POST-OPTIMIZATION TOOL FOR HYDROPOWER

Creating an optimization tool for hydropower production

Lappeenranta–Lahti University of Technology LUT

Master's Programme in Biorefineries, Master’s Thesis

2023

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Examiners: Professor Esa Vakkilainen

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ABSTRACT

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Master's thesis

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72 pages, 13 figures and 2 appendices

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Keywords: hydropower, optimization, post-optimization, Nordic electricity market, balancing capacity market, balancing capacity, reserve market

The main aim of this thesis was to be a part of ensuring sustainable and dependable electricity supply for energy intensive industries, such as biorefineries, in the future. In order to do so a post-optimization tool was created. The main objective for this post-optimization tool was to optimize the hydropower production based on the electricity demand of a set time period in order to maximize the value of water. Other aim for the tool was to highlight the unutilized market potential. This thesis was done for UPM Energy.

The basic principle of the tool was that it would work with perfect data, provided by UPM Energy, meaning only validated history data. This way, the tool could calculate the optimized result using mixed-integer linear programming in provided software interface. The tool would have to maximize the value of water using past price data of various electricity markets and within set out plant specific restrictions. For the purpose of this work the time period in history to be optimized was set to one week.

As the result of this work the optimized production scenario was compared to a real one. The main result of this thesis was that the tool does reveal the unutilized market potential very well. Based on the results of this thesis it would be extremely difficult to reach the optimized production philosophy because of the various time frames of each market. The main benefit from the tool was that it highlights the unutilized market potential suggesting a direction for future development in trading processes that could optimize the value of water and thus, ensure sustainable and dependable electricity supply long in the future.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT
LUT School of Engineering Science
Master’s Degree Programme in Biorefineries

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VESIVOIMAN JÄLKIOPTIMOINTITYÖKALU

Optimointityökalun toteutus vesivoimatuotannon optimointiin

Diplomityö
2023
72 sivua, 13 kuvaa, ja 2 liitettä
Tarkastajat: Professori Esa Vakkilainen, Apulaisprofessori Kristian Melin

Avainsanat: vesivoima, optimointi, jälkioptimointi, Pohjoismainen sähkömarkkina, säätösähkömarkkina, säätösähkö, reservimarkkina

Diplomityön tarkoituksena oli olla osana turvaamassa kestävää ja luotettavaa sähköntuotantoa energiaintensiivisille teollisuuksille, kuten biojalostamoille. Tämän mahdollistamiseksi luotiin jälkioptimointityökalu. Työkalun päätarkoitus oli optimoida vesivoimatuotanto sähkön kysynnän mukaan maksimoiden käytetyn veden arvo. Toinen työkalun tarkoitus oli tuoda ilmi hyödyntämätöntä markkinapotentiaalia. Tämä diplomityö on tehty UPM Energialle. Työkalulle annettiin vain validoitua historiadataa, eli työkalu toimi täydellisellä informaatiolla. Tällä tavalla jälkioptimointityökalu pystyisi laskemaan optimaalisen tuloksen käytetyn ohjelmiston käyttöliittymässä. Data oli peräisin UPM Energialta. Työkalun tulisi maksimoida veden käyttöarvo asetettujen laitoskohtaisten rajoitusten mukaisesti hyödyntäen sähkömarkkinoiden mennyttä hintadataa. Jotta tutkimuksen tulokset olisivat helposti tarkasteltavissa, rajattiin jälkioptimointityökalun aikahorisontti viikkoon. Työn tuloksissa jälkioptimoitua tuotantoskenaariota verrattaisiin todelliseen tuotettuun skenaarioon. Työn tärkeimpänä tuloksena voidaan pitää optimointityökalun kykyä esittää hyödyntämätön markkinapotentiaali. Tulosten perusteella optimisuunnitelmaan pääsy on kuitenkin äärimmäisen hankalaa johtuen eri markkinoiden aikaikkunoista. Työkalun päähyöty on kuitenkin markkinapotentiaalin korostus, jonka perusteella voidaan pyrkiä kehittämään veden arvon maksimoivia kaupankäynti menetelmiä.

ACKNOWLEDGEMENTS

It took a while. Thank you everyone.

In Tampere 12.6.2023

Joonas Pajunen

SYMBOLS AND ABBREVIATIONS

Abbreviations

AC	Alternating current
aFRR	Automatic frequency restoration reserve
CET	Central European time
CHP	Combined heat and power
CO_2	Carbon dioxide
DC	Direct current
Elbas	Electricity Balance Adjustment System Market
FCR-D	Frequency containment reserve for disturbances
FCR-N	Frequency containment reserve for normal operation
Hz	Hertz
mFRR	Manual frequency restoration reserve
MILP	Mixed-integer linear programming
MW	Megawatt
MWh	Megawatt-hour
Nord Pool	Nordic electricity market, Nasdaq OMX Commodities & Nord Pool Spot AS.
P_{max}	Maximum power output
P_{min}	Minimum power output
kV	Kilovolt
TSO	Transmission System Operator
€	Euro
%	Percentage

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1. Introduction

The power market has been in a constant tumult for the past year reaching to a levels where it has been titled a global energy crisis. The genesis of this crisis originate first from the unexpectedly prompt economic bounce back of 2021 following the pandemic lockdowns, as the expenditure levels started to rise resulting the production side having issues to match. However, the already disrupted power market went from bad to worse as the Russian invasion of Ukraine started in February 2022. Russia was the world’s largest fossil fuel exporter in 2021 as they produced the third largest amounts of crude oil and the second largest amounts of natural gas in the world, with also having the world’s largest natural gas reservoirs. Shortly after the start of the hostile invasion major trading between Russia and western world seized meaning that some of the existing contracts were terminated and no new contracts were to be signed. That meant that a major share of fossil fuel availability of the western world also became unavailable driving the world into a global energy crisis. (International Energy Agency 2023a, 2023b, 2023c, International Energy Agency 2022a)

The diminished trading between the western world and Russia resulted in scarcity of crude oil and natural gas in the global markets. All the power markets work with a similar principle where the price is determined via the production and consumption. In this case, a major share of crude oil and natural gas production became unavailable to the markets while the consumption stayed the same, resulting into higher prices. The price increases in the global markets hit Europe more than most since many European countries were highly dependable on for example Russian natural gas supply. Majority, meaning just short of 42 % of Europe’s electricity was generated via combustible fuels in 2021 and for comparison 25 % of electricity was generated via nuclear power being the second highest source of electricity. So when the main source of European electricity production gets multiplied manifold in price, that also results in increased electricity prices. (Eurostat 2023, International Energy Agency 2023a, 2023b, 2023c, International Energy Agency 2022a)

The energy crisis did not only rise the electricity prices, it also broadened the price variation of electricity between hours, days, weeks and months. When the electricity prices are hitting record highs in many European countries not only the electricity users need to start optimizing their consumption, but also the electricity producers need to start to optimize their production. In short this would mean that all the electricity producers that have the ability to adjust their production capability need to focus more on the peak consumption periods to ensure grid stability and to level out the peak prices. As the fossil fuel prices continued to increase, also the running costs for fossil fuel powered reserve powerplants increased resulting hydropower to became the most capable balancing power source in Europe. In multiple situations hydropower plants have the ability to store the fuel, water, in a lakes and ponds before the actual plant and optimize the water usage based on the hours with the utmost electricity demand. In order to target the periods of the highest electricity need in the grid, optimization models are needed. (Eurostat 2023, International Energy Agency 2023a, 2023b, International Energy Agency 2022b, UPM 2015)

Main focus on electricity production optimization is in the future, since all the physical trading will happen in the future. Forecasting the periods of the utmost electricity demand of the future and how electricity producers should bid their production capabilities are always based on some sort of a projection. For example for hydropower producers who have large reservoirs such as lakes to ration, would it be beneficial to use large sums of the water today, or could the electricity need be even greater tomorrow. How about this week or is the next week going to have even higher demand, how about next month and so on. No matter how well the future optimization model works, further you try to optimize into the future, higher of the margin of error. In order to further develop the optimization models for the future, the data of the concluded trades conducted based on future optimization need to be studied and evaluated. To better understand the past data, post-optimization models can be created.

In this thesis a post-optimization tool for hydropower production was created. The main aim of this work is to be a part of ensuring sustainable and dependable electricity supply for energy intensive industries, such as biorefineries, in the future. The main aim for the post-optimization tool was to optimize the hydropower production based on the electricity demand of a set time period in order to maximize the value of water. Other aim for the tool was to highlight the unutilized market potential. The tool would have to maintain all the set out restrictions related to hydropower production. As the end result the tool would have to show the optimal way of operation, but does not dissect what exactly resulted into this optimal plan. What is meant by this is that the tool would not tell that it allocated the production away from certain time period because for example there was a surplus of wind power. So the tool would have to give out the result how, but the why would still end up as the responsibility of the user. In order for the tool to create post-optimized scenarios it would have to work based on perfect data, meaning that the tool has all the relevant past data and calculates the most optimal way of operation. This thesis was assigned by UPM Energy so most of the initial data utilized to create this tool was confidential. However, the results of the post-optimization tool can be given as proportion comparisons in percentages and in visual comparisons between concluded and post-optimized scenarios. The final assessment on the post-optimization tools effectiveness would be the value creation comparison.

Before sharing the methods on how the post-optimization tool was created this thesis will present all the different markets hydropower producers can bid their production as part of Nordic electricity markets. After that the thesis will share an introduction to UPM Energy, share specifics on hydropower and discuss the current and upcoming role of hydropower production. Finally, the thesis will present the methods on the creation of the post-optimization tool, compare the optimized results to concluded ones and share a final discussion and conclusions on the effectiveness of the tool. The justification on creating a tool that could help hydropower operators learn from the past and to better allocate their production in the future is quite self-explanatory in the middle of a global energy crisis. However, when the global energy crisis recovers the need for optimization does not diminish. The ongoing Europe wide wind and solar power projects will ensure that the price of electricity will heavily fluctuate also in the future, just highlighting the demand of post-optimization in order to create more effective future optimization.

2. The Nordic electricity market

Maintaining the stability of an electric network is a constant balancing act between electricity production and consumption. There are no ways to store electricity in a large enough scale to maintain the stability of today's electricity networks, thus electricity production and consumption need to be in a constant equilibrium. To solve the challenges related to maintaining constant equilibrium there are rapidly evolving technologies that aim to make both, electricity production and consumption more flexible. Since the consumption of electricity is never a constant and electricity production is a business, there cannot only be the equilibrium of production and consumption. There will also be the equilibrium of supply and demand. The relation of these equilibriums determines the current and future price of electricity. To guarantee maintaining the stability of electric network with lowest possible cost, Nordic countries have joined the Norwegian founded wholesale electricity marketplace, Nord Pool. (Nord Pool 2020a, 2020f, 2020j, Åf-Consult Oy 2019, 31-42.)

The Nordic electricity market is a wholesale power market between the Nordic countries, Finland, Sweden, Norway and Denmark. The market design of Nordic electricity market in short is quite simple. Big electricity generators offer their production capacity to the Nordic wholesale market. More electricity generators there are and higher amounts of electricity there is available, lower the prices. From the market large customers, such as companies with industrial energy intensive applications can buy electricity to match their needs. The large customers have to compete against each other as well as other buyers creating the forecasted electricity demand. Other buyers mainly consist of various retail companies that buy the electricity from the wholesale market in order to resell it to small customers, such as home owners, through a retail market. More electricity buyers there are and higher the forecasted electricity consumption is, higher the realized market prices. (Fingrid 2021n, Nord Pool 2020j, Nordic Energy Regulators 2019, Kuula 2006.)

The actual physical trading of electricity in Nordic electricity market is done in three separate marketplaces: day-ahead market, intraday market and balancing market. The main difference between these marketplaces are the trading windows when the markets are open. Each of these marketplaces are better described in their own chapter later on. The name, Nordic electricity market can be miss leading since it does not mean that the trading happens only between the Nordic countries. Nordic electricity market as a regional market is integrated with other European markets in both physical and financial terms. Today the main constraint in the European market integration is still the physical constrains of the grid, or more specifically interconnections between the countries. Theoretically if there were no restrictions in the interconnections between countries, all European countries should have the same spot price of electricity. The Nordic power system has interconnections to Germany, Baltics, Poland, United Kingdom, Netherlands and Russia. The European market integration today connects 24 countries together allowing physical trading between countries far apart for each other as long as the interconnections between countries have the capacity to support it. (de Menezes et al. 2016 132-150, Fingrid 2021n, Nordic Energy Regulators 2019, Norwegian Ministry of Petroleum and Energy 2022.)

2.1. Nord Pool

Nord Pool, founded in 1993, is Europe's leading power market that offers trading possibilities in day-ahead and intraday markets. In the early 1990's Nord Pool (originally Statnett Marked AS) was founded shortly after the deregulation of the electricity market in Nordic countries as an independent company. In 1995 Norwegian Parliament agreed on the framework to establish integrated Nordic power market and Nord Pool, with their licence for cross-border trading, laid the groundworks on what we now know as Nordic electricity market. In the late 1990's Nord Pool made cross-border trading possible between Norway, Sweden and Finland, with Denmark also joining in early 2000's. The 1990's deregulation of the electricity market in Nordic countries meant that the state no longer had the control over the power market. This led to the liberation of electricity trading and introduced the free competition markets what we now known as day-ahead- and intraday markets. (Nord Pool 2020f, 2020i, 2020j, 2020k.)

Nord Pool is owned by Euronext, a stock exchange and trading service provider in Europe, and by Nordic and Baltic TSO's. Currently Nord Pool has 360 customers from 20 European countries. In 2021, 953 terawatt-hours of electricity was traded through Nord Pool, with 75 % of the trading concluded in the Nordic's and Baltic's day-ahead market. Nord Pool promises liquid, efficient and secure trading between all its customers. In efficiency analysis, Nord Pool has scored the highest efficiency numbers when comparing to other well established European electricity markets such as the Italian and Spanish markets. However, the main findings from the efficiency analysis were that there is still high demand and lots of room for improvement, also in Nord Pool's case. (Euronext 2023, Nord Pool 2020f, 2020i, 2020j, 2020k, Papaioannou et al. 2019 618-644.)

2.1.1. Day-ahead market

Day-ahead market is a closed auction of energy for Nord Pool customers. The goal of the daily auction is to match the orders of electricity producers and end-users for the next 24 hours starting from 00:00 o'clock CET the next day and ending to 00:00 o'clock CET the day after that. The day-ahead market closes every day at 12:00 CET and the results of the market are published hour later at 13:00 CET. Every hour of the day will have certain amount of electricity demand and certain amount of electricity supply. This relation between supply and demand forms the equilibrium for each hour resulting into the lowest cost of electricity produced for each hour of the day. Based on the need and availability of electricity the day-ahead market publishes bidding zone prices for each hour and out of the received bids the hourly price medium, or spot, is calculated for each bidding zone. (Nord Pool 2020b, 2020c, 2020d, 2020e, 2020i.)

So, the most important advantages of day-ahead market are establishing the spot price for each hour and meeting the needs of each customer in the most efficient and transparent way. One other important advantage of day-ahead markets is that from the market results each nations transmission system operator gets the data on how much electricity is planned to be imported or deported and how much is planned to be used or produced. With the help of that data the transmission system operators can start planning the measures to ensure the grid balance of the upcoming day (Fingrid 2021e, Nord Pool 2020b, 2020d, 2020e, 2020j, 2020k.)

