission capacity to and from NO3. The result from internal coordination for the entire period is presented in chapter 6.

The hypotheses is that internal balancing will be more profitable than external balancing when the intraday market liquidity is low. Congested transmission lines to and from NO3 will reduce the capacity for trading with other areas. Low transmission capacity means lower trading volume with other price areas which effects the liquidity and the bid-ask spread between buyer and seller.

In this section the potential profit from internal balancing for a power producer located in NO3 are evaluated for selected days with low initial intraday transmission capacity and where the requirements required for handling imbalances internally are met. Days with limited initial intraday transmission capacity are picked and analysed in depth to obtain the value of internal balancing. Days with low capacity to NO3 are used for the analysis of negative imbalances. There are not performed an analysis for days with positive imbalances, due to the fact that there are no days where the initial intraday transmission capacity from NO3 are limited and the requirements for handling imbalances internally are met. The requirements for internal balancing are that the run-of-river plant has an imbalance in the opposite direction of the imbalance for the reservoir hydro. This is because the reservoir hydro has to be able to cover the imbalance internally for the run-of-river plant.

Negative imbalances are simply days when the day-ahead commitments are larger than the actual production, so the deficit has to be bought in the intraday market or handled internally.

5.1 Transmission capacities

The work from Bellika and Cabrol [35] found that most of the trades of NO3 market participants happens with other price areas. They analyzed the price areas OPX, DK1, SE3 and FI, these areas were the areas that was most profitable to trade with for a market participant located in NO3. This analysis shows the importance of available transmission capacity when making trades in the intraday market since most of the trades are with other price areas, and the largest premiums are historically obtained when trading with other areas.

The volumes in the price area NO3 from the day-ahead and intraday market are presented in the table 5.1. It shows a trend against more aggregation against the intraday market in the recent years. This result can be seen in context with the increased wind power capacity installed in the area NO3 [2]. The traded intraday volumes are still low if they are compared against the day-ahead volumes, but increasing wind capacity in the area and more countries implemented in the Single Intraday Coupling (SIDC), can be potential drivers for further intraday volume-growth. Reservoir hydro producers has historically had a tradition for bidding marginal cost to the one-price cleared day-ahead market, versus the pay-as bid intraday market. Increased volumes and liquidity in the intraday market can motivate producers to take a larger participation in this market.

	2015	2016	2017	2018	2019	2020
Buy IDM	32	47	51	52	109	130
Sell IDM	89	68	70	70	82	143
Buy DAM				26970	27387	26742
Sell DAM				19086	22179	26080

Table 5.1: Day-ahead and intraday buy and sell volumes for NO3 in GWh. Data source: Nord Pool[36][37]

Low transmission capacities will decrease the capacity that can be traded with other price areas, where the largest capacities are traded and the best premiums are obtained historically [35]. The table 5.2 shows the average capacity and the lower quartile of capacity from 2018 to mid 2020, and the same data for the entire period modelled.

	01.01.2018 - 31.05.2020	01.02.2020 - 22.05.2020
Average capacity to NO3	4897	1655
Average capacity from NO3	7109	1186
Lower quartile to NO3	724	1341
Lower quartile from NO3	755	874

Table 5.2: Average and lower 25% of the initial intraday capacities to and from NO3 in MWh. The transmission capacities to and from NO3 are not symmetrical. Data source: ENTSOE[38]

5.2 Imbalances

While the reservoir hydro has a marginal cost due to the possibility of storing water, the only cost for the run-of-river hydro relies on start/stop costs. It is assumed that the run-of-river hydro bids the forecasted inflow to the day-ahead market. There are rules enforced by the TSO related to plan for balance, this is covered in section 2.1.3. This means that the run-of-river hydro should plan for balance and bid the production equivalent to the inflow forecast to the day-ahead market.

