TAMPERE UNIVERSITY OF TECHNOLOGY

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THE DEVELOPMENT AND CALIBRATION OF A MID-TERM PLANNING MODEL OF A CO-OWNED HYDROPOWER SYSTEM

Master of Science Thesis

Examiner: Professor Sami Repo
Examiner and topic approved in the Faculty of Computing and Electrical Engineering Council on 15 August 2012

ABSTRACT

TAMPERE UNIVERSITY OF TECHNOLOGY
Master’s Degree Programme in Electrical Engineering
MÄKIHARJU, JUHO: The Development and Calibration of a Mid-Term Planning Model of a Co-Owned Hydropower System
Master of Science Thesis, 66 pages
October 2012
Major: Power Engineering
Examiner: Professor Sami Repo
Keywords: Hydropower, production planning, production allocation, mid-term, optimization model, linear optimization

Conventional hydropower systems with substantial hydro reservoirs are typically planned 1-3 years into the future and production allocation is optimized accordingly so that the profitability of the power production is maximized. In a deregulated electricity market with more than 50 percent of the electricity produced with hydropower that creates challenges for hydroelectricity generating companies as optimal power production requires advanced and excellent quality price and inflow forecasts. These forecasts are gathered from several different sources and the optimal production plans are generated with them as input.

The models used for the optimizing processes are generally rather advanced applications which utilize different mathematical methods to calculate an optimal solution. In order to create a functional model the hydro system limitations and constraints must be familiarized with, and the essentials in hydropower production must be understood.

This thesis develops a mid-term linear programming hydropower optimization tool for a certain river system in Finland. The system is unique as it is consists of several hydro reservoirs and hydropower plants that are owned unequally by several different co-owners. The model’s results are used to give instructions to the actual operator on how to operate the assets in the river. All of the co-owners produce their own plans and the operator collects and combines them to create the final production plan.

The optimization tool creates results that optimize the whole system and not just one co-owners wishes. Hence the results are comparable to the historical and future plans. After extensive tests, it can be concluded that the optimization tool plans the hydro system in a more optimal way that creates more value for all the co-owners in the hydro system. The model suggests operating the river more dynamically and using the total available flexibility in the hydro reservoirs and not operating it too conservatively as before. As a result, the system’s improvement potential can be utilized and the owners of the system can benefit financially from it.

TIIVISTELMÄ

TAMPEREEN TEKNILLINEN YLIOPISTO
Sähkötekniikan koulutusohjelma
MÄKIHARJU, JUHO: The Development and Calibration of a Mid-Term Planning Model of a Co-Owned Hydropower System
Diplomityö, 66 sivua
Lokakuu 2012
Pääaine: Sähkövoimatekniikka
Tarkastaja: Professori Sami Repo
Avainsanat: vesivoima, tuotannonsuunnittelu, tuotannon allokointi, keskipitkä aikaväli, optimointimalli, lineaarinen optimointi

Perinteisesti suurten vesistöjen merkittäviä vesivoimavarastoaltaita suunnitellaan vesivoiman tuotannossa 1-3 vuotta tulevaisuuteen ja tuotantoa allokoidaan optimoidusti siten, että tuotetulle energialle saadaan mahdollisimman hyvä tuotto. Pohjoismaiden vapailla sähkömarkkinoilla, jossa yli viisikymmentä prosenttia sähköntuotannosta on vesivoimalla tuotettua, vesivoiman suunnittelu luo haasteita vesivoiman tuottajille, koska vesivoiman saatavuus vaikuttaa merkittävästi sähkön hintakäyttäytymiseen ja koska tarkat suunnitelmat vaativat erinomaisia hinta- ja tulovirtaamaennusteita. Näitä ennusteita saadaan eri tahoilta ja niiden avulla luodaan suunnitelmat tuotannon allokoinnille, joten ennusteet vaikuttavat suoraan vesivoiman tuotantosuunnitelmien osuvuuteen. Epätarkat tai heikot ennusteet vaikuttavat osaltaan negatiivisesti tuotannonsuunnittelun ja ne aiheuttavat mahdollisesti, jälkikäteen ajateltuna, vääriä päätöksiä vesivoiman tuotannonsuunnitteluprosessissa.

Mallit, joilla vesivoimaan optimoidaan, ovat tyypillisesti erittäin kehittyneitä työkaluja ja ne hyödyntävät erilaisia matemaattisia metodeja löytääkseen optimoidun tuotantosuunnitelman seuraaville vuosille. Toimivan optimointityökalun toteuttaminen on haastava prosessi ja se vaatii tarkkaa vesistön tuntemusta sekä vesivoiman tuotantoperiaatteiden ymmärrystä. Käytännössä kaikki vesistöt ovat uniikkeja, joten optimointimallit pitää aina räätälöidä halutulle vesistölle.

Tässä diplomityössä kehitetään vesivoiman optimointimalli keskipitkän aikavälin suunnitteluprosessiin. Malli on räätälöity yhdelle tietylle Suomalaiselle vesistölle, joka poikkeaa tyypillisistä vesivoiman tuotantovesistöistä merkittävästi, koska se koostuu useista varastoaltaista ja vesivoimalaitoksista, joiden omistuspohja on laaja ja monimutkainen. Kehitetyn mallin tuloksia käytetään tuotannonsuunnittelussa siten, että niillä ohjeistetaan vesistön operaattoria. Operaattori kokoaa kaikkien vesistön osaomistajien ohjeistukset ja tekee niiden avulla, omistusosuuksia painottaen, lopullisen tuotantosuunnitelman.

Optimointityökalu optimoi koko vesistöä yhtenä kokonaisuutena eikä pyri vain yhden osaomistajan kannalta parhaimpaan tulokseen. Tällä tavoin joen dynamiikka saadaan kuvattua riittävän hyvin ja tulokset ovat vertailukelpoisia historiallisiin ja nykyisiin suunnitelmiin nähden. Kattavan koejakson jälkeen optimointityökalu todettiin onnistuneeksi ja se optimoi vesistöä nykyistä tapaa merkittävästi paremmin ja samalla maksimoi, sovittujen rajojen puitteissa, vesistön käyttöä. Dynaamisempi vesistön käyttö lisää tuottoa vesistön omistajille, koska vesistöä käytetään paremmin hyödyksi lupaehtojen puitteissa eikä sitä operoida nykyisellä, konservatiivisen varovaisella, tavalla vaan vesistön koko käytettävissä oleva potentiaali hyödynnetään vesivoimatuotannossa.

PREFACE

This thesis has been written under the guidance of UPM Energy and for the Department of Electrical Engineering of Tampere University of Technology.

I would like to thank UPM Energy for giving me the opportunity to work on an extremely interesting project, which develops my understanding of mid-term planning and also improves my capabilities in my present duties. I would also like to thank M.Sc. (Tech) Matti Vuorinen, who acted as an instructor on UPM's behalf, for giving advice, instructions and guidance throughout the project.

Furthermore, I would like to thank Professor Sami Repo for fresh new ideas he presented and for the advice he gave on completing the thesis.

A special thank you is due to my loving parents. They have supported me throughout the process and without them I would not have gotten this far.

Finally, a massive shout-out to all of my friends: Some of you studied with me, which I am extremely thankful of, but most of you kept me sane by pulling me away from my studies and showing me that university life is not all about studying, it is much more.

Tampere, 23 October 2012

Juho Mäkiharju

CONTENTS

TERMS AND DEFINITIONS

CfD	Contracts for Difference
Day Unit (DU)	Hydropower discharge day unit. 1 DU = 86400 m3.
Elbas	Electricity Balance Adjustment System Market for intraday physical trading
Elspot	Day-ahead market for physical electricity trading
Governance Rule	Contract for hydro system planning and operating
Mid-Term Planning	Production planning with a time horizon of one week to three years
MW	Megawatt
MWh	Megawatt hour
NASDAQ OMX Commodities	Exchange for financial instruments
Nord Pool Spot AS	Administrator for the Nordic electricity market for physical electricity (Elspot and Elbas). Generally referred as Nord Pool Spot. Owners are Statnett, Svenska Kraftnät, Fingrid, Energinet.dk, Elering and Litgrid.
OTC	Over the Counter electricity trade
RoR	Run-of-the-River hydropower
Short-Term Planning	Production planning with a time horizon of present time to few weeks
TSO	Transmission System Operator
TWh	Terawatt hour

1 INTRODUCTION

The purpose of this thesis is to create and calibrate an optimization model for mid-term production planning of a unique co-owned hydropower system. This thesis includes a description of the largely hydro-dominant Nordic electricity market and how hydropower generation is planned and how it is produced with the different available methods. In addition, several hydro optimization techniques are presented with an emphasis on linear programming and also the Governance Rule is described. Lastly, the thesis includes a presentation of the created mid-term optimization model, its results and an assessment how useful the tool is in actual use.

1.1 Background

The deregulation of power markets in the Nordic region started in Norway in 1991 and Sweden, Finland and Denmark followed in the next few years. Also, during these years the different deregulated markets integrated into a common Nordic power market, which was fully achieved in 2000 when Denmark joined in. (Nord Pool Spot 2012)

As a result of the deregulation, the markets became open to competition and market parties started to focus on optimizing their electricity production against the price of the electricity to achieve the best possible value for their production and therefore maximize their revenue. The hourly price of electricity in the Nordic electricity market is determined separately for each hour in the Nordic power exchange, Nord Pool Spot, and the prices are not known beforehand. Hence, advanced forecasting techniques are used to estimate the future prices, which are needed in production planning.

Forecasting the prices requires in-depth understanding of the market fundamentals from the market parties and this knowledge can be utilized to optimize the production to the most profitable hours. This is especially important for hydropower producers who have access to water reservoirs. These producers attempt to optimally allocate water over time, taking into account the forecasted inflows and prices. When the hydro production is not profitable enough and there is room in the reservoirs, water can be stored for future use and when the prices are higher or the hydro reservoir situation requires it, water can be discharged to produce electricity.

In this thesis an optimization model for mid-term hydropower planning is developed, calibrated and studied in detail. The model uses available forecasted data, such as prices and inflows, as inputs and its goal is to maximize the revenue for the production companies of the river system in a way that satisfies the environmental regulations and the Governance Rule document. The time horizon of the model will be from the present situation to one to three years into the future, depending on what the mid-term planner would prefer to analyze. A daily resolution was chosen for the program, as requested, in order to achieve a highly detailed production plan. This resolution can be modified later on if needed. Overall, the model created should be robust so that as much of the code could be re-used in planning tools for other hydro systems. However, the details in the program are only from this hydro system in order to model it sufficiently, and they cannot be utilized in any other hydro systems.

1.2 Focus and assumptions

The aim of this thesis is to create a mid-term planning tool for co-owned hydropower production. The thesis will concentrate on production planning in the Nordic power market and focuses on utilizing the hydro system more optimally to meet the challenges of the integrated market and also to increase revenue from the hydro production.

The Nordic electricity market includes both physical and financial markets. The focus of this thesis is to optimally plan hydro production that is to be sold to the physical market. The financial market is not included in the scope of the thesis.

The optimization of the river system in question does not require nonlinear or stochastic programming and linear programming can be used instead. The linear programming modeling technique and the reason why linear programming was chosen as an optimization method for the modeling tool will be described in Chapter 4.1. The other possible hydropower optimization methods are briefly presented in Chapter 4.2.

Hydropower has a significant effect on the prices in the Nordic power market as it is hydro dominant. Therefore the large Nordic hydropower production companies can somewhat affect the electricity prices by planning their hydro assets. The size of the river system described in this thesis is not particularly significant in the Nordics and the companies involved in the hydropower system do not have the size to exercise market power. Hence it is assumed that the system described does not affect the prices in the Nordic power market and price forecasts can be used as input to the planning tool.

1.3 Research Objectives

The main objective of this thesis is to create a useful mid-term optimization program for co-owned hydropower production planning. It will take into account the present water reservoir situation, forecasted inflows and the rules stated in a Governance Rule document. In addition, it uses provided forecasted Spot prices to optimally use the reservoirs in the system and operate the river as efficiently as possible. The model needs to be robust as the basic structure serves as a model for other hydropower optimization tools but at the same time it is fine-tuned to a particular hydropower system so that the results are sufficient.

The hydropower system in this thesis is a regular river system but differs from other hydropower systems because of the complex co-owning structure of the reservoirs and hydropower plants. In order to make river operations easier and more efficient, a Governance Rule contract was created, which all involving parties have accepted. In short, the Governance Rule states that the hydropower plants are owned by several parties unequally but the hydro reservoirs are owned together and all parties have a right to say how the reservoirs are used.

Based on this model and analysis, mid-term planning can direct and give instructions to the river system's operator to allocate hydroelectricity production in a more optimal way for the parties involved. Hence, the optimization tool is for guidance only and the results are not used to actually operate the river system. Instead, the tool gives critical information as output so that mid-term can plan future power production in a more detailed fashion and also estimate the future revenue from the said production. The final production plan is also forwarded to the operator so that it knows how a co-owning company would like to discharge the hydro in the next several months and where do the companies want the system's reservoir levels to be at. All the instructions from the different co-owners are then aggregated by the operator and a real operating plan is created accordingly to meet the wishes of all the co-owners.

The success of the optimization model can be estimated by comparing the model's plans to the operator's actual plans. If the new model creates more value for the energy produced, then the new model is successful and it creates value for the co-owners. The way it is first tested is to optimize production against historical realized data and see if the model would have been more optimal than the operator's plans at the same time. Secondly, the quality of the results will be assessed by checking that the constraints are functioning as stated in the Governance Rule and the reservoirs stay within the agreed limits. Finally, the model will be used to optimize the future and the results are compared to the operator's future plans. The results should be similar as the inflow forecasts are identical but if not, the reason for the difference should be studied and decide if the operator's plans should be re-evaluated. That way the owners can be sure that their assets are used in an optimal way and the revenue from the hydro is maximized in the mid-term time horizon.

1.4 Structure of the Thesis

The thesis consists of eight chapters including an introduction and a conclusion. Chapter 2 gives an introduction to the Nordic electricity market. First the basic fundamentals, formation of the Spot price, different production methods and factors affecting the supply and demand, will be discussed. Chapter 2 also explains how the physical and financial markets work in the Nordic power market. Lastly the chapter covers the dominant role of the hydro power production and how it affects the market.

Chapter 3 of the thesis gives a detailed outlook on hydropower production. The chapter covers hydropower plants, what the hydrological environment is like in the Nordics and how the hydropower generation is scheduled. In addition, the chapter includes an overview of hydropower production in the Nordics, where the hydroelectricity production differs significantly even within the Nordic countries themselves but also from the hydropower production of the rest of the world.

Chapter 4 of the thesis presents different hydropower optimization techniques. There are several available depending on what the hydro system is like and what is needed from the optimization. The model created in this thesis is based on linear programming, as all the non-linear dependencies and restrictions in the hydro system can be linearized. In some other hydro systems a more complex nonlinear programing must be used to get adequate results. The other programming methods will be explained briefly.

The Governance Rule of the river system in question is introduced in Chapter 5. The rule includes detailed restrictions, which must be obeyed, and other critical data of the river system. In Chapter 6 the rules and restrictions of the Governance Rule will be put to use and the created optimization model is presented and explained.

Chapter 7 includes results of the created hydro optimization model and analysis how effective and useful the model is. In addition, Chapter 7 includes a discussion on how the created tool is put to use in the future and how it might be further developed. The conclusion chapter includes final analysis on the project and how effective the created model is.

2 NORDIC ELECTRICITY MARKET

This chapter provides an overview to the Nordic electricity market. Chapter 2.1 will explain the fundamentals of the market and Chapters 2.2 and 2.3 will describe the two different markets in the Nordic area, the physical and the financial, which together form the market as a whole. Chapter 2.4 will discuss and analyze the hydro-dominance of the Nordic power market and explain the benefits and the possible negative impacts from it.

2.1 Fundamentals

Between 1991 and 2000 the electricity markets in Norway, Sweden, Finland and Denmark were all deregulated. During the same time period the four Nordic countries integrated their markets to form a single Nordic electricity market, at the time called Nord Pool ASA. (Amundsen & Bergman 2005) This electricity market included both physical and financial power trading until 2002 when the physical market, Nord Pool Spot AS, separated from the financial energy derivative exchange. Then, in 2008, NASDAQ OMX Commodities acquired Nord Pool ASA. Presently the physical trade is done on the Nord Pool Spot power exchange and the financial instrument trade is on the NASDAQ OMX Commodities' side. (Nord Pool Spot 2012, NASDAQ OMX Commodities Europe 2012)

NASDAQ OMX Commodities is owned by the American multinational financial services corporation NASDAQ OMX Group, Inc. (NASDAQ OMX Commodities Europe 2012) Nord Pool Spot AS is currently owned by the Nordic Transmission System Operators (TSO's) Statnett SF, Svenska Kraftnät, Fingrid Oyj, Energinet.dk, Elering and Litgrid. The Norwegian Statnett and the Swedish Svenska Kraftnät own an equal share of 28,2 % and the Finnish Fingrid and Danish Energinet.dk both own 18,8 % of the company. In August 2012 the Estonian Elering and Lithuanian Litgrid both acquired 2 % share of the company. In addition the Latvian TSO, Augstsprieguma Tikls, will acquire a 2 % share of Nord Pool Spot when the new Latvian power market opens. (Nord Pool Spot 2012)

The Spot, or the system, price of electricity in the Nordic power market is formed day ahead for each hour at the Nord Pool Spot according to supply and demand on the market. The price is calculated separately for all hours of the day by calculating a balance point where the supply and demand bids are in equilibrium. This price is equal to the wholesale trading price of all the participant trading areas as long as there is a sufficient amount of transmission capacity available. If there's a lack of transmission capacity, the prices differ from the system price and area prices are calculated.

(Amundsen & Bergman 2005) A simplified way of presenting this delicate balance is shown in Figure 2.1.

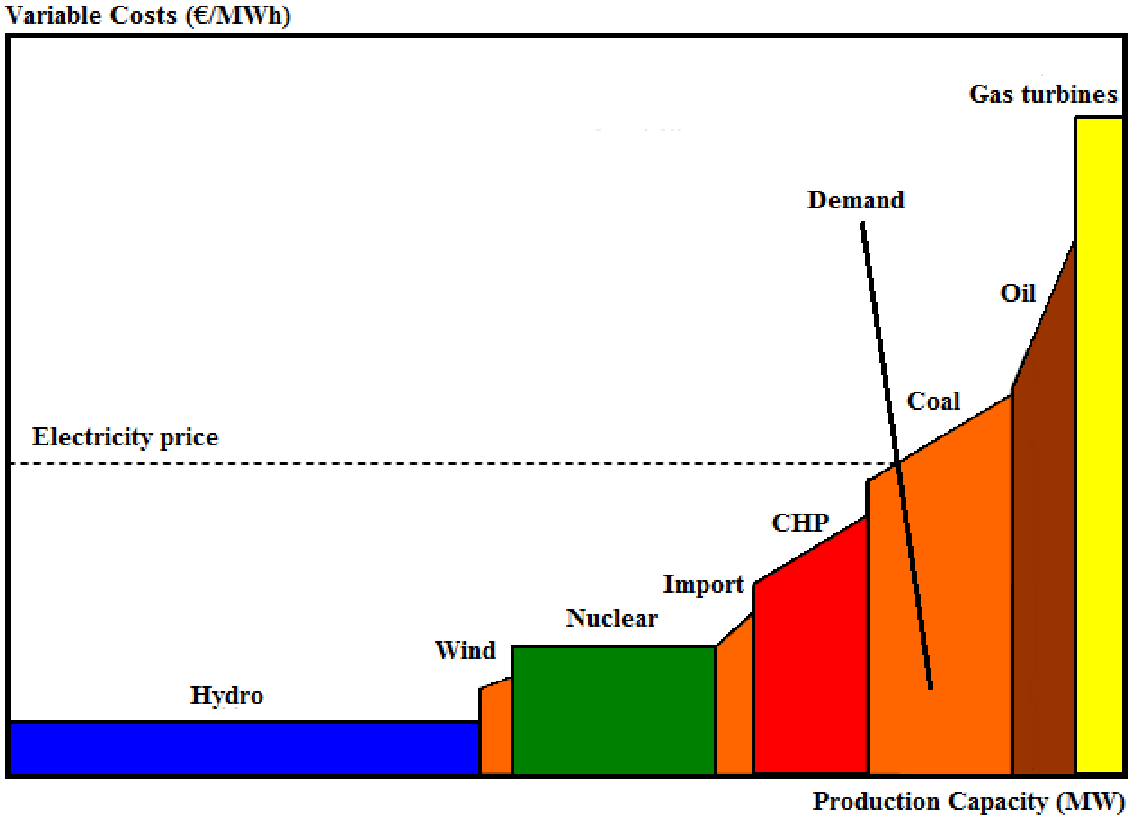

Figure 2.1. *Formation of the electricity price and a conceptual supply curve (EK 2009)*

Several market factors affect the Spot price formation. The most basic ones include weather conditions such as the current temperature, precipitation, the hydrological situation in general, wind conditions. In addition the availability of production capacity and the fuel markets affect the price formation significantly. In the Nordics the winters are frigid and heating during the winter time increases the demand of electricity significantly. This is seen as increasing weekly prices on a yearly level (Figure 2.2). More precipitation or wind, on the other hand, increases the pressure to produce more electricity, which usually results in decreasing prices. In addition to the yearly price profile, typically there are significant price differences also on a weekly level, between weekdays and weekends or holidays (Figure 2.3) and also between days and nights (Figure 2.4). This is all critical information as optimal production planning requires detailed price forecasts and proven models on how the price behaves in different situations. (MPE 2008)

