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Simulation of Hydro Power Expansion in Skellefte River

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Abstract

The aim with this project is to examine how an expansion of the Swedish hydro power capacity in Skellefteälven, a river in Northern Sweden, could benefit the power system such that bottlenecks are eliminated. The project also examines how a future need for additional power can be met. The results support an expansion of hydro power, partly to meet an increased power demand and partly to eliminate bottlenecks which would promote an optimal run. The report does not contain any economical aspects that would occur in an expansion. This project is a part of a project from North European Energy Perspective project, www.nepp.se.

Sammanfattning

Målet med projektet är att undersöka vinster vid en eventuell utbyggnad av vattenkraftverken i Skellefteälven på sådant sätt att flaskhalsar elimineras. I arbetet analyseras även hur ett framtida ökat effektbehov kan bemötas. Resultaten visar ett stöd för en utbyggnad av vattenkraftverk, dels för att kunna möta ett ökat effektbehov och dels för att eliminerade flaskhalsar främjar en optimal körning. Rapporten innehåller inte de ekonomiska aspekter som skulle uppkomma vid en utbyggnad. Detta är en del av ett större projekt inom North European Energy Perspective, www.nepp.se.

Nomenclature

Parameters

λ_t, $\mathbf{l}(w,t)$	Spot price for time t in Euro or SEK
$\mu_{i,j}, \mathbf{mu}(i,j)$	Marginal production equivalent
$\overline{M}(i), \mathbf{Mmax}(i)$	Maximum reservoir capacity for reservoir i
$\overline{Q}(i), \mathbf{Qmax}(i,j)$	Maximum discharge for station i and segment j
$\overline{S}(i), \mathbf{Smax}(i)$	Maximum spillage capacity for station i
$\rho(i)$	Penalty on change of discharged water for power plant i
$\mathbf{aq}(i,ii)$	Matrix defining from which reservoirs there exists an inflow of water
$\mathbf{EndRes}(i)$	Final reservoir content for hydro power plant i
fsTimeH	Flow time in hours for the spilled water to reach to next adjacent reservoir
fsTimeM	Flow time in minutes for the spilled water to reach to next adjacent reservoir
fTimeH	Flow time in hours for the discharged water to reach to next adjacent reservoir
fTimeM	Flow time in minutes for the discharged water to reach to next adjacent reservoir
Qavg	
$\underline{Q}(i), \mathbf{Qmin}(i)$	Minimum discharge capacity for station i
$\underline{S}(i), \mathbf{Smin}(i)$	Minimum spillage capacity for station i
$M(i,w,t=168)$	Final reservoir content for hydro power plant i
$M_{i,0}/\mathbf{M}(i,w,0)$	Initial reservoir content for hydro power plant i
$V_{i,t}, \mathbf{V}(i,w)$	Water inflow to reservoir i

Variables

$\delta_i^+, \mathbf{Dp}(i,w,t)$	Change of discharge, positive when increase in discharge otherwise zero
$\delta_i^-, \mathbf{Dm}(i,w,t)$	Change of discharge, positive when increase in discharge otherwise zero
$\mathbf{QflowT}(i,w,t)$	Flow reaching station i at time t
$\mathbf{SflowT}(i,w,t)$	Spillage reaching station i at time t

Z	Revenue - Cost in change of production
$M_{i,t}, \mathbf{M}(i, w, t)$	Reservoir content, reservoir i and hour t
$P_t, \mathbf{P}(w, t)$	Total power production hour t
$Q_{i,j,t}, \mathbf{Q}(i, j, w, t$	Water discharge from power plant i, segment j, hour t and scenario w
$S_{i,t}, \mathbf{S}(i, w, t)$	Water spillage from power plant i, hour t and segment w

sets

I	Set containing each reservoir and hydro power plant index i, $i \in I = \{1, 2, \ldots, 15\}$
J	Set containing each segment j, $j \in J = \{1, 2\}$
T	Set containing each hour t, $t \in T = \{1, 2, \ldots, 168\}$
W	Set containing each scenario w, $w \in W = \{1\}$

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1 Background

In times when the importance of renewable energy has risen and nuclear power, for political and economical reasons, may not be harnessed, it is important to analyze how hydropower can be a balancing power source for other volatile energy sources such as wind or photovoltaic.

1.1 Aim

The aim of this thesis is to study to what extent an expansion of some hydro electric power plants could result in an increase of power output and how it would contribute to the balancing of the power system. In addition, a secondary intention is to eliminate possible bottlenecks [16].

The Swedish government has, with the majority of the parties in the parliament, set up a number of goals to generate electricity from 100% renewable energy resources the year 2040 with the energy agreement. The agreement was set in 2016 and consists of the following goals [21].

- Sweden will have zero net emissions of green house gases to the atmosphere by the year 2045 and thereafter have negative emissions [25].
- By the year 2040 achieve 100% renewable power production. This is a goal and therefore does not forbid nuclear power, ergo it does not force a shutdown of nuclear power with political decisions [25].
- A goal for energy efficiency for the period 2020 to 2030 will be set by 2017 [25].

According to SCB, Statistics Sweden, the power production in Sweden consists mostly of hydro power and nuclear power, which is 80% of the total power generation while wind power accounts for a little more than 10% and solar power contribution is only 0.09%. Nuclear power is a base power and if it is phased out, a change needs to take place from almost only focusing on the delivered amount of energy to also ensure that there is enough power. A significant step is to review the regulations for the energy field and modify them so that they are customised to the power challenge [3, 25].

1.2 Delimitation

The thesis is delimited to only study Skellefteälven to make a general optimisation model where studies on expanding the capacity for different power plants are conducted. By use of mathematically optimising methods it is possible to select when the water is discharged to produce power. In this way the most advantageous benefit to society can be achieved.

2 Theory

There are multiple methods and different theories about how to optimise hydro power plants. A linear optimisation without integer variables is presented in this report.

2.1 Energy Generation

Most of the generated electricity today in Sweden comes from nuclear and hydro power plants. The river Skellefteälven accounts for around 4245 GWh of Sweden's energy generation [3].

2.1.1 Hydro Power

Hydro power is one of Sweden's largest energy resources. It meets around 40% of Sweden's energy demand. The oldest operational hydro power plant in Skellefteälven, the Selsfors power plant, was first used in 1944. According to Energimyndigheten, there is a potential for increasing the capacity from Swedish hydro power plants, mainly by increasing the the capacity of existing hydro power plants in the larger rivers, which Skellefteälven can be seen as [4].

Since the amount of generation must meet the demand at all times, a transmission system operator is responsible for the electrical stability [11]. The organisation responsible in Sweden is called Svenska Kraftnät and is responsible for the short term balance of the system. To accommodate the need of additional power in case of power shortage or if there is a deviation from the prognosis, Svenska Kraftnät is responsible for providing a power reserve. Today, this power reserve is mainly provided by hydro power, and hydro power will continue to be a crucial part of balancing the power system. With increased wind and solar power, the power system will be even more prone to power deficits. Thus the role as a balancing power will be more important for hydro power [15].

Hydro power is used for short term controlling, which means that the difference between demand and generation is being balanced during a day. A major part of the power demand and power generation during a day is programmable since there is a frequently recurring regularity of the demand and a possibility to forecast weather variations that affect the daily inflow. There also exists a shorter term, based per hour, planning for frequency regulation. Power trading is possible to do at the spot market Nordpool for the upcoming day. For the shorter term trading, per hour, there is also a market called ELBAS which is designed to balance the deviations between the generation and demand per hour. It is approximated that the day planning during winter time is 5000-6000 MWh/h and during the summer time is 3000-4000 MWh/h. This constitutes the difference between the power generation during daytime and the power generation during nighttime [6, 19].

2.1.2 Wind Power

The production and installation costs for wind power plants have significantly decreased and have at the same time increased in efficiency [12]. During the year 2017 wind power produced its highest ever generation with 17,270 GWh, which is 10.1% of Sweden's total energy generation and 12.3% of Sweden's total demand. Wind power comes in third place when it comes to the electricity contribution, far below nuclear power which had a generation of 63,009 GWh. One of the issues with wind power is the variation and uncertainty of how and when the wind blows, which can, in the worst case give a scenario for when it is forecast to be favourable wind and then turns out to be none. This creates a liability, other power sources must be available and regulate the remaining energy demand, since there must be the same production as there is utilisation at any given time, which can be minimised e.g. with wind farm diversification [18].

2.1.3 Nuclear Power

The electricity output from nuclear power plants has been stable for most of the time in Sweden since 1990 and has the benefit of being reliable. The top generation during a single year since 1990 was during 2001 at 79 TWh. Since the Swedish parliament introduced with the Energy Agreement, there is a goal of replacing the whole nuclear power output with renewable energy resources. Thus the nuclear power plants will not be used more than necessary. One of the challenges of being independent from nuclear power is to increase the regulation capacity to be able to compensate for the large quantity of energy that nuclear power generates. During the year 2016, the net generation from nuclear power plants was 63 TWh, which constitutes 37% of Sweden's total energy generation [2].

2.2 The Model

The basis of the Gams, General Elgebraic Modelling System, model was mainly created and developed by Carl Englund, Andreas Fagerberg [7] and by Fredrik Obel [20]. To have a cleaner model and to make the model more generic, an implementation in MATLAB was made by Daniel Risberg, which is used in this project with a few modifications. The theory for hydro power plant modelling is extracted from the book Effektiv drift och planering av kraftsystem, [26], by L. Söder and from the book Efficient Operation and Planning of Power Systems, [27], by L. Söder and M. Amelin. The idea of this model is to give an accurate picture of how a real life scenario would turn out. The model is deterministic, the results extracted from the model are optimised for the spot price parameters. The profit is calculated as the generated power times the spot price. The model is made in the General Algebraic Modelling System, GAMS, which is a high-level modelling system for mathematical optimisation.

The objective function and the constraint that controls the program are:

- The objective function:
  Maximise Revenue
  Revenue = (spot price) · (generation) - (cost for change in discharge)
- The hydrological balance: How much water a specific reservoir i contains during each hour. The current reservoir content is a function of the reservoir content the previous hour, how much water that flows to the reservoir

minus the water that is discharged and spilled from the power plant associated to the reservoir. The water that flows in consists of the discharge and spillage from directly upwards power plants and other types of inflow, e.g. rain water. The water between the hydro power plants in the beginning of the simulation are approximated with the mean inflow to the power plants.

- The power generation, which simply is the marginal production equivalent times the discharge.
- The lower and upper bounds for the discharge.
- The lower and upper bounds for the reservoir content.
- The lower and upper bounds for the spillage.
- The flow time for discharged and spilled water.

The following formula states the optimisation problem posed subject to the mathematical constraints. The definition of the variables can be found in the Nomenclature.

$$\begin{aligned}
\textbf{Maximise:} \quad & \sum_{t=1}^{T} \lambda_t \sum_{i=1}^{I} P_{i,t} - \rho_i \cdot \sum_{i=1}^{I} (\delta_{i,t}^{+} + \delta_{i,t}^{-}) \\
\textbf{subject to:} \quad & M_{i,t} = M_{i,t-1} + V_{i,t} - \sum_{j} Q_{i,j,t} \\
& + \sum_{i-1} (\sum_{j} Q_{i,j,t} + S_{i,t}), \quad i \in I, j \in J, t \in T \\
& P_t = \sum_{i} \sum_{j} \mu_{i,j} Q_{i,j,t}, \quad i \in I, j \in J, t \in T \\
& \overline{Q}_i \geq Q_{i,t} \geq \underline{Q}_i, \quad \forall i, t \in \mathcal{F} \\
& \overline{M}_i \geq M_{i,t} \geq \underline{M}_i, \quad \forall i, t \in \mathcal{F} \\
& \overline{S}_i \geq S_{i,t} \geq \underline{S}_i, \quad \forall i, t \in \mathcal{F}
\end{aligned}$$

To make the simulations look more realistic, a small cost for the change of discharge $-\rho \cdot (\delta_i^{+}(t) + \delta_i^{-}(t))$ is added to the objective function. The definition of the δ's are as follows:

$$\begin{aligned}
& \delta_{i,t}^{+} = Q_{i,t} - Q_{i,t-1} \quad \forall t \\
& \delta_{i,t}^{-} = Q_{i,t} - Q_{i,t-1} \quad \forall t \\
& \delta_{i,t}^{+} \geq 0 \\
& \delta_{i,t}^{-} \geq 0
\end{aligned}$$

The change of discharge, defined by $\delta_i^{+}(t)$ and $\delta_i^{-}(t)$, takes the difference which then is multiplied with a constant cost factor for each power plant. The cost factor can easily be changed for each specific power plant depending on its dynamics. The model is built such that the reservoir content for the optimised week's first and last hour are bound. This means that the optimisation is made for a specific amount of water that will pass through the river in one week, which leads to energy not being saved even though it may be beneficial. This condition can easily be changed to let the simulation use more or less energy. In this case a specific reservoir content is not necessarily set and the program will instead calculate how much water will be left in the reservoirs for future usage depending on how much the water is valued [27].