2.1.2. Intraday market

Intraday market is a continuous market where Nord Pool customers can trade electricity depending on their current and upcoming needs. Where in the day-ahead market the large quantities of electricity are traded for the upcoming day, in the intraday market the fine tuning of each customer's balance that happens on an hourly basis. Intraday market is open for trading each hour of current day, but the hourly market closes always on the delivery hour. This means that if some market participants have shortage or excess electricity in their balance during the delivery hour, there are no means to correct it from the intraday market. The market for the upcoming day opens at 14:00 CET allowing trading for each individual hour again from 00:00 to 00:00 CET. (Nord Pool 2020g, 2020h, 2020j, 2020k.)

Nord Pool's intraday market has market participants from 16 European countries allowing international trading. International trading however is only possible when the interconnections between the countries have enough headroom to support the added trade volumes. The capacity for cross-border trading is determined by each countries transmission system operators (TSO's) that calculate the free capacity in the interconnections based on the electricity flow results of the day-ahead market results as mentioned in the chapter before. International trading closes an hour before each actual delivery hour. After that the market contracts into just localized market for the last 60 minutes before the actual delivery hour. Usually the contraction from international market to localized market means that the majority of the bids also disappear from the market leaving only the localized bids open for trading for the last hour before the delivery. However, Nord Pool is offering new 15 and 30 minute products on several borders, for example when the international trading ends an hour before the delivery hour, Finnish power market participants can still trade for the next 30 minutes with Estonian power market participants before going totally localized market for the last 30 minutes. Intraday market works in the way of first-come, first-served, meaning that the best offers with highest buying- or lowest selling price, are the ones that get traded first. Usually, trading is the most active hour or two before the actual delivery hour when the electricity gets used. This happens because the most accurate information regarding the electricity needs or production capabilities is known just before the actual delivery hour. (Nord Pool 2020g, 2020h, 2020j, 2020k.)

Price of electricity in intraday market depends on the actual upcoming electricity need and the electricity availability. This means that the price in intraday market can largely vary from the spot price established in the day-ahead market depending on the current and foreseen situations. That also means that when there are no or only minor unforeseen variables affecting the grid, the actual price of electricity in the upcoming hour can be very similar to the spot price. What makes predicting the actual electricity balance tough for every hour are the variables affecting the grid. Variables, like the ever-changing electricity consumption patterns of people and variable power sources such as wind and solar power. The actual production amount from those variable power sources can largely fluctuate just depending on the weather, resulting to imbalances in the predicted production. Other things that could affect the prices are malfunctions of large electricity producers such as power plants. These types of imbalances in the grid can increase or decrease the electricity need in an hourly basis and thus, also increase or decrease the price of electricity also in the intraday market. (Fingrid 2021e, 2021i, Nord Pool 2020g, 2020h 2020j, 2020k.)

2.2. Fingrid

Fingrid Oyj is the Finnish transmission system operator (TSO). The main task of transmission system operators is to guarantee the grid balance of electrical networks within the borders of a nation so in Fingrid’s case, Finland. Fingrid is a customer-oriented monopoly, meaning that Fingrid is the only transmission system operator in Finland and its only task is to serve the customers, meaning citizens. Fingrid is not an electricity producer, but in cases where the grid balance has a deficit of electricity, Fingrid has some reserve power plants on call and boot ready to start electricity production in order to maintain the grid balance. Finland is part of the Nordic power system, meaning that the grid is connected to other Nordic countries and electricity is constantly flowing between the Nordics. The inter-Nordic system including Finland is also connected to Central Europe’s system and Finland also has transmission connections to Russia and Estonia. These connections on top of the Nordic power system add to Finland’s grid security, since Finland at the moment of writing this work is not yet self-sufficient in electricity production. (Fingrid 2021e, 2021i, Hiekkala 2021 3.)

Finland’s electricity system consists of transmission grid, power plants, regional- and distribution networks and eventually, electricity consumers. Fingrid is responsible of the transmission grid. Transmission grid is the high-voltage part of the grid that connects the power plants to the distribution networks and eventually to the electricity consumers. Finland’s transmission grid is 14600 kilometers long including close to 120 substations. To maintain and upgrade the nationwide transmission grid Fingrid set to invest in total of 1,2 billion euros throughout years 2015 to 2025, resulting into 110 million euros invested per year. As mentioned before Finland’s transmission grid is part of the inter-Nordic system. In practice that means that Finland has transmission connections with Sweden and Norway. The three main DC connections, two 400 kV connections to Sweden and a 220 kV connection to Norway, all located in northern Finland share border with either Sweden or Norway. On top of those connections there are 2 other AC connections to Sweden, 800 & 400 MW, both leaving from Rauma area and travelling at the bottom of the Bothnian sea to Sweden. Then there are the connections outside of the inter-Nordic system, meaning connections to Russia and Estonia. Finland and Russia have three main AC connections, each 400 kV, located in south-eastern Finland sharing a border and on top of that, two 110 kV connections in northern Finland that are also sharing boarder with Russia. Lastly Finland has two DC connections to Estonia, 350 MW and 650 MW, that are travelling at the bottom of the Baltic sea. (Fingrid 2021g, 2021h, 2021j.)

The electric network frequency in Finland is 50 Hz. The frequency is not constant, so to keep it as close to 50 Hz as possible is a never-ending adjustment process. Things that affect the frequency balance are disturbances in the grid. These disturbances can be foreseen medium scale disturbances such as whole nation turning on the lights, television and oven as they come home from work or unforeseen large-scale disturbances such as malfunctions of power plants. The standard frequency variation is set to vary between 49,9 and 50,1 Hz and higher variations than that can be considered disturbances. To keep the frequency at the 50 Hz range Fingrid needs power reserves, such as the before mentioned Fingrid’s own reserve power plants. In situations where the frequency starts to deviate on a lower level than 49,9 Hz the grid either requires more electricity production or less electricity consumption to maintain stability. In those kind of situations Fingrid can produce more electricity in-house with their own reserve power plants. However, those reserve power plants are not flexible enough to constantly maintain the grid balance, for example in situations where the grid balance starts to rise over 50,1 Hz, you need reserves that can produce less or consume more electricity to balance the grid. To ensure the grid balance, Fingrid is maintaining a reserve- and balancing energy markets. (Fingrid 2021e, 2021i.)

2.2.1. Reserve market

The reserve market is a possibility for independent power system operators to create added value by offering their reserves to Fingrid. The offered reserves vary from energy storages to power plants and from increasing electricity consumption to decreasing it. Fingrid has created standards and technical requirements that all the power system operators must meet in order to participate into the reserve market. For example, there are strict rules on how fast a certain capacity must be available and activated from the source. However, maintaining a reserve is not completely risk-free for the independent power market operators. In situations where the operator is not able to maintain and deliver the agreed upon reserve amount, the operator must pay Fingrid compensation. (Fingrid 2021c, 2021d, 2021f, 2021k.)

Every reserve bid has its own hourly price (€/MWh) set by the independent power system operators for the reserve market. The market works as an auction where Fingrid picks and chooses the most fitting bids for their upcoming balancing needs forecasted based on the next day’s Day-ahead market results, already known or planned powerplant maintenances and the headroom in the interconnection between the neighbouring countries. Fingrid maintains two types of markets for reserves, the hourly market and a yearly market. The main difference between these markets is that in hourly market every operator can leave their bids for the next day on a daily basis, but in the yearly market the tender is arraigned only once a year during autumn. In both cases final reserve price, meaning the actual payment prise of the reserve, is determined by the most expensive bid of the hour that was activated from the market. This means that more expensive bids will not get activated and all the less expensive bids will get activated and get the compensation based on the highest activation price. In the yearly market the price is determined once during the autumn tender and will remain same for every reserve producer during every hour throughout the year. (Fingrid 2021k.)

During normal operation Fingrid uses two types of reserves to balance the frequency deviation, automatic frequency restoration reserve (aFRR) and frequency containment reserve for normal operation (FCR-N). Both of these reserves are automatically activated on the power source to counter the current frequency deviation via Fingrid’s power adjustment signal. FCR-N is the only symmetrical reserve that is offered, meaning that the reserve can produce more or less energy according to the offered amount, where aFRR can only be offered to adjust up or down. Other key differences between FCR-N and aFRR reserves are that FCR-N reserve can be bid for both yearly- and hourly market where aFRR can be bid only for hourly market. (Fingrid 2021a, 2021c, 2021d, 2021f.)

To counter medium to large disturbances in the grid, Fingrid collects frequency containment reserve for disturbance (FCR-D) bids from independent power producers. FCR-D is similar to the FCR-N reserve in the sense that it can be bid for both yearly- and hourly markets, offered for every hour of the day and that it adjusts according to the Fingrid’s power adjustment signal. Where it differs from the FCR-N reserve is that it can be only offered separately as up- or downregulating reserve. In typical cases the amount of FCR-N, FCR-D or aFRR reserve offered to the market is mainly only the leeway on top of the normal operation of the power source. In this way the power system operators can earn added value on top their normal operation without affecting it drastically. With the types of reserves and level of compensation, in most cases it would not be financially sufficient to start or stop the power sources based on the frequency deviation. (Fingrid 2021a, 2021c, 2021d, 2021f.)

2.2.2. Balancing capacity market

Balancing capacity market is also a Fingrid maintained marketplace, where the independent power system operators can bid their balancing capacities. Balancing capacity, or manual frequency restoration reserve (mFRR) can be offered to regulate up or down, or in other words produce or consume less or more electricity depending on the bid. The bids can be given every hour of the day and minimum 45 minutes before the operational hour. Information that every bid needs to have include the amount of power (MW), price (€/MWh), weather the balancing capacity is from production or consumption, transmission area of the source and finally, name of the balancing resource. The amounts and prices of these bids can differ drastically because usually the price reflects on how much the balancing capacity execution would impact the regular operation and how much effort it requires. With upregulating bids, the independent power system operators are selling energy for Fingrid and with downregulating bids, buying it. (Fingrid 2019, Fingrid 2021b.)

Fingrid receives the list of bids from independent power system operators every hour, 45 minutes before the operation hour, and the list is set in order of price from lowest cost to highest. Out of that list Fingrid manually picks and activates the bids when necessary for balancing needs starting with the lowest possible cost to them. Sometimes when the balancing need is in a certain area of Finland, or when there are some disturbances in the interconnection between the neighbouring countries, Fingrid can pick, choose and activate a special adjustment from the bids that does not have to be the lowest priced one. In such situations Fingrid has to activate possibly a more expensive bid, that is specifically for that grid area in need, without activating all the lower cost bids as per normal operation. In both normal and special adjustment operation after the bid is activated the independent power system operators have 15 minutes to adjust their electricity production or consumption according to the ordered amount. Fingrid also always includes the stopping time of the activated balancing capacity bid that is by standard at the end of the current hour. In cases where Fingrid needs the activated adjustment to end before the standardly set end of the hour, they can activate a chosen end time that has the same 15-minute buffer meaning that the balancing power producers have to cease the adjustment 15 minutes after the end time activation. The stopping time can be anything within the current operation hour and the next operation hour will have all new bids from the balancing power producers again for Fingrid to pick and choose from when in need. (Fingrid 2019, Fingrid 2021b.)

2.3. UPM Energy

UPM Group is formed by multiple different and independent business units with one of them being UPM Energy. UPM Energy is a sustainability driven, energy focused business unit that aims to maximize the energy potential of its assets. UPM Energy is the second largest electricity producer in Finland. The annual electricity production capacity of all UPM Energy operations is approximately 1405 MW and out of that production capacity, 98 % of the electricity is carbon dioxide free. UPM Group in Finland produces in total of 2751 MW of electricity. (UPM Annual Report 2021, 44-45, UPM Annual Report 2020, 48-49 & 88-91, UPM Financial Report 2021, 12.)

In 2020 UPM Energy had 70 employees and 379 million euros of sales with 171 million euros of profit. In 2021 UPM Energy had 72 employees and UPM Energy had 526 million euros of sales with 270 million euros of profit. UPM as a company is committed to United Nations Global Compact's Business Ambition for 1,5 degrees Celsius to mitigate climate control and also has set own goals to create a future without a need of fossil fuels. UPM Energy as a part of UPM Group shares these values and goals. (UPM Annual Report 2021, 44-45, UPM Annual Report 2020, 48-49 & 88-91, UPM Financial Report 2021, 12, UPM Investor News 2020.)

2.3.1. Electricity production

As mentioned before, UPM Group as a whole produces 2751 MW of electricity in Finland. Total sum of electricity production comes from two halves. UPM Energy half has a total capacity of 1405 MW and the other half, 1346 MW, is from the cogeneration of heat and power on CHP-plants within UPM factories. The total capacity of UPM Energy's electricity production consists of different energy sources: hydropower 720 MW, nuclear power 588 MW and thermal power 97 MW. UPM Energy owns 8 hydropower plants and the rest of the hydro-, nuclear- and thermal power comes from major shareholdings (UPM Annual Report 2021, 44-45, UPM Annual Report 2020, 48-49 & 88-91, UPM Energy 2022b.)

In hydropower production UPM Energy is a shareholder of Pohjolan Voima Oyj (PVO), Kemijoki Oy and Länsi-Suomen Voima Oy (LSV), and operates the share owned facilities in Iijoki, Kemijoki and Kokemäenjoki. In nuclear power PVO is a major shareholder of Teollisuuden Voima Oyj (TVO). UPM Energy being a PVO shareholder, means that UPM Energy is also a shareholder of TVO owned Olkiluoto nuclear power plant, including the new Olkiluoto 3. Finally, UPM Energy also gets thermal power though the shareholdings of PVO. Thermal power is mostly produced using renewable biomass as the fuel. (UPM Annual Report 2021, 44-45, UPM Annual Report 2020, 48-49 & 88-91, UPM Energy 2022b.)

2.3.2. Electricity consumption

The reason why UPM is such a big energy producer is that it is also a significant energy consumer. The biggest energy consumption areas of UPM Group in Finland are Timber, Pulp and Paper. In pulp industry, the well optimized pulp production results producing more energy than it uses. Some of this energy is utilized in nearby UPM saw- or paper mills and for example, UPM Timber in Finland is certifiably using only emission-free electricity. The emission free electricity is generated by pulp production utilizing the sawdust and woodchips that are byproduct of UPM Timber, and then pulp production giving Timber back the energy that is generated as the byproduct of pulp industry. The biggest electricity consumers are paper mills. Almost all UPM paper mills in Finland also have CHP-plants on the mill site. CHP-plants provide paper machines the hot steam required and also produce some electricity via steam turbines. The paper industry still needs more electricity than it produces. (UPM Annual Report 2021, 44-45, UPM Annual Report 2020, 45-46, UPM Communication Papers 2022, UPM 2019.)

Based on that the profitability of paper production is highly dependent on the price of electricity and high electricity prices can massively cut the profits of paper production. Therefore, in some cases paper machines have even been momentarily shutdown because the price of electricity is too high to produce profitable paper (Lensu 2021). UPM has acted on this issue by also offering some consumption capacity to the balancing market. In cases where the electricity demand peaks and the electricity price momentarily rises so high it is financially more feasible to not produce any paper, UPM Energy offers some of the paper production capacity to be freed to the balancing market. In other words, UPM Energy sells the electricity reserved for paper industry to Fingrid maintained balancing market and back to the grid. This way UPM has also some flexibility in electricity consumption, not only in production. (UPM Annual Report 2021, 44-45, UPM Annual Report 2020, 45-46, UPM Communication Papers 2022, UPM 2019.)