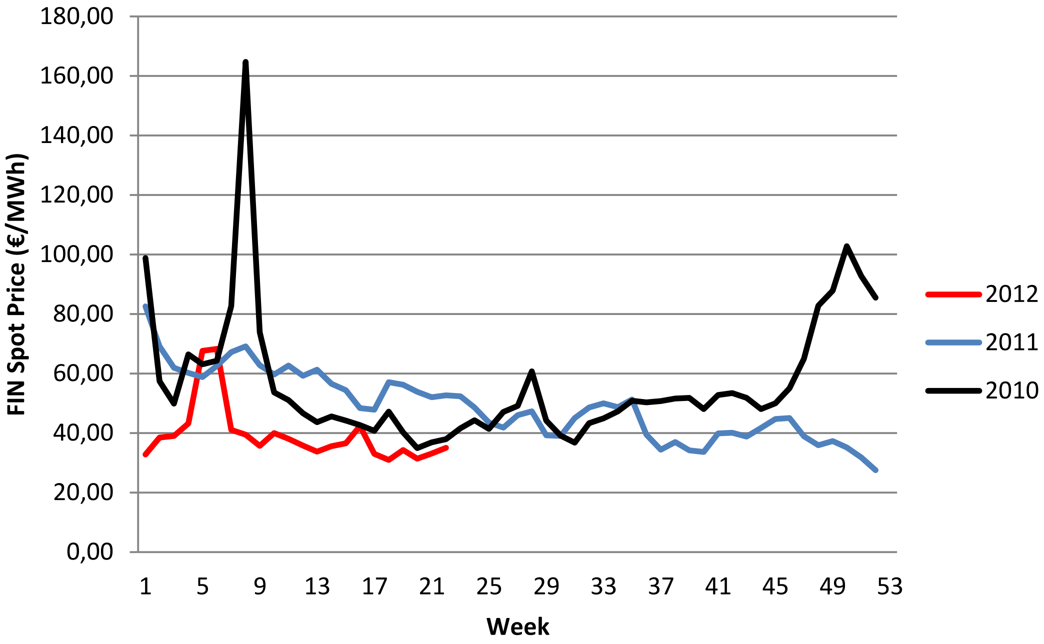

Figure 2.2. *Weekly Average Electricity Price (Nord Pool Spot 2012)*

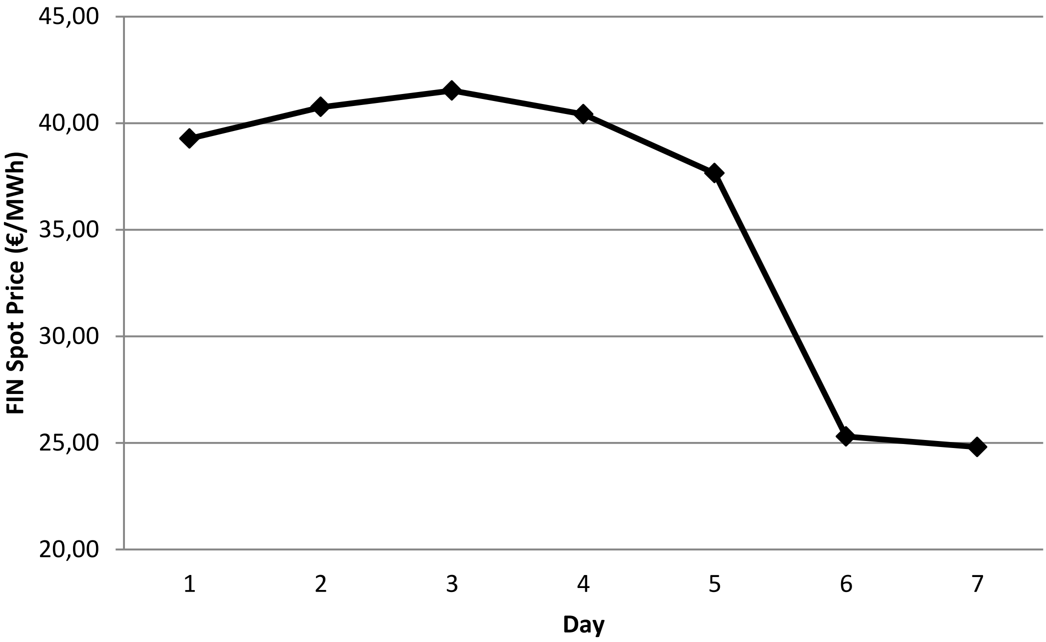

Figure 2.3. *Daily Electricity Price of Week 12, 2012 (Monday to Sunday) (Nord Pool Spot 2012)*

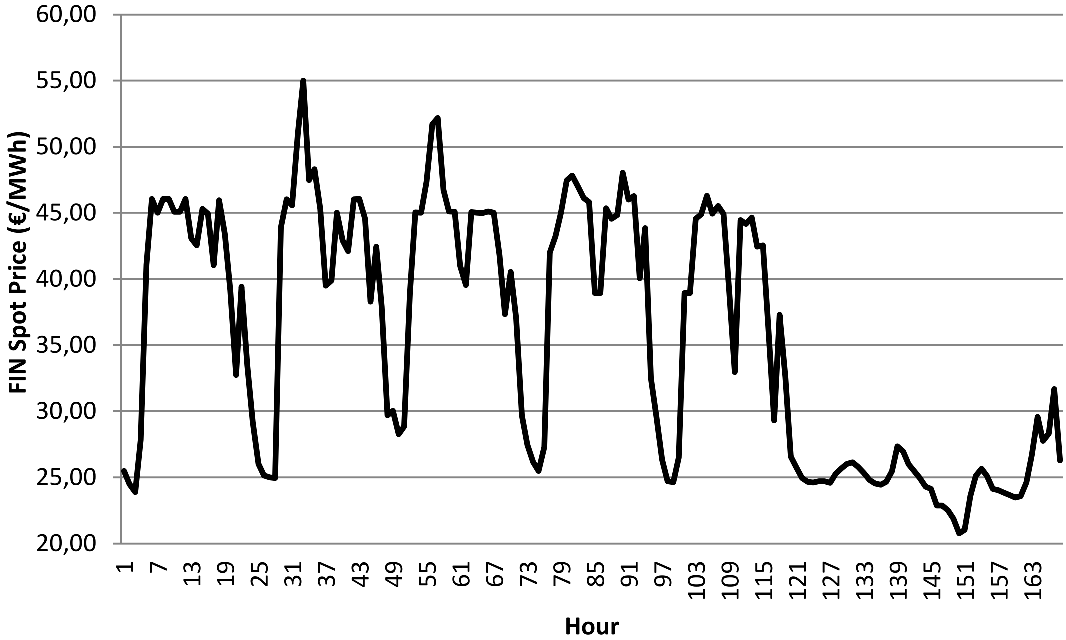

Figure 2.4. *Hourly Electricity Price (Week 12, 2012) (Nord Pool Spot 2012)*

Besides the weather related factors, the transmission capacity influences the price. If some parts of the integrated market have excess production, which cannot be transmitted to another area or halted for the time being, the area price decreases and the market works as it should. Conversely, if there is an area which requires more energy but there are transmission line limitations, then that area will form its own area price so that the more expensive production forms can start producing. Presently there are a total of 13 areas within the Nordic. One area for the whole Finland and also one for Estonia, two areas in Denmark, four in Sweden and five in Norway. (Nord Pool Spot 2012) Figure 2.5 presents the current Nordic market areas.

Figure 2.5. *Different price areas in the Nordic power market (Nord Pool Spot 2012)*

Recently the imports and exports have also affected the prices significantly. There is evidence that Russian imports to Finland have decreased considerably (see Figure 2.6) due to high Russian prices and low Nordic electricity prices. Before 2011 the Russian imports to Finland were nearly constant but as the Russian electricity imports have begun to act in a more market based fashion, the imports have decreased and together with capacity problems with the Swedish links the Finnish area price has been, at times, extremely volatile. (Fingrid 2012, Energiateollisuus 2012) There are also other special situations that affect the Spot prices, such as holidays and strikes that decrease prices as the industry consumption is low. (Lehikoinen 2007)

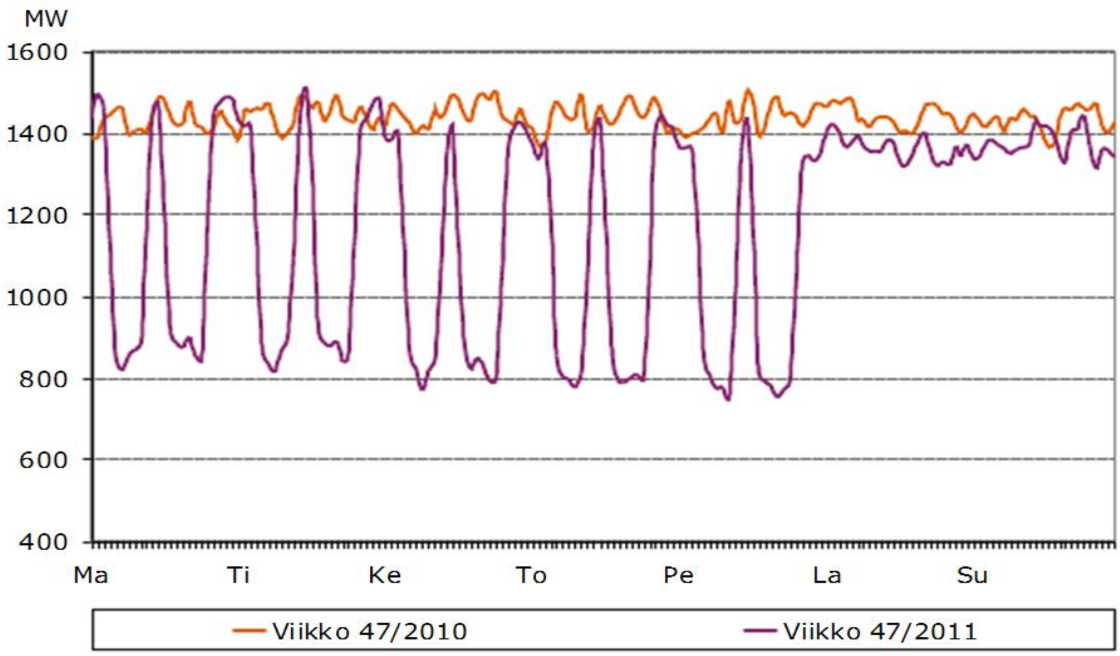

Figure 2.6. *Electricity imports from Russia to Finland (weeks 47 of 2010 and 2011) (Energiateollisuus 2012)*

2.2 Physical Market

Physical market in Nord Pool consists of two different markets; the auction based day-ahead Elspot and the intraday Elbas trading system. The trades completed on the physical market always result in a physical delivery of electricity from the producer to the end user with Nord Pool AS initiating the settlement. The day-ahead Elspot is the major power trading market where approximately 350 members trade power every day. The members place bids for buying and selling for each 24 hours of the day before 12:00 Central European Time (CET), after which the contracts are made with a certain price for delivery on the following day. The price for each hour is set where the sell and buy prices meet. In another words, the prices meet at the point where supply and demand are in equilibrium, which is a criterion for the power system as electricity is a non-storable commodity. (Nord Pool Spot 2012)

Besides the hourly bids, the trading members can place special linked bids, called block bids. Block bids must be at least three hours long and the bids are realized if the average price of the block's time period is either lower or higher, depending on the block bid type, than the price stated in the bid. These bids are extremely useful especially if the member owns high operational cost power plants that have start-up and shut-down costs.

The hourly and block bids are the main factors responsible for the electricity prices but transmission constraints also play a significant role. If there are no bottlenecks in the power connections, the 13 different areas that are linked to each other in the Nordic power market share the same prices. If the transmission capacity, on the other hand, is not sufficient, then the prices for the hours in question are regulated so that supply and demand is in equilibrium in the separated area alone. (Nord Pool Spot 2012) The depth of the Nordic power market integration is shown in Figure 2.7.

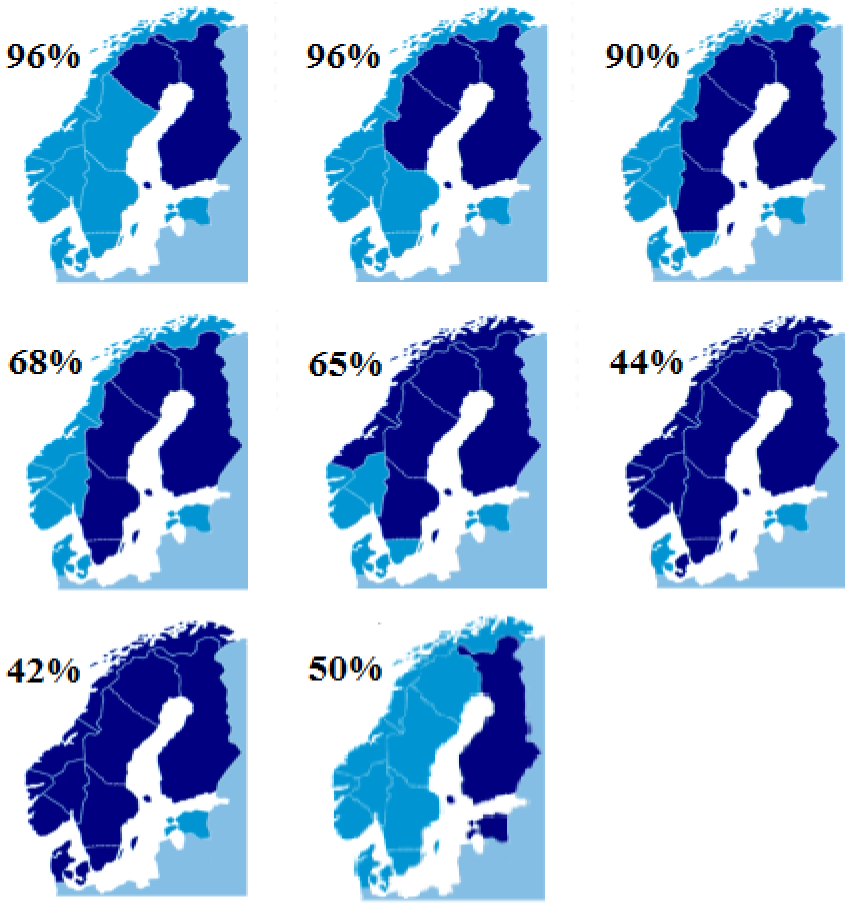

Figure 2.7. *Nordic power market integration 01.11.2011-31.12.2011 (Fingrid 2012)*

After the Spot price is cleared, the buyers and sellers can secure their, and the market's, balance on the intraday Elbas power market. The market opens after the day-ahead market closes and the participants can trade power volumes in real time until one hour before the delivery. This market supplements Elspot and covers the same areas as the day-ahead market but also Germany, Netherlands and Belgium. It is important to have such an intraday market as the share of unpredictable power production, such as wind, is growing. In addition it enables the market participants to secure the price risk in events such as power plant production failures so that only minimal amount of power is required from the regulating power market. Regulating power market is operated by the TSO's and it is always a price risk for the market members as the prices are not known beforehand. At times the participants can benefit from the regulating prices but they are challenging to predict as they normally fluctuate quite substantially. Hence, it is generally better to minimize the balance deviations by trading on the intraday market. (Nord Pool Spot 2012)

2.3 Financial Market

The financial market is a marketplace for financial contracts that are generally used for price hedging, risk management and other trading purposes. The market is provided by NASDAQ OMX Commodities and it includes only cash-settled contracts with no physical delivery of power. However, the price of electricity, which is determined on the physical side of the market, acts as a reference price for the financial contracts. By trading contracts the market participant is agreeing on either buying or selling assets at a certain future time and at a certain agreed-on price. (NASDAQ OMX Commodities Europe 2012)

The contract types available on the financial market comprise of power derivatives such as futures, forwards, options and Contracts for Difference (CfD) and the maximum time horizon is up to six years. Futures consist of day and week contracts and forwards include products for months and years. Options work similarly to futures and forwards but with a difference that, depending on the product, enables the other side of the contract to bail out of the deal. In such cases the other side of the deal only gets a premium from the deal itself. Lastly, CfDs are market contracts that can be used to hedge against the risk of differentiating area prices. (Rinta-Runsala & Kiviniemi 1999)

NASDAQ OMX Commodities is also a clearinghouse for all the contracts made on the financial market. Hence, they enter into each deal as counterparty and accept responsibility for the future settlements. This function reduces the risk for exchange members significantly and makes trading quick and effective. (NASDAQ OMX Commodities Europe 2012)

Some of the infrequent and unusual trades are traded on the Over the Counter market (OTC) but there is always a counterparty risk involved if the other participant in cannot for some reason meet the requirements of the deal. Conversely, that risk can be minimized by using a clearinghouse in the deal but generally clearinghouses are not used in OTC-contracts. (Rinta-Runsala & Kiviniemi 1999)

2.4 Hydro-dominant Market

The Nordic power market is considerably hydro-dominant and the amount of water readily available for electricity production is an important factor in determining the price of electricity. (Cooke 2012) The hydro reservoir levels throughout the Nordics define how much hydropower production can be allocated to meet the demand of electricity and also how much condensing power production is needed. As the price of electricity is determined by the most expensive production type needed, it is clear that fluctuations in the hydro assets can vastly influence the prices in the market. Figure 2.8 shows the shares of different electricity production types in the Nordic power system in 2010. From the figure we can see that hydropower generates approximately 50 % of the total electricity generated in the Nordic market, which, of course, varies somewhat depending on the year. The variance is due to the fact that the hydrological balance shifts from season to season. Hence, the share of condense production, which compensates hydro production, varies also. (Nord Pool Spot 2012)

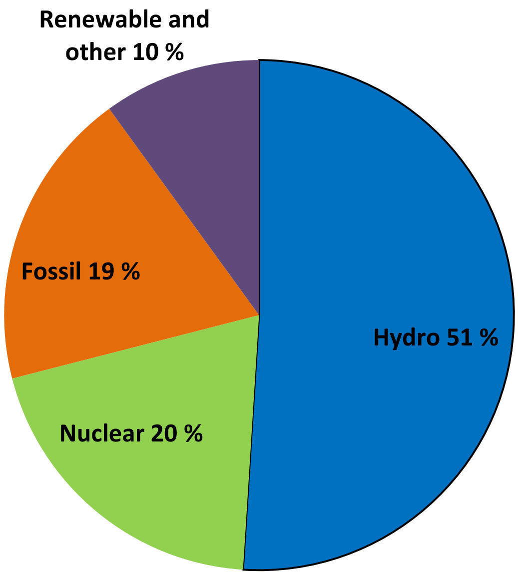

Figure 2.8. *Shares of electricity production types in the Nordics in 2010 (Cooke 2012)*

The production types are not distributed equally in the Nordics. In Norway, a great majority of electricity is generated from hydropower. Sweden has significant hydropower assets, especially in the North, but also nuclear and thermal power. Finland relies on thermal and nuclear production but also has a reasonably large share of hydropower. Denmark is very different from the other Nordic countries as majority of its electricity is generated with conventional thermal power. In addition to thermal power, Denmark produces electricity with wind power. The Nordic production split in 2010 is presented in detail in Table 2.1 and Table 2.2. (Nord Pool Spot 2012)

Table 2.1. *Production in TWh from varying energy sources in the Nordics in 2010 (Nord Pool Spot 2012)*

Energy source	Denmark	Finland	Norway	Sweden	Sum	Share
Wind power	7,8	0,3	0,8	3,5	12,4	3,2 %
Other renewable	2,6	10,4	0,1	11,9	25,0	6,5 %
Fossil fules	26,3	31,0	5,3	7,8	70,3	18,4 %
Nuclear power	0,0	21,9	0,0	55,6	77,5	20,3 %
Hydropower	0,0	12,8	117,3	66,2	196,3	51,4 %
Non-identifiable	0,0	0,7	0,0	0,0	0,7	0,2 %
Production	**36,8**	**76,97**	**123,4**	**145,0**	**382,2**	**100,0 %**

Table 2.2. *Fuel mix information for the Nordic area in 2010 (Nord Pool Spot 2012)*

Class of energy sources	Sum	Share
1. Fossils energy sources and peat (Natural gas, coal, oil, peat, non- renewable waste- and recycling fuels)	70,3	18,4%
2. Renewable source of energy (Hydro power, biofuels, wind power, solar power, renewable waste- and recycling fuels)	233,7	61,1%
3. Nuclear power	77,5	20,3%
4. Non-identifiable	0,7	0,2%
Total		

The importance of hydropower production in the Nordic power market can be seen from the impact it has on prices. The year 2011 is a very good example as the year started with low hydro reserves that gradually raised to median year figures and then even above. The system Spot price was inversely proportional to the hydrological situation, as can be seen from the Figure 2.9 below. Oppositely, during times of high inflow the hydropower producers can generate more electricity, which increases the section of hydropower in the conceptual supply curve (Figure 2.1). This, as was explained in Chapter 2.1, has a bearish impact on the Spot prices.