Table 1: List of power plants and their regulations [13].

List of power plants and their regulations with installed capacity						
Power plant (i)	Maximum Power [MW]	Maximum Discharge [m^3/s]	Maximum Reservoir Content [HE]	Flow Time (Q/S) Downstream [minutes] See Figure 1	Minimum Spillage [m^3/s]	Reservoir Level Above Sea (Min/Max) [m]
1 Rebnis	64	80	205560	2880/2880	0	460.7/477
2 Sadva	31	70	168000	2880/2880	2.6	499.5/513
3 Bergnas	8	160	216120	40/180-7200	15	418/420
4 Slagnas	7	160	768	240/240	16	413.5/414
5 Bastusel	97	170	8208	60/360	0	407.5/408.5
6 Grytfors	31	165	1248	15/15	0	331/332
7 Gallejaur	220	310	3600	30/360	0	309/310
8 Vargfors	105	320	4008	180/180	0	228.5/230.5
9 Rengard	36	220	1400	40/60	0	180/181
10 Batfors	41	280	1330	30/30	0	160.5/161.5
11 Finnfors	42	300	300	20/30	0	143.22/144.22
12 Granfors	39	240	280	20/30	0	122.5/123.5
13 Krangfors	65	240	330	20/30	0	103.83/104.83
14 Selsfors	62	300	500	20/30	0	73.6/74.7
15 Kvistforsen	140	300	1120	0/0	0	50.5/52

Table 2: List of power plants and their regulations [1].

List of power plants with their regulations and increased capacity						
Power plant (i)	Maximum Power [MW]	Maximum Discharge [m^3/s]	Maximum Reservoir Content [HE]	Flow Time (Q/S) Downstream [minutes] See Figure 1	Minimum Spillage [m^3/s]	Reservoir Level Above Sea (Min/Max) [m]
(1) Rebnis	80	100	205560	2880/2880	0	460.7/477
(2) Sädva	44	100	168000	2880/2880	2.6	499.5/513
(3) Bergnäs	10	200	216120	40/180-7200	15	418/420
(4) Slagnäs	9	200	768	240/240	16	413.5/414
(5) Bastusel	183	290	8208	60/360	0	407.5/408.5
(6) Grytfors	56	300	1248	15/15	0	331/332
(7) Gallejaur	220	305	3600	30/360	0	309/310
(8) Vargfors	134	310	4008	180/180	0	228.5/230.5
(9) Rengård	54	330	1400	40/60	0	180/181
(10) Båtfors	59	335	1330	30/30	0	160.5/161.5
(11) Finnfors	61	340	300	20/30	0	143.22/144.22
(12) Granfors	55	340	280	20/30	0	122.5/123.5
(13) Krångfors	92	340	330	20/30	0	103.83/104.83
(14) Selsfors	70	340	500	20/30	0	73.6/74.7
(15) Kvistforsen	159	340	1120	0/0	0	50.5/52

Figure 1 is a complement to Table 1 and 2 to illustrate where the discharged and spilled water flows from each station.

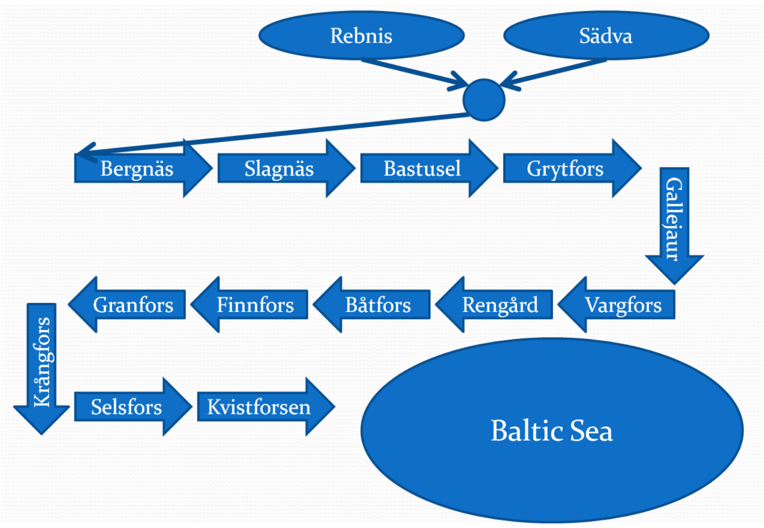

Figure 1: Diagram of flow routes [13].

As you can see in Table 1 and 2, we have all specified constraints given there. Table 1 shows the regulations for the hydro power plants today while Table 2 shows an alternative for how an increased capacity could be [1]. Additionally some power plants must discharge to some extent because of regulations. Kvistforsen is set to discharge at least 20 m^3/s while, after all of the simulations were made, it came to notice that the Rengård power plant seldom discharges less than 60 m^3/s because of vibrations that occur.

The modelling was made in GAMS, and the objective function was written as

$$\mathbf{Z} = \sum_{w \in W} \left(\sum_{t \in T} \mathbf{pi}(w) \cdot \mathbf{l}(w,t) \cdot \mathbf{P}(w,t) - \sum_{i \in I} \rho(i) \cdot \sum_{t \in T} \mathbf{Dp}(i,w,t) + \mathbf{Dm}(i,w,t) \right)$$

Since there is only one scenario worked on each time, $\mathbf{pi} = 1$. The equation above is the objective function and $\mathbf{Z}$ is what is maximised. $\mathbf{Dp}$ and $\mathbf{Dm}$ are purely virtual variables, defined as δ_i^+ and δ_i^-, respectively, in the beginning of this section. Depending on if the magnitude of the cost variable $\rho(i)$ increases or decreases, the oscillations of the discharge either increase or decrease respectively [26].

In GAMS, the hydrological balance is defined as,

$$\begin{aligned}
\mathbf{M}(i,w,t) =& \mathbf{M}(i,w,t-1) \\
&+ \mathbf{V}(i,w) \\
&- \sum_{j \in J} \mathbf{Q}(i,j,w,t) - \mathbf{S}(i,w,t) \\
&+ \sum_{ii} \mathbf{aq}(i,ii) \cdot (\mathbf{QflowT}(ii,w,t) + \mathbf{SflowT}(ii,w,t)) \\
&+ \sum_{ii > i \in I} \mathbf{Qavg}(ii,w) \cdot \mathbf{aq}(i,ii)_{|t \leq \mathbf{fTimeH}(ii)} \\
&+ \sum_{ii > i \in I} \mathbf{Qavg}(ii,w) \cdot \mathbf{aq}(i,ii) \cdot \frac{60 - \mathbf{fTimeM}(ii)}{60}_{|t = \mathbf{fTimeH}(ii)+1}
\end{aligned}$$

To verify the results, a comparison to a reference case is made. The reference case contains historical data for how the power stations have run during a specific week during winter, $\mathbf{Q}(i,j,w,t)$ and $\mathbf{S}(i,w,t)$, the reservoir content $\mathbf{M}(i,w,t)$ and the inflow, $\mathbf{V}(i,w)$. Some assumptions were made for the reservoir content. The data received specified the reservoir content such as how many metres above the sea the water level was. In addition, it is known how many metres above the sea the maximum and the minimum reservoir contents are. Since the flow times can take up to 2880 minutes, there is a significant amount of water to take in regard to the river, between the reservoirs. The last two rows in the above equation compensate for the water between reservoirs by using the average flow of water river. How much water in percent of the total allowable the reservoir contains is then approximated by the equation below.

$$\begin{aligned}
\text{Maxlevel} &= 500 \text{ metres} \\
\text{Minlevel} &= 400 \text{ metres} \\
\text{Currentlevel} &= 490 \text{ metres} \\
\text{Percent_Water} &= \frac{\text{Currentlevel} - \text{Minlevel}}{\text{Maxlevel} - \text{Minlevel}} = \frac{490-400}{500-400} \cdot 100
\end{aligned}$$

The model had the initial reservoir content, $\mathbf{M}(i, w, t = 0), \forall i \in I, \forall w \in W$, and the final reservoir content, $\mathbf{M}(i, w, t = 168), \forall i \in I, \forall w \in W$, as input parameters. $\mathbf{Qavg}(ii, w)$ and $\mathbf{aq}(i, ii)$ are parameters extracted from an Excel file which contains the regulations and parameters for each power plant. **Qavg** is the total yearly average inflow of water to each respective reservoir per hour and is used to make an estimation of how much the power plants produce the first few hours until t is larger than the flow time. The flow time is defined in the leftmost columns in Table 1 and Table 2. **fTimeH** is the total amount of whole hours it takes for the discharged and spilled water to get from one power plant to another and **fTimeM** (flowtime mod 60) is to get the remaining minutes. The equations to calculate **QflowT** and **SflowT** are presented below.

$$\begin{aligned}\mathbf{QflowT}(i, w, t) =& \frac{\mathbf{fTimeM}(i)}{60} \cdot \sum_{j \in J} \mathbf{Q}(i, j, w, t - (\mathbf{fTimeH}(i) + 1)) \\ &+ \frac{60 - \mathbf{fTimeM}(i)}{60} \cdot \mathbf{Q}(i, w, t - \mathbf{fTimeH}(i))\end{aligned}$$

$$\begin{aligned}\mathbf{SflowT}(i, w, t) =& \frac{\mathbf{fsTimeM}(i)}{60} \cdot \mathbf{S}(i, w, t - (\mathbf{fsTimeH}(i) + 1)) \\ &+ \frac{60 - \mathbf{fsTimeM}(i)}{60} \cdot \mathbf{S}(i, w, t - \mathbf{fsTimeH}(i))\end{aligned}$$

The power output, $\mathbf{P}(w, t)$ is calculated with a stepwise linear function of $\mu(i, j)$, in GAMS denoted as $\mathbf{mu}(i, j)$, multiplied by the discharge $\mathbf{Q}(i, j, w, t)$ as defined below.

$$\mathbf{P}(w, t) = \sum_{i \in I} \sum_{j \in J} \mathbf{mu}(i, j) \cdot \mathbf{Q}(i, j, w, t)$$

Where the $\mathbf{mu}(i, j)$ is a parameter calculated by the following formula.

$$\begin{aligned}\mathbf{mu}(i, 1) =& \frac{\mathbf{Pmax}(i)}{0.75 \cdot \mathbf{Qmax}(i, j = 1) + 0.95 \cdot 0.25 \cdot \mathbf{Qmax}} \\ \mathbf{mu}(i, 2) =& 0.95 \cdot \mathbf{mu}(i, 1)\end{aligned}$$

The parameter **mu** with its indices $(i, j) \in (I, J)$ is called the marginal production equivalent and when multiplied with the discharge $\mathbf{Q}(i, j, w, t)$ it gives the power production. Each hydro power plant has its own marginal production equivalent which are denoted by the $i \in I = \{1, 2, \ldots, 15\}$, and they are in turn divided into two segments $j \in J = \{1, 2\}$ where $j = 1$ denotes the first 75% of the maximal discharge capacity and $j = 2$ denotes the remaining 25% of the capacity. The power generation increases linearly as the discharge increases within the first and second segment with the difference that every additional discharged water within the second segment has a lower efficiency. Segment

$j = 1$ has the highest efficiency whereas segment $j = 2$ has 5% less efficiency. Other constraints for this model are the following:

$$
\begin{aligned}
\mathbf{M}_(i, w, t = 168) &= \mathbf{EndRes}(i), \quad i \in I, j \in J, w \in W \\
\mathbf{M}(i, w, t) &\leq \mathbf{Mmax}(i), \quad i \in I, j \in J, t \in T, w \in W \\
\mathbf{Q}(i, j, w, t) &\leq \mathbf{Qmax}(i, j), \quad i \in I, j \in J, t \in T, w \in W \\
\sum_{j \in J} \mathbf{Q}(i, j, w, t) &\geq \mathbf{Qmin}(i), \quad i \in I, j \in J, t \in T, w \in W \\
\sum_{j \in J} \mathbf{Q}(i, j, w, t) &= \mathbf{Dp}(i, w, t) - \mathbf{Dm}(i, w, t), \quad i \in I, j \in J, t \in T, w \in W \\
\mathbf{S}(i, w, t) &\leq \mathbf{Smax}(i), \quad i \in I, t \in T, w \in W \\
\mathbf{S}(i, w, t) &\geq \mathbf{Smin}(i), \quad i \in I, t \in T, w \in W \\
\mathbf{Q}(i, j, w, t) &\geq 0, \quad i \in I, j \in J, t \in T, w \in W \\
\mathbf{M}(i, w, t) &\geq 0, \quad i \in I, t \in T, w \in W \\
\mathbf{S}(i, w, t) &\geq 0, \quad i \in I, t \in T, w \in W \\
\mathbf{Dp}(i, w, t) &\geq 0, \quad i \in I, t \in T, w \in W \\
\mathbf{Dm}(i, w, t) &\geq 0, \quad i \in I, t \in T, w \in W
\end{aligned}
$$

2.3 The Electricity Certificate System

The electricity certificate system was put in place to promote the expansion of renewable energy resources. The idea was to create a support system to increase the renewable power output in a cost effective way. The energy resources that are granted are wind power, some hydro power, some bio fuels, solar power, geothermal power, wave energy and peat [5].