2.3.3. Energy control room

UPM Energy leaves Day-ahead bids in the Nord Pool's Day-ahead market every day of the year. Based on the sales and buys in the Day-ahead market UPM Energy forms production and consumption plans for all their assess for the upcoming day. When UPM Energy sells or buys electricity to the grid in the Day-ahead market that is also a promise that they can and will produce or consume the amount of energy. Therefore, UPM Energy is balance responsible for Fingrid. Balance responsibility for Fingrid means that UPM Energy has to follow the guidelines of the Balance agreement and Nordic Imbalance Settlement Handbook in their everyday operations. In short, this means that UPM energy, an electricity market party, has to always strive to maintain their own electricity production and consumption in balance, and Fingrid, an open supplier, will handle balancing any occurring deviations in the UPM Energy's balance. UPM Energy's central control room located in Tampere is in charge of maintaining the electricity balance of all UPM operations in Finland. As part of that energy control room is also in charge of UPM Energy's hydropower production and intraday trading. Energy control room is operated by a team of six in a way that at least one team member is always present no matter the time or day. As discussed before, electricity markets are an ever changing challenge and that also affects the procedures of energy such as UPM Energy's energy control room quite a bit. For example, all balancing capacity offers to Fingrid are either maintained or conveyed in the energy control room. So in situations where the grids balancing need increases and Fingrid activates some mFRR offers it also requires more focus from the control room team. In such situations process automation and optimization are vital for efficient operation. (Fingrid 2021m, Pohjolan Voima 2021a, UPM 2021b.)

Total of 18 hydropower plants are operated and monitored from the control room. The 18 hydropower plants include the before mentioned eight UPM owned hydropower plants and also the ten share owned ones. In challenging situations, the focus can not only be with the hydropower operations, so to help the load on energy control room team, different automation and optimization procedures have been implemented and constantly developed. For example, last year PVO-Hydropower in co-operation with UPM Energy implemented a river wide automation to one of Finland's longest rivers, Iijoki, operated by the UPM Energy control room team. The main advantage that the automation has is that it controls the river as a one entity. So in practice the automation calculates and shares the production plans between all the hydropower plants along the river. This is not beneficial only on economic point of view, but more importantly it is beneficial on environmental point of view. As the balancing capacity need increases in the future as the weather-dependent production capacity grows, river automation that controls the river as one entity reduces the overall variations in rivers. (Pohjolan Voima 2021a, UPM 2022b, UPM 2021b.)

3. Hydropower

Hydropower is one of the oldest renewable energy sources. Despite being an older invention, hydropower is globally still the largest renewable energy source and due to automation, optimization and modernization of the processes, arguably the most important. In 2019, 61 % of the total renewable energy in the world originated from hydropower. In 2016 the share was 71 %. This does not mean that the amount of hydropower production is decreasing per say. It means that the share of other renewables such as wind and solar is increasing. The problem with increasing the hydropower production the same rate as other renewables in the world is that the possibilities to construct new hydropower plants are getting sparser. Most of the more desirable hydropower plant locations are already converted to energy production and the other possibilities for new facilities are not financially as viable. Increasing the hydropower production capacity is starting to become an issue particularly in the Nordic countries where the share of hydropower in the total electricity production is vital, not only as an energy source, but also as a balancing capacity source. (Energiateollisuus 2021, International Renewable Energy Agency 2021, Motiva 2021, Moran et al. 2018 11891-11896, Mäkiharju 2012 15-24, U.S. Department of Energy 2021.)

When considering hydropower plants overall costs, they are quite low due to the long lifecycle estimation. For example, most of the Finnish hydropower plants were constructed from the early to late 1900-hundredths making the oldest ones now around 100 years old. With that sort of a lifecycle, the investment costs are already paid up and the only running costs left are the operational- and maintenance costs. That, combined with fewer suitable new hydropower plant locations getting sparser, is the reason why currently the most common way to increase the overall hydropower production capacity is by upgrading the already existing hydropower plants. Usually the upgrades to the process happen during larger mandatory renovations. Depending on the age and state of hydropower plants the upgrades are usually based on the modernization of the current process. Modernization could mean a lot of things from bigger mechanical changes like upgrading the turbine and generator or increasing the head, to technology based upgrades such as new automation- or optimization solutions. (Fortum 2014, Motiva 2021, Moran et al. 2018 11891-11896, U.S. Department of Energy 2021.)

3.1. Working principle of hydroelectric power plant

Every hydropower plant works with the same basic principle of generating electricity from moving water, or more specifically, converting potential energy of water into mechanical energy. In short, flowing water turns the turbine that is connected to a generator that generates electricity to the grid (Figure 1).

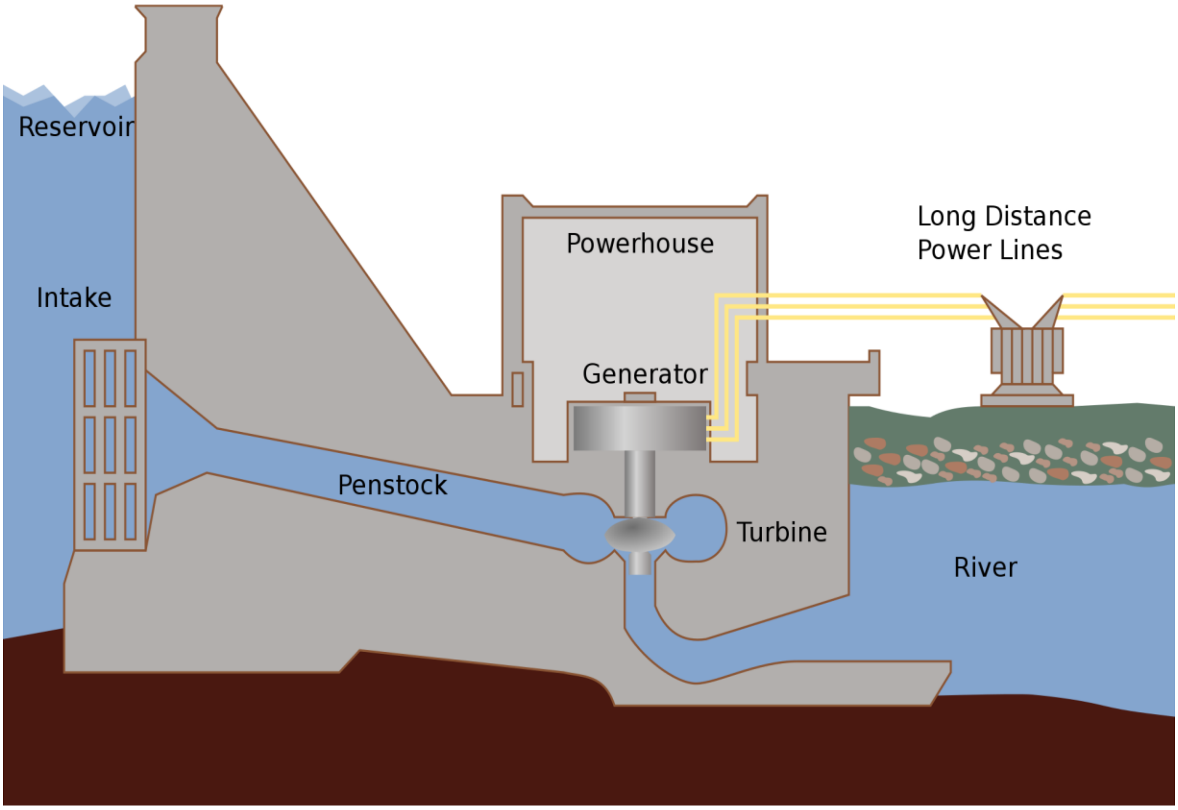


Figure 1. Hydropower process, water flowing from left to right (Energy education 2021).

Hydropower electricity production is dependent on the following formulas:

$$E = mgh = \rho V g h$$

Where E is potential energy [J], m is mass of water [kg], g is gravitational acceleration constant [m/s^2], h is height of the fall, or in short, head [m], ρ is water density [kg/m^3] and finally, V is the volume of water [m^3].

Definition of power is the rate of energy production and based on that turbines power output can be defined:

$$P = \eta \rho g h q$$

Where P is power [kW], η is efficiency and q is the volumetric flow rate [m^3/s].

Based on those equations the yield of electricity from hydropower production is mainly dependent on the two key variables, head and flow rate. Higher the head and flow rate, higher the yield of electricity. In practise also the efficiency is variable and has to be considered. With hydropower turbines the efficiency is dependent on the flow rate and thus, also constantly changing. Too high of a flowrate could make the turbine lose some of its efficiency, resulting into much larger water use and not much higher electricity output, while too low flow rates could lead into cavitation. Cavitation is a phenomenon that happens when water enters a turbine at a high a pressure resulting into vapour bubble formation due water boiling at lower temperatures under the high pressure or more specifically, when waters flow static pressure falls below the vapour pressure. The vapour bubble formation is not an issue at itself, but when these vapour bubbles start bursting, it results into pressure waves that can disturb the turbine frequency. Disturbances in the turbines frequency can lead into unwanted vibrations that could cause damage to the turbine. (Kumar & Saini 2010 374-383, Mäkiharju 2012 15-24, Pelkola 2018 14-21, U.S. Department of Energy 2021.)

While the before mentioned formulas are true, they do not give a good overall representation on the hydropower process, but more specifically, true values only on that particular moment with those particular values. The production capacity of hydropower changes constantly, for example when the water level before the plant decreases, that also decreases the head. That means that to produce the same amount of power as before with the now lower head, a larger flowrate is needed. That larger flowrate yet again decreases the water level before the plant and now with even more rapid phase. This non-linear relationship is more commonly known as head effect. Combining the head effect with the efficiency changes in the turbine with flowrate dependency and the real time running hydropower calculations start to look more complex than just the two before introduced formulas could suggest. This is why hydropower optimization models that do future-, real-time- and history calculation are more and more important every day. (Energiateollisuus 2021b, Mäkiharju 2012 15-24, Pelkola 2018 14-21, U.S. Department of Energy 2021.)

Since hydropower production is highly dependent on the flowrate and head, it is then also highly dependent on the amount of water available. One advantage of hydropower is that the power source, water, can be stored in storage pools located usually nearby or just before the hydropower plant. Storage pools can be either man made artificial pools created while also constructing the hydro power plant or just natural ones such as a lakes and ponds. Water is usually flowing to the storage pools from a river that is originated from a lake above with a larger run-off area. In Finland rivers that have multiple hydropower plants along the way from the origin and eventually to the sea, can be imagined to be like stairs. Water is flowing from the top of the stairs to the bottom and each step is either a storage pool or a hydropower plant. Storing water enables hydropower to be produced especially during the hours of peak electricity usage and demand. One advantage that hydropower also has are the prompt start- and stopping times. Hydropower turbines can be started up from a holt to a full production within mere minutes with fairly small starting costs. Same applies to bringing the generator from full production to a stop. This alongside with the storage pools makes it possible to variate the daily production and produce hydropower especially during the peak electricity consumption hours. (Energiateollisuus 2021b, Länsi-Suomen Voima 2021, Motiva 2021, Mäkiharju 2012 15-24.)

3.2. Hydropower production in Finland

Hydropower production is highly regulated and monitored in Finland. There are multiple laws and authoritative parties that control the obligations and regulations related to hydropower production. Everything starts from the Water Act (587/2011). Water Act is the type of a general law that controls everything from the water use to the construction guidelines close to water. In some projects related to working closely with water systems the Water Act is not enough by itself and you will also need to comply with the Environmental Protection Act (527/2014) regulations. In Finland to get a permission for construction and operation the hydropower plants need to also comply and follow all the Finnish regulations, such as Nature Conservation Act (1096/1996), Act on Environmental Impact Assessment Procedure (468/1994) and Rapid Conservation Act (35/1987), but also with the European

Union regulations such as Natura 2000 legislation and Community action in the field of water policy (2000/60/EC). (Finlex 2022, EUR-Lex 2022, European Environment Agency 2021, Kemijoki 2021, Pohjolan voima 2021b, Ympäristöhallinto 2013.)

In the most typical cases hydropower production can store the power source, water, and use it during the hours of high- and peak electricity demand. This results in water levels being higher before starting the production and lower when ceasing the production. In practice this usually means that the water levels are high in the morning after filling the water reservoirs during the low consumption hours of the night and low in the evening after using most of the available water reservoirs during the high electricity demand hours in the daytime. This type of a water use optimization is possible only between the established environmental limits. Every hydropower plant has its own specific environmental limits for minimum and maximum water level. Some plants have fixed limits throughout the year where some have changing ones depending on the time of the year and the season (figure 2).

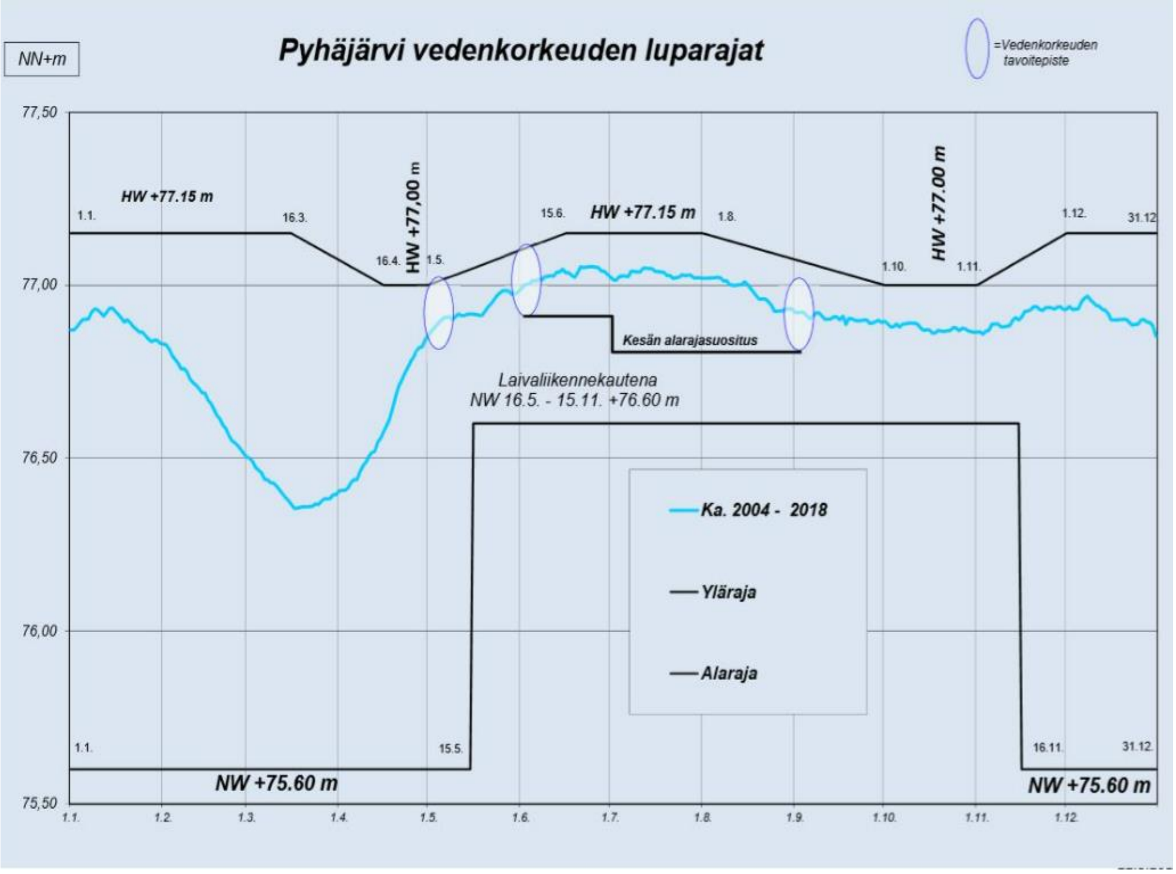


Figure 2. Environmental limits of the lake Pyhäjärvi (black) and average water level from 2004 to 2018 throughout the seasons (blue) (Pohjolan Voima 2021b).