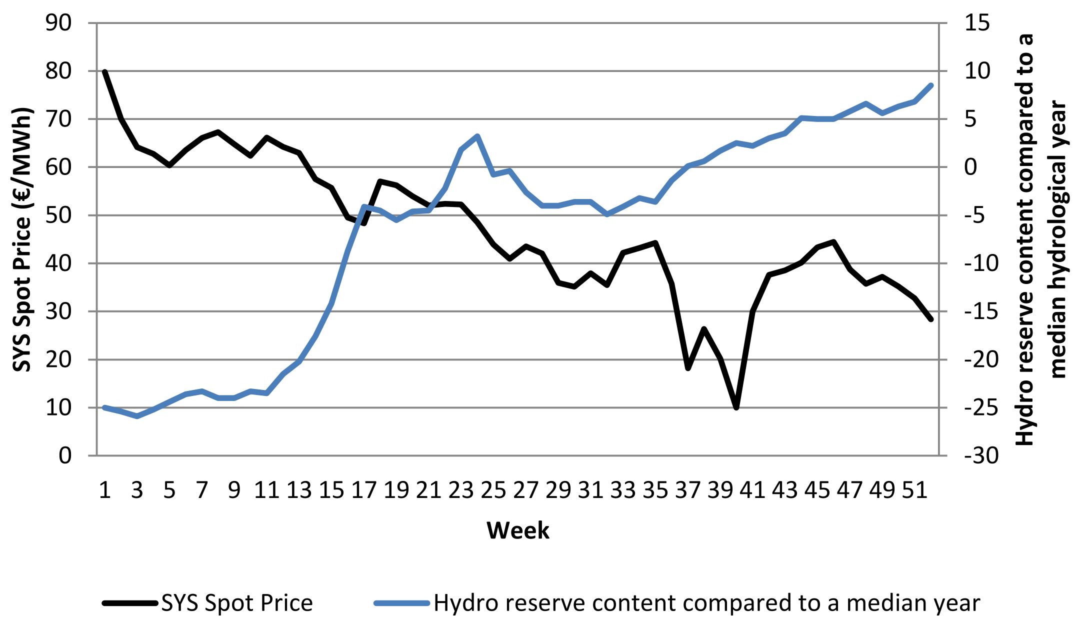

Figure 2.9. *Comparison of hydrological situation and its effect on electricity prices in 2011 (Nord Pool Spot 2012)*

3 HYDROPOWER

Hydropower production is dependent on the physical production units and their ability to produce electricity but as the technology is stable and long lasting, the largest factor to the amount of hydropower generation available comes from the existing hydrological situation. This chapter gives a general idea on what hydropower production is and what basic knowledge is needed in order to understand how it affects the Nordic power market. Chapter 3.1 deals with hydropower plants in general, Chapter 3.2 explains and introduces different hydropower plant types, Chapter 3.3 is about the hydrological environment and Chapter 3.4 gives in introduction to generation scheduling of hydropower. Lastly, Chapter 3.5 will explain hydropower in the Nordics, as the hydrological environment here is unique to the rest of the world and hydroelectricity is the largest production method.

3.1 General

Hydropower has a crucial role in balancing the production and consumption of electricity. The plants can be started and brought to stop quickly, water can be in many cases stored to reservoirs and used later on when there is greater need for it and in some parts of the world, not only in the Nordics, hydroelectricity is the dominant production type, covering approximately 16 percent, or more than 3 400 TWh, of global electricity consumption. In countries such as Norway, Brazil, Canada and Venezuela hydroelectricity accounts to more than half of the electricity produced. (Worldwatch Institute 2011, IEA ETSAP 2010, MPE 2008)

Hydropower is also an extremely cost efficient method of producing electricity. There is a major investment cost in the beginning but after that the other costs are considerably low. For example the operating cost is low due to the level of automation involved and there is no fuel cost. Hence, the total cost of hydroelectricity is radically lower when compared to other traditional ways of producing electricity and this makes hydropower plants desirable in the eyes of most power companies. The low cost and flexibility of production are also reasons behind why, in most places, the plants are built already or due to environmental reasons it is prohibited to build more. (EURELECTRIC 2000)

3.2 Hydropower Plants

Hydropower plants use turbines to convert water’s potential energy into mechanical energy. That mechanical energy is then converted to electrical energy by generators. All hydropower plants function in this way. Besides the similarities of all hydropower plants, there are some differences that originate from the location, type and size of the power plant. (Bøckman et al. 2006)

Figure 3.1 shows a schematic of a general hydropower plant. It illustrates how the water's energy is transformed into electricity with turbines and generators. Essentially, the water is stored at the dam, after which it flows through the penstock to the turbine, which rotates the generator in order to generate electricity. This electricity is then transmitted to the consumers via high voltage power lines. (U.S. Department of Energy 2012)

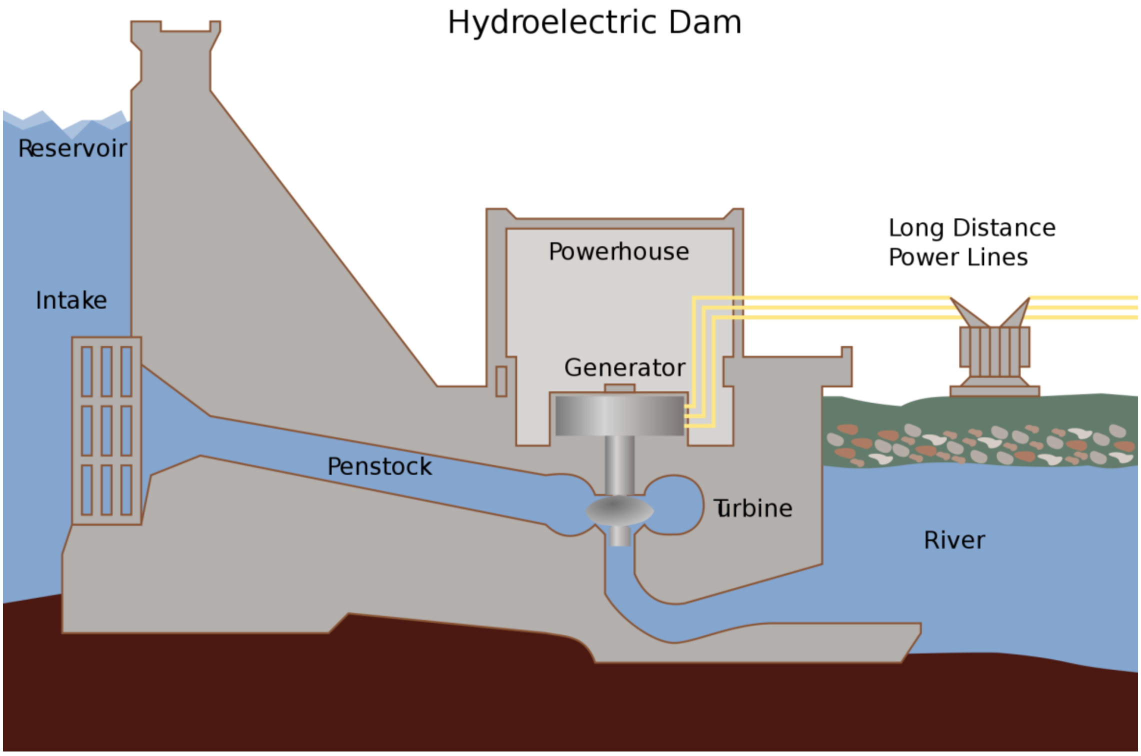

Figure 3.1. *Schematic of a hydropower plant (U.S. Department of Energy 2012)*

The amount of electricity, or power, a hydropower plant can generate depends on the volume of flowing water through the turbine and the head. Head is defined as the height difference between the source of the water, or the reservoir, and the tail water. The power produced can be represented with the equation

$$P = \frac{mgh}{t} \tag{3.1}$$

where P is the power produced, m is the mass of the water, g is the gravitational acceleration of the Earth, h is the head of the plant and t is the time scope. Basically, the equation 3.1 shows how the potential energy of the water is transformed into kinetic energy. This kinetic energy then rotates the turbine and enables the plant to produce power. As there are always some losses involved in this process, only approximately

80-90 % of the potential energy is transformed into kinetic energy. Usually the power generated is presented in megawatts (MW) and the energy produced in megawatt hours (MWh). (Kemijoki Oy 2012)

As stated, the power output of a hydropower plant is directly proportional to the head and volume of the flowing water but this dependency is not purely linear. As the discharge from the plant increases, the tail water tends to rise and this generally decreases the power output as the head of the plant decreases also. In addition, hydropower plant units are constructed for optimal flow of water and lower or higher discharges may reduce the unit's electricity output (see Figure 3.2). Furthermore, spillage, or passing water through the flood gates, from the plant does not contribute to the electricity production and might even decrease the head and therefore decrease the power output. Hence, spillage should be avoided unless the inflow and reservoir level situation seems to be getting critical and regulation levels could not be maintained without it. This is typical especially during springtime as rains and the melting snow create heavy inflows throughout the Nordics. (Cook & Walsh 2008)

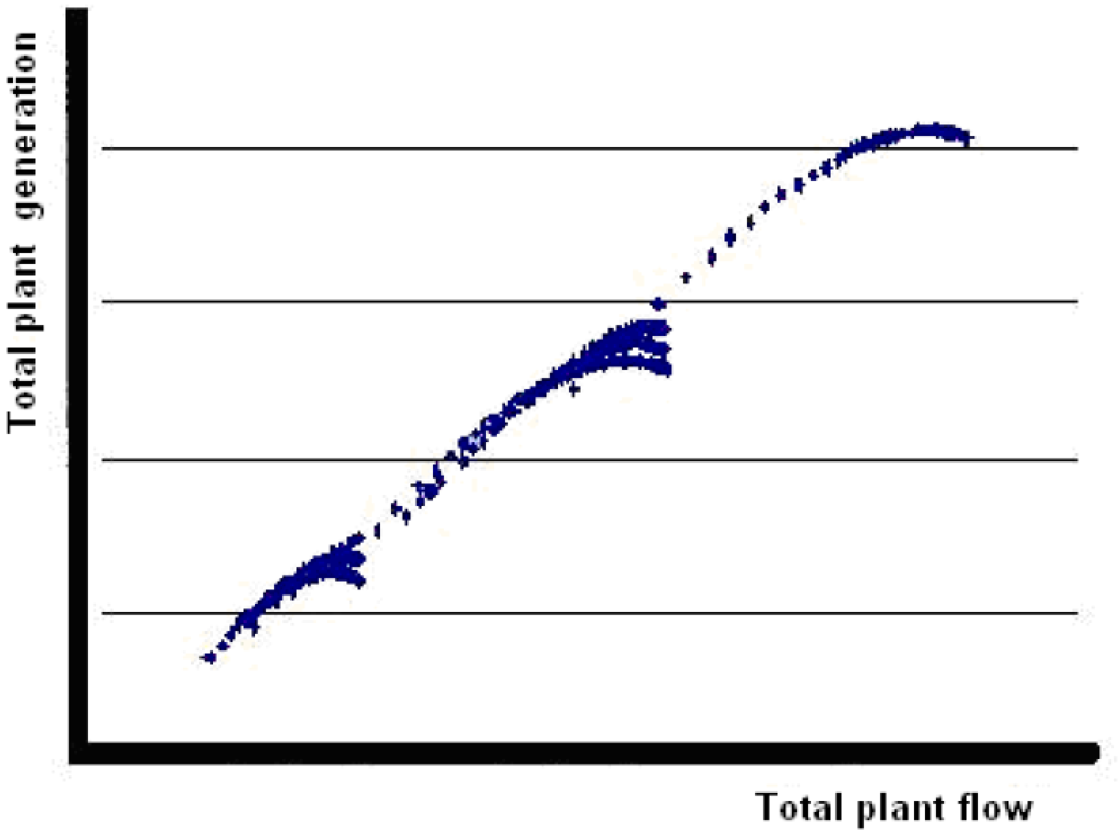

Figure 3.2. *An example of a typical production function of a three unit hydropower plant (Cook & Walsh 2008)*

3.2.1 Conventional hydropower

Conventional hydropower plants utilize dams and reservoirs to harvest energy from the water. The dams prevent water from running past the turbines and create man-made lakes or hydro reservoirs where the water can be stored and then used according to the needs of the production company and environmental regulations. The use of reservoirs brings flexibility to the usage of water which in turn is beneficial to the electricity market as a whole as the power is typically generated during the more expensive hours when it is economically most profitable and therefore also needed the most. Furthermore, conventional hydropower production is typically halted during the low consumption hours, which in turn balances the market during night time, weekends and holidays. (MPE 2008)

Reservoirs are built as high as possible from the sea level in order to maximize the head of each plant and the power output of the prevailing river system. Depending on the size of the reservoir they can be categorized as short-term, seasonal or over-seasonal. Short-term reservoirs allow water to be stored for short periods, for example during night-time or over the weekend, and then used during day-time or when it is financially more beneficial. Seasonal reservoirs, on the other hand, can collect a significant amount of the seasonal inflow and they can be operated with more flexibility over a longer time period. Over-seasonal reservoirs are the most valuable reservoirs as they can store several years' worth of hydro and the water can be saved until the price is more profitable in the eyes of the river system owner. (Energiateollisuus 2012)

Another profitable quality of conventional hydropower is the possibility of using it in the regulating power market. As the Nordic power system must be kept in balance at all times, a regulating power market has been introduced and its purpose is to enable the transmission system operator's to utilize different flexible production or consumption units to the needs of the power system. Conventional hydropower is extremely useful in these types of markets because the production can be halted or increased effortlessly and fast.

3.2.2 Run-of-the-river hydropower

Run-of-the-river hydropower (RoR) is a hydropower type that practically does not have any reservoir capacity. Thus, run-of-the-river hydropower minimizes the impact on the local surroundings and keeps the river as close to the natural state as it can possibly be. Because of the minimal effect of RoR to the environment, it is therefore often seen as more environmental or "green" than hydropower that requires massive man-made hydro reservoirs that alter the environment considerably. It is often used in rivers where the natural flow cannot be altered due to, for example, environmental regulations. (IEA ETSAP 2010)

Run-of-the-river hydropower production can be estimated quite easily from the inflow forecasts and it is usually defined as base power for the power system because it is always in production if there is water available. Due to the same reason, RoR hydropower is generally not used in the regulating market as it is more difficult or against the regulations to alter the flow of the river. Nevertheless, some of these hydropower plants are bid on the regulating power market for down regulation and can decrease production by rather spilling the water if the power system requires it.

3.2.3 Other types of hydropower

While nearly all of the world's major hydropower plants are categorized as either conventional or run-of-the-river, there still are other significant hydropower types available. These types include pumped-storage, small, micro and pico scale hydropower. Pumped-storage is a useful type of hydropower used for balancing purposes. During low consumption hours, water is pumped from low altitude to higher altitude and then that water is used for electricity production during hours of higher consumption or higher prices. It balances the grid well and creates revenue for the operating company as water can be pumped to the storage using relatively low prices and then used for electricity production when the prices are higher. The efficiency of the power production does decrease from this but in cases when consumption and the prices change radically within a certain time period, it is still profitable for the production company and beneficial for the TSO. (IEA ETSAP 2010)

Small hydropower is usually defined as hydropower plants with less than 10 MW of production capacity. They are mostly used in isolated areas or connected to industrial power networks as cheap and environmental way of producing electricity but exceptions are common especially in relatively flat areas where more powerful hydropower plants are not possible. Often small scale hydropower is installed in rivers without regulation reservoirs. (MPE 2008) Micro scale hydropower plants are defined as plants that produce up to 100 kW of power. They are often used in developing countries and connected to small communities. Pico scale hydropower produces a maximum of 5 kW of power and they are mostly used for extremely small communities in the third world countries that require a very small amount of electricity. Micro and pico size hydropower plants are generally not connected to national grids as they are mostly power sources for small villages in areas where larger grids are not very common or close by. (Energiateollisuus 2012, Renewable Energy Policy Network for the 21st Century 2010)

3.3 Hydrology

Hydrology is the study of water on Earth and it is of key importance to hydropower producers as the knowledge of water distribution and movement is critical in generation scheduling of hydropower. Several different kinds of models, both physical and statistical, are applied in forecasting the becoming hydrological environment in order to gain all the possible information needed to optimally conserve and plan the water resources available. This process also utilizes the form and location of the water in order to forecast the inflow in detail. (Linsley et al. 1982)

3.3.1 Hydrologic cycle

Hydrologic cycle, also known as the water cycle, describes the movement of water on Earth. Water moves and changes states continuously but the amount of water on Earth remains constant (see Figure 3.3). In the hydrologic cycle, water is stored in different reservoirs, for example in oceans or in lakes, in the liquid state. The sun, together with the wind, forces the water in the reservoirs to evaporate into the atmosphere where it condensates and eventually forms clouds. These clouds are then moved by the wind and at some point the water vapor precipitates back to the surface. On the ground this precipitation is partly collected in the reservoirs but it might as well be absorbed by the Earth's surface. The absorbed water forms underground flows that finally merge with the reservoirs. Then the cycle starts again. (Linsley et al. 1982)

Additionally, water can take alternative routes. For example water can be stored in ice or snow and sublimate directly to water vapor. Snow and ice can also melt to form either aboveground rivers or underground flows that transport the water to the bigger lakes and oceans. Vegetation stores water as well and from there it generally transpirates directly to water vapor. (Linsley et al. 1982)

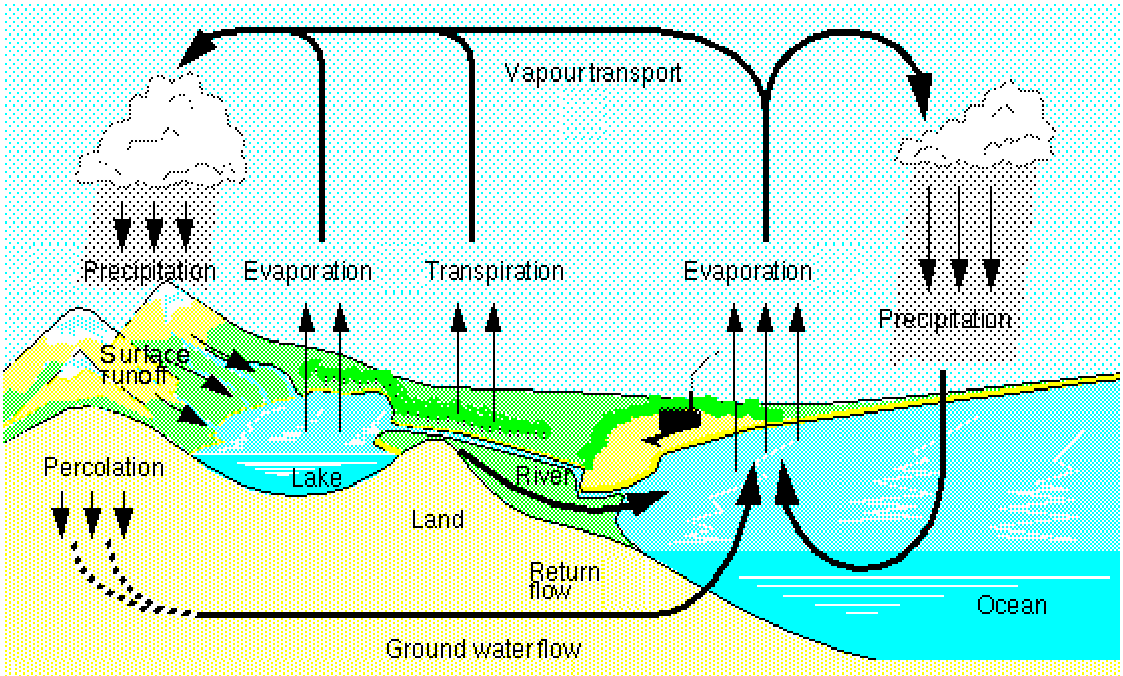

Figure 3.3. *Hydrologic cycle (Anheier et al. 2007)*

3.3.2 Hydrologic environment in the Nordics

The hydrologic environment in the Nordics is quite diverse as the different seasons are very unlike and even years change considerably. This can be seen from, for example, historical reservoir inflow data, which shows approximately how dry or wet the year was (Figures 3.4 and 3.5). Furthermore, even though the countries are close to each other and quite small, the weather conditions are not alike.