In 1 § Law (2011:1200) the Swedish Parliament states that, from the date 2018-01-01, this law aims to promote the production of renewable power[22]

- within the common electricity certificate market with Norway which to the
  - year 2020 reach the target to finance 15.2 TWh additional renewable power production
  - year 2030 reach the target to increase the electricity certificate system with 18 TWh new electricity certificates, and
- year 2020 reach the target to finance 30 TWh of new renewable energy compared to the year 2002. [23]

It is also stated in 5§ Law (2011:1200) that for a hydro power plant to be entitled to the benefits of the electricity certificate system, the hydro power plant must have been put in operation after the end of the year 2002. The same paragraph also states that if this is not the case, an increase of a hydro power plant capacity can entitle said power plant to the electricity certificate system but exclusively for the increased capacity of the plant [22].

2.4 Aspects of Hydro Power Planning

Everyone with a facility connected to the national grid must pay a charge to Svenska Kraftnät. The idea is to cover the costs for operation and maintenance of the grid network and pay for the purchase of electricity losses in the network [14]. A future challenge for Svenska Kraftnät is how to deliver electricity from hydro power plants from Northern Sweden to Southern Sweden, to compensate for the occurring difference between supply and demand when the wind power cannot deliver because of too strong winds or no wind at all. Many of the hydro power plants in Skellefteälven are connected to the regional grid, for an example Gallejaur and Bastusel. The hydro power plant in Vargfors on the other hand is directly connected to the national grid and is therefore used as a balancing power source. Hydro power plants connected to the regional grid can also be used as a balancing power, to do this a contract is needed with an actor connected with the national grid. For an example, Rengård is connected to the regional grid but can be used as a balancing power via a connection to the national grid through the substation in Vargfors [24, 17].

For an example, the hydro power plant in Vargfors cannot use its full balancing power because the power plant in Rengård, with its lower capacity, could risk having a lower or higher reservoir level than the ones regulated, see Table 1 and 2. A problem that occurs for the discharged water with bottlenecks is that the reservoirs that are located downstream in the river are too small to manage larger changes of the discharged water from the power plants upstream. It is therefore important to realise the difficulties caused by bottlenecks in reaching the full potential when it comes to using hydro power plants as a balancing power. This will be increasingly important when more weather dependent power sources such as wind and solar power are introduced to the power system. When operating hydro power plants at their maximum capacity, the machinery wears at a quicker rate and the risk of unit failure increases. As soon as a hydro power plant runs badly. e.g. with vibrations, the unit must run further away from its maximum capacity or be shut down. In this project, it is not taken into account that different hydro power plants has different owners that does not share exactly how they intend to run the power plants. In reality, this is mostly the case which leads to an uncertainty to other hydro power plant owners who in turn must have a greater safety margin, e.g. have a greater amount of capacity unused [24, 17].

2.5 The Electric Market - Nord Pool

Nord Pool is a power market which offers trading, clearing, settlement and other services in day-ahead markets and intraday markets. It is active in multiple European countries and is owned by the Nordic transmission system operators Statnett SF, Svenska Kraftnät, Fingrid Oy, Energinet.dk and the Baltic transmission system operators Elering, Litgrid, and Augstsprieguma tikls. During 2017, 512 TWh of power was traded on Nord Pool's platform whereas the Nordic and Baltic day-ahead market constituted 394 TWh, the UK day-ahead market constituted 111 TWh and the Nordic, Baltic and German intraday market constituted 6.7 TWh [8].

2.5.1 Day-ahead Market

The main trading takes place in the day-ahead market where contracts are formed between sellers and buyers for the delivery of the power the following day. This is where the price is determined. The day-ahead market is driven by planning. The buyer needs to judge how much energy it will need the next day and also how much it is willing to pay for this energy, for each hour for the next day. The seller decides how much it can deliver and at what price, for each hour. The market closes at 12:00 CET and after that, no more bids for power which will be delivered the following day can be submitted. After the deadline, the system calculates the price based on supply and demand. The hourly prices are then made public to the market, typically at 12:42 CET. The announced hourly prices are followed by settling trades. From 00:00 CET, the energy is physically provided to the buyer according to the contracts [9].

2.5.2 Intraday Market

The intraday market covers the Nordic, Baltic, UK and German markets. It is a complement to the day-ahead market and helps secure the balance necessary between supply and demand in the Northern European power market [10].

The majority of the volume handled by Nord Pool is traded on the day-ahead market. For the most part, the balance between supply and demand is secured here. However, incidents may take place between the closing of the day-ahead market at noon CET and delivery the next day. A nuclear power plant may stop operating in Sweden, or strong winds may cause higher power generation than planned at wind turbine plants in Germany. On the intraday market, buyers and sellers can trade volumes close to real time to bring the market back in balance. At 14:00 CET, the capacities that are available for Nord Pool's intraday trading are made available. The trading takes place every day, one hour before, in this continuous market. The intraday market's importance has increased significantly since the amount of wind power has increased on the grid. Since wind power is more intermittent and does not give any energy output when the wind is too strong or too weak, the power generation is more volatile and needs balancing. This will probably become more important since the wind turbine parks are increasing and the dependence on wind power will increase due to Sweden's national goal of only being dependent of renewable energy resources [4, 10].

3 Simulation

The simulations are made for one week during a week in winter. To validate the results, a direct comparison has been made with a real life run of the power plants.

3.1 Explanation of the Simulations

In this chapter, 7 different simulations are made mainly to compare the differences between increased and simulated capacity. One of the simulations, No Expansion of Installed capacity, is strictly to compare the behaviour between the model and how the power plants really run. The second subsection, Increasing the Capacity of the River to Eliminate Bottlenecks, simulates the model with original capacity with the same model but with an increased capacity. The amount of water used, time span, spot price and other parameters are the same except the capacity.

The Flat Price Scenario is a fictional scenario where the whole week has the same spot price for every hour. This is to illustrate how the hydro power plants would run if the need for short term balancing power did not exist. In the subsection Historic Normal Winter, the simulation of an ordinary winter week where the spot price has high peaks to show how the hydro power plants could be of help during times with a high power demand. The Simulation Wind Shift, Low/High and High/Low is a scenario that is expected to occur more frequently in the future when there are more weather dependent power resources.
In the subsection, Optimising for 417 Weeks, the effects of an increased capacity is illustrated by simulating the original capacity with the increased capacity, just as in subsection 2. The difference is that in this simulation is that spot prices for 417 different weeks was used to make a comparison between how beneficial an increased capacity of the hydro power plants could be compared to the original capacity when prices are fluctuating. That is also why the weeks are not ordered in chronological order but in a way that the week with the lowest volatility, or standard deviation, is the first week and the week with the highest volatility is the last week.

3.2 No Expansion of Installed Capacity

In Scenario 1, we compare a reference case with a simulation called the original capacity. The reference case is a real run that the companies have made. The original capacity case uses the same parameters as the reference case, which mainly consists of the starting reservoir content and the final reservoir content. Figure 2 shows the discharge for each hydro power plant and hour. As illustrated in Figure 2, the blue line is what was simulated and the red line is the reference case. The simulation clearly has more heavy changes than the reference case, which does not change heavily. However, the reference case has more frequent changes in discharge but the changes are of smaller magnitude. One explanation for this phenomenon is that there is a cost added to changes in discharge due to the tendency of linear programming problems to have a jumpy solution. The lack of mathematical constraints specifying how quickly the discharge can increase

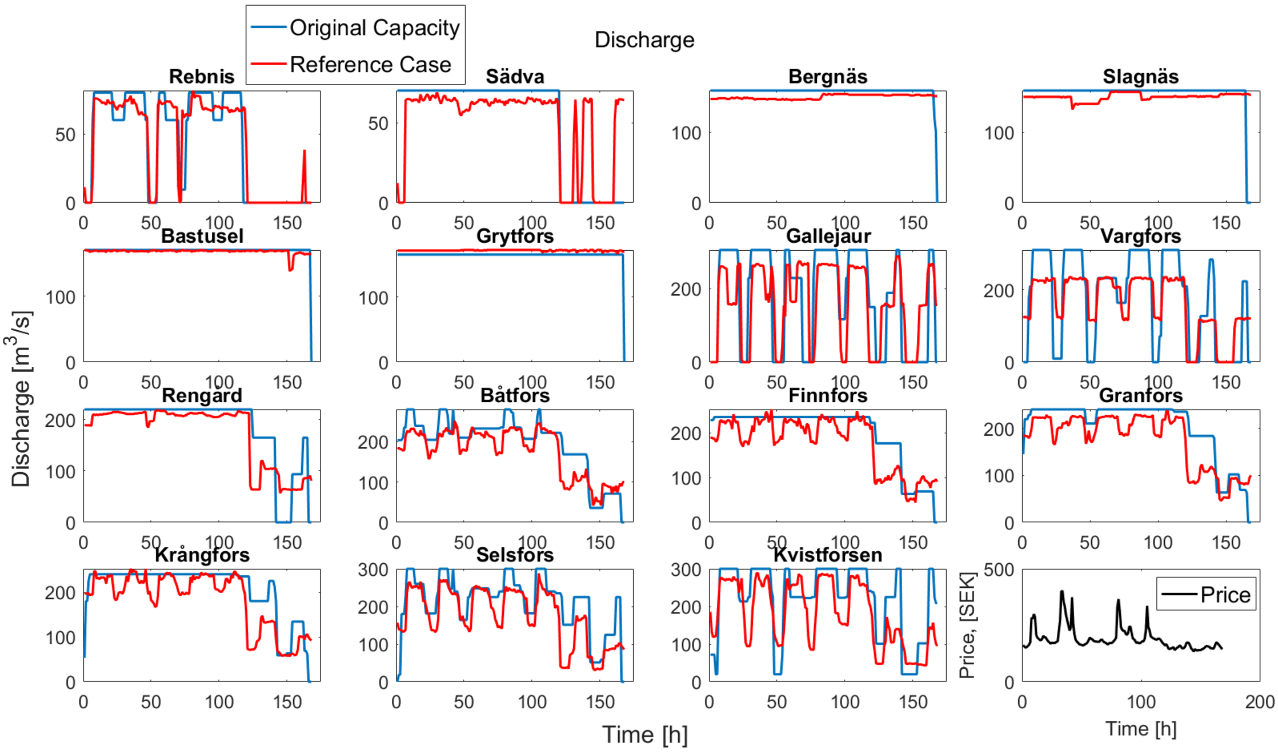

Figure 2: Plot of discharge for each power plant in Skellefteälven

and decrease is yet another reason for the differences between the simulated discharge and the discharge for the reference case. One can increase or decrease the oscillating behaviour by decreasing or increasing the cost, ρ on the delta functions, $\delta_i(t)$ respectively.

Figure 3 illustrates the combined power production of every power plant during the simulated week. Although the changes in the simulated week occur more violently the sign of the derivative, i.e. when the production increases and decreases are mostly synchronised. The total power generation for the simulated case is 119,958 MWh and for the reference case is 107,668 MWh. The approximated efficiency of the power plants in the simulated case are not validated with what their real efficiency is which could explain a couple percent of difference between the simulated and real power generation. The other major difference in generation will be discussed in chapter 4.