Like shown in figure 2, the environmental limits of lake Pyhäjärvi changes throughout the year. From the figure 2 it is easy to see the preparation for spring floods by lowering the water level and also how fast the water level recovers ones the snow starts to melt. The figure 2 also shows the raised lower environmental limit of lake Pyhäjärvi during summer months to support water transport season and on top of that an even higher lower limit recommendation to support recreational activities. (Finland's environmental administration 2013, Kemijoki 2021, Pohjolan voima 2021b.)

The strict environmental limits are constantly monitored by authorities such as Centre for Economic Development, Transport and the Environment. The regulatory authorization holders, meaning usually a power company, state or municipality, are responsible for always following the environmental limits. Breaking these limits could result in fines or losing the operational and regulation rights for the water system. On top of these strict environmental limits hydropower plants in some cases also have these so called recreational boundaries, like the one shown in figure 2. These recreational boundaries are not as strict as the environmental limits, but in the spirit of keeping everyone pleased from the hydropower producers to the individual fishermen or summer cottage residents, these limits are treated as such during the recreational seasons. (Finland's environmental administration 2013, Kemijoki 2021, Pohjolan voima 2021b.)

In some cases, the hydropower plants have also flow limits. There are different types of flow limitations depending on the situation and location. For example, there are hydropower plants that are not allowed to diverge on average more than a couple of cubic meters per second from the incoming flow. Then in other situations the flow characteristics could be limiting the hydropower operation in a way that the average daily flow should be above some set amount, or there could be a minimum flow that needs to be always siphoned no matter the time, day or season. Then there can be water systems that are regulated in a way that changing the flow more than a few dozen cubic meters per second is not allowed within a set period of time, for example within 24-hours. All these flow limits are created and based on serving the environmental needs. For example, the required daily average flow could also have maximum and minimum values for a certain time period. This type of a period usually is connected to some fish stock examination or plantation (Koljonen et al. 2017 6-24, Åf-Consult Oy 2019 23-25.)

The share of hydropower electricity produced in Finland varies from 10 to 20 % of the overall electricity production capability. Such variation is the result of different weather conditions and seasons. For example, years that have low amounts of precipitation and snow result in less run-off to rivers and lakes and eventually significantly decreases the amount of hydropower production capacity. Then there can also be years that have a thick snow cover from the winter and when spring comes and the snow starts to melt, the amount of run-off water to rivers and lakes increases so much it all cannot be only siphoned through hydro turbines without breaking environmental limits. In Nordic countries hydropower producers are responsible for flood control in such situations. (Fingrid 2018, Fortum 2020, Energiateollisuus 2021, Hønsi 2019, Koillis-Satakunnan Sähkö Oy 2022, Länsi-Suomen Voima 2021, Motiva 2021, Mäkiharju 2012 15-24, Rahimi et al. 2019 41-52, Rummukainen 2012.)

During winter and early spring, the Nordic hydropower producers have to monitor the amount of snow, the water value of the snow and the upcoming outdoor temperature forecasts in preparation for the snow cover to start melting. Years that have thick snow cover with high water value stored in it require measures to be taken in advance. When the spring flood is forecasted to be heavy hydropower plants regulatory authorization holders usually siphon the storage pools, lakes and ponds to a level closer to the minimum environmental limit. This way the pools have more capacity to take in the water from melting snow cover and the increase in the water flow is not forced at its limits immediately (figure 2). During especially spring floods, portion of the water most commonly has to be siphoned through the pass-through hatches located in the hydropower plants. In such situations hydro turbines are usually running at their maximum capacity throughout the day and still some water needs to be siphoned through the hatches. That could be considered as wasted renewable electricity but the only way to solve such situation would be to expand the current hydropower plants with new or larger turbines. This would not be a sufficient option since strong spring floods are not a guarantee. In situations where the spring flood ends up very minor, the extra capacity or added turbines might go unused for a long periods of time and the previous capacity would have been fully adequate. (Fingrid 2018, Fortum 2020, Energiateollisuus 2021, Hønsi 2019, Koillis-Satakunnan Sähkö Oy 2022, Länsi-Suomen Voima 2021, Motiva 2021, Mäkiharju 2012 15-24, Rahimi et al. 2019 41-52, Rummukainen 2012.)

Other thing that supports the fact that the hydropower production capability should not be designed based on the peak hydrological situation is that the seasons with a heavy flood also affect the electricity prices especially in the hydropower dominant Nordic electricity market. During heavy nationwide spring floods almost every hydropower plant is running at their maximum production rate throughout the day. Since the hydroelectricity share in the Nordic countries is so vast, in situation where the hydropower production is close to its maximum production rate throughout the day and multiple days in a row, it can also result in lower electricity prices in the Nordic electricity market. This combined with high yield in wind power and the lowest consumption hours, most commonly during the night, electricity prices can and have gone even to a negative price value. In such cases the amount of electricity produced is so much higher than the consumption that the electricity consumers actually gain money via using electricity. Based on that to design the hydropower plants production capability to match even the highest hydrological situations is not always financially feasible. (Fingrid 2018, Harjumaa & Kokkonen 2021, Jantunen 2020, Kanerva 2012, Koillis-Satakunnan Sähkö Oy 2022, Ollus 2020, Parviala 2020, Rummukainen 2012.)

3.3. Producing and maintaining balancing power reserves with hydropower

As discussed before, the electrical grid needs balancing power to maintain stability with varying production and consumption. Hydropower is a great source of balancing power and can operate in every current balancing market. Operating in every balancing market means that hydropower is capable adjusting from daily to a yearly balancing power needs and is actually the only power source that also has the production capabilities to react from a second, to a minute to an hourly need. For example, in situations of unforeseen disturbances in the grid, hydropower covers 90 % of the balancing power need in Finland. The way hydropower plants are operated enables the production capability to be bid for every market in the same time. For example, if a hydropower plant with a P_{max} of 20 MW is sold in a day-ahead market to a 10 MW production for the 8 o’clock hour, that leaves 10 MW to be bid for other markets within the same 8 o’clock hour assuming there is enough water in the reservoir. If every bid goes through for the 8 o’clock hour the hydropower plant’s production could look something like the two examples expressed in the figure 3. (Energiateollisuus 2021a, Kemijoki 2021b, Åf-Consult Oy 2019 5-8 & 16-29.)

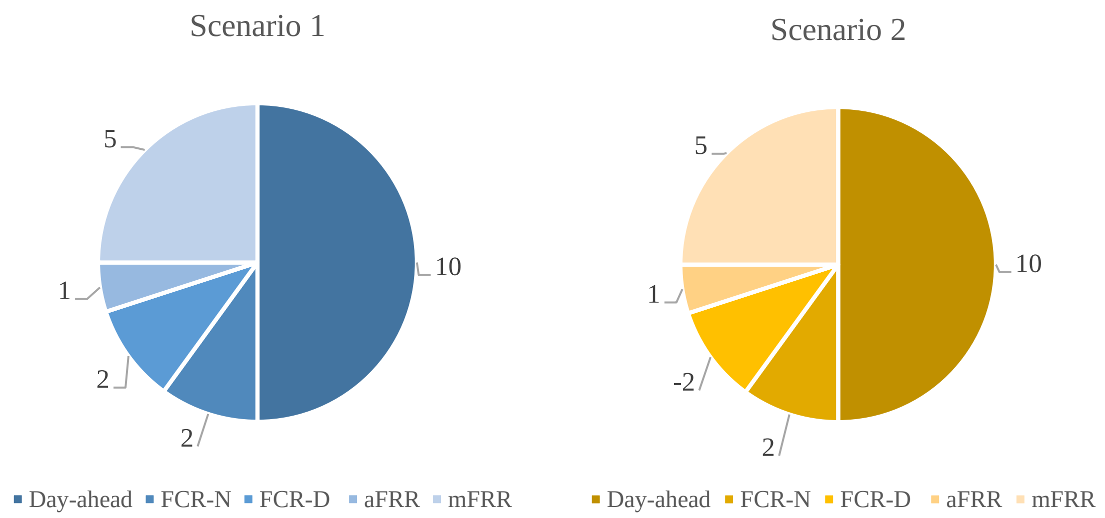


Figure 3. Same 20 MW P_{max} hydropower plant sold for maximum production in separate markets but with different scenarios (Pajunen 2022).

In the two scenarios in the figure 3 the hydropower plant is sold to its maximum production capability, 20 MW. In both scenarios the starting situation is the same, 10 MW has been sold in the day-ahead market. That leaves 10 MW reserve to be bid at different markets in scenarios one and two. In both scenarios, 2 MW of FCR-N reserve and 1 MW of aFRR reserve has been sold. FCR-N reserve can adjust both ways depending on the grid frequency, so out of the sold maximum production capacity of 20 MW, the hydropower plant could end up producing anything between 16 and 20 MW. FCR-D and aFRR reserves can be bid to adjust either up or down. The aFRR reserve in both scenarios is bid to adjust up. In scenario one a FCR-D up bid has gone through and in scenario two a FCR-D down bid. Even though a FCR-D down bid has gone through in the scenario 1, it does not free up more production headroom to other markets such as mFRR. So in practice the hydropower plant has a higher production capability, but the un-used capability has been reserved for the grid adjustments. Finally, in both situations 5 MW of mFRR up reserve has been sold to that particular hour. So in the end, both scenarios sold the same amount of production capability to the markets but will end up producing different amounts, scenario one 16 to 20 MW and scenario two 14 to 18 MW respectively. In the end the production level can be anything between these approximated minimum and maximum amounts. The variation between the minimum and maximum production will depend on the current balancing need in the grid. For example, FCR-D reserves will get activated only due disturbances as the name suggests, so the amount of actual FCR-D reserve produced could be just a fraction of the sold amount depending on the need. The variation for the aFRR and FCR-N reserves is dependent on the normal deviation of the grid frequency, since both of them get activated automatically via frequency meter obedience. The only reserve that does not get automatically activated based on frequency meters connected to the hydropower turbines is the mFRR. The mFRR reserve bids sent by hydropower producers get only activated if necessary by Fingrid and then the hydropower producers have to produce the agreed upon amount on the agreed upon timeframe. With all reserves, the hydropower producers will get compensated based on the maintained capacity. In situation where hydropower producers are unable to maintain the agreed upon reserve capacity they will end up compensating the unmaintained amount to Fingrid. (Fingrid 2021a, 2021c, 2021d, 2021f, 2021l, Energiateollisuus 2021a, Kemijoki 2021b, Åf-Consult Oy 2019 5-8 & 16-29.)

Maintaining the FCR reserves can be a bit challenging while planning the water use and estimating the value of water. When bidding the FCR reserves to the reserve markets hydropower producers need to be fully committed to produce the offered amounts. For example, for tomorrow every hour of the day couple of megawatts of FRC-N, FCR-D and FCR-D Down reserve is sold to the market. Then some large disturbance happens in a grid during that day resulting into deficit of electricity in the grid and the FCR-D and FCR-N reserves adjusts the production up by a couple megawatts for the whole day, while FCR-D Down will not get activated at all. Such situation would result in a lot more water use. The water that the reserves used will have a value based on the prices of the FCR-D and FCR-N reserves, but that price needs to be for example higher that the next day’s spot price in order to maximize the value of water. In most cases that is not the reality since the prices for hourly market of FCR-D and FCR-N are usually from couple of euros to tens of euros. However, if the same amounts of reserves were to be bid for the day after that and some opposite disturbance happens where there is a constant surplus of electricity in the grid resulting into the FCR-N and FCR-D Down reserves being activated for the whole day. That results into a lot less water use than planned and creates additional value since the unutilized water can now be bid again to any valid markets. Based on that a hypothesis can be made that in a long run the up and down regulating reserves will always end up evening out each other’s water usage resulting in no additional water use. Same situation applies to aFRR Up and aFRR Down reserves. Based on that hypotheses all the capacity that is not sold to spot, intraday or mFRR markets should be bid to reserve markets. In such situation the timeframes of bidding times in each market becomes an issue. (Deman et al. 2020, Fingrid 2023, Fingrid 2021a, 2021c, 2021d, 2021f, 2021l.)

For example, aFRR reserves are bid before even day-ahead results in Nordic electricity market so the aFRR market has a lot of optimization potential especially in uncertain water situations. Then the FCR reserves are bid after the day-ahead results but in order to leave some room for possible intraday and mFRR market trades all the free capacity is not to be fulfilled with FCR reserves. Although, filling up all the free capacity with FCR reserves could be beneficial in certain situations, for example there is no guarantee that the next day's intraday prices would be favorable for the current water situation or that Fingrid needs any mFRR activations during the next day. In such situations not bidding the excess capacity to FCR markets would be unbeneficial but foreseeing such situations accurately is near impossible. Such situation however can be seen accurately with history optimization, highlighting the need for a post optimization tool.

Maintaining capacity in the mFRR market is highly dependent on the current water situation. As mentioned before mFRR market differs from the other balancing capacity markets with the time frame of bidding and that Fingrid activates the bids manually. Since the hourly market closes just 45 minutes before the possible delivery hour hydropower operators should have a good understanding of their current water situation and bid the adjustment capacity accordingly. In practice this would mean that if the hydropower operators storage pools have a shortage of water the mFRR up capacity would be bid with a higher price since the capacity might have to be bought back in the near future and the mFRR trades need to cover the expenses of those intraday trades. Same applies in situations where the water situation starts from a good level but a continuous trade of mFRR up adjustment lasts for a couple of hours draining the storage pool in a higher rate than what was planned for the day. In such situations the hydropower producers might have to increase the bid prices on an hourly basis since the water value increases as the storage decreases and the risk of acquiring the needed capacity back with a fair price also rises. Same principles apply with the mFRR down trades, just in reverse. When the storage pools are empty and there is no interest lowering them from the current level the mFRR down capacity can be bid on an expensive price, meaning that the hydropower producers buy capacity from TSO's. Then again, if the storage pools are full the mFRR down capacity could be bid in a very low price. There could be situations where the storage pools are so full that if some mFRR down capacity is required and the production rate is decreased the environmental permits could be infringed. In such situations the pricing might go to negative since the production rate needs to be constrained and some of the water has to be siphoned through the bypass hatches. When running water through the bypass hatches that can be considered wasted renewable energy since some of the storage is released not producing any electricity. In such situations a negative price of mFRR down capacity is needed, meaning that the TSO's end up paying the hydropower producers for producing less electricity. (Brijs et al. 2015 53-60, Fingrid 2019, Fingrid 2021b.)