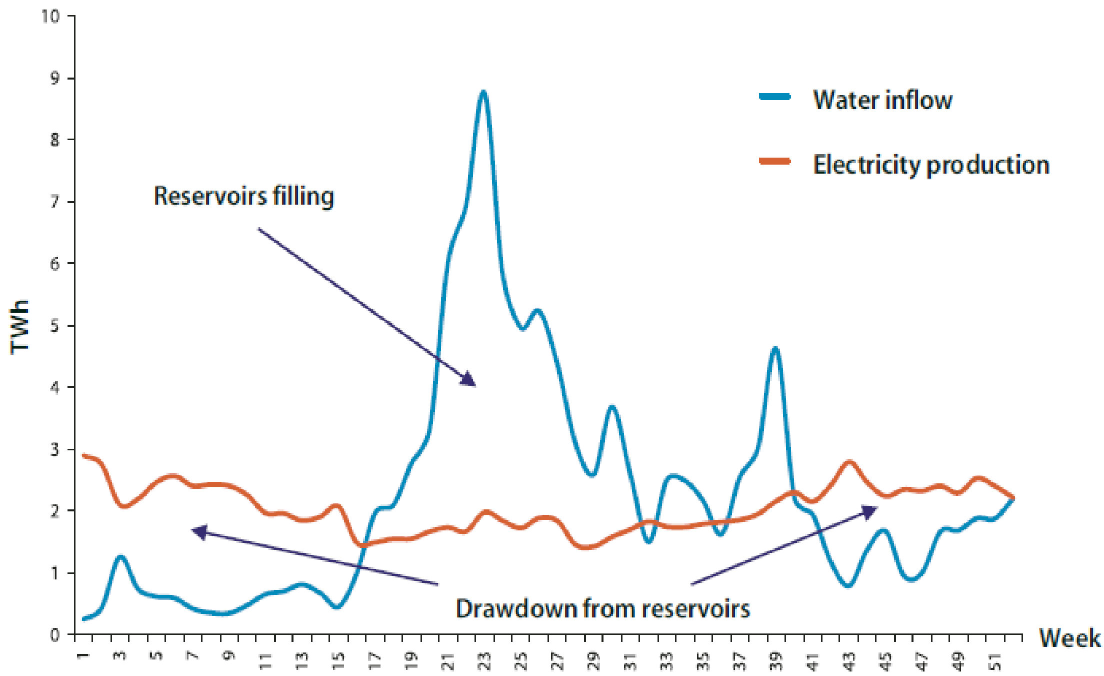

Figure 3.4. *Variations in water inflow to hydro reservoirs and electricity output in Norway in 2004 (MPE 2005)*

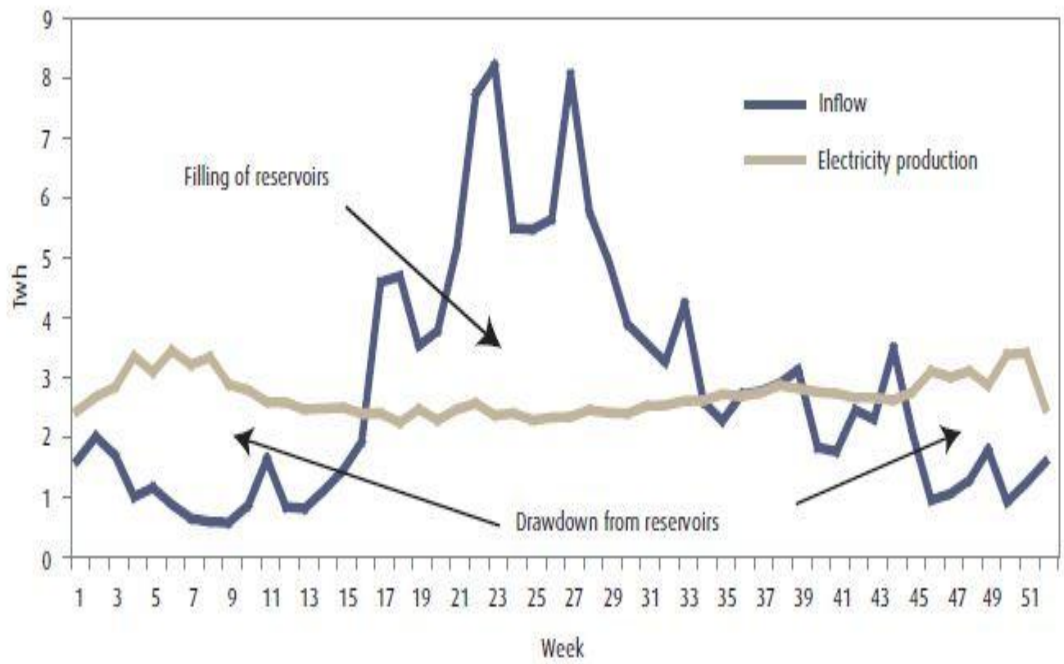

Figure 3.5. *Variations in water inflow to hydro reservoirs and electricity output in Norway in 2007 (MPE 2008)*

During the winter time most of the water comes in the form of snow and the lakes freeze. The solid state of water is not usable in hydropower production until springtime when it melts. In the springtime the melting snow and ice results in extremely large inflows and even flooding. This generally forces the hydropower producers to produce as much as possible beforehand to create space for the incoming water in the hydro reservoirs. After the spring and early summer, the rest of the summer time is typically rather stable. The fall is usually rainy, especially in Norway, and the water is collected in the reservoirs to be used in the winter when incoming water is limited and consumption is higher. (MPE 2008)

Still, the environment changes yearly and these aforementioned principles might not always apply. There have been extremely dry years, such as 2003, when the fall rains didn't arrive and much of the reservoirs were used already before the high consumption, in another words more expensive, winter time. This created a problem for the hydro producers as to when they should use their scarce assets. (Amundsen & Bergman 2005) On the contrary, after a dry period in 2010 and early 2011, the fall of 2011 was extremely wet and it surprised many of the producers as the reservoirs filled to the maximum. Together with a considerably snowy winter the situation in the spring and early summer of 2012 became so challenging with the inflows that many had to spill their water in order to prevent flooding. As the Nordic electricity market is hydro-dominant, the situation lead to very low Spot prices on market. (Fedetskina 2012)

3.4 Generation Scheduling of Hydropower

The hydrological environment is constantly followed and analyzed by the hydropower producers. The producers have a natural interest in their hydro reservoir levels and in the forecasted inflows as the electricity generation is scheduled accordingly together with the future price forecasts. As the forecasts are rarely absolutely correct and might change unexpectedly, they also create a challenge for the planning of hydro assets. In the areas where hydropower is mostly run-of-the-river type, generation scheduling is not a major problem as electricity is produced depending on the inflows and the water cannot be stored. In the case of conventional hydropower, the problem is evident. If the reservoir is small, only minor scheduling can be done and this mostly means intraday scheduling. In the case of larger reservoirs, the time horizon is so long that scheduling is extremely challenging as the forecasts are uncertain after a certain period of time. (Fosso et al. 1999)

Generally in the long-term scheduling of hydropower the production is planned with a time horizon of several years. This is done by forecasting the monthly and weekly water allocations that result in the optimum operational strategy. In mid-term generation scheduling, the water is forecasted in greater detail but the time horizon is not as long. To be realistic, mid-term also has to take into account the daily profiles as conventional hydropower is rarely used during night time. Short-term scheduling, on the other hand, is typically a few weeks into the future and there the water is scheduled by the hour to optimize the profit from it. The difficulty in producing these plans is in balancing the income in the short run against the expectations about the future income. (Fosso et al. 1999)

3.5 Hydropower in the Nordics

Hydropower is a major electricity production method in the Nordics and all the different hydropower production types are present. In Finland most of the hydropower is produced with run-of-the-river types of hydropower or the reservoirs are considerably small. The hydropower production in Finland is also minimal compared to the production levels in Sweden and especially in Norway. On a national scale hydropower is, nevertheless, a major production method and accounts to approximately 10-20 % of the produced electricity, depending on the year. The future of the Finnish hydropower is at the moment very stable as old hydropower plants are maintained on a high level and capacity increase investments are very common but new major hydropower plants cannot really be built as the environmental regulation prevent such investments. (Energiateollisuus 2012)

In the Nordics, Norway is the country that relies the most in hydropower production. In Norway close to all of the electricity is produced with hydropower plants and the hydropower plants are generally of the conventional type, or at least belong to a system with extensive reservoirs, and hence they can regulate their production well and maximize the income by producing only during the relatively higher prices. Nevertheless, the whole Nordic power market and transmission system benefits from the Norwegian hydro as it provides the Nordics with fairly cheap electricity and it also works as a major balancing power supplier so that more expensive production methods are not needed. However, new investments on high voltage direct current (HVDC) sea cables from Norway to countries outside of the Nordic electricity market might affect the Nordic electricity prices in the future and reduce the amount of affordable hydropower generated electricity readily available for balancing power markets. Besides hydropower, Norwegians have developed gas-fired power and wind power in the recent years to their power production palette but Norwegian power generation will still continue to be dependent on precipitation levels in the foreseeable future. (MPE 2008)

Hydropower production in Sweden is also very extensive and it covers roughly 45-50 % of the total annual production of electrical energy. In the recent years the Swedish hydro has increased slightly but like in Finland and Norway, it is highly developed and most of the remaining possible power plant locations are protected. (Swedish Energy Agency 2011, Uppsala Universitet 2011) The hydropower in Sweden is divided between conventional and run-of-the-river so that the country has hydro available as base power but also as peak power for a more flexible use. In Sweden’s case the largest hydro reservoirs together with the major hydropower plants are situated in the mountainous North and the smaller RoR plants are generally in the Southern part of the country. (Swedish Hydropower Association 2012)

Hydroelectricity production in the Nordics covers approximately half of the total electricity produced. The world as a whole only produces approximately 16 % so it is clear that the amount of hydropower in the Nordics is extremely considerable and water, as a clean and a renewable energy source, benefits the whole region. Other areas with considerably large hydro assets in the world are mostly in wet mountainous areas, such as in the Alps or in South America. Majority of the possible future hydropower developments, on the other hand, are situated in South-Eastern Asia. (Swedish Energy Agency 2012, MPE 2008, Worldwatch Institute 2011)

Although hydropower production is similar everywhere on Earth and the methods are nearly the same, the Nordic hydropower production has one particularly interesting aspect that is not common in the warmer areas of the world. In the Nordics the hydro reservoirs and rivers freeze in the winter and the precipitation comes in snow. These issues create challenges in hydropower plant operations as the river system operators must be able to handle frazil ice conditions and potential ice rafts that could clog the turbines and generally make river operations more difficult. Moreover, arctic winters involve operational restrictions in hydropower production as the discharge rates must be decreased during the formation of an ice cover in the reservoirs as a firm ice cover prevents harmful mid-winter conditions. In addition, forecasting the spring time inflows is extremely challenging due to the winter-time precipitation in snow. Estimating the snow’s water value is not very accurate and hence the spring-time inflows might vary significantly from the forecasts. (Alfredsen, 2011)

4 OPTIMIZATION OF HYDROPOWER

Optimization may be described as the science of determining the best solutions to mathematically defined problems. It can also be defined as choosing the most optimum elements from a certain set of available alternatives. It is either done to maximize or minimize a real function by choosing different values from the allowed set and calculating the outcome. The outcome that gives the "best available" values within the defined constraints is the optimal result. (Snyman 2005)

There are several kinds of different mathematical optimization, or alternatively mathematical programming, methods of hydropower but the purpose is always to acquire the optimal result in whatever is optimized. The hydro system studied in this thesis is fairly modest and linear programming will be utilized in the optimization model. Linear optimization is discussed in more detail in Chapter 4.1. In Chapter 4.2 the other major hydropower optimization techniques will be presented and explained why they are not reasonable in the model created. The created model itself is presented in Chapter 6.

4.1 Linear Programming

In this thesis linear optimization has been used to model the hydro system and it is written

$$\begin{aligned} &\max_x c^T x \\ &s.t.\ Ax \leq b \\ &and\ x \geq 0 \end{aligned} \tag{4.1}$$

where x is a vector of variables, c is an objective vector, b is a vector of constants related to the constraints and A is a constraint matrix.

It is possible to optimize the system linearly as all the significant nonlinear dependencies and restrictions, such as the turbine head and efficiency variations, were possible to be converted into piecewise linear form as both of them can be modeled with discharge functions. This way the method is at the same time as simple, short and still functional as possible. The simplification of the model also shortens the time-consuming calculation times and enables the use of more simple software. In general, these are the same reasons why linear programming is used in many hydropower optimization tools. The models are easy to construct, they are easy to understand and the imprecision that comes from the non-linear dependencies is normally so minute that it is lost in the inaccuracy of, for example, the price and inflow forecasts. In addition, the hydro system sizes are generally so enormous that they pose a real challenge to the modelers. Hence, linearization of the system is preferred. (Barros et al. 2003)

Research on the usefulness of linear optimization of hydropower production has been active in the recent decades and the results have been promising. A 1989 study for reservoir operations at Manitoba Hydro in Canada found linear programming a promising method for hydro optimization. (Reznicek & Simonovic 1989) Furthermore, a 2003 study on Brazilian hydropower system showed that “even the simplest linearized model without iteration is sufficient for planning purposes.” (Barros, et al. 2003) In 2001 a study on linear optimization of Norwegian hydropower concluded that it is computationally efficient, simple and suitable for hydro generation planning. According to the study it can also be easily extended into different scheduling application in different surroundings. (Chang, et al 2001) Therefore linear programming appears to be a suitable and a versatile method for hydropower optimization and production planning. With it the hydro system can be modeled adequately and the results are usable in the real world planning processes.

4.2 Other methods

There are several other mathematical programming methods in addition to the linear optimization. These programming methods optimize more complex issues that cannot be depicted in a linear way and are useful in hydropower optimization as not all nonlinear dependencies can and should be linearized.

4.2.1 Nonlinear Programming

While linear optimization is an extremely useful mathematical method to solve a multitude of problems, the objective function and the constraints have to be either linear or can be modified to become linear. If the problem cannot be transformed into linear form, a nonlinear programming method of the following type (Equation 4.2) can be utilized. This is convenient as many real-world problems are nonlinear. (Bazaraa et al. 1993)

$$\begin{aligned} &\max_x f(x) \\ &s.t.\, g(x) \leq b \\ &and\ h(x) = c \end{aligned} \tag{4.2}$$

where *f(x)* is an objective function, *g(x)* is the inequality constraints and *h(x)* is the equality constraints.

In hydropower optimization nonlinear programming can be used if, for example, the turbine head behaves in a nonlinear way. According to Catalão, et al. it is crucial to include the nonlinear elements of hydropower in the optimization process to develop competitive plans in a profit-based electricity market as they create more value and increase profit compared to classic optimization, such as linear programming, methods. (Catalão, et al. 2005) Other studies also suggest that nonlinear programming achieves better results in hydropower optimization than the classic linear hydropower optimization. (Mariano, et al. 2007)

A major weakness of nonlinear programming is the fact that it can generally solve a global optimum only in convex problems and this is significant in hydropower optimization as usually hydropower systems are non-convex. A convex set is a set where every pair of points in the set can be joined together by a straight line that is also contained within the set. (Boyd & Vandenberghe 2004) In hydropower optimization the goal is to maximize production and profit and that requires concave problems, whereas convex problems are typically required in minimization problems. Some nonlinear programming methods have been created that tackle the non-convex sets in hydropower optimization problems but these are typically less efficient and hence nonlinear programming should only be used for convex problems. (Chachuat 2007) Besides, the hydro system this thesis deals with is possible to depict in a linear way. This makes linear programming a more suitable optimization method for the planning tool as the model will hence always find a global optimum.

4.2.2 Dynamic Programming

Dynamic programming is a potent algorithmic paradigm in which problems are solved by first identifying a collection of smaller sub-problems and then solving them in order of smallest first. The idea is that the answers to the easier problems are used to help solve the larger ones. According to mathematicians, dynamic programming as a solving technique is a “sledgehammer” or a “brute force” method and it is used in cases when more specialized methods fail. Generally this method costs a bit of the efficiency when comparing to the more elegant methods as typically the computing time increases with the size of the problem and hence compromises in model accuracy and resolution must be made. (Dasgupta et al. 2006) A dynamic programming model can be written

$$\max_{u(t)} G\big(x(t_f), t_f\big) + \int_{t_0}^{t_f} F(x(t), u(t), t)\,dt$$

such that

$$\begin{aligned}
&\dot{x}(t) = f(x(t), u(t), t) \\
&g(gx(t), u(t), t) = 0 \\
&h(x(t), u(t), t) \leq 0 \\
&x(0) = x_0 \\
&x_L \leq x(t) \leq x_U \\
&u_L \leq u(t) \leq u_U
\end{aligned}$$

where *x(t)* is a state variable, such as water content or energy, and *u(t)* is a control variable, which in this case is the total combined discharge and spillage.

In hydropower optimization dynamic programming is often used in long-term scheduling. Ferrero, Rivera and Shahidebpour studied dynamic programming in 1998 and concluded that it “can directly handle the non-convex, nonlinear and stochastic characteristics present in [long-term hydro scheduling].” The method is therefore usable in hydropower optimization but in very large multi-reservoir hydropower systems the computing times have been reported to increase significantly. (Ferrero et al. 1998) Moreover, the mid-term hydropower optimization tool has to be simple and efficient and therefore a “brute force” technique is not the most suitable method for this problem.

4.2.3 Stochastic Programming

Stochastic programming is an optimization method for problems that include a certain amount of uncertain parameters. It is versatile and useful in several areas of science and economics and widely used in hydropower scheduling optimization as well. As the problems that are solved with stochastic methods include random parameters, the theory combines concepts of optimization theory, the theory of probability and statistics and also functional analysis to solve the optimal result. (Shapiro et al. 2009)

Stochastic optimization is a modern mathematical optimization method for hydropower scheduling and it is widely used nowadays as optimal long-term power production scheduling has several uncertain factors, such as price forecasts and electricity demand, embedded into it. These, to some extent, random parameters can be solved with stochastic methods and as a result a feasible solution is given that satisfies all of the possible constraints. In some studies it was even found out that a long-term inflow forecasts must be dealt as stochastic variables and stochastic programming is a necessity in long-term generation scheduling. (Fosso, et al. 1999)

As many of the parameters used in the model are stochastic by nature, a stochastic mathematical programming method could be used in the mid-term planning tool. However, as linear programming already creates satisfying results and the different forecasts are sufficient quality-wise in the mid-term planning time-frame, it is not necessary to create a mathematically more complex model. Also, the method of planning the hydro system in a way that creates compatible plans from the different co-owners requires that many of the forecasts used in the process are the same. The presumptions hence stay the same, which supports the usage of linear optimization. In addition, many of the old optimization models for other hydro systems utilize linear programming methods and this new prototype is easier to expand to the other planning models if the optimization method is the same. In the future the planning tools could be improved into taking account the uncertainties in the parameters as well but that is not in the scope of this thesis.

4.2.4 Genetic Algorithms

Genetic algorithms are modern stochastic searching algorithms that are inspired on genetics and evolution theory. It uses heuristic methods to solve complex real-world problems in an extremely robust way that has been proven effective at finding optimal solutions. Similarly to stochastic programming, it is usable in several areas of science and economics, especially as an alternative to more orthodox and more time consuming techniques. (Gil et al. 2003, Chang & Chen 1998)

In hydropower production optimization it can be used to solve hydro generation scheduling problems in a flexible way that reduces computational times. Gil et al. studied it in 2003 and obtained near-optimal results in short-term hydro scheduling in reasonable times considering the size of the studied system. (Gil et al 2003) The method has also been used successfully in China and the results have been attractive. (Chang & Chen 1998) As the mid-term model in this thesis neither requires extensive computational times nor needs genetic algorithms to solve an optimal solution, this method was not considered for the model. It still is extremely attractive in hydropower optimization so it might be analyzed in more detail in upcoming projects.

5 GOVERNANCE RULE

The hydro system in question has a Governance Rule that states how it can be operated and what has to be taken into account when scheduling the hydropower of the said system. Similar Governance Rules are very typical in hydropower as the environment is of critical importance when planning hydropower production. Operating the power plants within the agreed rules and regulations keeps residents of the area satisfied as the hydro reservoirs are used in a way that keeps them close to the natural levels, if at all possible. Also, regulating the usage of the river system prevents flooding and enables better living conditions for the resident near the water front. In addition the luxury of using the reservoirs for leisure activities supports the limits set by the Rule and further elevates the trust between the operating companies and the local residents.

Chapter 5.1 discusses the Governance Rule in general and presents a depiction of the hydro system the Rule regulates. In Chapter 5.2 the more detailed restrictions and conditions are examined.

5.1 General

The river system in question is owned unequally by several different parties and the river's usage is governed by a set of rules called the Governance Rule. The Rule assembles all the essential rules and regulations into a singular document to make hydro system operations and planning easier for the involving parties. The rules in the document are tailored for the exact hydro system and they cannot be applied to other river systems.

The Governance Rule first portrays the hydro system and its special qualities. It defines the different streams and reservoirs the system consists of and also shows the catchment areas. Basically, the beginning of the Rule is a short preview of the system that has to be understood before analyzing the more detailed rules and regulations of the document. After the initial preview of the system a more detailed look on the different reservoirs is given and the regulation limits are also defined. In addition, special discharge rules are specified for each power plant of the system and they must be obeyed at all times. Floods, extremely large inflows and possible dry seasons are exceptions and they are defined separately. Figure 5.1 depicts how reservoirs in the hydro system are graphically visualized in the Governance Rule and shows the minimum and maximum levels where the reservoir's surface must be maintained. There are similar figures for all different hydro reservoirs in the Governance Rule and from them one can also estimate the average discharges and reservoir levels.