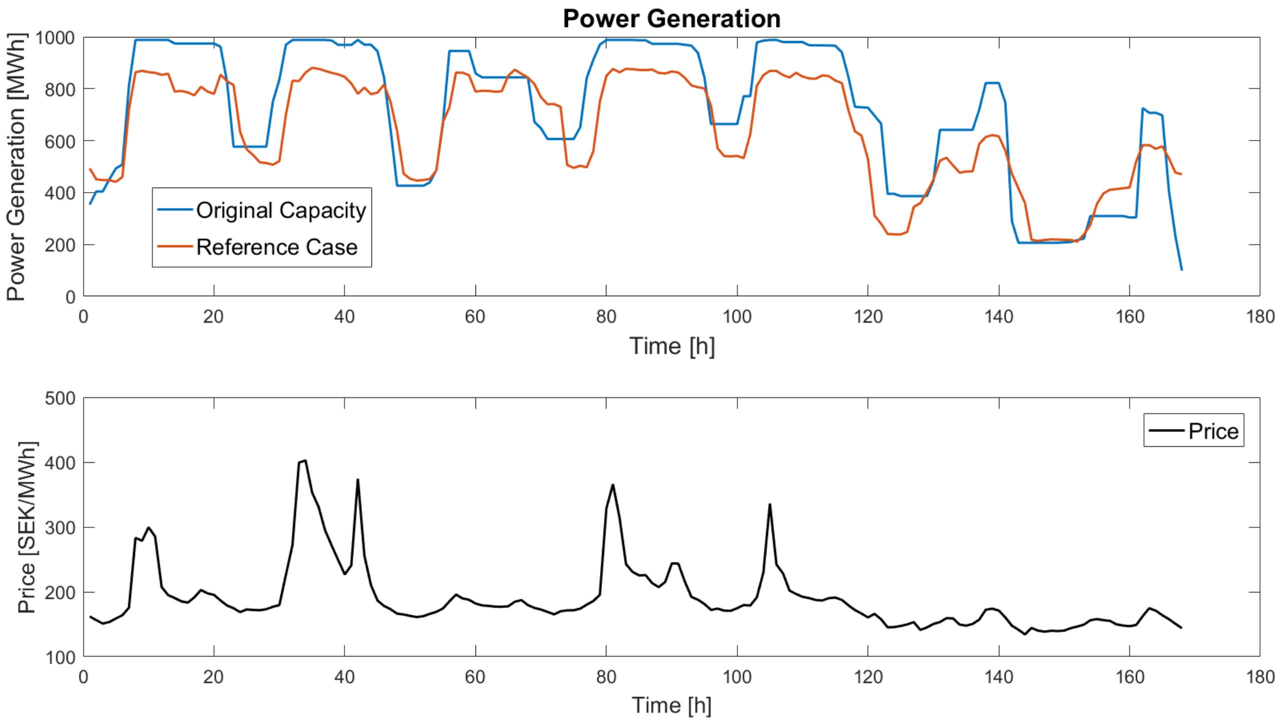

Figure 3: Plot of the power production for each hour of the week for the whole Skellefteälven

3.3 Increasing the capacity of the river to eliminate bottlenecks

In this scenario, a comparison between two different scenarios is made. Where the first scenario is exactly the same as the simulation parameters with installed capacity and the second scenario denotes the case when the power plants get an increased capacity. The increase in capacity was made in a way to eliminate bottlenecks, thus every power station at least has the same discharge capacity as the power plant directly upwards. The parameters for the increased capacity are taken from [1]. The capacity is thus increased by 30%.

As expected, when increasing the ability to discharge more water, the power output is also increased. But a comparison with the simulation from the first scenario is of interest to see the difference in how the power plants are discharging water and how the power generation looks over time. In this case, it is also interesting to see how the reservoir content is affected by the increased capacity of the hydro power plants and is therefore displayed as Figure 6 where an illustration of the increased volatility is presented.

The power generation increased with 9,676 MWh by the increased capacity of the power plants. It is clear from Figure 4 that we have higher peaks of the discharge during some hours. These peaks occur when the price is higher and it is more profitable to generate power. It also has lower generation during other hours of the week than the scenario without increased capacity to compensate for the extra power generation, thus meeting the constraint of final reservoir content. With the increased capacity, the power generation for the first 120 hours of the week is 127,171 MWh compared to the original installed capacity, which generated 99,017 MWh. In the remaining 48 hours, during Saturday and Sunday when the electricity prices are lower, the generation for the increased capacity case was 2,464 MWh compared to the original installed capacity, which generated 20,941 MWh.

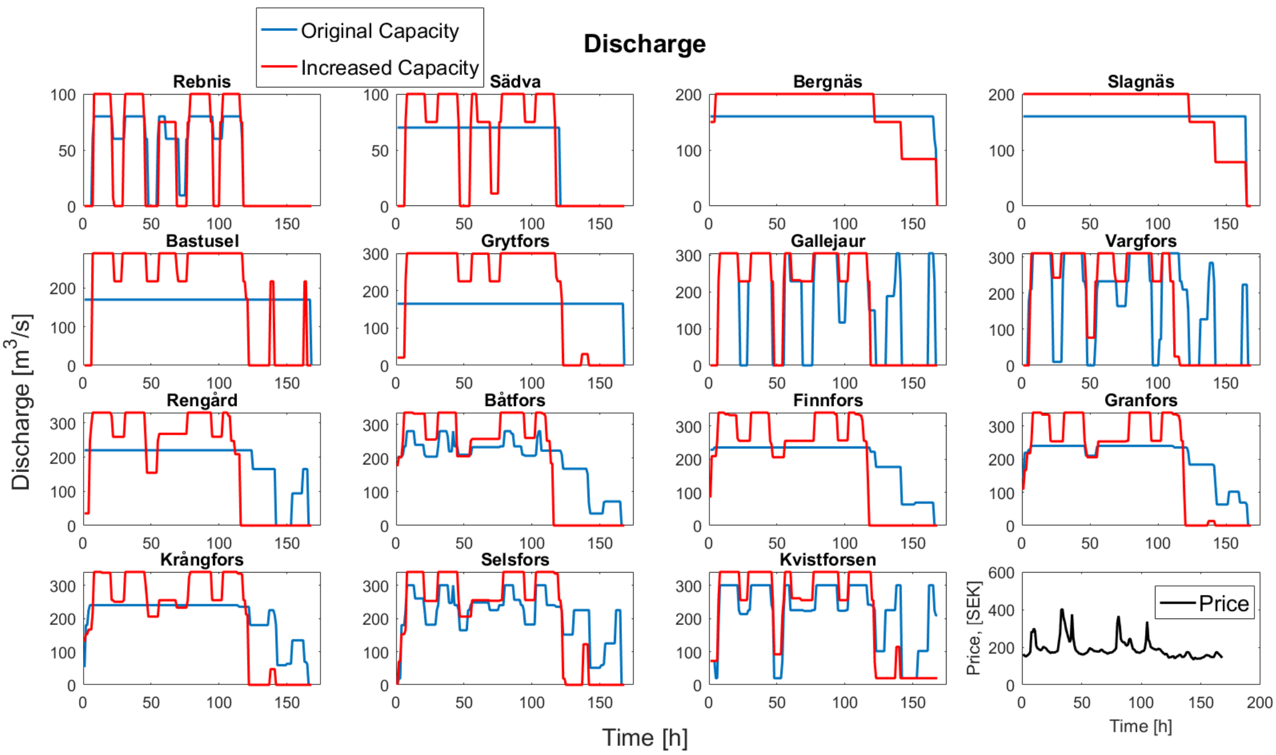

Figure 4: Plot of discharge for each power plant in Skellefteälven

When the ability to discharge at a higher rate becomes available, the power generation also increases when it is more profitable to produce, yielding a lower power generation at other times. This result is illustrated by Figure 6. Keeping in mind that the model has a constraint of a final reservoir level, this is expected.

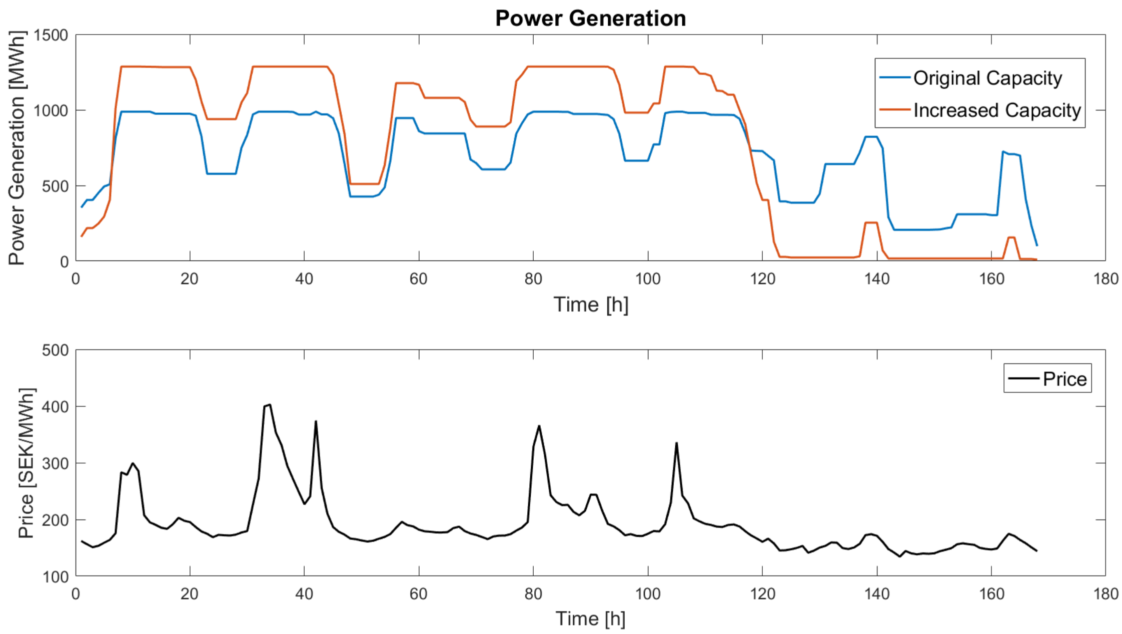

Figure 5: Plot of the power generation for each hour of the week for the whole Skellefteälven

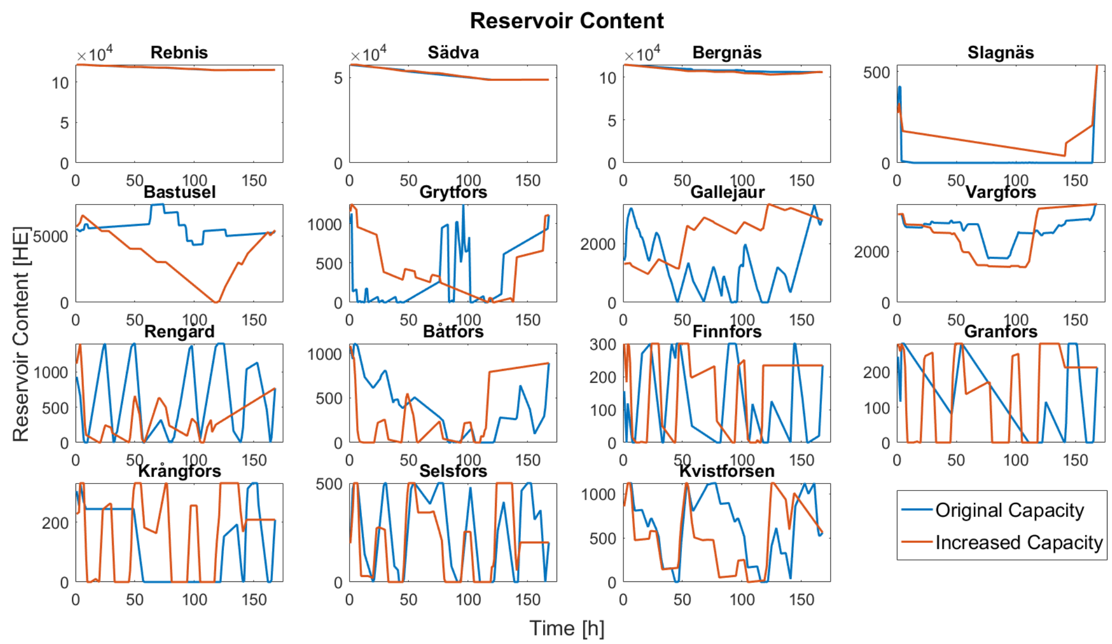

Figure 6: Plot of the reservoir content for each power plant in Skellefteälven

3.4 Flat Price Scenario

The scenario with a flat price is strictly theoretical and its occurrence is highly unlikely when there exist different varying power resources. Even in an assumptive case where the only power resource is nuclear power, the price would not be completely flat since the demand goes up and down and the power plants have to be shut down for maintenance. Nevertheless it is of interest to run a scenario with a flat price to confirm how the power plants would run in a scenario where there is no price volatility. It is illustrated in Figure 7 and in Figure 8 each plant is run on the highest efficiency, thus producing the most possible power with the disposable water in the system, which is expected.