For the producer there are various approaches to handle imbalances. The producer can sit-back and let the TSO handle their imbalance in the balancing market according to a two-price clearing system, the producer can send an updated production plan to the TSO to get imbalance clearing in the balancing market according to an one-price clearing system or the producer can trade the imbalances in the intraday market. The two first methods are described in section 2.1.3, while the last method are described in detail in this chapter.

This thesis does not include the possibility for letting the TSO handle the imbalance. To find the value of internal balancing in a pay-as-bid intraday market for the run-of-river hydropower plant, the cost of imbalance [28] is established in equation 5.1. This equation is used for calculating the imbalance cost for plant-wise imbalance clearing for the run-of-river hydropower plant.

$$c_{imb} = -\frac{\sum_{t=1}^{N}(Q_{act}(t) - Q_{forc}(t)) * \pi_{imb}(t)}{\sum_{t=1}^{N} Q_{actual}(t)} \tag{5.1}$$

c_{imb} is the average specific imbalance cost per MWh run-of-river power produced in the time period, t. Q_{act} and Q_{forc} are the actual production and the day-ahead commitments for the run-of-river hydropower plant. Since the model clears the imbalances in the intraday market, the imbalance clearing price π_{imb} will depend on a two-price clearing system. This is illustrated in constraints 5.2 and 5.3. The constraints simply states that if the actual production is lower than the day-ahead commitments, the clearing price will be the intraday bid price, if the actual production is larger than the day-ahead commitments the clearing price will be the intraday ask price.

$$\pi_{imb}(t) = \pi_{BID}(t) \qquad if\ Q_{act}(t) < Q_{forc}(t) \tag{5.2}$$

$$\pi_{imb}(t) = \pi_{ASK}(t) \qquad if\ Q_{act}(t) > Q_{forc}(t) \tag{5.3}$$

5.2.1 Bid-ask-spread

The bid-ask spread is a dynamic difference between buyer and seller, and changes continuously throughout the day. The buyer bids the maximum price that he wants to pay for a given volume, while the seller ask for the minimum price he wants to sell a given volume for. The difference between the buyers bid price and the sellers ask price is called spread. The bid-ask spread can be considered a measure of the supply and demand for a particular product. Since the bid represents demand and the ask represents the supply for a product, a change in the spread between these two prices would actually reflect a change in supply and demand for the given product [39].

The volume or depth of the bid and ask price has a large impact on the bid-ask spread. If fewer participants place limit orders to buy or sell a product the spread may widen significantly due to fewer bid and ask prices. The spread is the transaction cost. Price takers buy at the ask price and sell at the bid price. The bid-ask spread can be seen as a measure for the market liquidity. Liquidity for a product can be described as how much volume can be bought or sold without affecting the market price. If the depth of the bid-ask spread is large (large liquidity), a buyer or seller can trade large volumes before affecting the market price. Little depth of the bid-ask spread means low liquidity and even small volumes traded will affect the market price (increase the spread) for a given product [39].

The model in this thesis is deterministic so it will only take the best trades from the order book since it has perfect insight into the order books. The bid and ask prices for this analysis is the buy and sell price the model obtains throughout the day for each product. Since the model has perfect insight into the order books, the spread between bid and ask price will for our analysis be the spread between the best buy and sell orders.

5.3 Negative imbalances

In this section days with negative imbalances for the run-of-river hydropower plant and low initial intraday capacities to NO3 are analyzed in detail. As described in section 5.2.1 the spread will increase with lower market liquidity. One fair assumption is that congested transmission lines to and from NO3 will reduce the market liquidity in the intraday market due to fewer participants to trade with and thus increase the bid-ask spread.