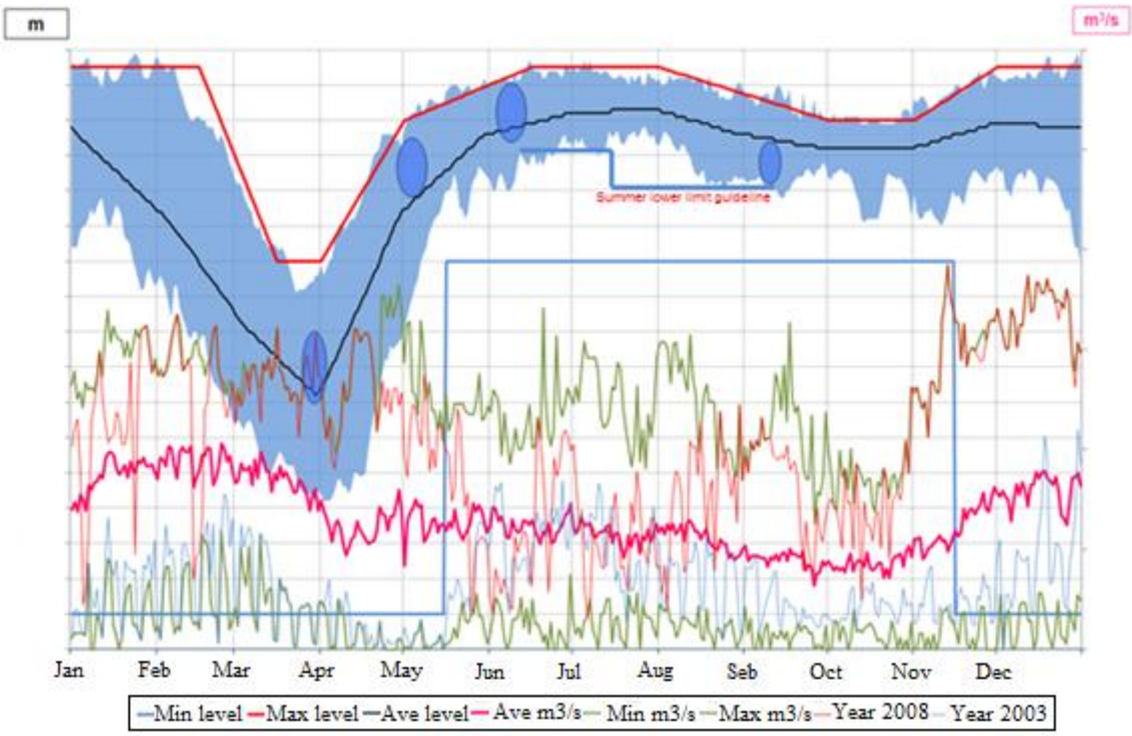

Figure 5.1. *Depiction of a hydro system's limits with historical data (Governance Rule)*

The document sets strict rules on the reservoir levels and discharge quantities but does not, however, direct the co-owners on how and when to operate their assets. The hydro reservoirs are owned by all the involving parties and the co-owning companies can direct the reservoir levels within the stated limits. This enables the different parties to analyze the current and future situation and plan their production accordingly. To help the planning process, some physical properties of the plants and reservoirs are predefined.

In addition to the rules and regulations, the document presents expectations on how to operate the river system. For example at certain times of the year fast changes in reservoir surface levels are not desired. These expectations are generally agreed-on as for example fish spawn might be affected by rapid changes in discharge rates and reservoir levels. Operating within the expectations and guidelines benefits all the parties so that the environment is respected in all the ways possible and the environment is not exploited in a harmful way.

A depiction of the hydro system in question is presented in Figure 5.2. It includes five different hydro reserves, marked by the letter R, of different size and eight hydropower plants, described by the letter P. There is a ninth plant regulating the hydro reservoir R4 but that is not modeled as it is operated by another party separately. R2 is also regulated by another party. From these reservoirs the co-owners and river operator only get the inflow and discharge forecasts. The optimization hence includes reservoirs 1, 3 and 5 together with the hydropower plants 1 to 8. The operation of that area in the hydro system can be influenced by the co-owners of the system and reservoirs 2 and 4 are separate from this.

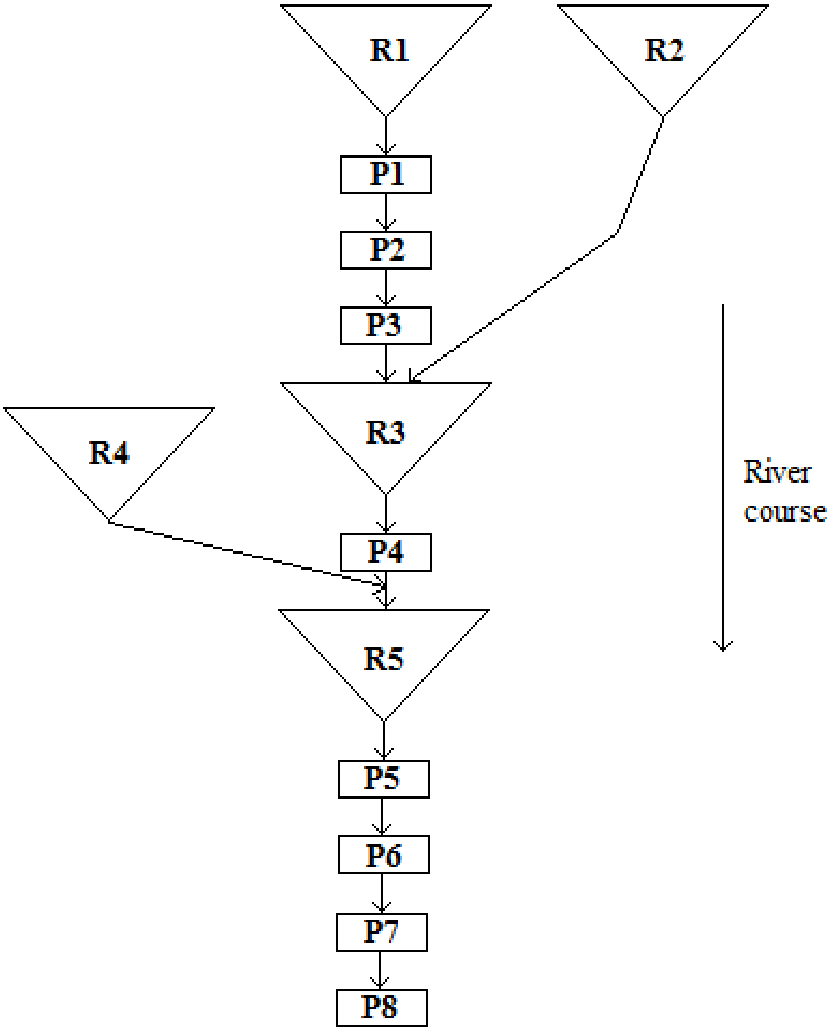

Figure 5.2. *A depiction of the hydro system (Governance Rule)*

The Governance Rule also defines how to operate the system in exceptional situations, such as in floods or in frazil ice conditions. In these situations, the system can, and should, be operated abnormally without legal consequences as it minimizes damage to the power plants and also to the structures at the water front. The co-owning companies also work together to prevent harmful effects by forecasting and minimizing them with proactive measures. Forecasting nature's behavior is, nevertheless, challenging and some events cannot be forecasted. However, generally flooding occurs in the springtime and frazil ice conditions during the winter when the river is not yet fully covered by ice. The negative effects of these annual situations are generally minimized sufficiently.

Furthermore, the Rule explains how the operation council, or representatives from the different stakeholders, should function and how the different reservoirs should be used. As the reservoirs are shared together but not equally, there are some preconditions on how they can be used; for example compensation must be given to the owners of a reservoir if its levels must be regulated heavily due to the conditions downstream. The Rule explains the equations how the compensation is calculated and also how the compensation is divided between the associated parties.

5.2 Restrictions and conditions

The Governance Rule sets restrictions on how the river system must be operated. The restrictions concern the following factors (Governance Rule):

- Each hydro reservoir has dynamic upper and lower surface level limits that change according to predefined dates. The profiles are the same every year.
- The aforementioned surface levels can deviate from the set limits under severe conditions, such as flooding or frazil ice conditions.
- Besides the upper and lower surface levels, there are recommended levels where the reservoirs should be kept. Dry and wet years have different recommendations.
- Each hydropower plant has special discharge and spillage limits and capabilities. These are defined in the Governance Rule.
- Spillage should be avoided at all times.
- The discharge and spillage limits can be altered if the reservoirs must be operated in a special way in order to keep them between the set limits.
- The Rule explains and defines the associated parties and the shares they own. There are a total of six associated parties in the river system but some of them are owned by multiple different companies so the total amount of stakeholders is considerably larger.
- The document defines how compensation is calculated and given to different co-owners in special cases.

The set restrictions and conditions are included in the optimization program so that the tool creates only feasible results.

6 OPTIMIZATION MODEL

The objective of this thesis is to create and analyze a mid-term optimization model for co-owned hydropower plants in order to maximize profit. The model uses and analyzes different input data against pre-defined constraints to create an optimal way of operating the hydro system with its reservoirs and rivers. The goal of this process is to acquire the maximum profit from the hydropower assets and to make sure the operating company itself is doing an adequate job planning the production in an optimal way. The Planning Company's share of the water system and its different hydropower plants are also included in the model as to depict our future sale volumes and incoming revenue.

The tool is made for mid-term planning and it is developed to be highly usable. The design focuses on user needs and requirements, which is important as the tool should support planning procedures and not make the process more difficult or extremely time consuming. Furthermore, the model must be functioning properly at all times and it must be performing in a way that mid-term planning can trust its results. Obviously, the results must still be analyzed by a professional that implements his or her knowhow on them but the results should be, even without further modifications, precise enough to be used in real life production planning.

In Chapter 6.1 the development of the model is discussed. Chapter 6.2 explains and presents the objective function of the model. Chapter 6.3 examines the model constraints. The model results are further presented in Chapter 7.

6.1 Model development

Before a mid-term hydropower optimization model can be created, the behavior of the hydro system and the information in the Governance Rule must be studied extensively. It is vital that the different variables in the system are known so that the created model is functional and as close to the real world river system as possible. After the hydro system is familiar and all the possible restrictions are known, it is possible to create a model that optimizes the hydro system according to the restrictions. In addition to studying the river, its reservoirs and the hydropower plants, the programming language and its syntax must be familiarized. It is critical that the model is created in an optimal way with a minimum amount of well written code so that the calculation times are reduced and the code is easy to understand by others.

The model itself is created in stages. First stage is to define the goal of the model and create an objective function that satisfies that goal. After the objective function is determined, the different parameters, decisions and constraints are set respectively. The constraints are defined further in Chapters 6.2 and 6.3.

The input data, or the parameters, in the model include the time-period which will be optimized, the Spot forecasts, minimum and maximum reservoir levels, summer-time reservoir minimum levels, minimum and maximum discharges and spillages for each power plant and the inflow forecasts for each reservoir and plant. In addition the reservoir start levels are included and mid-term can define the stop levels according to their wishes. In order to avoid unreasonable day-to-day changes in the reservoir levels, a maximum deviance was also defined for each reservoir separately according to the expectations of the Governance Rule.

The created optimization model has more than 50,000 nonzero variables if the optimization time-period is more than 195 days and the first tool that was chosen as a solver for the model supports a maximum of 50,000 nonzero variables. For mid-term planning it is vital that the tool supports planning at least one running year forward. Therefore another more advanced solver was utilized and the program was transported into it. The new solver is more advanced and it allows optimization times far greater than one year forwards as it has no size restrictions.

6.2 Objective function

The objective of a mathematical optimization program is always to either maximize or minimize the result. The function indicates how much each variable contributes to the value that is optimized in the problem. In this model the goal is to maximize the revenue from the hydroelectricity production and the function of the model is written

$$G = SALE_{TOT} - PEN_{TOT} \tag{6.1}$$

where $SALE_{TOT}$ is the total sales of the optimization period to the Nordic electricity market and PEN_{TOT} is the total penalty costs during the same time-period.

The optimization model has to keep the reservoir levels within the set upper and lower limits. In order to satisfy this rule, a penalty system was created to the model itself. The tool wants to optimize the revenue from the hydropower production and as the penalties for breaking these reservoir limits were set to be extremely large, the model will keep the levels at acceptable levels if it is at all possible. The penalty equation is

$$PEN_{TOT} = \sum_t PEN * (x_{up}(t) + x_{down}(t) + x_{dev,pen}(t)) \tag{6.2}$$

where PEN is a constant cost that is substantial enough to prevent unnecessary reservoir minimum and maximum level offenses and excessively large day-to-day level deviations. The penalty cost is set to a substantial constant value as the reservoir level violations are extremely unwanted and they should be limited only to cases when violating the limits are necessary because of the physical or environmental situations in the system and regular "legal" plans cannot hold the levels in the acceptable zone. Furthermore, the total penalty cost increases linearly with the offenses because if, for example, the total penalty would be a certain set amount, the model would not behave in a logical way if, for some reason, the minimum or maximum levels would have to be violated. $x_{up}(t)$ in the Equation 6.2 is the deviation over the maximum reservoir level, $x_{down}(t)$ is the deviation under the minimum reservoir level and $x_{dev,pen}(t)$ is the day-to-day deviation in the reservoirs needed if the inflows decrease significantly or grow too large and the maximum daily deviance limit must be broken. In these cases even minimum discharge or maximum discharge and spillage, respectively, do not keep the daily deviance within the acceptable zone.

6.3 Constraints

As in most mathematical problems, there is a set of conditions that must be satisfied in order to achieve an acceptable result. These conditions are called constraints and the model constraints are presented in Chapters 6.3.1 and 6.3.2.

6.3.1 Hydro balance equations and reservoir constraints

Before any optimization can be done the model must be constructed and the hydro balance equations must be calculated and designed for the unique river system. The equations must take into consideration the hydrological features of the system, the inflow forecasts and also the discharge from the previous plant upriver.

The model was first designed without time delays but ultimately the delays were needed to model the system in more detail. This way the tool models the real world hydro system better than before as there really are delays of several hours between some of the hydropower plants. As the model's time resolution is in days, the time delays of hours are constructed in fractions of a day.

The first matter that must be defined before the equations can be constructed is the reservoir water content in the beginning of the optimization time period. This must be set for all the reservoirs and in the model they are set as follows

$$x(0) = x_{start} \tag{6.3}$$

where x_{start} is the starting level of the reservoir for the optimization period in Day Units (DU). The level itself comes directly from the measured reservoir levels as an input to the model.

The general reservoir hydro balance equation is therefore

$$x(t) = x(t-1) + v(t-1) + q_p(t-1) + w_p(t-1) - q(t-1) - w(t-1) \tag{6.4}$$

where $x(t)$ is the present reservoir water content, $x(t - 1)$ is the previous day's water content, $v(t - 1)$ is the inflow to the reservoir x, $q_p(t - 1)$ is the previous hydropower plant's previous day's discharge into reservoir x, $w_p(t - 1)$ is the previous plant's previous day's spillage into reservoir x, $q(t - 1)$ is the previous day's discharge from reservoir x and $w(t - 1)$ is the previous day's spillage from reservoir x.

Mid-term planning generally wants the reservoirs to be at certain levels after some time. The end levels are decided and set in the optimizing tool itself and the model is constructed in a way that the reservoir levels are forced to be at the chosen levels at the end of the optimizing period. The end level has to satisfy the following equations

$$x_{final} = x(N-1) + v(N-1) + q_p(N-1) + w_p(N-1) - q(N-1) - w(N-1) \quad (6.5)$$

where N designates the number of days in the optimization time-period. x, v, q_p, w_p, q and w mark the reservoir, inflow into the reservoir, discharge and spillage into the reservoir and discharge and spillage from the reservoir, respectively.

Furthermore, the different reservoirs have minimum and maximum levels that must be respected at all times.

$$x_{min}(t) - x_{down}(t) \leq x(t) \leq x_{max}(t) + x_{up}(t) \quad (6.6)$$

where $x_{min}(t)$ is the minimum reservoir level and $x_{max}(t)$ is the maximum water content. $x_{down}(t)$ and $x_{up}(t)$ are the deviations from the minimum and maximum reservoir levels that result in penalties but are needed to make the model more robust.

To satisfy the Governance Rule, a limit for reservoir deviation during a day was created. These restrictions prevent enormous and fast changes in discharge rates and therefore keep the changes in the reservoir surface levels acceptable. They are written

$$x(t) \leq x(t-1) + x_{dev} + x_{dev,pen}(t) \quad (6.7)$$

$$x(t) \geq x(t-1) - x_{dev} - x_{dev,pen}(t) \quad (6.8)$$

where there are two different types of deviations. x_{dev} is the allowed legal day-to-day reservoir surface level deviation and $x_{dev,pen}(t)$ is the penalized deviation that is needed to make the model as robust as possible.

For the power plants in the river with no reservoirs, the hydro balance equations are different. Hence, the hydro balance equation only takes into account the possible inflow, discharge and spillage from the previous plant and discharge and spillage through the plant in question. The equation is written

$$v(t) + q_p(t) + w_p(t) - q(t) - w(t) = 0 \tag{6.9a}$$

where v is the possible inflow to the plant, q_p and w_p are the discharge and spillage from the previous upriver plant and q and w are the discharge and spillage from the plant in question. In case of delays the same equation is written

$$v(t) + a * q_p(t) + (1 - a) * q_p(t - 1) + a * w_p(t) + (1 - a) * w_p(t - 1) - q(t) - w(t) = 0 \tag{6.9b}$$

where a is a multiplier signifying how much of the available water is from the day t and how much of it is from the previous day. If, for example, there is a 12 hour delay between the plants the coefficient a would be 0.50 and thus half of the available water would be from the previous plant's previous day's discharge and spillage and the rest would be from the present day.

The discharge of water has to satisfy the guidelines set by the Governance Rule and the technical capabilities of the power plants. The maximum and minimum discharges are

$$q_{min}(t) \leq q(t) \leq q_{max}(t) \tag{6.10}$$

where $q_{min}(t)$ is the minimum discharge and $q_{max}(t)$ is the maximum discharge. These discharges vary extensively between the plants in the hydro system.

In addition to the discharges through the plant, there is also a limit for the spillages as well. In this thesis minimum spillage is always zero. The equation for spillage is

$$0 \leq w(t) \leq w_{max}(t) \tag{6.11}$$

where $w_{max}(t)$ is the maximum spillage.

6.3.2 Determining the energy coefficients and total sales

In this thesis, the energy coefficients of each plant have to be calculated separately as they are not publicly available and neither are they presented in the Governance Rule. The reason why linear optimization produces satisfying results in this model is because the production functions of the hydropower plants can be modeled as piecewise linear. Actually they are not linear but are extremely close and therefore this linearization can be done efficiently without significant uncertainties. This can be seen in Figures 6.1 and 6.2 where two different production plants' production functions are presented in scatter chart form. The available data for the chart in Figure 6.1 is extremely extensive. There was not as much data for the power plant in Figure 6.2 but there was enough for the model's purposes.

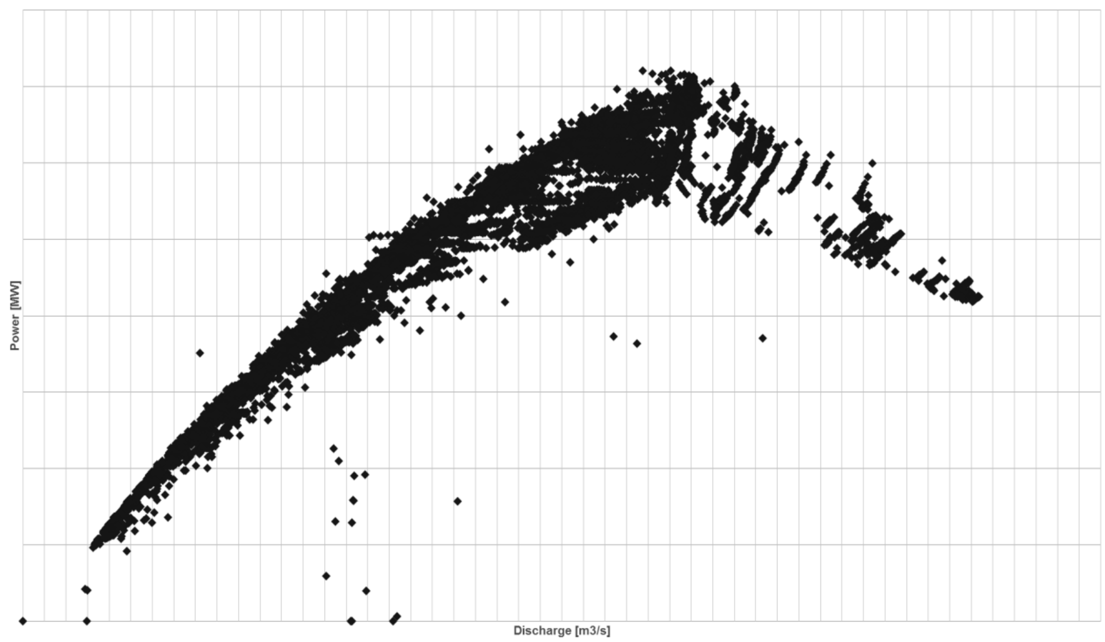

Figure 6.1. *Production curve of a hydropower plant*

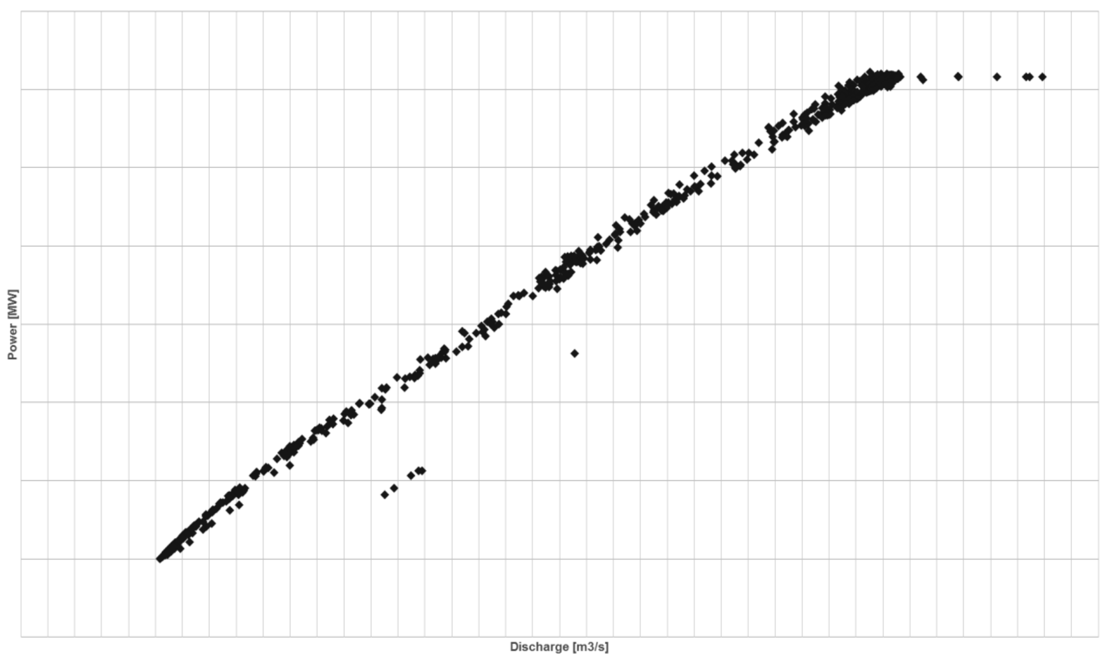

Figure 6.2. *Production curve of another hydropower plant*

There is a particularly large size difference between the plants in Figure 6.1 and 6.2 but they behave very similarly when there is no spillage. The maximum discharge for the plant in Figure 6.1 is at the point where the power production's gradient becomes negative. For the plant in Figure 6.2 it is at the point where the power production does not increase further. After those points, spillage is needed to increase the total discharge through the power plants. The differences between the behaviors of the two plants are significant only when there is spillage needed. The other plant's tail water reacts to increased discharge easier because there is less room for the water and it is not designed for such amounts of outflow. All the hydropower plants in the system behave more or less in a similar way and hence they can also be modeled with linear equations.