When adjusting or deciding the pricing of any bid in any market hydropower producers along with every one else participating in electricity markets needs to be mindful of their actions. When deciding or changing the price in any market, whether it's in day-ahead-, intraday-, FCR-, aFRR- or mFRR market, the set price needs to be justified. In practice this means that every price that every balancing market participant bids needs to have some reasoning behind it. This is mandated to maintain a transparent and fare market for everyone. For Finnish electricity market participants, the fairness of the market is constantly monitored by Finnish Energy Authority and Nord Pool on Fingrid's behalf. These market surveillance parties make sure that every electricity market participant plays by the same REMIT (Regulation on Wholesale Energy Market Integrity and Transparency) rules. In short how the market surveillance operates is that they see all the trade patterns of the market participants and each time some party differs from their patterns the market surveillance can send a request where they question for the reasoning behind the pattern breaking trades. Based on the answers of the market participants the matter can conclude there, have further investigations or even results in the end on some sanctions. To help resolving and justifying the current and upcoming price levels of hydropower production, tools such as post optimization could be utilized. The tool could suggest that the past prices were too high or too low in certain markets for the current hydrological situation giving the market participants some added validation for the price adjustments. (Energiavirasto 2022a, 2022b, 2022c, Fingrid 2022.)

4. Current and upcoming role of hydropower in frequency control

The balancing electricity for frequency control in Finland is imported from other countries, produced via hydropower or produced using fossil fuel-based power sources, such as combined heat- and power plants (CHP). Although many CHP-plants are mainly using renewable fuels such as wood chips and sawdust, the actual balancing capacity, especially in the peak load reserve plants, is mainly relying on fossil fuels such as coal, oil and natural gas. The big challenge in the future is going to be ensuring the Finnish grid balance with decreasing dependency on imported electricity and fossil fuels. Producing electricity without fossil fuels is not the problem. For example, the share of renewable energy produced has kept increasing in Finland throughout the years and in 2021 54 % of electricity produced was fossil free. The problem is the type of production capability. Some renewable energy sources, or more specifically wind- and solar power, can end up hurting the grid balance more than helping it in certain situations and thus, increasing the dependency of fossil fuel operated reserve power sources and imported balancing electricity. (Energiateollisuus 2021a, Kvick 2020 10-14, Känsälä & Hammar 2018 3, Mansikkamäki 2021 3-6.)

The issue is not with the varying production capability of solar- and wind power per se, but with the lack of production flexibility. Every hour there is an estimate on how much wind- and solar power the grid will receive, but the actual amount is impossible to foresee accurately. For example, there can be situations created just by unpredictable weather where there is more wind- and solar power available than the grid can accept, and in worst scenarios the wind turbines or solar panels must be disconnected from the grid momentarily. These types of situations are more common in countries where there is a lot more wind power production in condensed areas, such as parts of China and United States. However, it means that in some situations there would be renewable electricity available, but it is not accepted to the grid because other non-renewable sources are unable to limit their production either enough, fast enough or cost efficiently. In Finland, these types of situation where wind- or solar power sources must be disconnected from the grid do not occur that often because the share of wind power (11,7 %) and solar power (0,4 %) from the total production is fairly small and the windfarms are spread out through the nation. However, if the planned wind power projects in Finland go through in the upcoming years the total capacity could about double. Doubling the current amount of wind- and solar power would mean that also the frequency control capacity in relation to them must also be doubled, yet again increasing the dependency on imported electricity and fossil fuel operated reserves. (Energiateollisuus 2021, Energy Institute 2018, Huuki et al. 2021 18-24, Kvick 2020 10-14, Penttinen 2011 3-7 & 28-29, Känsälä & Hammar 2018 3, Sweet 2021.)

This is where hydropower comes in. Hydropower, being fairly cheap to produce after initial construction costs, is not only one of the most important frequency control operators, but the most important renewable one. Hydropower is unique in a way that it is the only technology currently capable operating in every single frequency control market, from fast response reserves to a yearly ones and from increasing balancing electricity production to decreasing it. Hydropower is also unique when comparing to all the other balancing operators in a way that the turbines can be started from a complete stop to production and otherwise in just mere minutes. Depending on the environmental permissions different hydropower plants have different operating restrictions. Some of the plants could be operating based on the rivers natural runoff and some could have even large storage pools allowing wide flexibility to produce more or less electricity depending on the current need. However, even the runoff river plants can participate in the balancing market, but only by offering to produce less energy. In these cases, the amount of water going through the generator is limited or even temporarily seized and bypassed through the hatches. Seizing the energy production and bypassing the water is not affecting the current river runoff in anyway which allows such way of operation. In these type of a situations the case is similar to disconnecting solar- or wind power from a grid because of electricity surplus, so there would be renewable energy available, but the grid is unable to accept it. The main difference is that in these situations' hydropower turbine can be limited to a certain level of electricity production where solar power cannot and with wind power it is not financially feasible because some windfarms sill operates with fixed compensation on the amount of electricity they produce. Blame however for such a waste of not producing renewable energy goes again for inflexible fossil fuelled power sources that cannot be efficiently operated on low enough levels to meet the current consumption. At the same time these type of cases also highlights the flexibility of hydropower and the demand of it. So, the demand of hydropower's flexibility in frequency control is already high and Finland with increasing base production capacity with Olkiluoto 3 and expanding the fleet of varying power sources such as wind- and solar power, the frequency control capability is only going to get more critical. In hydropower's case this could mean that the production focus starts leaning more on the frequency control market from the current focus, spot market. This kind of a change in the production philosophy will be hard to validate. Because of that, a long-term optimization tools with history data collection might be the ones that reveal such a need for a change in the system (Lönnqvist 2017 40-41 & 86-87, Muikku 2018 34-37, Åf-Consult Oy 2019 20-29 & 32-36.)

There are also various other projects and research trying to discover the best solution for this evolving frequency control need such as expanding demand-side flexibility to commercial and residential applications, storing electricity, and creating hydrogen from water though electrolysis using surplus electricity. The main advantage of hydropower when comparing to the upcoming solutions is that it is already proven and capable to operate at every current frequency control market. After saying that, there is still room for improvement. For example, UPM Energy has invested into ultra-capacitor power system that was recently constructed and now in operation. The project was a true pilot since this is the first time ultra-capacitors are being integrated with hydropower production, and more specifically to frequency control using hydropower. Ultra-capacitors are electricity storages that can release large amounts of energy within milliseconds and in this case are operated via optimization- and control unit that follows the grid frequency. When combined with hydropower plants that operate in frequency control market, they will reduce the need of rapid adjustments of the turbine power, since the energy can be either released or stored from the grid into the ultra-capacitors. By reducing the need of fast reactions of the turbine the ultra-capacitors can reduce the wear of hydro turbines. If the now patented ultra-capacitor project becomes a mainstream application in all hydropower plants, that will only further highlight the need of hydropower optimization for efficient and feasible operation in the long-term. (International Renewable Energy Agency 2020, Mason et al. 2019 1-3, Mansikkamäki 2021 29-30, UPM 2021a, Åf-Consult Oy 2019 32-36 & 39-40.)

5. Post-optimization tool

The purpose for creating this post-optimization tool is to maximize the value of water in the future. The purpose for this tool is sort of backwards when considering the working principle of this tool. The tool is for post-optimization and the optimization happens purely with history data. The tool will not give any suggestions on how to use water for electricity production in future, but instead tells you how it should have been used in the past for optimal result. From there it is possible to see for example the market areas where the most value is lost, learn form that data, and improve upon those areas in future.

The main goal for the optimization tool is to post-optimize the hydropower production of the past 7 days. The tool will be built in a way that the time horizon can be expanded, decreased and modified based on the users liking. That allows also some long-term optimization, for example weekly, quarterly or annually. Post-optimization happens purely in the history and uses only perfect data. Perfect data means that there are no gaps in knowledge and the future will not be considered. Post-optimization tool will be created in ABB Oy developed Vtrin-software using Economic Flow Network -interface (EFN) (ABB 2022). All the tools and education required for the software was provided by UPM Energy.

ABB advertises the capabilities of their software in a following way: “Calculate the optimum use of supply resources to meet the predicted consumption at minimum total cost”. That sentence contains the core target of this post-optimization tool. The tool will be constructed from multiple logical sub-processes that will be linked into each other and as a result gives what would have been the optimal way of operation. The optimization calculations behind the tool utilizes mixed-integer linear programming (MILP) to solve the optimal result (ABB 2022).

The process created for this tool in this project is an imaginary one. It however has some similarities and references to actual operational hydropower plant processes, allowing comparisons between selected and fitting real-life data and the optimized results that will be the end-result of this work. The data that the tool will receive is real-life data that has been multiplied with some undisclosed variables to make it differ from the actual numbers that are determined unpublishable. The given data will also be the data the optimized results will be compared to.

5.1. Planning

For the purpose of this work an imaginary process was created that would have two hydropower plants at a river X (Figure 2). Both hydropower plants have one turbine. The river is set to start from a lake Y, that in the case of this work can be considered as a simple storage pool with a certain volume. Storage pool will create some leeway for the production necessities of the hydropower plants and allow optimization. Storage pool will work with strict limits, meaning that when it is full, optimization has to run the water through hydropower plants and when it is empty, no water can be used. There are no storage pools in between the two power plants, so basically the same amount of water that goes through the hydropower plant 1 (G1) also has to go through the hydropower plant 2 (G2) (Figure 2). The production capabilities of the hydropower plants are not equal, the main difference being the head. The G2 plant is set to have a slightly bigger head than G1, resulting on average 20-25 % higher electricity production capability. This design choice was made to create variance to the overall optimization process. Otherwise it could be considered that the G2 would not have participated into the optimization process at all because if being identical and having identical amount of water to use, no variation could be created.

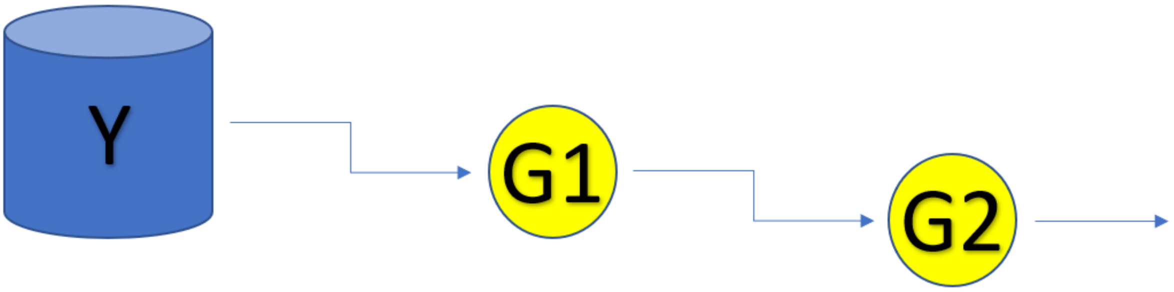


Figure 4. River X, starting from the lake Y and running through the two, G1 & G2, hydropower plants (Pajunen 2022).

There will be an incoming water flow variable into the lake Y that will raise the level of the storage pool if water is not run through the power plant G1. Optimization will be given a starting level of the lake Y in the beginning of the 7-day period, incoming water data for the lake Y and the amount of water that was siphoned from the lake Y through the power plants during the past 7 days. The power plants will have a maximum and minimum limits on how much water can siphoned through the generator when it is on and how much electricity is produced with each amount of water flow. Based on that data the optimization will run the same amount of water in the same amount of time but in the most optimal way it determines without breaking the storage pool limits. In cases where the incoming flow to the lake Y is so large that the generators cannot keep up, a possibility to run the water through the bypass hatches located at the G1 and G2 is also added. The bypass hatches will allow optimization also during possible flood periods.

To determine the amount of water to be siphoned at an optimal time the water will have to be given a value. Value of water will be determined using the hourly price data of electricity of the past 7 days, from spot prices to hourly Elbas market price and from reserves to balancing electricity. Out of all the price data the optimization recognizes the highest yield for each hour and stresses the most water to be utilized during those hours within the pre-set limits laid out in the last paragraphs. The value result for the water could be any mixture of price data between all the markets. As the final result the post-optimization tool will give a comparison between how the water was run during the past 7-days and how it could have been run to maximize the value of water.

5.2. Methods

First, the tool has to be given some operating restrictions. First operating restrictions to apply are the storage pool's maximum and minimum values for water level so the tool will see when and how it can siphon the water. The maximum and minimum limits were modelled in a way that the tool can never break them resembling environmental limits. The storage pools limit in this work could be set to be anything, but in real applications the limits would be the environmental limits set in the environmental permit. For this tool to be comparable the water level and environmental permits maximum and minimum values were taken from an undisclosed real-life data that is also publically available at the Finnish Environment Institute, Syke. However, the hourly water level data would not be applicable for the tool since after optimization, the amounts of water and the hours of operation might vary a lot based on what the tool determines to be the most fitting. The water level data would only be used in the end when comparing the water usage of the optimization model and real-life applications. To allow the variation in the storage pool, the water usage was represented via a virtual water level calculation of the storage pool Y. To calculate the variation of the virtual water level, the tool needed to be given volume and pool coefficients. The working principle for both, volume and pool coefficient, were obtained from an already existing optimization model and modified to fit this model and data. So at that point the storage pool had operating limitations and it needed incoming and outgoing flows. Again, the data for both were obtained from real-life applications. The incoming flow would tell the optimization how much the virtual water level calculation would rise if any water would not be siphoned through the hydropower plants. The outgoing flow would then tell the tool how much water it can utilize in the set time period. That would also be one of the key variables to keep an eye on throughout the process, since the amount of siphoned water needs to be same in both, real-life and optimization model for the results to be comparable. In the end both, water usage and the virtual water level calculation should end up in the same value as the real life data for this tool to be comparable. Before the overall water usage could be optimized, the hydropower plants needed to be modelled and the water needs to be given a value.

The first issues to solve with the hydropower plant modelling are the non-linear energy generation functions. As explained before, the peak power of a hydro turbine is dependent on the height difference of reservoir water level before the turbine and the tail water level after the turbine. Depending on the height difference, the required water flow through the turbine to produce certain amount of power can vary a lot. For the tool to understand such a dependency, height-, flow- and energy fragments needed to be created. Each fragment includes turbine specific data on how it operates with certain height, flow and energy level dependencies. For the purpose of this work a pre-calculated fragments were obtained from an already existing optimization model to lower the risk of overall troubleshooting. After testing the pre-calculated fragments some issues were detected with the compatibility. That meant that some of the fragments needed to be recalculated or modified to fit and behave better. One example of a recalculated fragment was the relation between the changing head and the maximum power output, P_{max}, for the G1 plant. To determine the relation between these variables, data from an undisclosed operational hydropower plant was obtained. The actual values of the operational hydropower plant are hidden in the Figure 3 but it describes the relation between the head and P_{max} within a one-year span.