The first day in the period that are analyzed in depth is 02.02.20. For this day, the initial intraday transmission capacity is 1144MWh which is lower than the definition of limited capacity to NO3 presented in table 5.2. The capacity to NO3 are used for this day, since the analysis focuses on how the reservoir hydro can cover the imbalances from the run-of-river hydro. For this day the day-ahead commitments are larger than the actual production for the run-of-river hydro as illustrated in figure 5.1. This means that the run-of-river hydro producer has to buy this production from the intraday market or let the reservoir hydro cover the missing production. The reservoir hydro has a larger production than the day-ahead commitments and has to sell the surplus production in the intraday market as illustrated in figure 5.1. This makes this day great for evaluating the value of internal balancing since the reservoir hydro producer actually has production capacity to cover the imbalances from the run-of-river hydro plant.

The day-ahead market price, and the intraday bid and ask price for each hour/product of the actual day are illustrated in figure 5.2. The intraday bid and ask price are simply defined as the average intraday buy/sell price the model obtains for a given volume for each individual product/hour.

To determine the potential profit from internal balancing for selected days the total revenue from common imbalance clearing is compared against plant-wise imbalance clearing. The results are presented in table 5.3. The table shows a potential profit from shifting from a plant-wise clearing approach to a common imbalance clearing approach for 02.02.20. Figure 5.1 and 5.2 shows the day-ahead commitments, actual production and prices for this day. The run-of-river hydro has a total imbalance for this day of -2.4MWh. Instead of acting as a price taker and buy this at ask price, the reservoir hydro covers the imbalance, and sell the rest of the surplus at bid

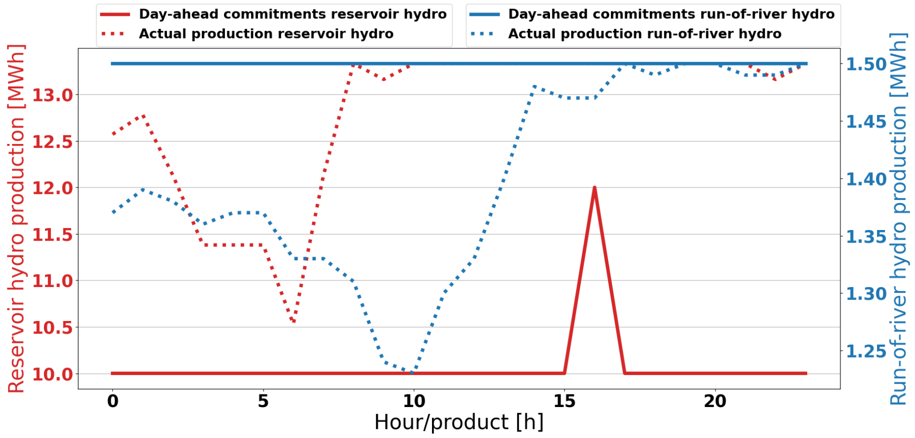


Figure 5.1: Initial and actual production for Mørre and Usma, date 02.02.20. The day-ahead commitments are from historical data, the actual production is obtained from the model. The actual production used for the run-of-river plant in the model is also from historical data.

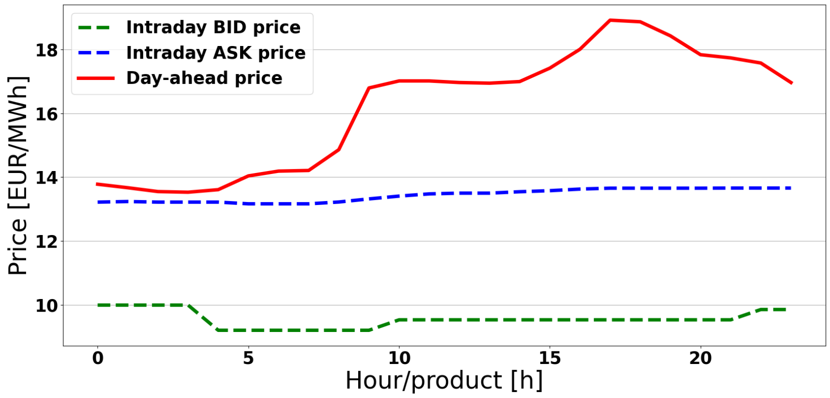


Figure 5.2: Day-ahead price and intraday bid/ask prices, date 02.02.20.

price. The imbalance volume for the run-of-river hydro times the spread between the bid-ask price will be the additional revenue generated from this approach. Even if the total revenue gain is small for this day, there could occur scenarios with larger imbalances and where the reservoir hydro has capacity to cover the imbalances.