Due to limits set by the equipment, suitable power generation can only be started if the discharge is over the minimum level as otherwise the equipment might break from cavitation. This minimum level is defined for each turbine separately and can be seen from the scatter charts as the points where the power production starts. After the minimum discharge is surpassed, the power production is close to being linear and the small nonlinear differences are caused by, for example, different weather conditions. When the plant is discharging water close to its maximum its production is generally not increasing, and might even decline, as the tail water tends to rise when discharge rates are extremely large. This is also the reason why spillage generally decreases power production and has to be included in the energy calculations. If spillage is not considered in the calculations, the plants could spill water without consequences in the model and it is not desired in real world production scheduling.

The energy coefficients for the optimization were defined from this data and the charts were modeled by piecewise linear functions that are presented in Figures 6.3 and 6.4. Both charts model only the discharge area of the production curve and they do not show the effect of spillage. The effect spillage has on energy production is defined separately for each plant and a negative coefficient for it was created, so that the model recognizes spillage as not beneficial for profit creation.

Figure 6.3. *Linearized power function of the hydropower plant in Figure 6.1*

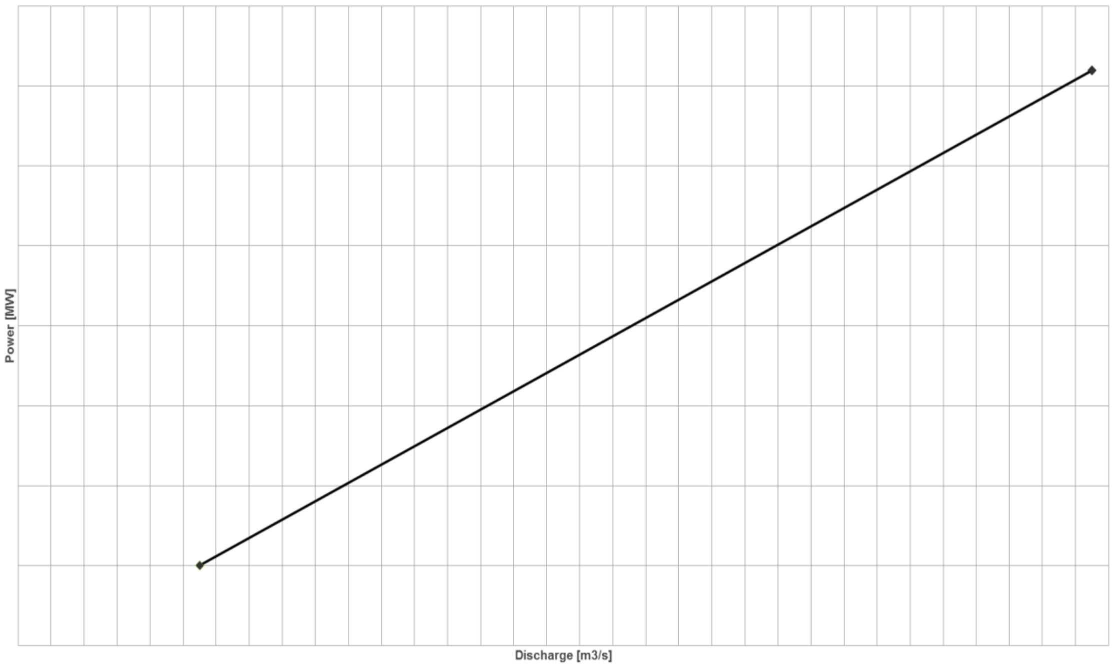

Figure 6.4. *Linearized power function of the hydropower plant in Figure 6.2*

The energy coefficients of different plants were defined from the functions presented in Figures 6.3 and 6.4 and they are written in the following form

$$\begin{cases} P_i(t) \leq e_{q1} * q_i(t) + e_{c1} + e_{w1} * w_i(t) \\ \dots \\ P_{n_i}(t) \leq e_{qn_i1} * q_i(t) + e_{cn_i} + e_{wn_i1} * w_i(t) \end{cases} \tag{6.12}$$

where $P_i(t)$ is the hydropower plant i's produced power during day t, e_{q1} is a multiplier that converts discharge into energy, e_{c1} is a constant needed to model the linear functions and e_{w1} is a, generally, negative coefficient used to model the spillages effect on power generation. As can be seen from the Formula 6.12, there can be several different energy equations for one hydropower plant, depending on how the discharge rates affect the power production.

Some hydropower plants in the river system operate according to the prices and try to maximize revenue by only producing at times of higher consumption when prices are higher. This is possible for plants that can halt discharging and store water in the reservoir instead. It also must be stated in the Governance Rule if this is possible. As a result of this, the model was created in a way that recognizes this possibility and the energy coefficients of these plants were divided into day and night equations. These were written in the following way

$$P(t) = P_d(t) + P_n(t) \tag{6.13}$$

$$P_n(t) \geq 0 \tag{6.14}$$

$$P_n(t) \geq a * q_{min}(t) + b \tag{6.15}$$

$$P_n(t) \geq P(t) - h_d * PMax \tag{6.16}$$

where $P(t)$ is the produced power during day t, $P_d(t)$ is the day time produced energy, $P_n(t)$ is the night time produced energy, a and b are special coefficients for each plant, h_d is the amount of hours during day time and $PMax$ is the maximum power generation capability. The distinction between the night and day energies are needed to make the model's plans more realistic but they are not extremely precise due to the purpose of using the model's plans for mid-term planning.

The day and night energies of the different power plants are then combined to form equations for total daily day and night production.

$$P_{TOT,d}(t) = \sum_i P_{di}(t) \tag{6.17}$$

$$P_{TOT,n}(t) = \sum_i P_{ni}(t) \tag{6.18}$$

The total day and night productions are then utilized in calculating the daily total sales from the system to the Nordic electricity market.

$$SALE_{TOT}(t) = s(t) * [S_{c,d} * P_{TOT,d}(t) + S_{c,n} * P_{TOT,n}(t)] \tag{6.19}$$

where $SALE_{TOT}(t)$ is the daily total sales, $s(t)$ is the forecasted daily Spot price, $S_{c,d}$ is the price coefficient for day hours, $P_{TOT,d}(t)$ is the day time power sold to the Nordic electricity market, $S_{c,n}$ is the price coefficient for night hours and $P_{TOT,n}(t)$ is the night time power sold to the market. The model receives the price coefficients as input data from the market analyst's forecasts.

After the daily power sales are calculated, they are summed together for the whole optimization time-period to form the total sales.

$$SALE_{TOT} = \sum_t SALE_{TOT}(t) \qquad (6.20)$$

where $SALE_{TOT}$ is the optimization period's total sales to the Nordic electricity market. This is then used in the objective function together with the total penalties to maximize optimal hydropower scheduling for the optimization's time-period and thus also maximize the revenue from the hydro system.

7 MODEL RESULTS IN MID-TERM PLANNING

In this thesis a real hydro system has been studied and analyzed and the optimization tool created models this system as closely as possible. In Chapter 7 the functionality of the model is evaluated and its results scrutinized. Chapter 7.1 describes how the model allocates production in different situations and the results are critically examined to make sure they are at the same time optimal and feasible. In Chapter 7.2 the usability of the created tool is assessed and the possible future use is explained.

7.1 Allocation of Production

The goal of this thesis is to create a mid-term hydropower planning tool for actual use. The tool has to be efficient and it has to model the hydropower system as closely as possible so that the results it gives are satisfying and hence it can be utilized in the planning process.

In order to test the planning tool, gather information on how the tool allocates production and see how efficient it is, a series of tests were executed with it. First, realized data was used to analyze the behavior of the model and see if the results are comparable to the actual behavior of the river and the realized hydropower production from it.

After the model has passed enough backtracking tests successfully and it models the system adequately for its purpose, it is applied in its actual future planning process and forecasted data is used as input to the model. The results from these tests are compared with the actual plans and different yearly scenarios. After completing these tests effectively, the planning tool is utilized in the real planning process parallel to the previous methods and the results are scrutinized to see if the model produces reasonable plans that seem better, financially or from nature’s perspective, than what the previous methods would generate.

Finally, a decision is made on the future use of the planning tool. Either it is accepted as the production allocation planning tool and its results are actively used in mid-term hydropower planning or it’s not satisfying enough and it needs to be developed further. That is for the actual users to decide and that process is explained further in Chapter 7.2.

7.1.1 Historical Optimization

Historical backtracking is a common method used to analyze planning models and gather information on their applicability as optimization tools. If the results from the historical data are reasonable and acceptable, then the models have potential to become part of the planning process. If the results for some reason are not feasible or otherwise irrational, then it is clear that the models need to be improved and developed further.

The model itself can be modified to allocate production with certain limitations or even without any limitations. Financially the results between optimization with strict constraints on, for example, the day-to-day surface deviations and optimization without the day-to-day limitations can be substantial. Without limitations the results always seem financially more beneficial but the surface levels of the hydro reservoirs can deviate enormously between days, as can be seen in Figure 7.1. Nevertheless, the nature and the expectations of the Governance Rule are always taken into consideration when planning the production and limits are set into the model in order to achieve at the same time possible and financially viable results.

Figure 7.1 represents one of the system's hydro reservoirs in 2011, where the realized surface levels and prices are graphed together with the optimization tool's plans with and without the surface level deviation limitations. The minimum and maximum levels in the reservoir are marked with red lines and the surface has to stay inside those levels. Green line is the actual realized surface level in the reservoir, blue is the optimization tool's suggestion with limitations included and brown is the optimization tool's suggestion without limitations included in the procedure. The black line is the daily realized Finnish Spot-price in 2011. The optimized levels are very different to the actual realized surface levels. The optimization with limitations clearly satisfies the recommended day-to-day deviations and produces more income for the co-owners. The optimization without limitations produces a plan that is possible to achieve in a technical sense but is not recommended as the Governance Rule limits too strong surface level deviations.

The plan with satisfactory limitations included increases the income from the river by up to 4 % on a yearly level and without the limitations the figure is closer to 5 % more. It is therefore clear that the optimization is very beneficial for the co-owners but limitations are needed as the river system is more controllable and the financial benefits from the operation without, for example, deviation limits is rarely worth the risks involved in the extremely aggressive river operations. Furthermore, as the backtracking is done with realized inflows and prices, the results are fairly optimistic but nevertheless significantly better than the actual operations.

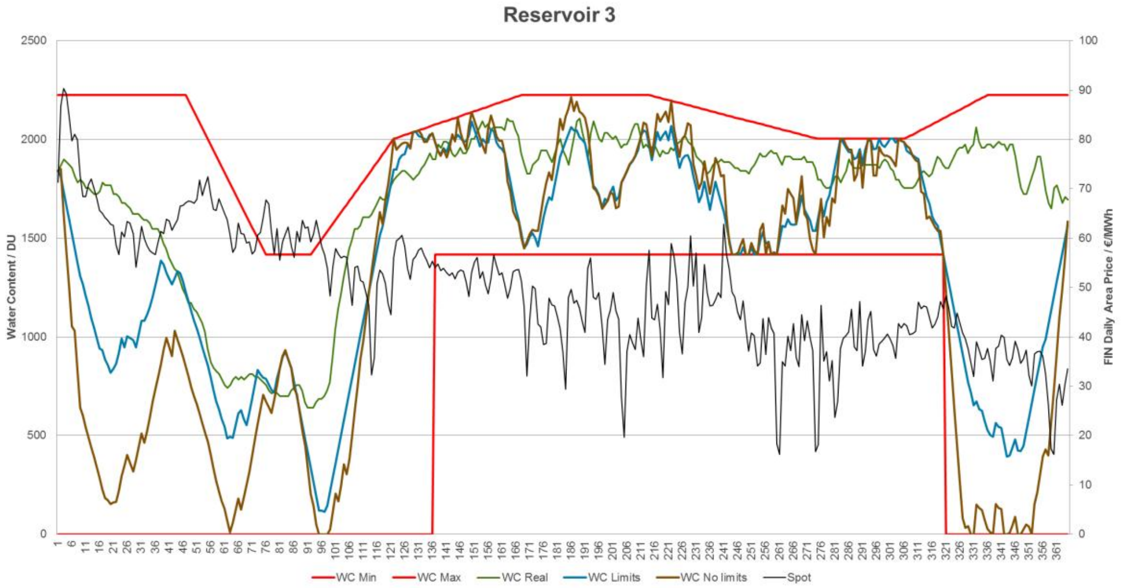

Figure 7.1. *Optimization without limitations and with limitations included in Reservoir 3 in 2011*

As the limits have to be included in the actual tool, the backtracking tests are completed with them included. Even with them included, it is seen that the model creates more dynamic allocation results in order to increase the income from the hydro and when compared to the historical data, it is clear that the river system has been operated quite modestly and more cautiously than what is required by law and made possible by the Governance Rule. Therefore, the operation does not maximize the flexibility of the river system and the governance rules. Figures 7.2, 7.3 and 7.4 show the surface levels for a particular hydro reserve in the system from three different kinds of hydrological years, dry, average and wet. The optimization model's suggested plans are also included for those particular years together with the daily Spot-price profile. From these figures one can see how the tool optimizes the hydro production.

The red lines in the figures are the minimum and maximum reservoir levels, black line is the daily Finnish Spot-price, green marks the actual realized surface levels and blue marks the optimization tool's suggestion.

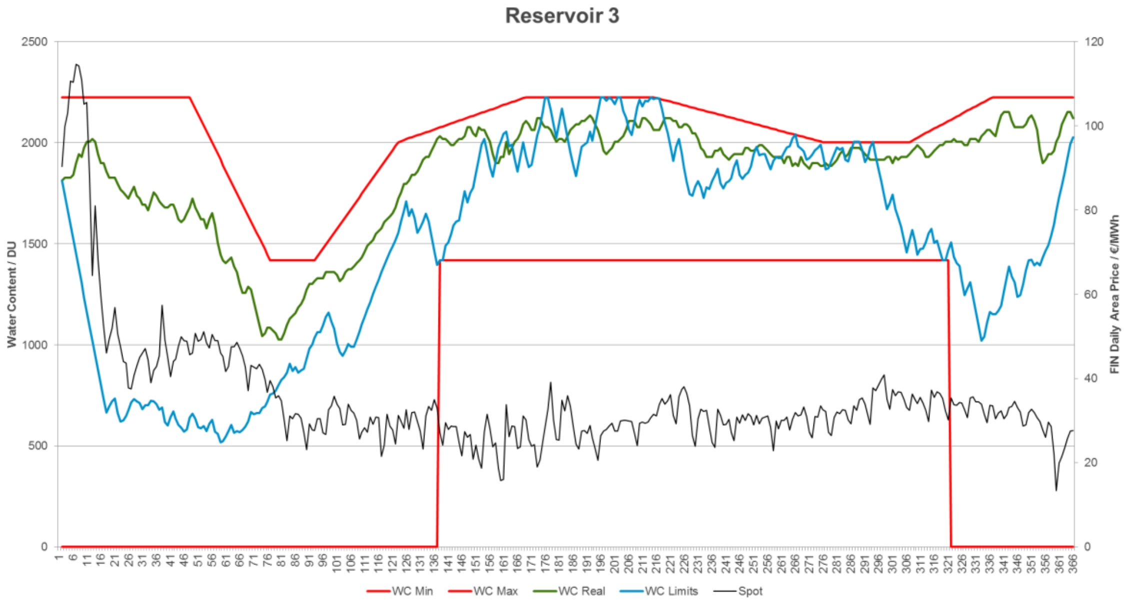

Figure 7.2. *Optimization of a dry hydrological year (Reservoir 3 in 2003)*

The year 2003 was a dry hydrological year with fairly high Spot-prices in the first months of the year. The tool suggests aggressive power production during the first months and creates the required lower surface levels earlier than required. Then it fills up the reservoir to the summer-time recreational levels and keeps the levels high until the higher fall prices. In the fall the model suggests increased generation and then filling up the reservoir before the winter as the prices fall at the end of the year. Typically such behavior would not go directly to the actual plans as it would have been scaled down considerably. The sharp surface level rise at the end of the year in Figure 7.2 is due to the model's feature that there must be a goal level at the end of the optimization time-period which the tool must try to achieve.

The model's plans and the realized surface levels are not completely comparable as the model creates its plans with realized data and not forecasts. The operator of course had only the forecasts which include some uncertainty in them. However, the January prices were so high that in all scenarios the reservoir should have been utilized more than what actually happened. The model's plans would have created approximately 18 % more income from the river system, most of it coming from the differences in the January operations, and it would have benefited all of the system co-owners.

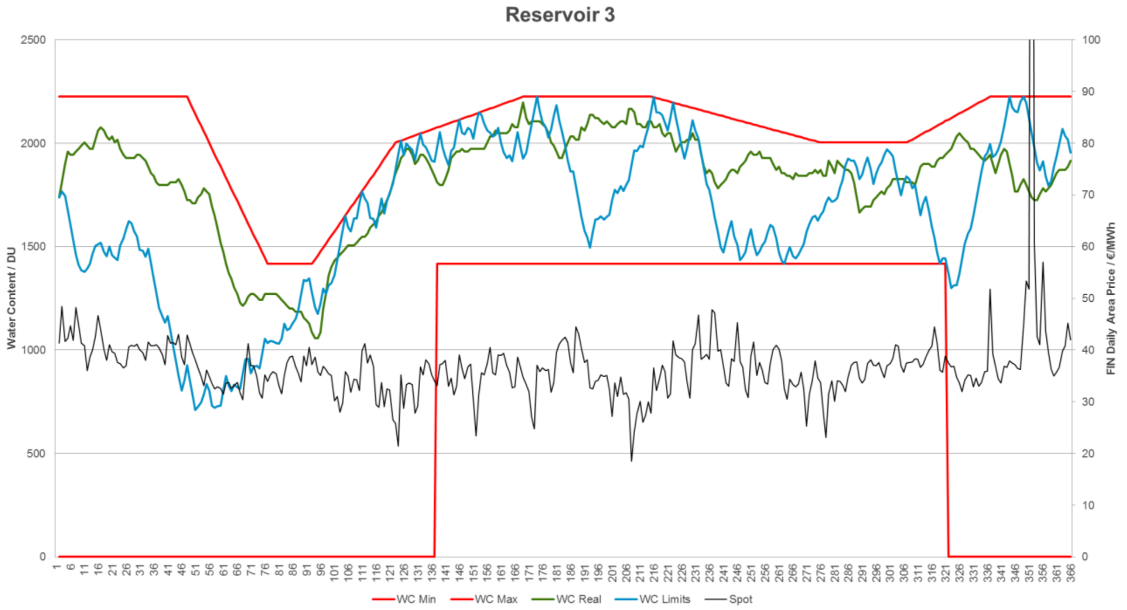

Figure 7.3. *Optimization of an average hydrological year (Reservoir 3 in 2009)*

2009 was an average hydrological year in the Nordics with steady inflows. The prices were fairly stable throughout the year with the exception of the December spikes. The actual surface levels in the Reservoir 3 are also similar to planning tool's suggestion but still the tool creates more value by utilizing the reservoir more when prices are higher. The benefit of utilizing the reservoir more, even in stable conditions, creates significant value to the co-owners. In the year 2009 the model's plans would have increased the revenue from the river by roughly 6 %.