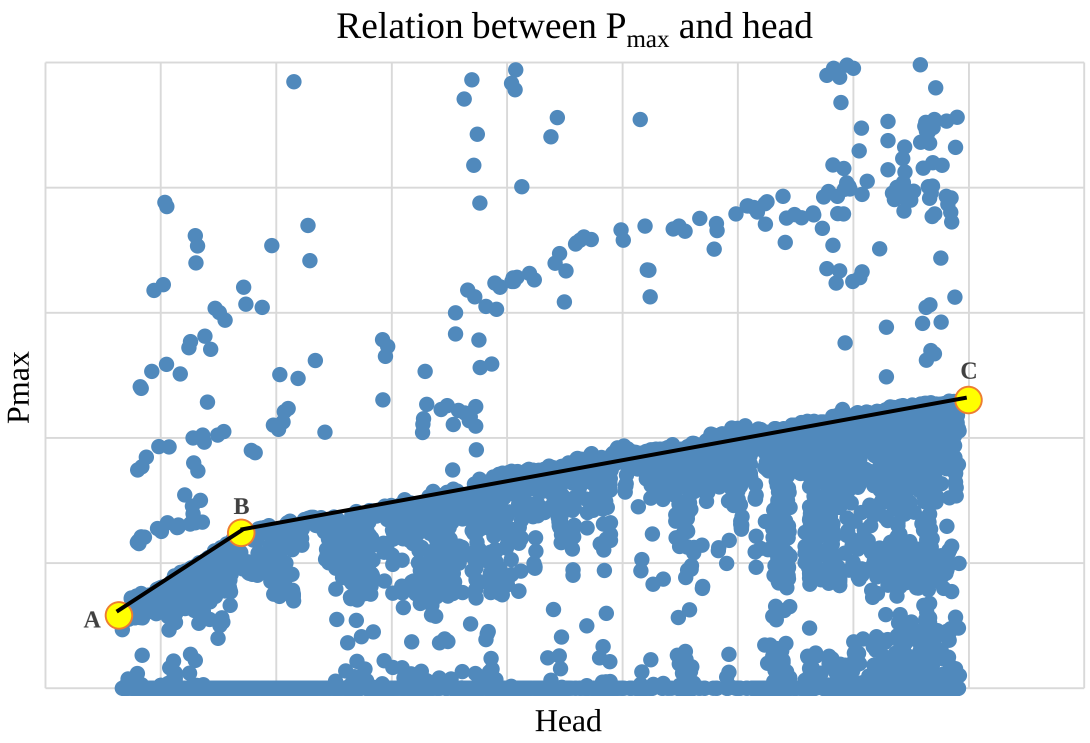


Figure 5. Relation between P_{max} (y-axis) and head (x-axis).

Based on the Figure 3, two distinct slopes can be seen: from the point A to B and from the point B to C. Based on those slopes two linear equations were created, again from A to B and from B to C. With those two linear equations applied, the optimization tool can always determine what is the maximum power output with the current water head for the G1 plant. The G2 plant did not get similar head dependent production fragments because the working principle for that plant was based on the amount of water coming in from the G1 plant and G2 having to always run just that amount. The G2 plants maximum production capacity was added as a fixed maximum value. The tool would always calculate the current production of the G2 plant based on the pre-calculated production fragments that included the turbine specific production capabilities with any amount of runoff from the plant above. With the maximum operating values set to the turbines, the optimization tool always sees the maximum amount of water that can be siphoned through the turbines. In situations where the amount of water coming from above is larger than the turbine can siphon, a portion of the water has to be siphoned through the bypass hatches. Other way to avoid such situation would be to siphon more water beforehand so the storage pool has more leeway before closing on the environmental permit limits and the optimization should always follow this type of a working principle. Bypass hatches were modelled in a way that the water will not have any value when siphoned through there, just like in real-life. After modelling the bypass hatches, an unexpected optimization philosophy was found. During peak electricity consumption hours when the prices were also high, the tool understandably wanted to operate the G1 plant at its maximum production capability, but on top of that it also wanted to bypass a lot of water through the plant. The reason why the optimization wanted to bypass large amounts of water through the G1 plant was to push the G2 plant at its maximum production. Such situation was possible because the G2 plants production capability only follows the incoming flow and in situations such as this one the incoming flow was so high the G2 plant was in its maximum production. The optimization tool was not wrong with such type of a production philosophy being more profitable, but the model was not able to consider one flaw that happens only in practise. As mentioned before, in many hydropower plants, the bypass hatches are located near the actual plant where the turbine is. When the bypass hatches are opened it will divide the water flow before the plant and have an effect on the head. So the tool was correct when it wanted to operate the G2 plant at its maximum capacity, but in practise that would mean taking some losses on the P_{max} of the G1 plant, evening out the overall benefit. Based on that, a cost was given for the models bypassing to avoid such situation. The costs work very simply in the optimization model, all the water that was run through the turbines create price data specific positive values and all the water that is run through the bypass hatches create fixed small cost negative values. This was done just to make the overall estimation of the optimization efficiency more simple, but the topic definitely needs more attention in the future.

The P_{min} values were taken from the same undisclosed data source used for the P_{max} calculations. The P_{min} values were modelled to work in a way that the turbine cannot operate between the set P_{min} value and zero production. That means that the optimization can only start the hydro turbines to a production above the set P_{min} value. So for example if the turbines minimum operating value is set to be 5 MW of production, the optimization tool cannot set the turbine to produce just 2 MW even when the end results could be even more optimal that way. The hydro turbines were also modelled to work in as a pair. That means that when the G1 plant is on, also the G2 plant needs to be on. This was done in this way because the G2 plant does not have a storage pool in front of the turbine, so the water that is coming in from G1, always has to be also siphoned through G2. In real life situations there would be some delay between the two plants as the water travels from the first one to the second, but in terms of this type of an optimization and with just two production plants, it was not relevant to be added to the optimization model. Now with all the turbine fragments intact, the tool can always determine the current state of operation and sees how much water needs to be used to produce certain amount of power.

After those restrictions the next step is to create value for the water. Value of water will depend on the electricity price data on different electricity markets. First electricity price data from markets to be added to the tool are the Spot prices form the Day-ahead market, the hourly market price from Elbas and the hourly price data of balancing power from Fingrid. These three are the first to be included because those are the ones that actually use the water reservoirs. What is meant by that is the fact that when offering reserves, such as FCR or aFRR, only the capacity is bid and the actual activation of the reserves and the related water usage is never a certain. So, every time the tool sees it profitable to sell the water to any of those three before mentioned markets, it will also have to implement the production plans exactly how it sold the water. For the tool to determine which market to favour at which moment, the price data had to be imported to the tool. First the tool was only modelled to sell the water to all the markets in the most beneficial way, but later it would also be modelled in a way that it could buy capacity back from the market when seen beneficial.

Spot prices were pretty easy to add to the tool since all you need is the pre-released price data of the upcoming day available to the public. What made it also easy with the spot prices was the fact that there were no external limitations, other than the optimizations own ones, on how much energy could be sold into that market with that price. What is meant by that is the fact that there were no quantity limitations, for example that only 10 MW could be sold for this price. So, in situations where the spot price ended up being the highest when compared to all the markets the optimization would sell all the capacity to there. Elbas prices on the other hand have comparatively more limitations. The Elbas prices were a bit harder to implement since they are constantly changing. One way to do it could be to use the average price of sold electricity on the concluded hour. That represents the average price of the hour the best but does not guarantee that the price would have been exactly that for the exact trade amount. That is why a decision was made to utilize the data on so called ‘leftover bids’. Leftover bids can be considered to be the most valuable open bids, at both buy and sell sides, that were not traded at the end of the trading hour. With that data it can be more accurately represented that at least the bids with those prices and amounts could have been traded. The left over bids were added to the model in certain amounts of 5 MW steps, each step having price specific data within. The amount of 5 MW steps added corresponded to the undisclosed maximum production capacity of both hydropower plants combined. In cases where the highest leftover bid could have been for example 100 MW, all the added 5 MW steps could have been traded with the price that was connected to the 100 MW bid. In cases where the highest bid was only 1 MW, the optimization model would get the price for that 1 MW but the rest of the steps would have different, lower prices, according to the bids. So in some cases where the leftover Elbas prices would be higher than any other market price, the optimization model would determine that it would have been most profitable to sell all the production capability in Elbas on that specific hour. However, if there were only a few megawatts offered for highest price when compared to the other markets, the optimization would sell only a fraction of the capacity there and the rest of the capacity to other markets if profitable.

After the tool knows how to sell the water to spot and Elbas markets, the price data from balancing capacity markets can be added. The price of balancing power was determined by using the balancing electricity price. Balancing electricity price is determined based on the highest balancing bid activated on the markets. In case no balancing bids are activated by Fingrid, the price of the balancing power is based on spot. This in the case of optimization means that every time the balancing electricity price is higher than spot the optimization model sees best to sell all the capacity to that market. The problem with that are the different timeframes of trading. The spot trading happens on the day before and the activated balancing capacity bids come during the actual production hour with 15-minute reaction time. In practise if an electricity producer was to save all the capacity to balancing power market they would have to bet first on not selling any production to spot and second, on the next day having some additional electricity need in the grid. So, in real life such way of operation would be huge risk taking especially if the storage pools are small and some water has to be siphoned daily. The balancing need in the grid could also be only downwards, meaning a need for less electricity production. In the case of this work however such way of operation can be allowed since one of the key aim of this work was on highlighting the unutilized market potential.

So, the tool knows how to sell water with the optimal value. To make the end result even more optimal, the tool needed to be modelled to know how to also buy water. The markets are the same for buying water, spot-, Elbas- and balancing markets. The way buying water makes the end result even more optimal is based on the time and price differences between the markets. For example, when working perfectly, the tool sees an opportunity to sell all the production capability to spot, but not necessarily because the price was optimal, but because the tool sees that it could buy some of the sold production capacity back from the Elbas market with a cheaper price when comparing to spot. Such trading is also possible in real life creating added value. The tool could also see that after buying some of the sold capacity back it should also adjust the production down based on the highest accepted price for balancing power in Fingrid. So in situations as this the tool might sell all the production capability to market but end up buying or adjusting all the production off. With this way of operation, the tool can make some added value and save water for the peak electricity consumption hours with higher prices. Such way of operation in real life would be risky and hard to execute in constantly profitable way, but with perfect information the tool is able to do so. The final thing to add to the tool are the reserve markets. The reserves added were FCR-D up and down, FCR-N and aFRR up and down. Price data for every reserve was obtained from hourly reserve markets. In real-life reserves have a risk of creating costs in terms of fines if the whole amount of sold reserve capability cannot be adjusted accordingly for some reason. In the tools case these fines are not applicable since it only sells the capacity to the market when it is sure it can produce it. Figure 6 shows the simplified input data and working principle of the tool.

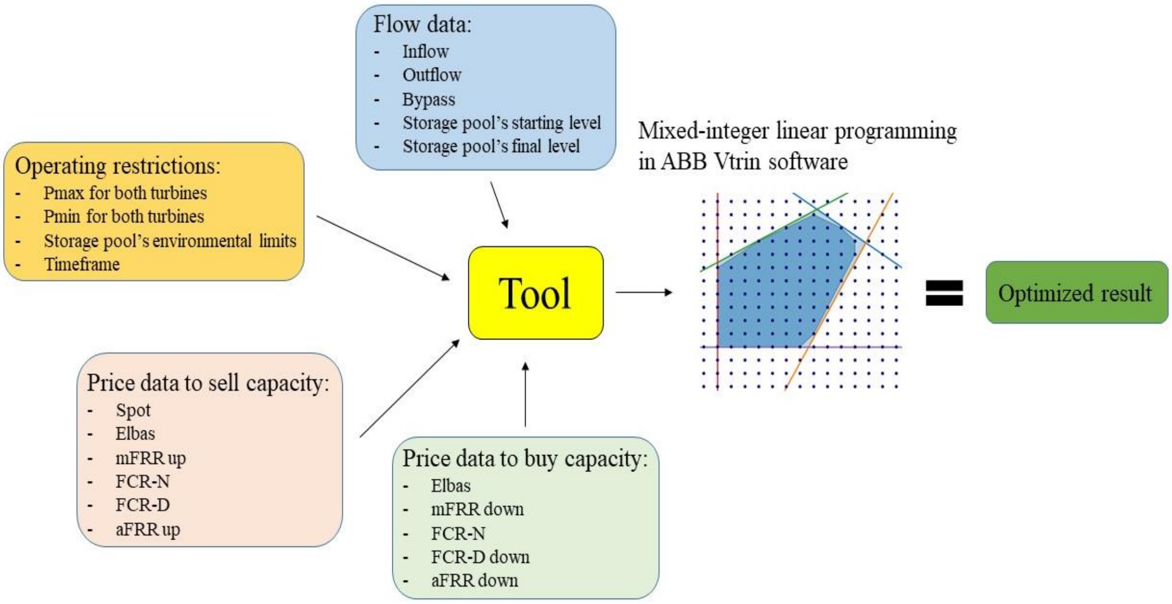


Figure 6. Simplified input data and working principle of the tool

6. Tool’s calculation results

Some of the data in these calculations cannot be shared publicly, thus some of the upcoming figures will not include any scales or concrete values. The results are demonstrated in some cases as percentages and in other just as in visual comparisons without any reference scaling. The lack of concrete values in the calculation results however does not hinder the readability or comparison ability of the tools effectiveness.

First thing to check from the calculations is that the tool utilizes the same amount of water during the set 7-day period. The tool sees the amount of water in cubic meters the hydropower plants utilized in the real life scenario and based on that data it will siphon it in the optimal way. Figure 6 shows the amount of water in percentages on both what real life and the tool used in the set 7-day period. From the figure 6 it can be seen that the tool utilized slightly less water than what was siphoned in real life.

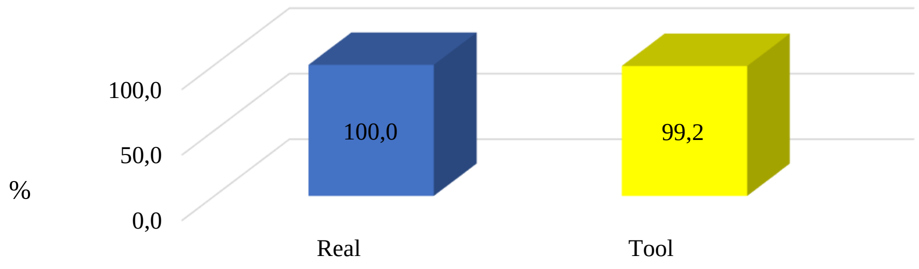
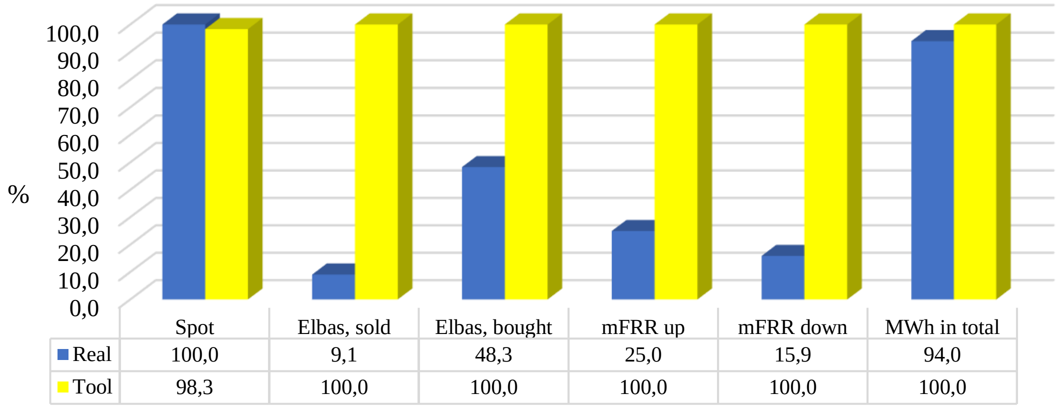


Figure 6. Comparison between the amounts of water in percentages siphoned during the 7-day period.

This could be because of the set P_{max} and P_{min} values restrict the utilization of water a bit. For example, the tool sees that even if it was to start the hydropower plants only for an extra hour with minimum production, it might then use more water in total than the real life scenario and thus, cannot do so. If the amount of siphoned water would need to be exactly the same the tool might have to siphon the missing water through the bypass hatches to match the numbers, and as mentioned before, bypassing the water was set to have a small fine, meaning that if some water was bypassed, the overall scenario is likely no longer optimal. In this situation error of a less than a percent is acceptable and rest of the comparisons can continue.