Date	Avg transmission capacity to NO3 [MWh]	Avg transmission capacity from NO3 [MWh]	Avg BID price EUR	Avg ASK price EUR	Revenue plant-wise imbalance clearing [EUR]	Revenue common imbalance clearing [EUR]
02.02.20	1144	1855	9,9	13,7	593	602
15.02.20	1199	1300	7,7	11,9	-20	-9
18.02.20	1094	1406	5,7	7,5	127	180
11.04.20	2201	816	1,3	3,2	-30	-3
01.05.20	2214	406	2,7	4,7	-548	-536

Table 5.3: The table shows transmission capacities, average bid-ask intraday prices and the revenues from clearing imbalances plant-wise and with a common approach for days when the run-of-river hydropower plant has negative imbalances.

5.3.1 Discussion of the results

The results from internal balancing for the selected days are presented in table 5.3. The additional value for the coordinated scenarios compared to the uncoordinated scenarios relates to reduced imbalance costs. The costs of imbalance clearing for the run-of-river hydropower plant with an uncoordinated approach are calculated with the equation 5.1 for each hour. All of the days are analysed in the same way as illustrated for 02.02.20 in figure 5.1 and 5.2. The days for February that are selected for further analysis in table 5.3 are days with limited initial intraday transmission capacity to NO3. For all of the days, the run-of-river plant has negative imbalances, while the reservoir hydropower has positive imbalances. The two last days that are picked in the table 5.1 are days with high initial intraday capacity to NO3 and are used for comparison. The reason for selecting few days are that this analysis tries to quantify what happens for the entire period modelled in chapter 6. A few days will show the potential of internal balancing. The days selected also needs to have a negative imbalance for the run-of-river hydro, low initial intraday transmission capacity to NO3 and the reservoir hydro needs to have a positive imbalance to be able to cover the imbalances from the run-of-river plant.

For the modelled period there are few days where the run-of-river plant has positive imbalances while the reservoir hydropower has negative imbalances. Therefore there is not performed an analysis for internal balancing for days with positive imbalances for the run-of-river hydropower and negative imbalance for the reservoir hydropower, simply because there are almost none of the days in the modelled period where this criteria is met and internal balancing can be performed.

The relationship between congested initial intraday transmission capacity and low intraday liquidity is hard to verify. This is due to few days where the plants can perform internal balancing and the transmission capacity is congested at the same time for the period modelled. Since the intraday bid and ask price are obtained from the model, which is fully deterministic with perfect insight into the order books the value of internal balancing will represent a best-case scenario, and represent a spread that can be difficult to obtain in real-life.

Chapter 6

Results and discussion

In this section the results from the entire period modelled will be presented. For a more detailed analysis of individual days see chapter 5.

The period modelled is from first of February to twenty-second of May. In this period there are in total thirteen days that are removed. That means that approximately 83% of the period are modelled. Some of the days are removed due to errors in data, others are removed because the intraday order book have negative intraday buy prices. Currently the model can not handle negative intraday buy prices realistically so these days are removed. Historically, negative intraday prices are unusual.

The results from plant-wise imbalance clearing can be seen in table 6.1. For the entire period the run-of-river power plant has in total a negative intraday commitment. This means that the day-ahead commitments are larger than the actual production in total for the period, and the result is that the run-of-river producer has to buy this deficit in the intraday market for plant-wise imbalance clearing.