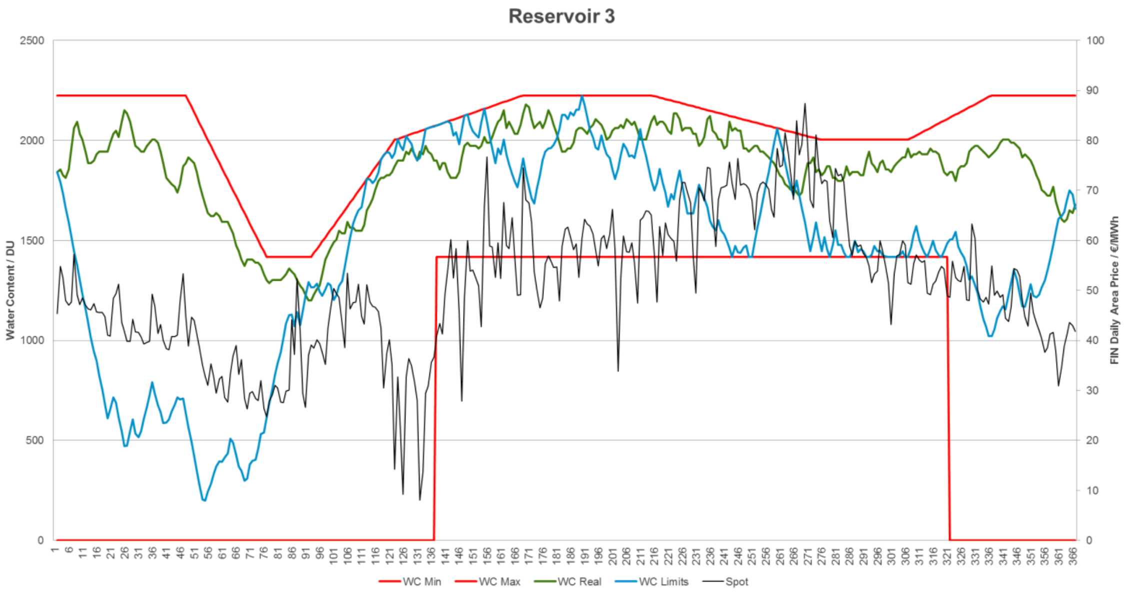

Figure 7.4. *Optimization of a wet hydrological year (Reservoir 3 in 2008)*

The year 2008 was a wet year with high Spot-prices. The operator kept the surface level of the Reservoir 3 close to the maximum nearly throughout the year. The model, on the other hand, suggests that discharging more in the beginning of the year is beneficial as it reduces the amount of spillage significantly and less energy is therefore wasted. Also, the model utilized the whole summertime recreational window, which is financially beneficial. In 2008 the model's plans would have increased the income from the hydro system by a bit over 7 %. It was a good hydro year from the operator as well but with a bit more dynamic operation the income would have been even better.

The optimizing tool works in a similar way for the hydro reservoirs 1 and 5 in the system as well. Figures 7.5 and 7.6 show how the model would operate the other reservoir surface levels during average hydrological years. The model respects the maximum and minimum levels and the day-to-day deviation limitations but at the same time tries to increase the revenue from the system. Reservoirs 2 and 4 and their surface levels and discharges are not included in the planning tool as they are operated and regulated by different parties. Hence, the data from those reservoirs are only used as input to the planning model.

In Figure 7.5 the Reservoir 1's realized surface levels during the summer were kept under the minimum levels due to construction near the hydropower plants. Hence the results are not fully comparable as regularly the summertime surface levels are significantly higher. In addition, other recent average hydrological years have similar kinds of surface level challenges and they were also not very comparable so the year 2011 was chosen. Nevertheless, the results from the optimization are quite close to the realized surfaces and it can be seen that the optimization tool maximizes income by discharging more during the winter-time in the benefit of the hydro system co-owners.

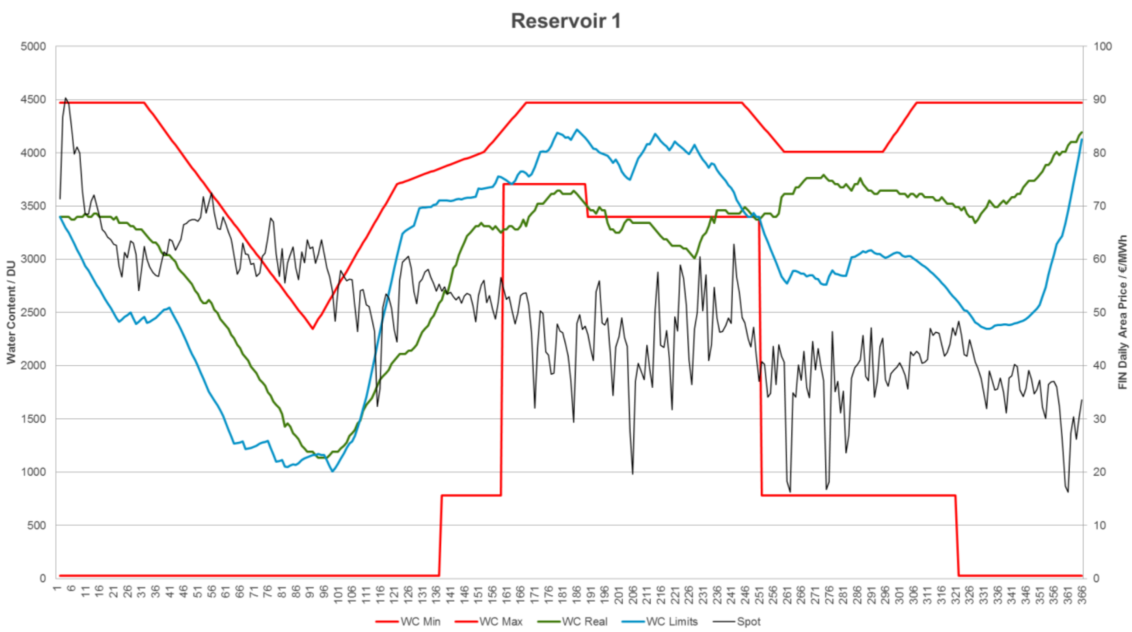

Figure 7.5. *Optimization of an average hydrological year (Reservoir 1 in 2011)*

In Figure 7.6 the realized surface levels of the Reservoir 5 are lifted to the typical summer levels fairly early due to the spring-time flooding in the hydro system. It is possible to do that according to the Governance Rule in some situations and these situations happen reasonably often in this hydro reservoir. The optimization tool's suggestion shows a surface level that is within the limits but the tool can be easily modified to allow upper limit "violations" in some hydrological situations when they are allowed.

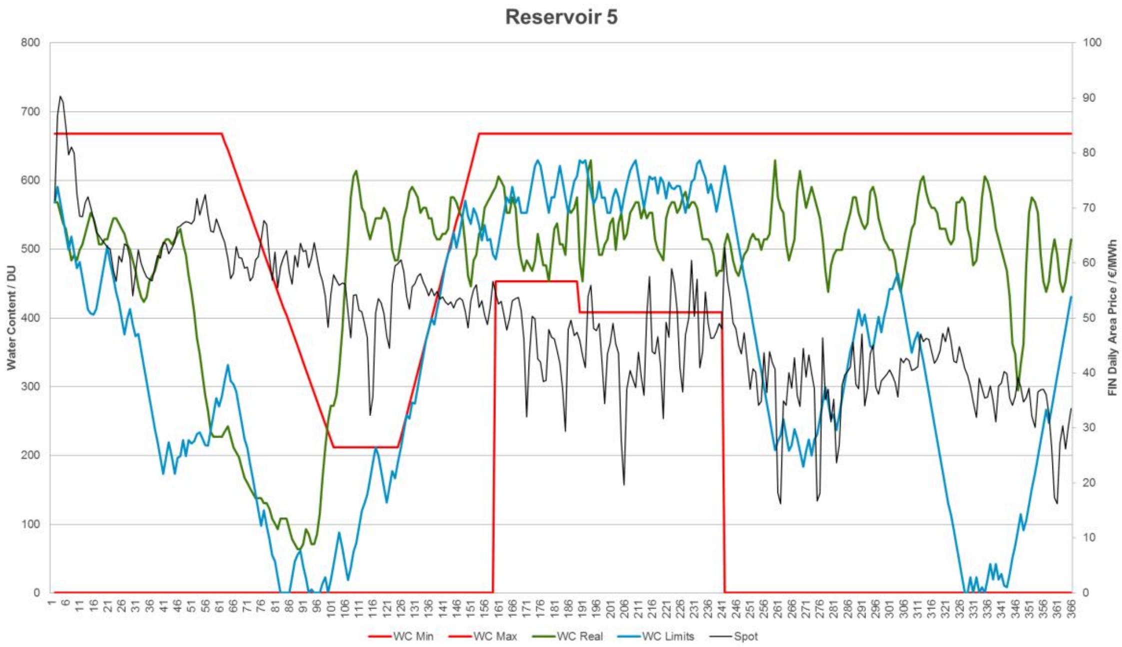

Figure 7.6. *Optimization of an average hydrological year (Reservoir 5 in 2011)*

Overall, the model's plans are to maximize the whole river as one. Hence, the overall optimal solution is not always optimal in some parts of the system but in general view the plans are beneficial.

The surface levels are extremely important to keep within the limits set by the law and what is agreed in the Governance Rule. Breaking these limits usually cause problems in the hydro system, discussions with the environmental officials, unhappiness in the locals and even penalty fines. The discharge and spillage limits have to respected as well in order to keep the river in balance and operational throughout the whole hydro system. In addition the discharge rates are important as they indicate how much energy can be produced. As is with the surface levels, the tool optimizes the discharges and is a bit more active with the changes in the discharge rates than the current methods. That can be seen from the Figures 7.7, 7.8 and 7.9. Actively alternating the discharges cause more work for the operator but it can be achieved as hydropower plants adjust to the changes effortlessly as the plants in the system are highly automated and very modern. The model also tries to minimize spillage and it does that quite well, as long as the forecasts are of good quality.

In Figures 7.7 – 7.9 the actual realized combined discharges and spillages are marked with the green lines and the model's proposals are marked with the blue lines.

The red line portrays the maximum discharge capacity of the plant. If the combined discharge and spillage go over that line, spillage was required.

Plant 4 in Figure 7.7 regulates the Reservoir 3 and it has a maximum discharge capacity of 420 m3/s. In 2011 spillage due to flooding was not required as the capacity of the plant and the reservoir could contain the inflows. Due to the increasing inflows near the end of the year, the discharge rate was significantly increased and discharge was needed during night-time also. Otherwise, the whole year was quite normal and only day-time power production was needed. The model's suggestion is similar to the actual discharge rates but the changes in them are more agile. Quick changes in the discharge rates are already used in the operation of this plant and therefore the model's results are extremely satisfactory. Generally this plant is only used during day-time and stopped during the night-time and when prices are low.

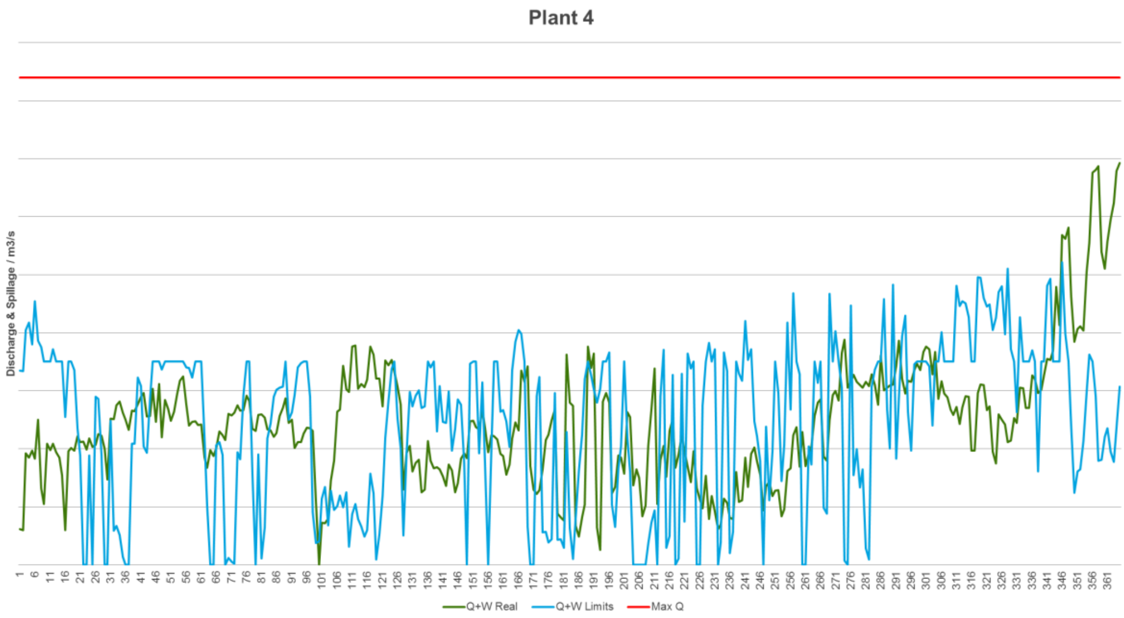

Figure 7.7. *Combined discharge and spillage (Plant 4 in 2011)*

The wet year of 2008 was challenging even for Plant 4 which generally is extremely versatile and adopts into many hydrological situations as it controls a rather large reservoir, has a generous maximum discharge rate and it does not have to discharge hydro at all times. However, the first half of the year had very heavy inflows and same happened again in the fall and early winter resulting into almost nonstop production which is rare for Plant 4. During summertime, hydropower production was decreased.

The discharge plan from the model is again similar but utilizes the reservoir more as it stores water during the weekends and at night-time and uses the hydro for power production during day-time and higher prices. According to the model, during wet years it is financially beneficial to produce operate Plant 4 at almost maximum capacity during day-time and reduce production during weekends and night-time.

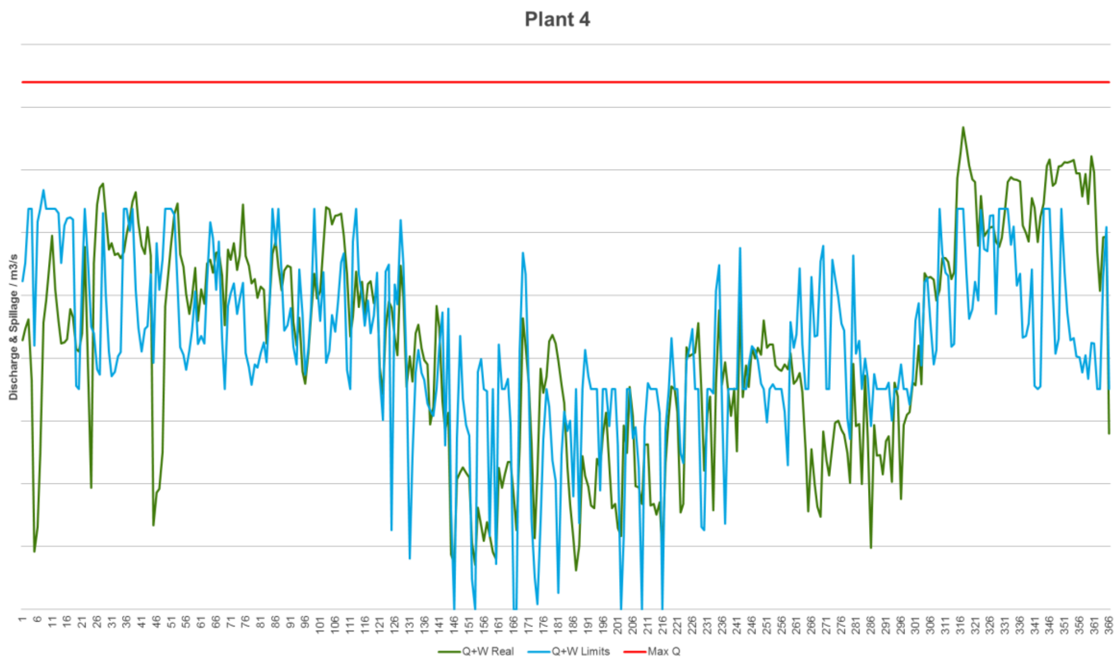

Figure 7.8. *Combined discharge and spillage (Plant 4 in 2008)*

Figure 7.9 shows the fifth plant in the system, which regulates the Reservoir 5. It has a maximum discharge capacity of 320 m3/s. As mentioned before the year 2008 was heavy with inflows and as the Plant 5 has a smaller maximum discharge capacity, spillage was required. The difference in the realized discharge rates and the model's plans are substantial in the latter half of the year when the inflows increased. The operator did not prepare the reservoir for increasing inflows and had to spill water in the last months. The model uses realized inflow data so it tried to minimize the spillage by discharging more in the months prior to increasing inflows. Still, the plans are quite similar and it is clear that the operator's actions were acceptable and more aggressive behavior is not even largely possible in the Reservoir 5 as it is much smaller than the other reservoirs in the system.

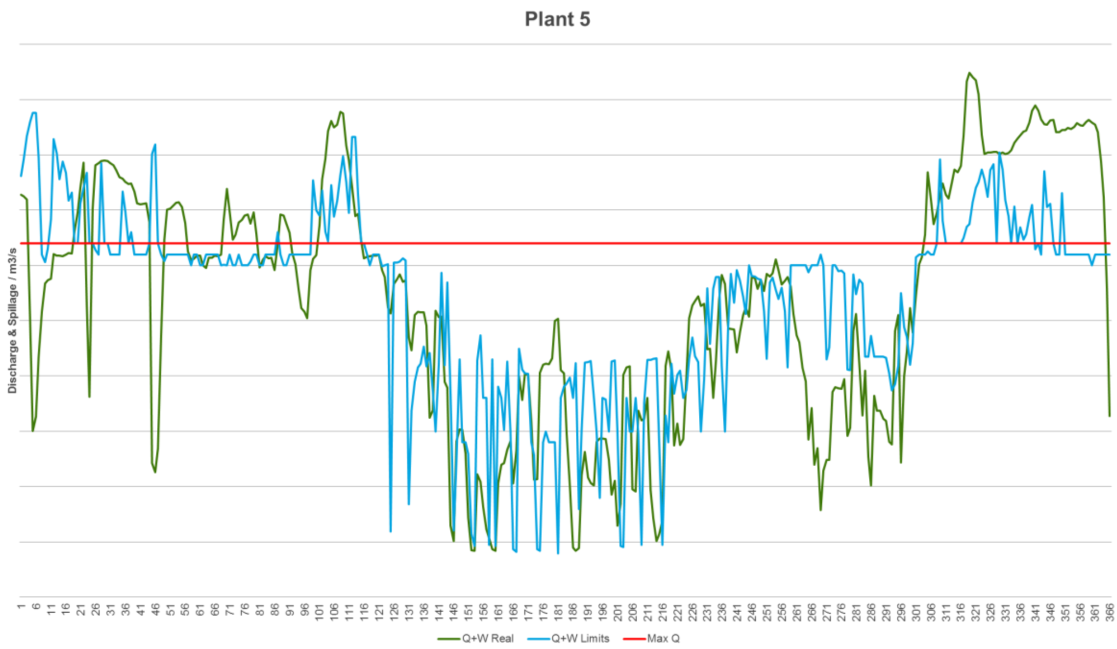

Figure 7.9. *Combined discharge and spillage (Plant 5 in 2008)*

A more optimal way of planning the hydropower results in more income to the companies co-owning the hydropower plants in the hydro system. The model results from the realized historical data are not fully comparable to the actual realized operations as the forecasts might have changed during the optimization time period but the mid-term plans are generated weekly so that there is always the best available data present in the analysis, which compensates the difference to some extent. Nevertheless, as the results from the model are financially significantly better in all of the tested years, it is obvious that the hydro system should be planned in a less orthodox way and the reservoirs could be utilized more within the set limits. This benefits both the co-owners and also the whole market as the electricity production is scheduled for the most needed times when the prices are higher. The increased utilization also prevents flooding and spillage from unexpected heavy inflows so that the hydro system can be operated in an improved fashion in the short-term time-period. Radical and unexpected flooding cannot always be forecasted well in advance so understandably that will always stay as a slight risk in the mid-term plans.

7.1.2 Calendar Year Optimization

The results from the future production allocation optimization are more challenging to analyze as there are no realized data available. Therefore, knowledge of the river behavior is critical and the results can be analyzed by comparing them to the operator’s plans and historical data. When comparing the production allocation to historical data, it is necessary to analyze the forecasts and other inputs with care and choose a similar historical time period in the analysis to get comparable results.

There are two different ways of mid-term planning the hydro assets. Either plan a calendar year from the beginning of January to the end of December, where the realized history is visible and used in the planning process, or plan a running year, where the planning begins from the next week and runs through the following 365 days. Normally the running year method is utilized in the mandate directives, which mid-term gives to short-term, as it serves the purpose of the mandates better and the plans are precise for one year forward. After that the plans are, more or less, developed from price and inflow forecasts that are not as refined and the generated plans are mostly for giving an approximate idea what the future income from the hydropower production is going to be. The goal of mid-term planning this particular hydro system is to optimize the surface levels in the reservoirs and give the target levels as instructions to the operator, who then plans the hydro production according to the combined wishes of the co-owners.