First things to compare are the amounts of MWh’s sold to different markets. MWh comparisons can be seen from the figure 8. The first market where the production capacity is sold is the Spot market. When comparing the amounts of MWh’s sold to Spot market, both tool and the real life scenario are quite close to each other (figure 8). The first big difference can be seen in the amount of MWh’s sold in Elbas market. With the Elbas prices the tool saw fit to sell over 90 % more production capacity to Elbas than what was sold in real life. In situations such as this where the amounts of production capability sold in Spot market are quite close, such a large difference in sold Elbas amounts can be only explained by the tool seeing it fit to buy some of the production back on a cheaper price. Otherwise the amounts of utilized water could not match. Buying the capacity back from Elbas on a cheaper price is also exactly what happened in this scenario. The tool bought over 50 % more production capability back from the Elbas market when compared to the real life situation (figure 8). More on this topic in the end of results when comparing the value creation of both scenarios.



	Spot	Elbas, sold	Elbas, bought	mFRR up	mFRR down	MWh in total
■ Real	100,0	9,1	48,3	25,0	15,9	94,0
■ Tool	98,3	100,0	100,0	100,0	100,0	100,0

Figure 8. Comparison between MWh produced in percentages for different markets during the 7-day period.

Based on mFRR data the tool also saw profitable to adjust the production up 75 % more and down 84 % more than what was adjusted in the real life (figure 8). The amount of down adjustment being the second largest difference between the scenarios can be explained with the sold amounts in Elbas. Since the tool is working with a perfect information, it is able to oversell the production capacity to the market because it sees that it can adjust it down in the same hour or later on with a cheaper price. This is exactly how the tool was designed to work, highlighting the unutilized market potential.

The last bars in figure 8 are the most important ones when talking about comparability. After all the sales and buys during the 7-day period are calculated together the tool ends up selling 6 % more energy to the market than what was sold in real life scenario. Based on the figure 8 it can be determined that the tool sees that it can produce more energy with the same amount of water than the real life situation. Since the amounts of water utilized are close enough to be equal, the reason why the sold production amounts variate a bit from each other can be traced back to the re-calculated energy fragments shown in figure 5. These fragments are extremely close to being true, but in a 7-day span the difference between the real life scenario and the optimized one gets multiplied. The overall MWh production difference per machine per hour ended up being very minor after calculating it. The actual number of difference will remain hidden in order to keep all the delicate information disclosed. Some of this difference however came also from the fact that the tool was more efficient keeping the waterbed high and thus increasing the head, efficiency and overall production capability. At this stage, the difference between the produced amounts can be accepted but it will have to take into account when doing value creation comparisons.

Next results to be compared are the hourly MWh divisions during the 7-day period. In figure 9 the hourly data is shown on how the production divided during the 7-day period and to what market the production was sold each hour. The scale in both figures is the same to enable visual comparison. Same figures are also available in larger and more readable form in appendixes 1 and 2. The first thing that appears from the figure 9 is that during the two scenarios, there was only a brief moment close to the end of the 7-day period when both scenarios had both hydropower plants off production at the same time. Other than that the tool would have kept the hydro power plants on production more often and on average lower production while on when comparing to the real life scenario.

Both scenarios adjusted their production down and bought some production capacity back from Elbas during the first half of the figure 9. The most notable difference there is the value creation of the tool. The tool sold much higher production capability to the spot market and then adjusted it down with a cheaper price. Both scenarios also adjusted their production up and sold some production capacity in Elbas three quarters in the figure 9.

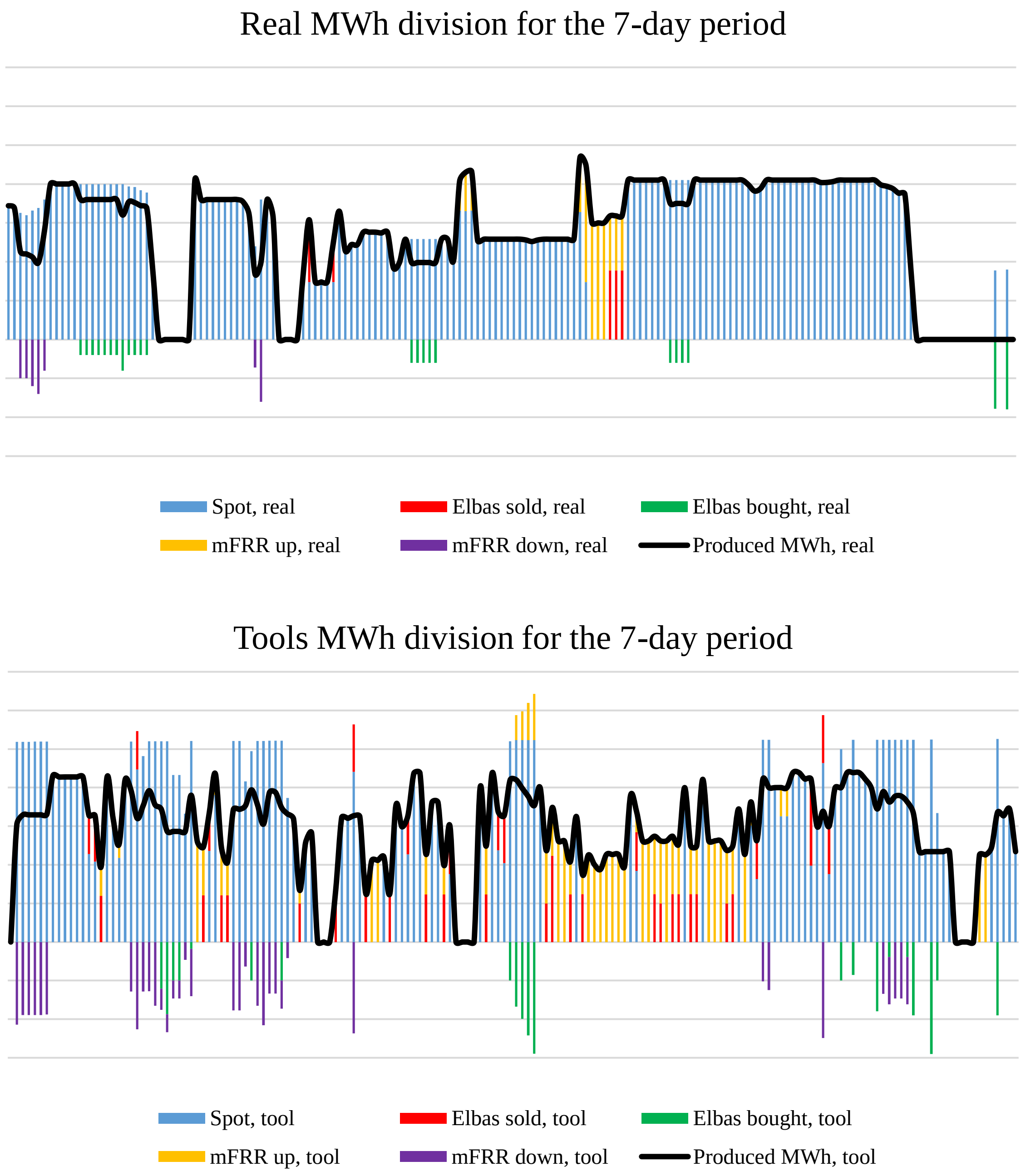


Figure 9. Division of real and tools produced MWh in different markets during the 7-day period.

The most notable similarity there is that in both scenarios the hydropower plants were planned to be off production based on the Spot and Elbas sales, but the mFRR up prices were beneficial to keep the power plants on production during that time. That is also the main difference when comparing the productions three quarters in the figure 9. Where in real life there was an 8-hour period of mFRR up adjustment and some Elbas sales, the tool saw beneficial to adjust up and sell the capacity to Elbas almost the whole third quarter. The last important detail that comes out from the figure 9 is that right in the middle of the tools graph there is a 4-hour period where the tool saw beneficial to first sell too much capacity to Spot market, then buy some of that capacity back from the Elbas market and finally, adjust the production back up a bit from the mFRR market. Such scenarios and additional value creation possibilities are exactly what this tool was designed to highlight.

When comparing the two MWh division graphs side by side in figure 10 it can be seen that while in production the graphs follow similar overall patterns throughout the first half of the 7-day period. Main difference during the first half are the hours when the production was seized and the peak production hours. Other than that the graphs behave close to each other on average. In the second half the difference is more pronounced. Right in the middle of the graph there is a big difference between the peak production hours of the tool and real life scenarios. Where in real life there were two distinguished sharp peaks in production the tool saw fit to produce a wider production peak in the middle of the peaks of real life. After that the tool saw fit to produce on average a lot less electricity after the peak and actually move some of that production capability to the end of the graph where the real life scenario was seized for a longer period of time. When comparing side by side the production division graph reveals another interesting find. Just left from the middle there is a period where the tool saw fit to seize the production but in real life that same period was the second highest production peak that also included some mFRR adjustment up (figure 9 & 10). Based on such behaviours it would be interesting to go back and see the actual price data and analyse what caused such a difference.

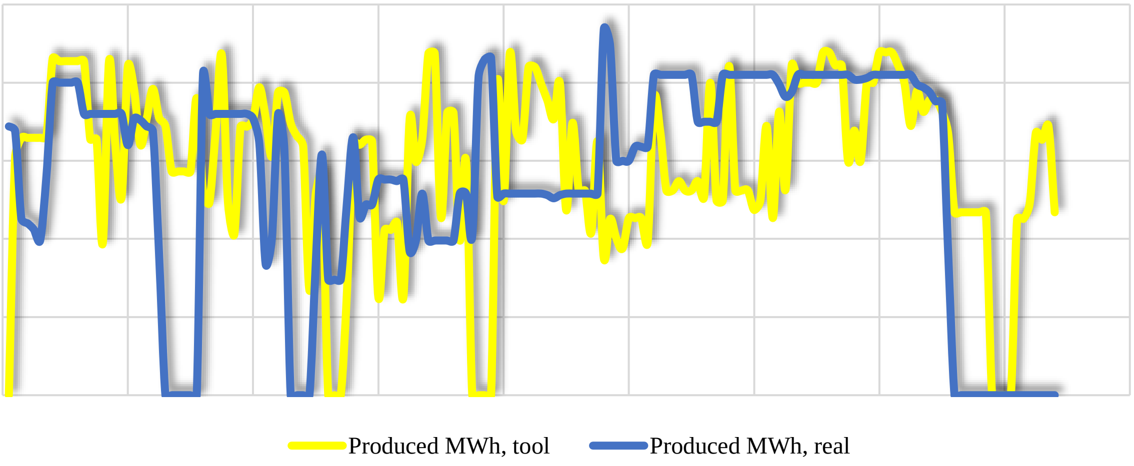
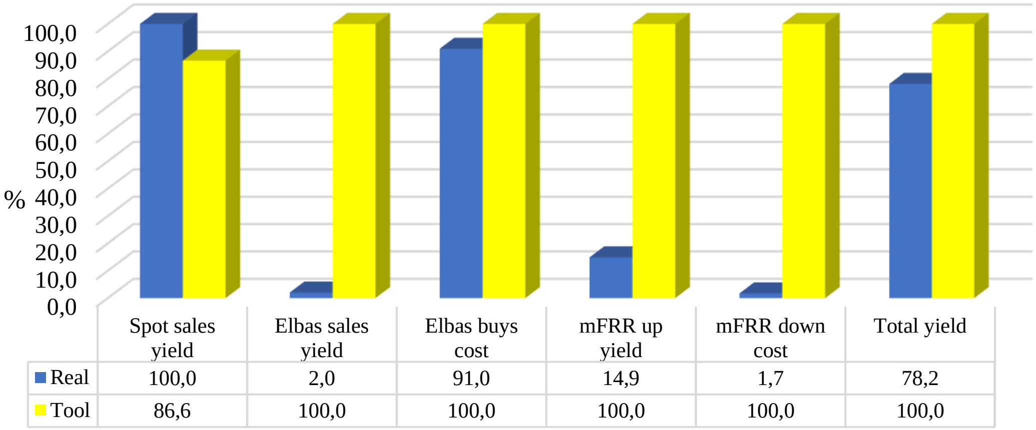


Figure 10. Comparison between the real and tools production scenarios for the 7-day period.

Next comparisons are done between the value creation of the tool and real life. Figure 8 showed that the Spot sales between the tool and real life were quite close to each other. From figure 11 it can be said that in real life the Spot trading actually managed better when comparing to the tool since the sold amounts were quite close. The main reason explaining this is that the tool sees the opportunities to oversell the production to Spot market. So the actual Spot sales of the tool might not be the most optimal, but the end result after Elbas trades and mFRR adjustment would be. The amount of value created based on the tools Elbas sales versus what was sold in real life also support that. When comparing the numbers from the figure 8 and 10 it can be seen that while the tool sold 91 % more capacity to the Elbas market, it also made 98 % more profit out of that sold amount. Then the tool had to buy some of that capacity back from the Elbas market, and from figure 8 we can see that it bought 52 % more capacity back when comparing to the real life. The interesting fact here is that the costs related to buying some of that capacity back from the Elbas market are quite close to each other. That results in the tool actually spending only 9 % more while buying almost double the capacity back from the Elbas market (figure 8 & 10).



	Spot sales yield	Elbas sales yield	Elbas buys cost	mFRR up yield	mFRR down cost	Total yield
■ Real	100,0	2,0	91,0	14,9	1,7	78,2
■ Tool	86,6	100,0	100,0	100,0	100,0	100,0

Figure 11. Value creation comparison between the real- and tools production scenario.

Although the graph shows about 22 % higher created value for the tools overall sales, the total yield of the tools sales is only 19 % bigger after taking into account that the tool saw that it could sell 6 % more energy to the market with same amount of water when comparing to the actual scenario. The truth is currently somewhere between the 19 and 22 % since some of the difference was caused by the calculated energy fragments and some by the tool maintaining higher water head and thus higher energy efficiency.

Second to last results to compare are the reserves. The reason why the reserves were not added to the created value comparison is the way those were modelled into the tool. The reserves do not use any water in the tools scenario although they occupy some of the production capacity. This is because although the reserves were sold to the market it is not guaranteed that there is a need in the grid to fulfil the reserve as explained before. Also some of the reserves adjust up and some down and in a long run the actual utilization of water evens out. From the tools calculation results it became clear that since the reserves do not utilize any water the tool would fulfil all the un-utilized production capability with reserves in a way that all the production was always sold to the market. This is not a realistic scenario since based on the need in the grid the power plants might end up utilizing a lot more or lot less water if the reserves get activated. Other reason why the reserves were not fully comparable was because in the real life situation the power plants might not be bid to participate in all the reserve markets every day. Since what reserves were sold and when are also not public data no real life comparisons could be done. What could be done however is comparisons of how big of a share from the total production capacity sold to the market the tool saw fit to fulfil with reserves (figure 12) and what ended up being the overall share of tools balancing power from the total sold amount (figure 13).