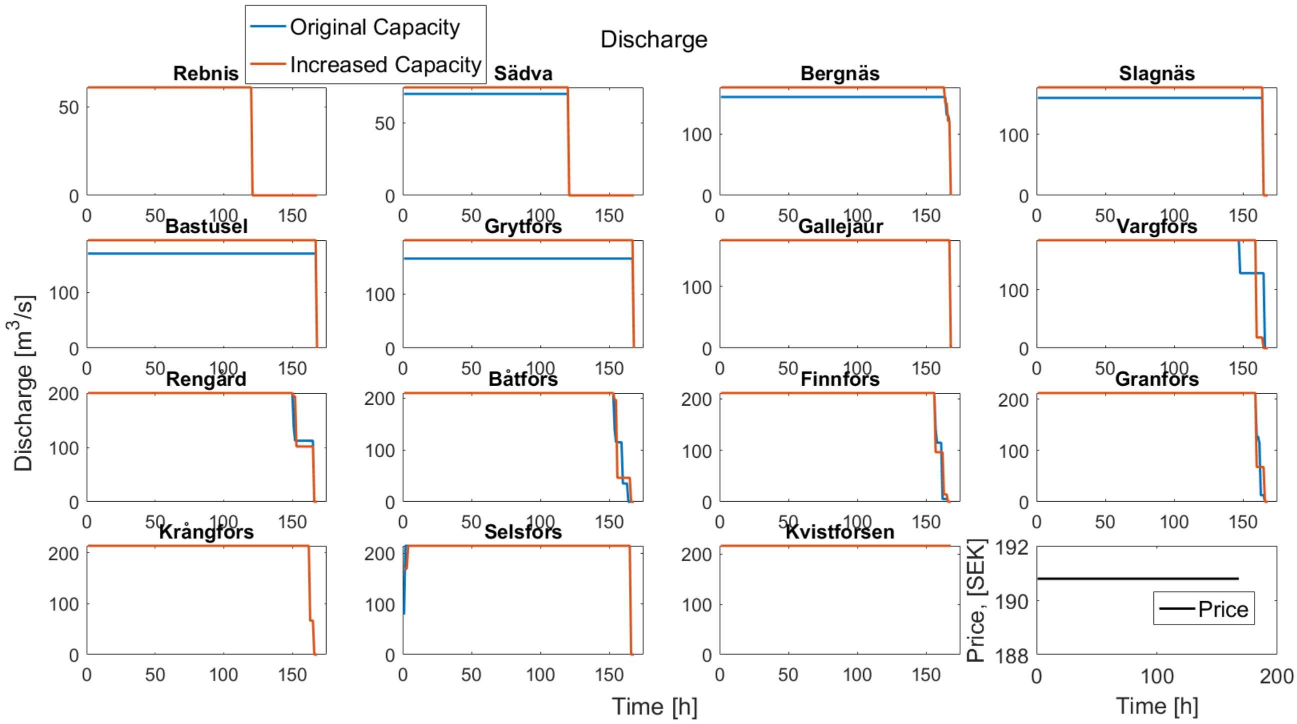

Figure 7: Plot of the discharge for each hour with flat spot prices for every station in Skellefteälven

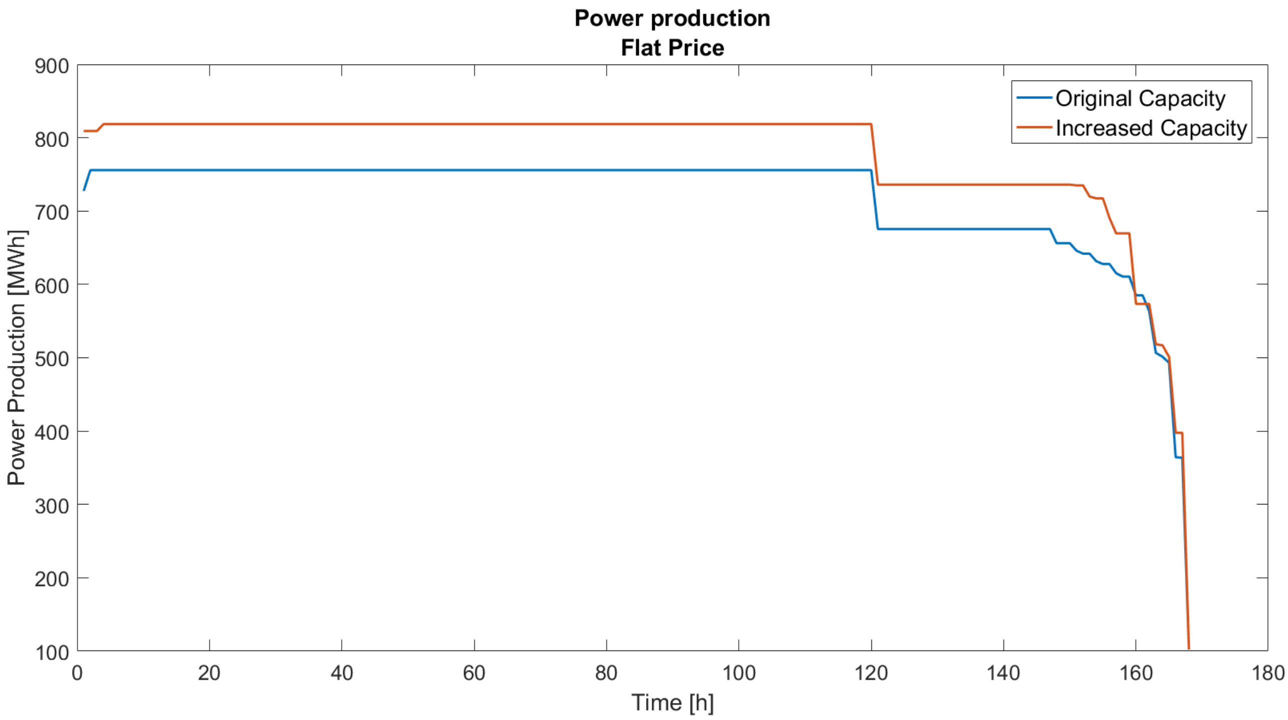

Figure 8: Plot of the power production for each hour of the week for the whole Skellefteälven

3.5 Historic Normal Winter

The largest deviations in price occur during the winter. Thus a simulation of a historic winter week is relevant. Having an increased capacity would yield a revenue of approximately 10,400,000 Euro while the original capacity would have a total revenue of 8,900,000 Euros, yielding an additional revenue of 1,500,000. Figure 9 illustrates the optimal discharge plan for the period and Figure 10 illustrates at which hours the power is produced for the original and increased capacity together with the spot prices for the period.

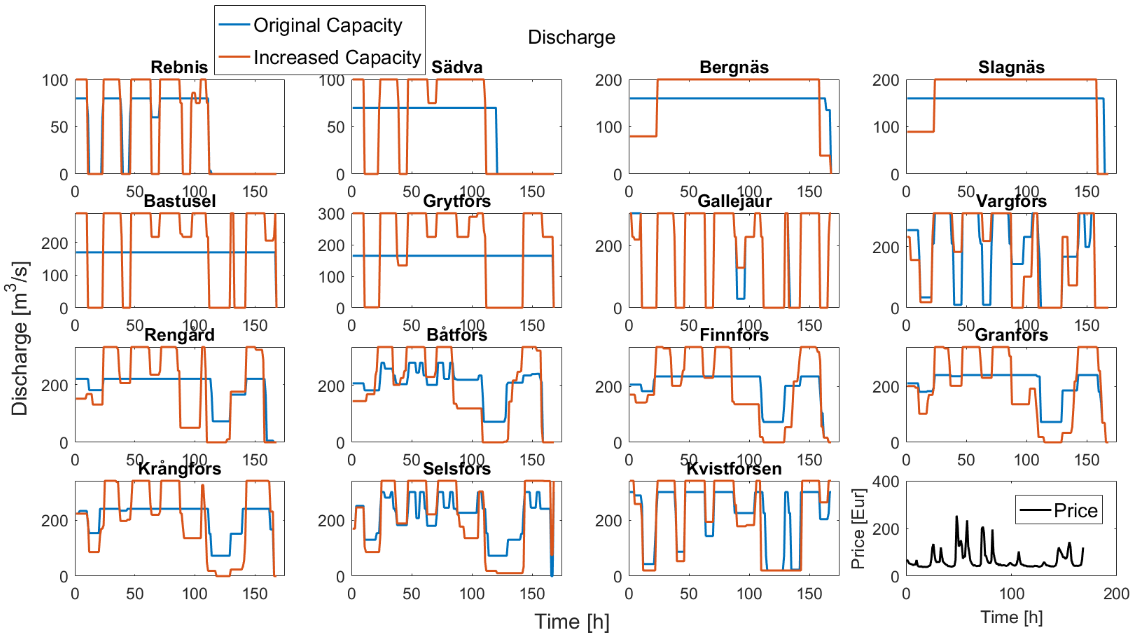

Figure 9: Plot of the discharge for each hour and station in Skellefteälven for a historic winter week

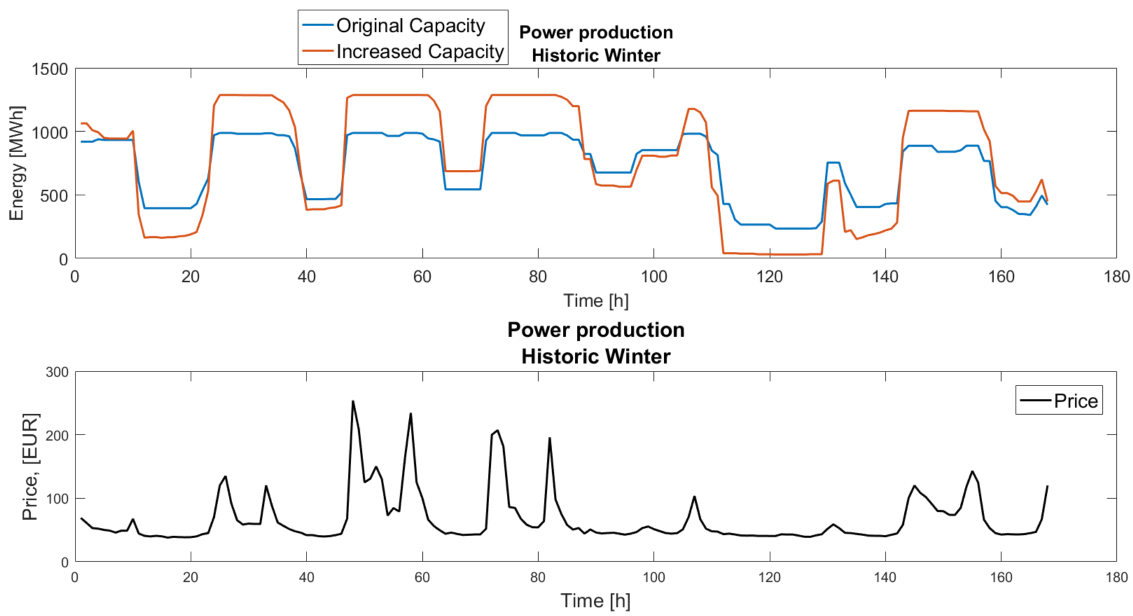

Figure 10: Plot of the power production for each hour of the period for the whole Skellefteälven and the spot prices

3.6 Simulation Wind Shift, Low/High

When a good ratio of wind energy is produced consequently during a period of time, it puts a great amount of pressure for energy resources to compensate for the the inevitable lack of wind which will eventually follow. This simulation examines the ability of the hydro power plants to compensate for such losses. It is clearly shown in Figure 11 that most of the hydro plants discharge a low amount of the disposable water during the first half of the week, when the electricity spot prices are low and produce more during the periods with increased electricity spot prices. Figure 14 illustrates how the power production follows the higher spot prices. It is important to note that the production is not at a minimum despite the spot price being at a low level. There are multiple reasons for this result. One is the ability to transport the water to reservoirs connected to other plants to be used during hours with high demand, denoted with high spot prices. An additional reason is that a certain amount of disposable water is set to be used as a constraint. The consequence is thus a power production since discharging is considered to be of a higher value than spilling the water. The case where an increased capacity of the power plants is available is illustrated by the red line in Figure 12, which shows that the power production is in a significantly lower level than the case with original capacity. The effects of an increased discharge ability make it more profitable to halt the production and use the disposable water when needed most.