	Run-of-river hydropower	Reservoir hydropower	Total
Day-ahead commitment [MWh]	3994	20 073	24 067
Day-ahead revenue [EUR]	31 878	188 649	220 527
Intraday commitment [MWh]	-12	390	378
Intraday revenue [EUR]	-890	6032	5142

Table 6.1: Result from separate coordination in the intraday market.

In table 6.2 the result from the model with coordinated intraday bidding is presented. The total revenue with common intraday participation is also presented in the table. As the result indicates, the total revenue from intraday market participation is better with a common approach than for a plant-wise clearing approach. The results also shows that the total commitment for intraday trading is lower with a portfolio based coordination. The advantage of a portfolio based approach is the possibility to always use the unit with the lowest marginal cost to cover the commitments.

Since the run-of-river plant has zero marginal cost, this plant will be preferred as long as there are sufficient production here and the reservoir hydro plant has storing capacity. If the total production for this plant are larger than the day-ahead commitments, the additional production has to be sold in the intraday market, or it could be used to cover some of the commitments for the reservoir hydropower plant. Then the reservoir hydropower plant can save water for later usage when prices are expected to be more profitable.

The other scenario for the run-of-river hydropower producer are when the day-ahead commitments are greater than the total production, in this case the difference between the production and commitments has to be bought in the intraday market. Instead of buying production capacity, this could be produced by the reservoir hydropower. This is only profitable if the intraday buy price is greater than the marginal cost of the reservoir hydropower. As mentioned earlier, the water value depends on reservoir level, inflow and the expected market prices in the future.

The tables 6.1 and 6.2 presents the revenues from the day-ahead production and the intraday trading for both plant-wise imbalance clearing and a coordinated intraday bidding approach. The total commitments from the day-ahead and intraday market are also presented. The revenues from the coordinated intraday bidding approach are higher than the revenues for plant-wise imbalance clearing. For the entire period the sum of the total committed intraday volume is also lower for the coordinated approach. This can be due to the fact that the commitments are met in total, instead of trading each imbalance at the market. The penalty cost are removed from the results.

	Total
Day-ahead commitment [MWh]	24 067
Day-ahead revenue [EUR]	220 527
Intraday commitment [MWh]	298
Intraday revenue [EUR]	5907

Table 6.2: Result from separate coordination in the intraday market. The revenues are in euro and the commitments are in MWh.

6.1 Discussion

For the entire period modelled, the results indicate a profit from shifting from a plant-wise clearing of imbalances to a common intraday bidding approach. There could be several reasons for this. One of the reasons are that the intraday market liquidity are low for the period due to low initial intraday transmission capacities as illustrated in table 5.2. The average initial intraday capacity to and from NO3 for the entire period are significantly lower than the average capacity from 2018 to the end of the period. This can also be seen in context with the increased production capacity installed in N03 in recent years, and not equivalent increase in the transmission capacity with other areas. Another reason is the wet winter of 2020, which creates a surplus of power for the area which contributes to limited initial intraday transmission capacity.

This thesis finds internal balancing profitable, as previous literature in the field also has done [15][27]. The paper [15] uses a synthetic description of the intraday order book with an assumption of the bid-ask spread of $+-15\%$ of the day-ahead price with a correction factor of $+-1\%$ for each MW of imbalance. The paper only optimizes for one day to evaluate the value of internal balancing. This thesis uses real-life order books, and models a longer time horizon to find the value of internal balancing. The paper [27] also finds value of internal balancing, but models the balancing market instead of the intraday market.

The relationship between market liquidity and congested transmission lines can be further analysed in future research with even longer periods modelled. The period in this thesis is special since the average initial intraday transmission capacities are low. Lower transmission capacity can result in lower intraday liquidity which can increase the intraday bid-ask spread, and thus making it more profitable to perform internal balancing. Table 5.1 shows a trend in the recent years against larger trading volumes in the intraday market, if this continues the liquidity will increase, and thus the spread probably decrease, making it less profitable to perform internal balancing. Internal balancing can still be profitable on days or periods with limited intraday liquidity e.g. congested transmission capacities as this thesis find. An important question regarding internal balancing are how the intraday liquidity is affected if all of the producers starts to balance internally instead of using the pay-as-bid intraday market.