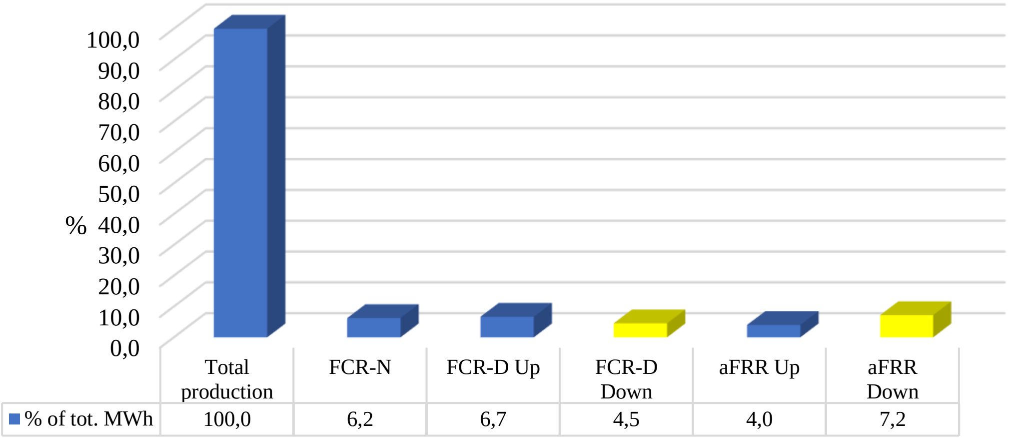


Figure 12. The overall share of reserves sold when comparing to the total production.

From figure 12 it can be seen that all the tools sold reserve amounts were quite close to each other when comparing to the total production capacity. That does not necessarily mean that all the reserve prices in different markets were very similar during that 7-day span. What it actually means is that the peak prices of the reserves were quite close to each other since the tool would always pick the most beneficial reserve to fill the unsold production capacity. What the similar sold amounts of reserves also meant was that the tool utilized similar working principle when bidding those that it used with spot, Elbas and mFRR markets. So first the tool saw fit to sell some reserve to adjust production up if necessary and then right after saw beneficial to sell the adjustment down to match it. This is very possible scenario also in real life and the grid balance will determine which reserves get activated and how much adjustment happens.

What also makes the reserves hard to compare at this point is the core working principle of the tool. Now in situations where the reserve prices would be higher than spot, Elbas or mFRR prices, the tool would sell all the capacity to reserve markets. Selling all the capacity to reserve markets is not a possible way of operation in real life since the actual amount of realized reserves and thus water usage cannot be accurately foreseen. To avoid such situations, the cap for the amount of each reserve sold was created as explained before. However, in such situations the tool would still sell all the excess capacity to reserves until it hit the cap. That type of a situations also distorts the final results a bit because, as explained before, the reserves do not use any water in the tools scenario.

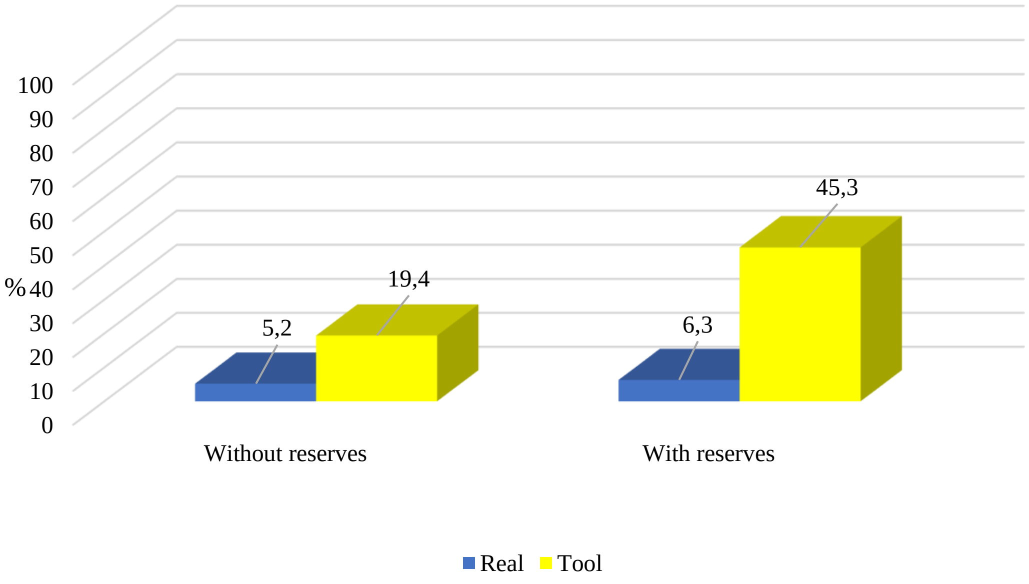


Figure 13. Comparison between the overall shares of balancing power sold to the market between real life and tools scenarios and how would the amounts differ if the reserves were also considered.

The last results to examine are the shares of balancing power out of the total sold production (figure 13). In the scenario based on real life data the share of balancing power was only 5 % out of the total production when the reserves were not taken into account, and only slightly bigger, 6,3 % when the sold reserves were considered. The tool saw beneficial to sell almost 20% of the production capacity to balancing markets when the reserves were not considered. This result highlights the market potential of the balancing markets since the tool was designed to maximize the value of water and in the end it saw beneficial to sell almost 15 % more capacity to balancing markets. The difference is even greater when the sold reserves are considered. When the tool was allowed to fulfil all the unsold capacity and sell it to reserve markets the tool ended up selling almost 40 % more capacity to balancing markets when compared to the real life situation, yet again highlighting the unutilized market potential.

7. Discussion and conclusions

The main set out aim for the post-optimization tool was to maximize the value of water. Based on the data presented in the last paragraph, it is clear that the tool increases the value of water. Total yield of the tools scenario was from 19 to 22 % higher than the real life scenario. The difference in yield between the two scenarios would have been even greater if the sold amount of reserves were taken into account. However, it is too early to declare that the tool would be able to maximize the value of water in all situations since the tool is still in development phase. Inside the EFN-interface where the tool calculates the optimal scenario, the result of the MILP-calculation is either true or false. This means that if the tool cannot reach the optimized result, some value is always wasted due inferring restrictions and the tool will produce a false result. In this specific time frame the result of the overall calculation was true, meaning that the tool was able to maximize the value of water in this specific time frame with the set out restrictions. Yet only after infusing the tool with production side of software and having a few test optimization cycles can the optimized data be analysed and the tool proven to deliver the optimized result no matter the timeframe. What can already be declared however, is the fact that the tool is efficient in bringing the unutilized market potential to light.

From figure 8 and figure 11 it can be seen that the biggest unutilized market potential in this specific time frame were the Elbas and mFRR markets. That result is logical in a sense that forecasting Spot prices for the upcoming day, although not easy nor incredibly accurate, is still more accurate than forecasting actual realized Elbas prices or the balancing need in the grid for the upcoming day. As explained before, all the imbalances in the grid will not affect the spot prices after the price publication, but can have drastic effects on the Elbas and mFRR markets. Based on figure 9 in order to maximize the yield, the bidding philosophy for some days would had to be to oversell the capacity to Spot market and trust that it can be either bought with a cheaper price from the Elbas market, or the grid balance to have an over dosage of electricity resulting into down adjustment in mFRR market. On other days the bidding philosophy would have to be to not sell anything to the Spot market and trust that either the Elbas prices would peak higher than the Spot prices or the grid to have shortage of electricity resulting into high mFRR prices. Such a bidding philosophies can result into much worse outcomes since while bidding to a Spot market there is no perfect data available.

When comparing the Spot sales and Spot yields in figures 7 and 10, it can be seen that in the real life scenario only 2,7 % more capacity was sold to the Spot market when compared to the tools scenario. However, the real life scenario created a 13,4 % bigger yield when comparing the Spot trades only. This at first might seem surprising since the tool was working on a perfect data maximizing the value of water and should always come up with higher yield scenarios. What surprises is the fact that in typical trading patterns the Spot market and sales are the ones that have the most emphasis on as seen in the figure 9's real life scenario. So for the optimization tool to lose in value creation in the most emphasised market has to have a reason behind it. As mentioned before, this can be explained via the tool overselling the capacity to Spot market on hours when the Spot prices might not be at their highest, because the tool saw that it could buy or adjust some of the oversold production capacity down creating added value. In figure 9 just 24 % of the hours in the tool's scenario were only sold to the Spot market, meaning that 76 % of the hours created added value resulting in higher yields than just the spot market. When compared to figure 9's real life scenario 70 % of the hours were only sold to Spot and 30 % had some added value, so almost the opposite shares.

Based on this one future development for the tool could be to modify it to just sell all the capacity to spot in certain test scenarios. This way the actual Spot trading could be compared head to head and see on average how much value is lost between the optimized and realized scenarios with variable time periods. In such test scenario, longer the time frame more different the outcome. Such comparisons would be interesting to review and learn from in cases such as the tools, where there is a storage pool to regulate. As mentioned before, Spot market has the most emphasis since it is the only sure way to sell the capacity to the market along with Elbas. In both scenarios the Spot market did have the most emphasis, meaning that even though the spot sales may not always create the highest yields, they do most of the time. In the figure 9 it is shown that even in the optimized scenario only 14 % of the time the capacity was sold only to Elbas market, supporting that the Spot is the most important market to focus when the capacity has to be sold. However, the tool also revealed that the markets with the most unutilized potential were mFRR and Elbas. So a balance between the most important market and wasted value creation is needed.

Based on this one possible future development idea came true. In order to minimize the risks of mFFR and Elbas prices, the tool could be set to sell a flat production profile to Spot market for a certain time period. After that the tool could again optimize the flat production plan using all the mFRR and Elbas data and create the optimized flat profile scenario. Yields of such scenario would then again to be compared with the real life scenario. This would differ from the original set out goal of the tool and might even have to be a whole separate tool. The benefit for such scenarios would be to see if the optimized flat profile production plans could consistently result in higher yields than the real life scenarios. Reason for creating such scenarios would be again to minimize the risk of not bidding the production capacity to Spot, but more importantly that such scenario would be more likely to be replicated in real life with aggressive mFRR and Elbas market bidding. Since the optimized scenario is near impossible to reach, flat optimized always will have some trade-offs and the real-life scenario has some unutilized value potential, the optimal real-life scenario would be a mixture of all those scenarios, maximizing the value of water in an applicable way.

Even though all the three scenarios, real life, optimized and flat optimized would be compared side by side, the end result stays the same: the tool does not make the future trading any easier, but is does highlight the unutilized market potential. That is the most important result of this tool and why it was created. Long term, the tool can be utilized as the trendsetter for future development projects aimed to improve specific trading methods and processes. Short term it can be utilized as an assist for decision making in the moment while trading, although it needs to always be taken into consideration that the market in the future might not follow the trends of past. For example, for hydropower, there might become a time when the Spot is no longer king and the capacity would be more beneficial to be focused for example to the balancing markets. From figure 11 it can be argued that during certain time periods the change might already be here. Although there are multiples things still to solve before the tool is actually fully running in the production side and in reliable a daily use, it already delivers on its goals.

The main aim of this work was to be a part of ensuring sustainable and dependable electricity supply for energy intensive industries, such as biorefineries, also in the future. As mentioned before, hydropower is already the most important source of balancing power. Based on the finding of this work the most unutilized market potential for hydropower is in the balancing markets. This supports the hypothesis that it could be beneficial for hydropower operators to allocate more production capacity from Spot market to balancing markets. Such a hypothesis only reinforces hydropower’s status as the most important balancing power source and highlights the importance of hydropower production for the whole grid. To switch from a Spot focused methodology the traders would have to have a firm data and proof of such effect to modify the core trading patterns. This tool can collect and present the data in case such scenarios would come true, proving to be a part of ensuring sustainable and dependable electricity supply for energy long in the future.

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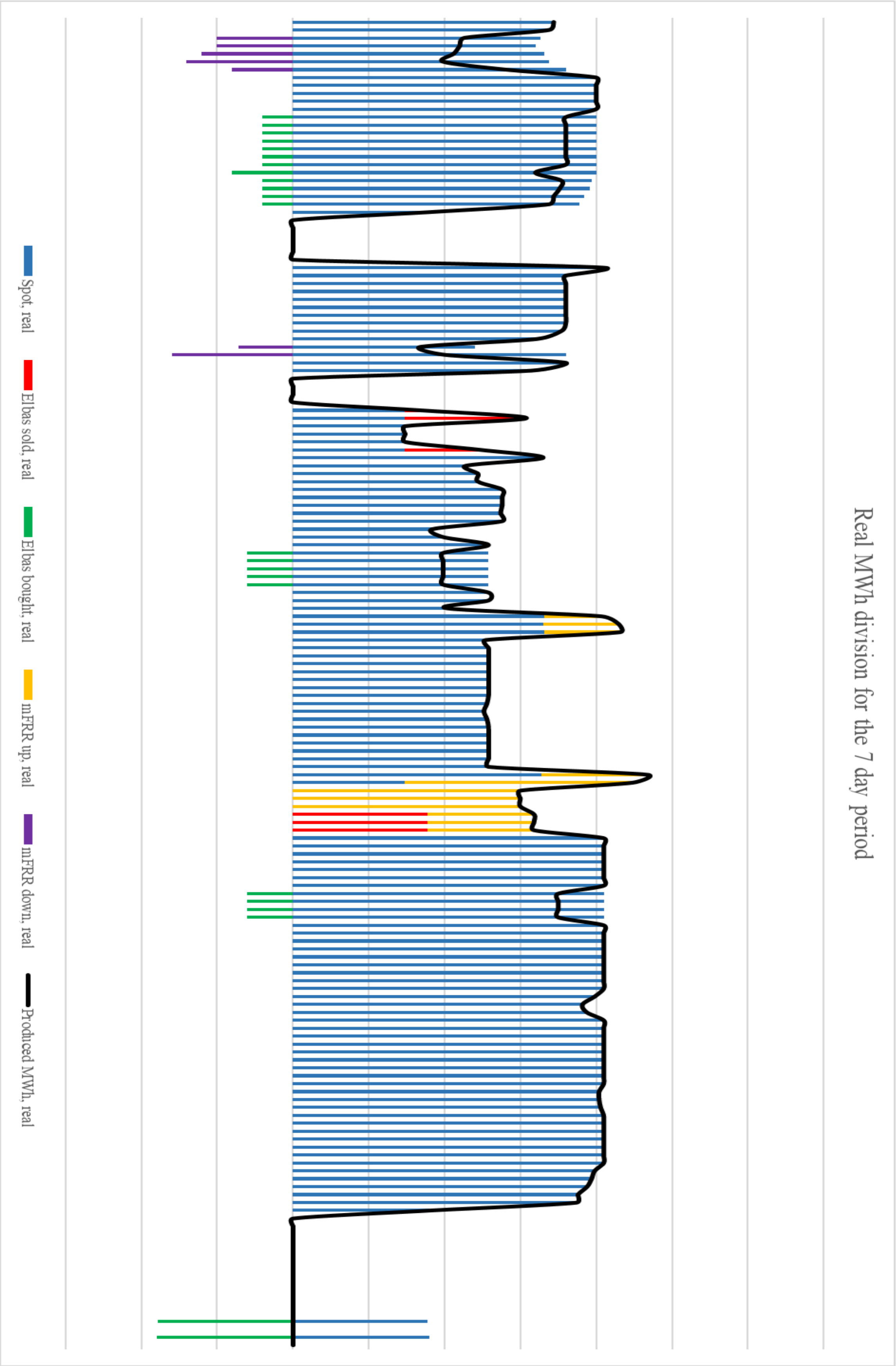
Appendix 1. Division of real produced MWh in different markets during the 7-day period.



Appendix 2. Division of tools produced MWh in different markets during the 7-day period.