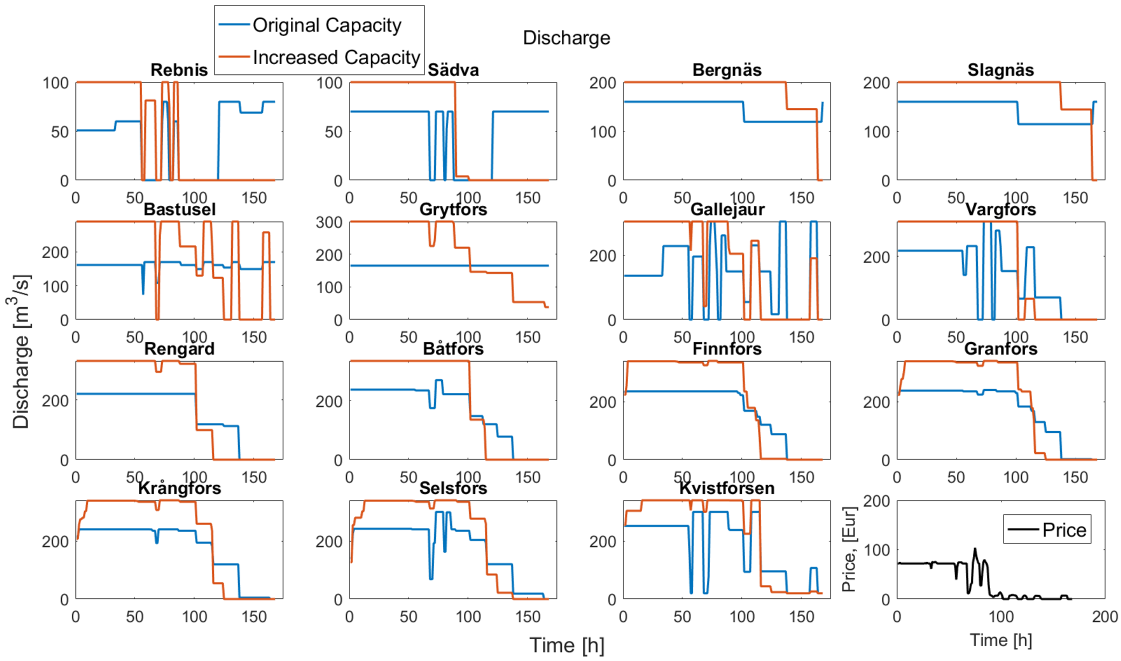

Figure 11: Plot of the discharge for each hour and station in Skellefteälven for a week when a wind shift occurs

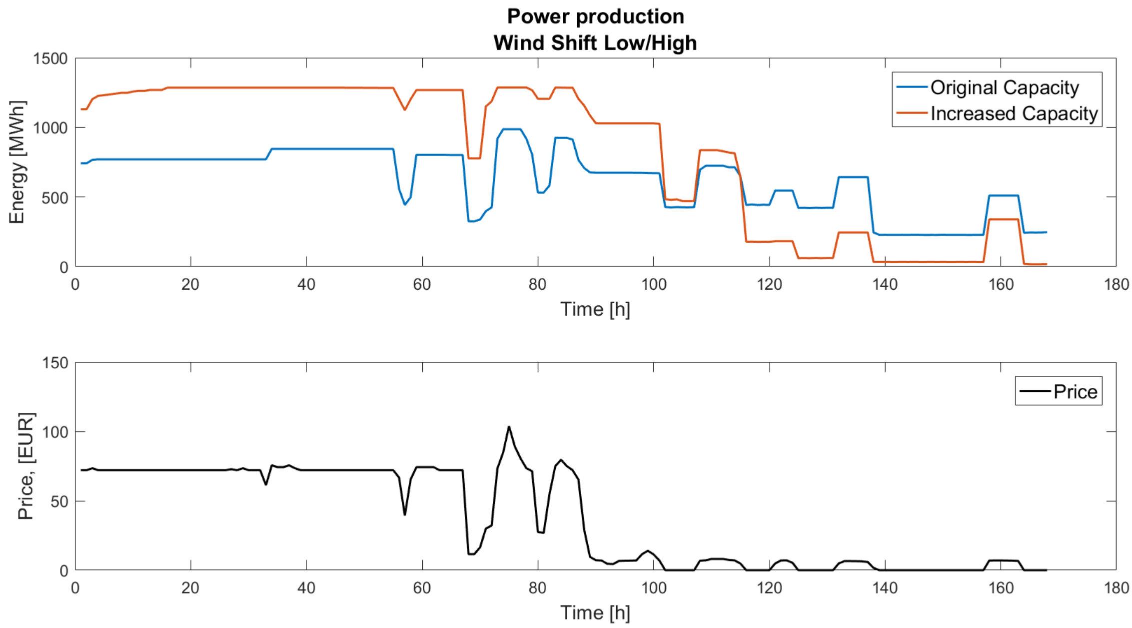

Figure 12: Plot of the power production for each hour of the period for the whole Skellefteälven when one wind shift occurs and the spot prices

3.7 Simulation Wind Shift, High/Low

When a switch is made during mid week, from a low amount of wind production to a high ratio of wind energy produced consequently during a period of time, it puts a great amount of pressure for energy resources to compensate for the lack of electricity in the grids. This simulation examines the ability of the hydro power plants to compensate for a low production of energy from other resources, say wind. It is clearly shown in Figure 13 how most of the hydro plants discharge a low amount of the disposable water during the first half, when the electricity spot prices are low and produce more during the periods with increased electricity spot prices. Figure 14 illustrates how the power production follows the higher spot prices. It is important to note that the production is not at a minimum despite the spot price being at a low level. There are multiple reasons for this. One is the ability to transport the water to reservoirs connected to other plants to be used during hours with high demand, denoted with high spot prices. An additional reason is that a certain amount of disposable water is set to be used as a constraint. The consequence is thus a power generation, since discharging is considered to be of a higher value than spilling the water. The case where an increased capacity of the power plants is available is illustrated by the red line in Figure 14 which shows that the power production is in a significantly lower level than the case with original capacity. The effects of an increased discharge ability make it more profitable to halt the production and use the disposable water when most needed.

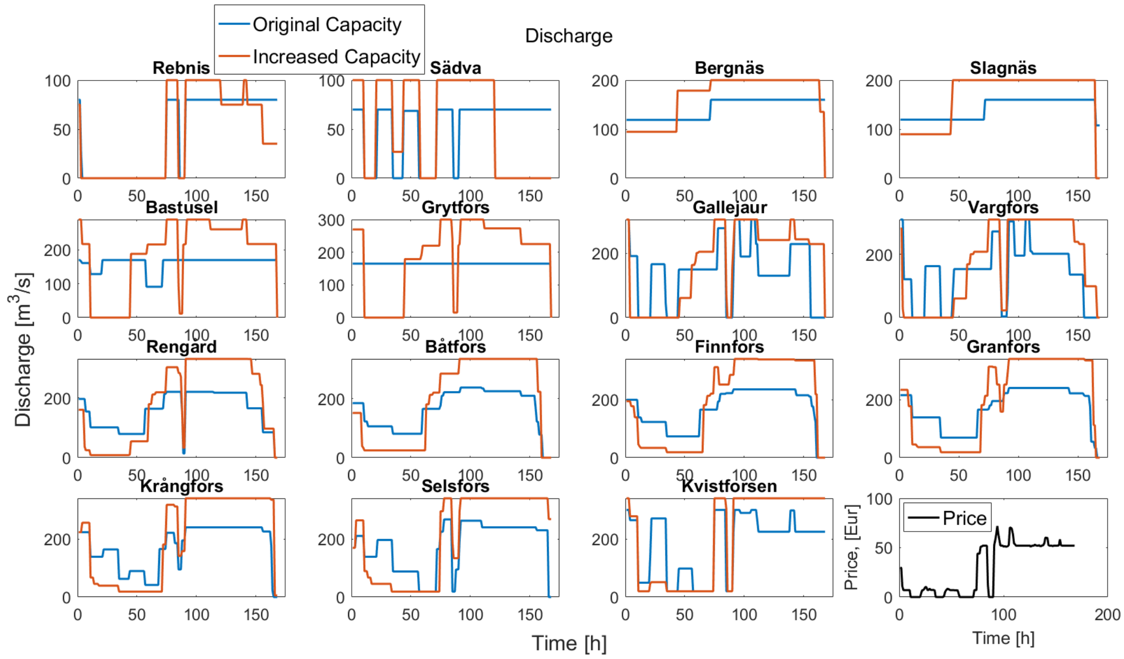

Figure 13: Plot of the discharge for each hour and station in Skellefteälven for a historic winter week

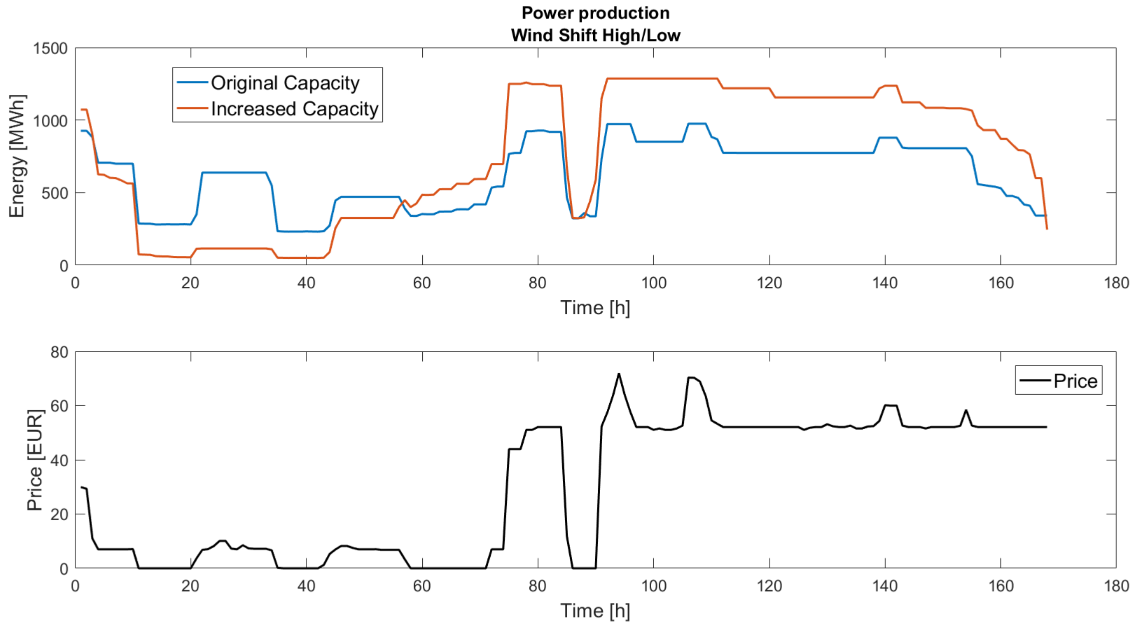

Figure 14: Plot of the power production for each hour of the period for the whole Skellefteälven when one wind shift occurs and the spot prices

3.8 Optimising for 417 Weeks

To have a sense for how an increased capacity would be beneficial when the power production is oscillating, it is important to simulate how the power plants would run during different scenarios. This is achieved through simulations for different prices. When the supply is high, the price is lower and vice versa, thus when there is high wind production the electricity price will be lower than during a period when there is less wind. These simulations will therefore be carried out for different electricity prices for the years 2010 to 2017, ceteris paribus.

Figure 16 illustrates how the revenue changes depending on the volatility of the spot price, which in this report is defined as the standard deviation of the spot price. Since the revenue is calculated as Revenue = Produced Power·Spot Price, the revenue will be higher for weeks with a high average price but low volatility than for weeks with a low average price but with high volatility. To have a fair comparison, the revenue is calculated as Revenue = Produced Power · (Spot Price − Average Price). Thus if the volatility is zero, the (Spot Price − Average Price) will be zero and the revenue will be shown as zero. Another way of performing the measurement for how the volatility can lead to an increased volatility affecting the revenue is by using the median price instead of the average price, as illustrated in Figure 17. It can be argued as that this way of measurement is better because it is not being as skewed as the average price is by a few large values. First, Figure 15 is a histogram that illustrates how the volatility has been for every week since 2010.