Future research should include a dynamic water value to better represent the marginal cost for the reservoir hydro plant throughout the day. Rapid changes in marginal cost could make internal balancing less profitable.

Section 5 in this thesis only evaluates days with negative imbalance for the run-of-river hydropower producer while the reservoir hydropower has a positive imbalance. For this analysis it is assumed since the reservoir hydro already has a positive imbalance, the marginal cost are lower than the price obtained in the intraday market. Using a dynamic water value for these days could change the marginal cost for the reservoir hydropower plant and reduce the benefit of internal balancing.

The initial reservoir input should also be from the previous day modelled in future work. This thesis uses the real-life reservoir level as input for each day for the reservoir hydropower plant. This means that the reservoir hydro can use more water each day than the initial reservoir level for the next day indicates. The head level the model obtains for each day are compared to the initial head level. Future work should include reservoir coupling between days.

Chapter 7

Conclusion and future work

This master thesis has investigated the value of internal intraday bidding coordination for clearing imbalances versus external clearing of the imbalances in the intraday market. There has been built a bid model for bidding in the intraday market and a hydropower model that includes a reservoir hydropower plant and a run-of-river hydropower plant. The model uses a rolling horizon approach with hourly stages for each bid and production hour of the intraday market. The input to the model is historical data, and for each stage of the rolling horizon the model maximizes a deterministic optimization problem. The models objective is to maximize the revenues from trading in the intraday market. The model are tested for both plant-wise imbalance clearing in the pay-as-bid intraday market and common imbalance clearing with a shared intraday load commitment in the pay-as-bid intraday market.

The model uses only real-time deterministic data and shows a best case scenario with perfect insight into the order books. All information regarding production and prices are known at every stage of the rolling horizon. This still shows the potential for internal handling of imbalances in a pay-as-bid intraday market.

There are performed a case study on a power producer located in the price area NO3 with a portfolio of intermittent and flexible production units. The thesis have obtained a base-case where all imbalances are traded in a pay-as-bid intraday market. The base-case is compared against a case where the imbalances can be covered internally and/or against a pay-as-bid intraday market, depending on what yields the highest revenues.

The result from this thesis are valid for internal imbalance clearing with other sources of intermittent production units like wind power. With the increased share of wind power in the European power markets, producers are to a larger extent managing combined portfolios of flexible production sources and intermittent renewable energy sources.

The results from this thesis shows that internal intraday coordination is more profitable than handling the imbalances plant-wise in a pay-as-bid intraday market. An important aspect of this analysis is that the potential profit from internal balancing in a pay-as-bid intraday market will increase with increased bid-ask spreads in the intraday market. If the trend continues with more volume traded in the intraday market as shown in table 5.1, the market will become more liquid and the spread could decrease, thus reducing the profits from internal intraday coordination. Another important question is what happens with the liquidity in the intraday market if a larger share of the power producers handles their imbalances internally rather than to use the intraday market?

Power producers will according to normal market theory benefit from a liquid and efficient market, where the transactions costs are small. Internal balancing can still be applied for days with less liquidity in the intraday market due to e.g. constrained transmission capacity. This analysis shows a profit over a longer time horizon with internal intraday coordination, both on days with sufficient transmission capacities to and from NO3 and days with limited transmission capacities. This result can be due to the fact that the liquidity in the intraday market is still low compared to the day-ahead market or the fact that this model has perfect insight into the intraday order book, and are able to take advantage of this. This thesis can not conclude that internal coordination will be profitable for all periods, due to improvements that can be made in the modelling and the special characteristics of the period modelled.

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