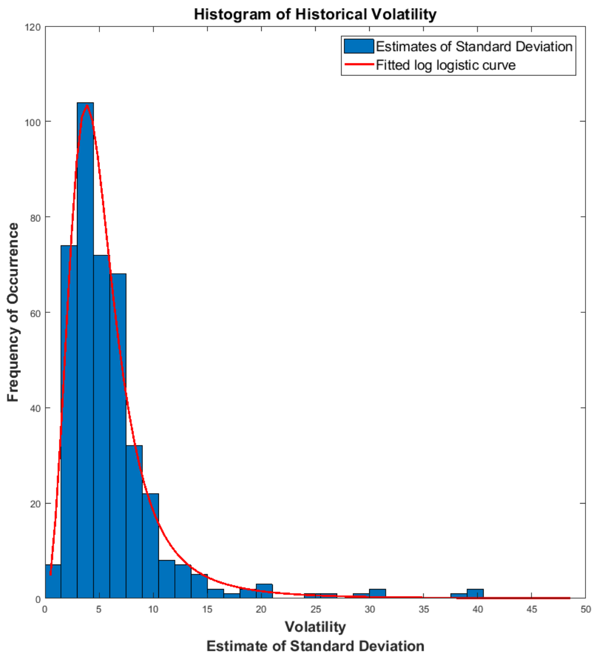

Figure 15: Distribution of the volatility

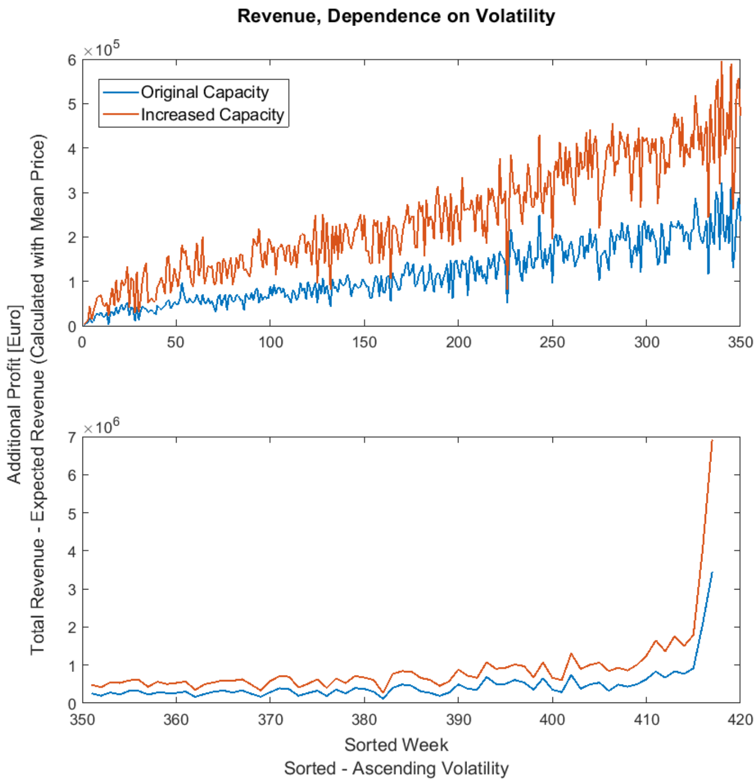

Figure 16: Plot of total additional revenue for each week in Skellefteälven calculated with the mean price

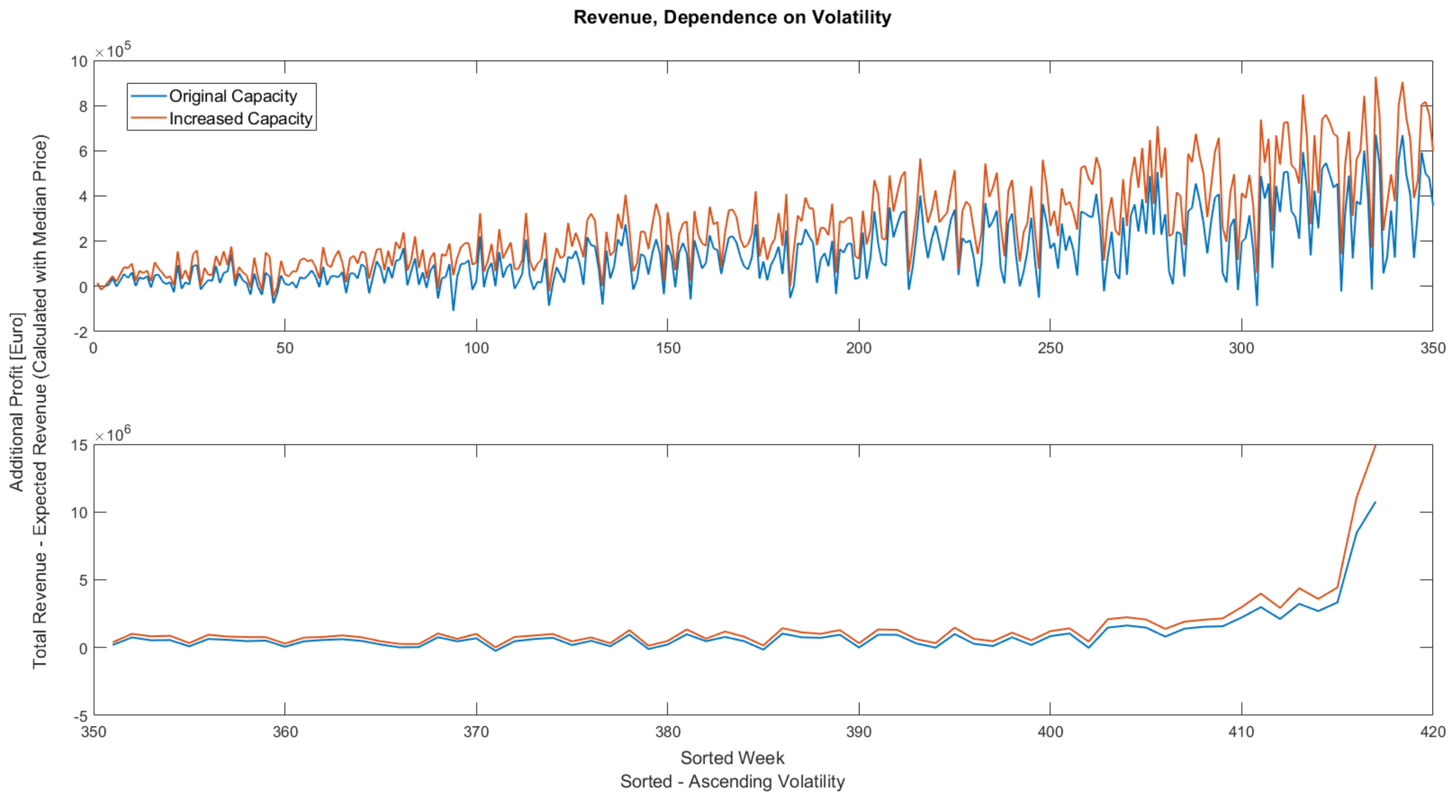

Figure 17: Plot of total additional revenue for each week in Skellefteälven calculated with the median price

As can be seen in Figure 15, the volatility of the prices can be described as a log logistic distribution. It illustrates that although the most extreme values are not most common, they should be taken into consideration since once they occur, they have a significant effect on the outcome. Two of the most extreme values are not shown in Figure 15, one of which occurred between 22 February 2010 and 28 February 2010. The second most extreme value occurred between 4 January 2010 and 10 January 2010.

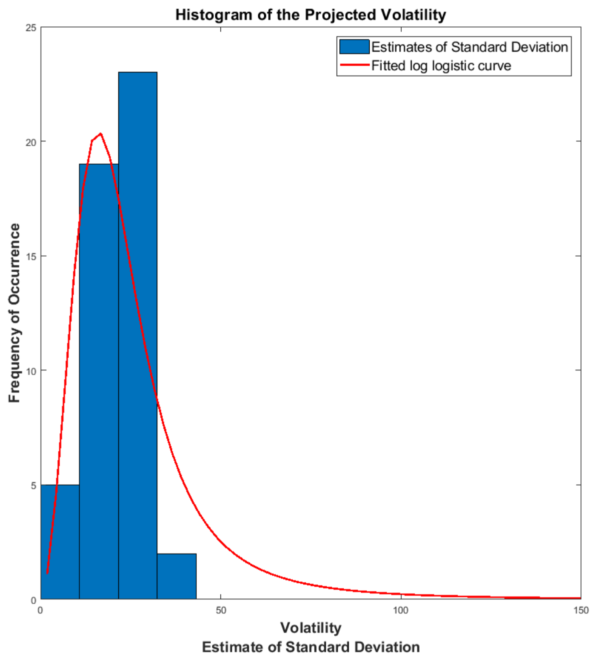

Figure 18: Distribution of the volatility

Comparing the volatility of the historical prices to the volatility of the projected future prices, illustrated in Figure 18, is important to be able to make a comparison and draw conclusions for which combination of power sources are the best equipped to handle the future electrical market. Figure 19 illustrates the two probability density functions with the where the bottom x-axis represents the volatility for the black curve and the top x-axis represents the volatility for the red curve. The y-axis has the same scale for both curves and represents with what probability a volatility occurs for the curves.
There is a correlation in total production which coincides with the volatility. Figure 20 illustrates how the power production is being affected by the change in volatility. Generally speaking, a higher volatility should affect the power production in a negative way since when the price culminates, it is profitable to maximise the power output for those hours. The disadvantage is that the efficiency gets lower, but the greater power generation can still be preferable. For the increased effect, the maximum produced power is 3% higher than the minimum power production. The production was at its minimum during week

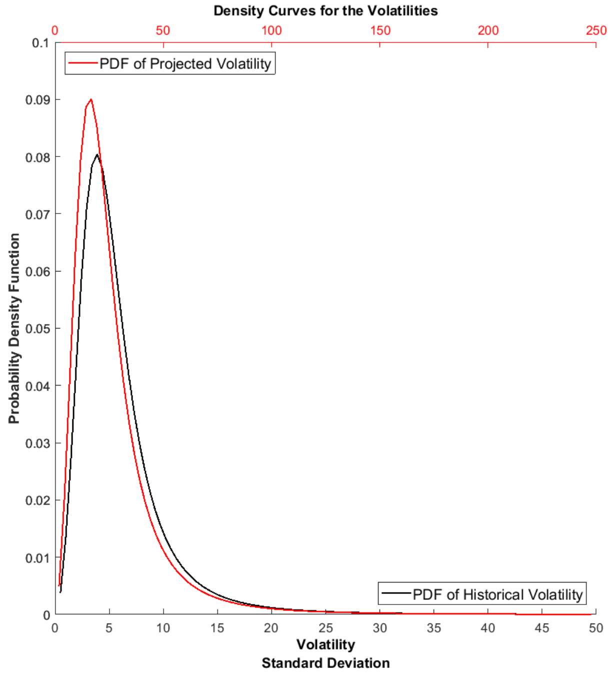

Figure 19: Distribution of the volatility

136, between the dates 2012-08-06 and 2012-08-12, and its maximum during week 64, between the dates 2011-03-21 and 2011-03-27. To have a sense of why this occurs, we can analyse Figure 21 and Figure 23. During week 64, Figure 21, the price is consistent and does not change much. Thus it is more efficient to keep the production at the point where we have the maximum efficiency contrary to week 136, Figure 23, where it is more profitable to generate less energy during the first few days with lower electricity prices to then increase the power production to its maximum when the price is above the mean price. As a result of this, less energy is generated as a consequence of efficiency losses. This is explicitly illustrated for the 64$^{\text{th}}$ and 136$^{\text{th}}$ weeks in Figure 22 and Figure 24 respectively.

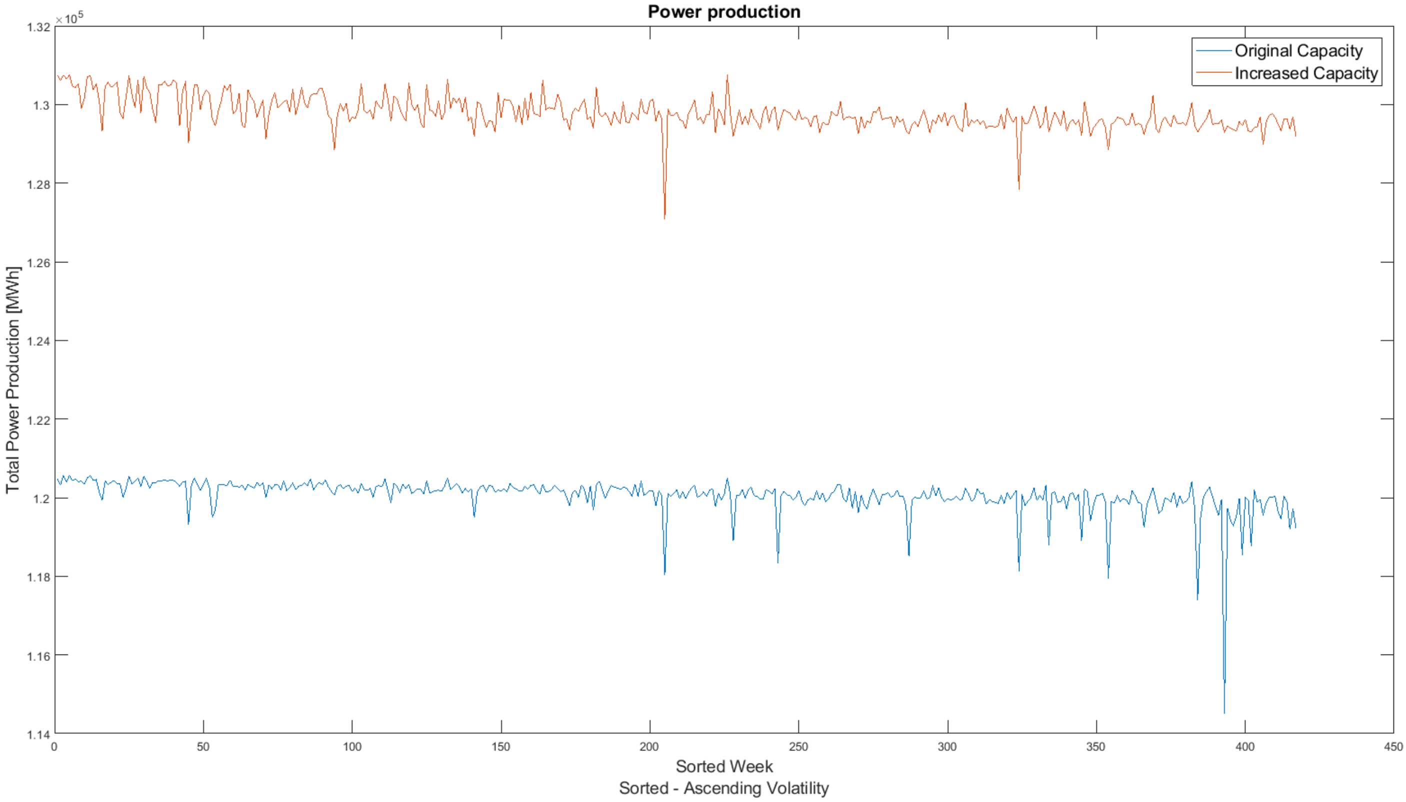

Figure 20: Plot of the power production for each simulated week in Skellefteälven

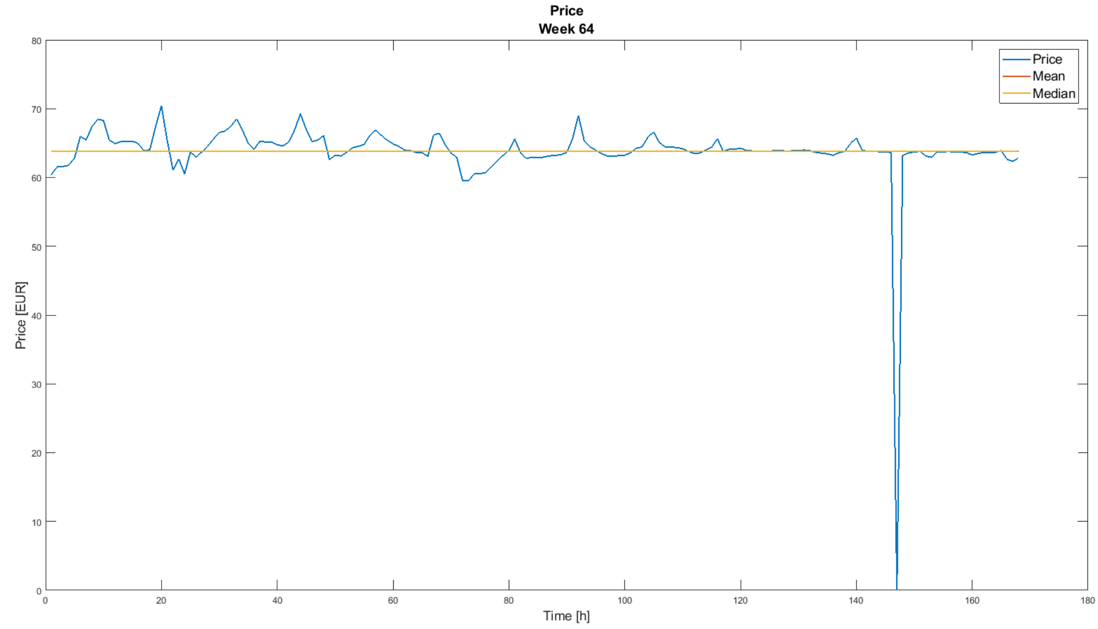

Figure 21: Plot of the spot price for the week with the highest power production

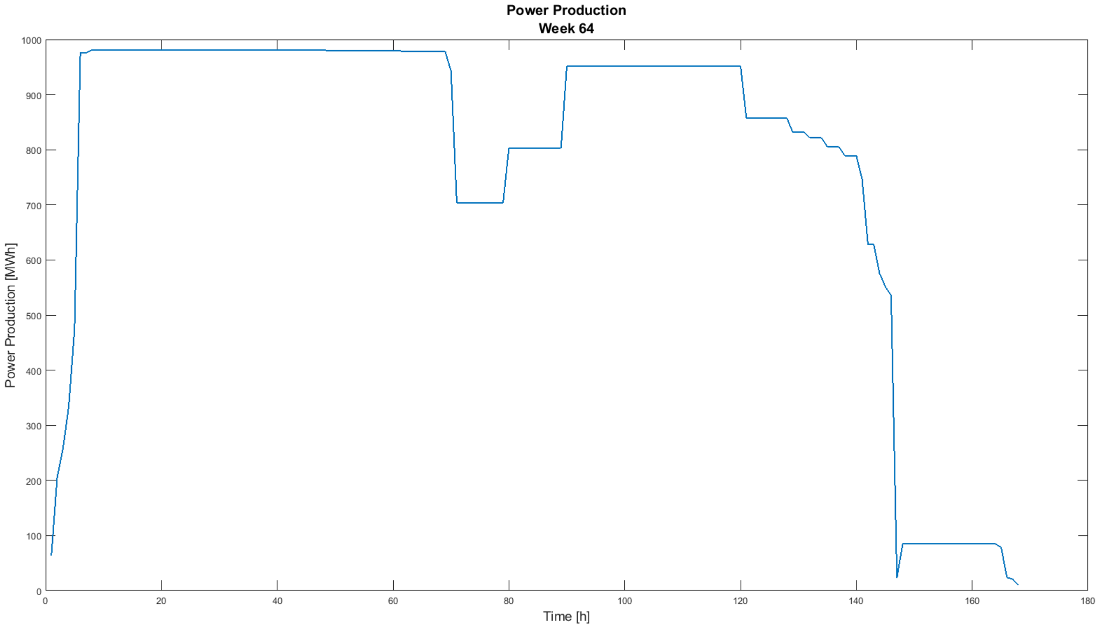

Figure 22: Plot of the produced power for the week with the highest power production

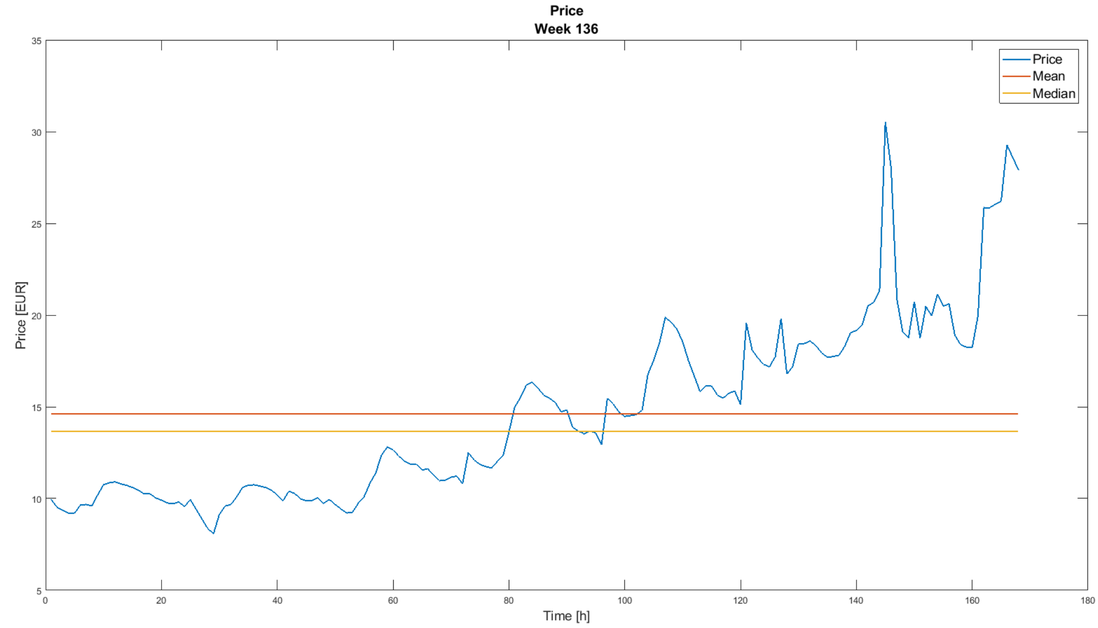

Figure 23: Plot of spot price for the week with the lowest power production

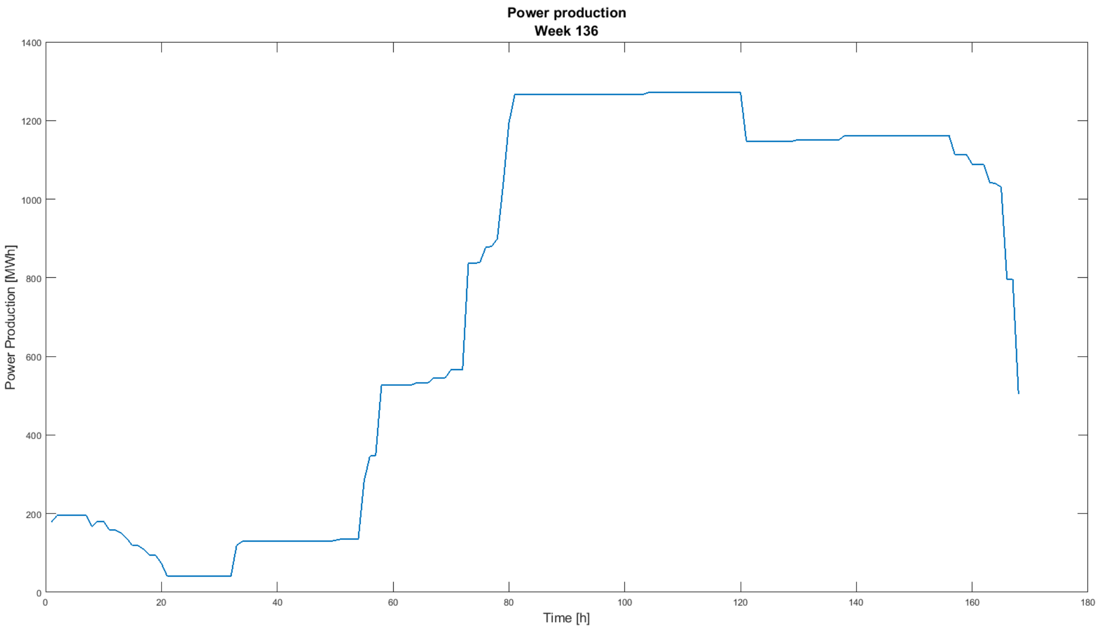

Figure 24: Plot of the produced power for the week with the lowest power production

4 Conclusion and Discussion

Throughout this report, it has been clear that increasing the capacity for hydro power is highly beneficial for society considering that there would be a larger quantity of regulating power during the hours of high demand or during the hours when the spot prices reach their extremes. To know if the expansion of the hydro power plants is beneficial for the companies owning those plants, a net present value analysis must be made. How and when the expansion should be made has not been analysed for the hydro power plants and is outside the scope of this thesis.

The calculations for how much water a reservoir contained is not accurate and the amount of water used in the simulations, both for the increased and original capacity cases, differs from the reference case. After making the calculations from the reference data for how much water was used, in Figure 2, we could see that the the simulated case does not perfectly fit the lines of the reference case. It must be noted that the discharge curves mostly have the same gradient. Thus the problem does not lie with the model but the input parameters, mainly the starting and ending reservoir contents. Thus the model has a satisfactory accuracy but the precision could be enhanced. It is on the other hand important to note that the objective of this thesis is not to replicate an already given case or to enhance the method of hydro power planning. The aim is to note how an increased capacity of hydro power plants can help meet demand out in times when there is increased uncertainty in generation from other resources. Eliminating the bottlenecks helps with eliminating forced spillage and the increased capacity may also prevent unnecessary spillage.

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