In Figure 7.10 a current year optimization is presented on Reservoir 1 in a way that shows the realized surface levels and the model's results separately from the historical data. The time of optimization was in mid-July and the surface level forecasts are from the operator's plans, the inflow forecasts are from the Finnish environmental agency and the price forecast is a combination of short-term price forecasts and real closed future and forward system price curves. In the real mid-term plans the planners use actual Finnish Spot-price forecasts from several different service providers. As can be seen from the figure, the operator does not plan to actively use the whole window that allows the surface levels in the reservoir to fluctuate significantly more than in the plans. The model's suggestion, alternatively, keeps the surface levels close to the maximum at the beginning of the fall and increases power production when the Spot-prices are forecasted to rise. If a more exact price forecast would be used as input, the surface levels would fluctuate more but with a flat profile the model's plan is quite close to the operator's plans. Depending of the actual operator's generation allocation, the model's results are financially from a similar result to up to 3 % increase for the whole river system.

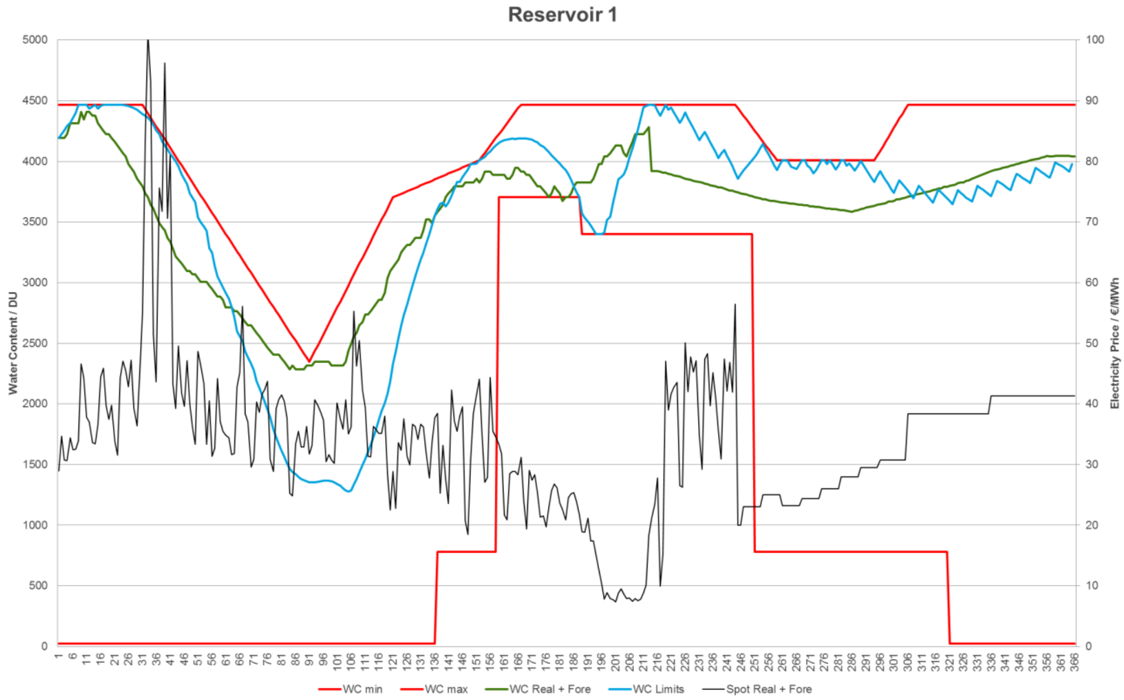

Figure 7.10. *Current year optimization of Reservoir 1 (optimized on 7/2012)*

Figure 7.11 depicts the Reservoir 3 and shows how it would be operated according to the model. The operator is conservative in its plans and the model creates better results because it utilizes the reservoir's hydro in a dynamic and financially in a better way.

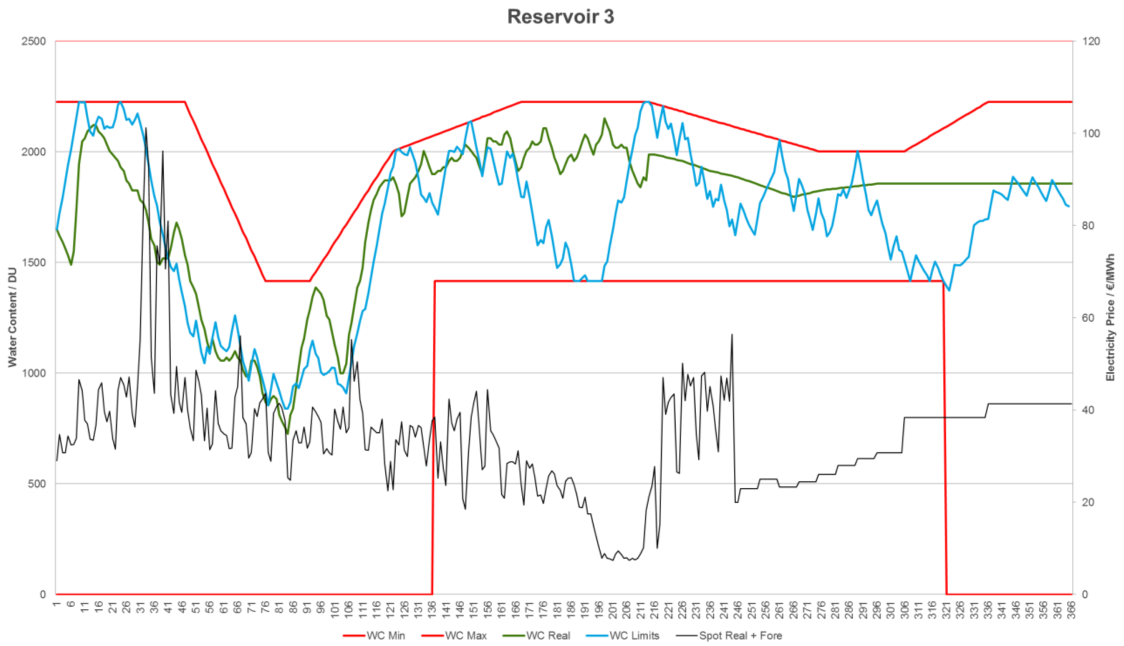

Figure 7.11. *Current year optimization of Reservoir 3 (optimized on 7/2012)*

Figure 7.12 presents the third reservoir in the system and shows the optimal way of utilizing its surface levels. It is clear that the operator would like to keep the surface level in the Reservoir 5 at close to maximum for the last months. On the contrary, the model suggests that discharging more water in the beginning of the fall is beneficial and before winter the surface should be raised again to the desired levels that need to be defined in the optimization tool. This plan seems excessively aggressive but Reservoir 5 is a smaller hydro reservoir in the system and it naturally fluctuates more than the larger ones. Therefore it would be moderately effortless to control the situation and not break the minimum and maximum surface levels.

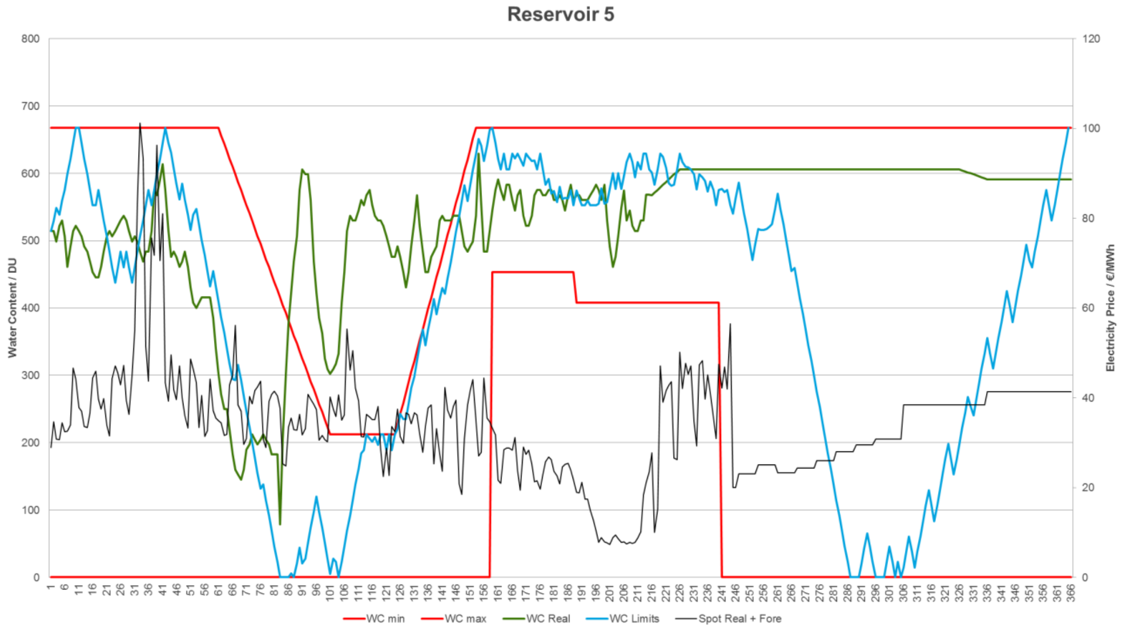

Figure 7.12. *Current year optimization of Reservoir 5 (optimized on 7/2012)*

7.1.3 Running Year Optimization

Running year optimization is presented Figures 7.13, 7.14 and 7.15. The time period of the figure is from August 2012 to August 2013. The thin black line marks the Spot-price forecast generated from realized forward closing prices, the red lines mark the minimum and maximum levels, the green lines mark the operator's plans and the blue lines mark the model's suggestion.

According to the price and inflow profiles, the river system should be operated in a more dynamic way than the operator's conservative plans. The model suggests using the hydro in the reservoirs already in the fall time as the inflow forecasts imply strong inflows in the winter-time also. This way the operator could minimize the potential upcoming spillages and produce as much energy as possible during the fairly strong Spot-prices.

The most radical plans can be altered in the optimization tool by setting mandatory surface level targets into the model. That way, if the plans are too aggressive, the mid-term planner can direct the plans to a more reasonable direction.

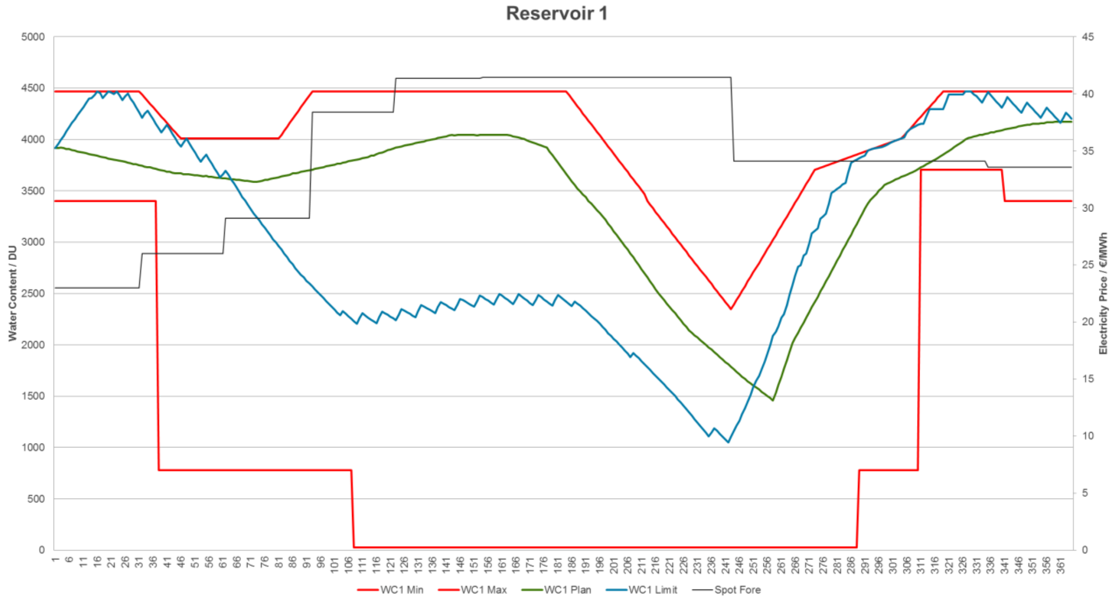

Figure 7.13. *Running year surface level optimization of Reservoir 1*

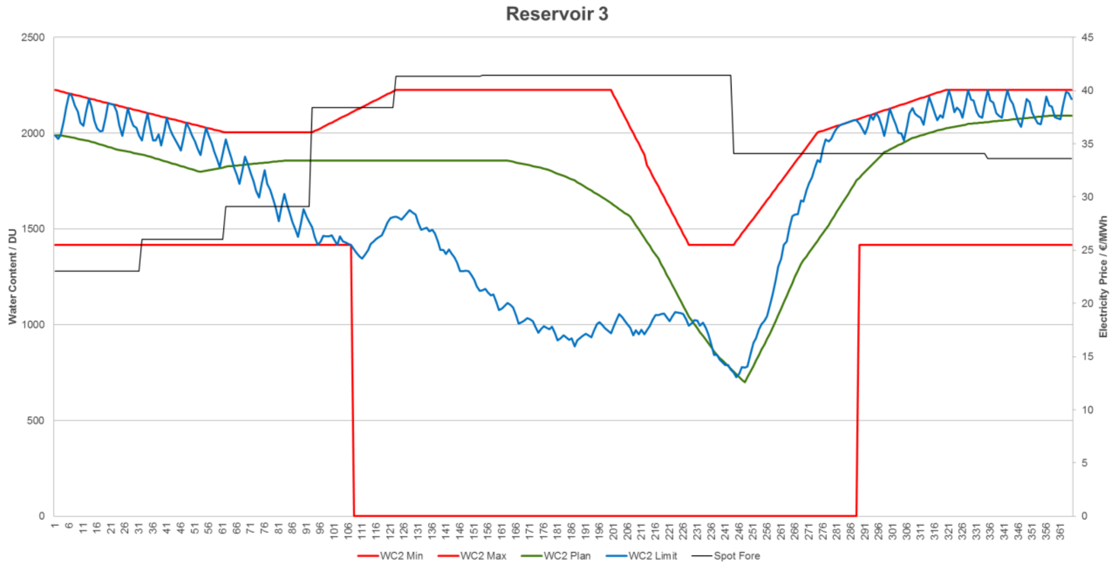

Figure 7.14. *Running year surface level optimization of Reservoir 3*

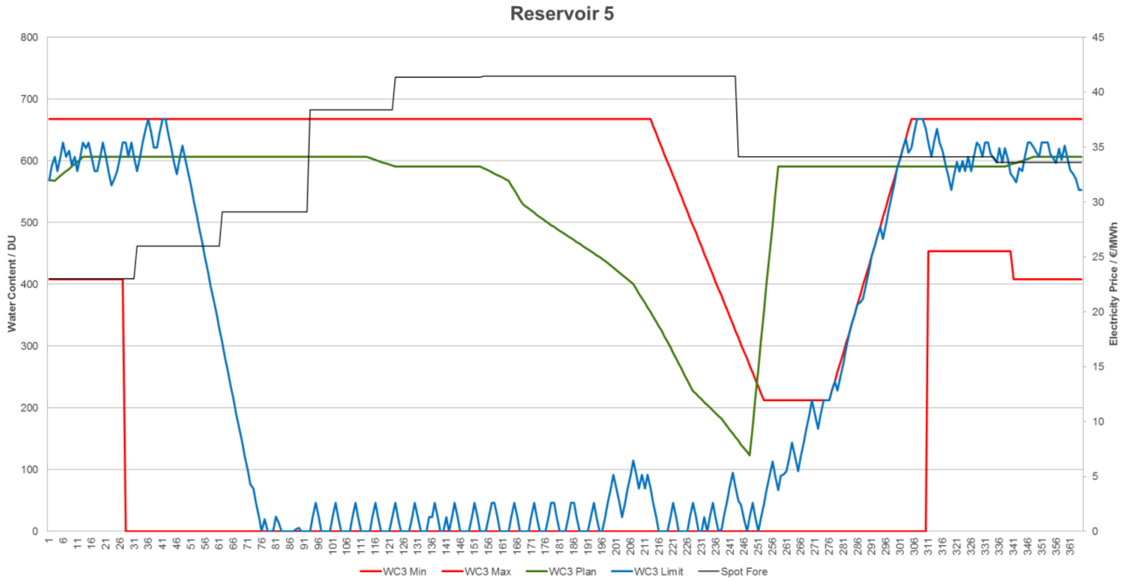

Figure 7.15. *Running year surface level optimization of Reservoir 5*

As can be seen from Figure 7.16 the discharge rates could be reduced in the spring and the surfaces could then be lifted to the required summertime levels. According to the model the suggested plan would also prevent spillage completely during the running year time period. It is also obvious from the discharge figure that the inflows are forecasted to be extremely strong during the next year and as the surface levels in the reservoirs are already reasonably high, heavy discharging should be planned.

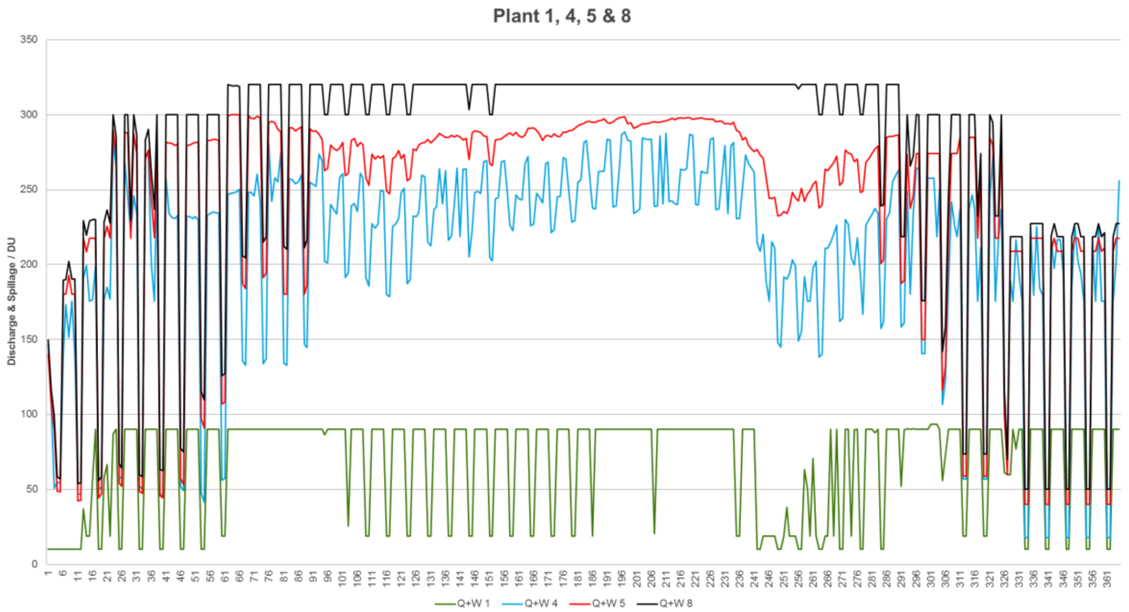

Figure 7.16. *Running year discharge optimization of the hydro system*

The surface and discharge optimizations are only suggested plans and they should be evaluated by a professional before further operational plans. In reality the surface levels are generally not lifted to the maximum levels as there usually is a small marginal to the maximum. This way sudden rain, increased inflows or plant failures do not lift the surfaces over the limits. The forecasts are also analyzed before they are used in the model as if they seem irrational, the model's suggestion will not be useful in the planning process.

In addition, the planning process is repeated at least once a week. That way the operator does not have to rely on old plans and they are always up to date and have the best known information available. The co-owners also keep contact with the operator at all times so that the information required to operate the river system is up to date and accessible for the parties who need it.

7.2 Applicability and Future Use

The applicability of the created mid-term planning model was studied by comparing the model's results with the realized and forecasted plans. The results were exceptionally promising and better than expected. At the same time they were feasible and realistic and hence the goal of the thesis was fulfilled and mid-term planning can begin using the model in their planning processes.

The weakness of the planning model comes from the weaknesses of linear programming. It produces only one "best available" result and is extremely aggressive in the plans unless there are several constraints prohibiting excessive river usage. The model also takes all the input as truths and, for example, inflow forecasts can at times differ significantly from the realized inflows which generates risk in the plans. Therefore, the results need to be checked by a planner so that overly aggressive operation is avoided and that the plans are achievable.

Because of the weaknesses of the model, it should be used carefully at first and its plans should be analyzed critically. In addition, the plans should be discussed with the operator and confirmed that they are possible as sometimes the weather conditions prohibit certain river operations. Also, if the river operations are more dynamic than before, the environment should be monitored with care if the more active hydro utilization produces some unwanted results. Furthermore, vast changes in the river operation should be communicated with the locals and it is important to remember to keep the land owners and recreational users satisfied and informed about the situation.

The planning tool itself is already functional but it is, as of yet, not completed. Further development will make it more usable and esthetic. These are requirements for the tool as it will be used by several people and it is still fairly complicated to operate. The objective is to have a finalized product soon that is easy to use with only minor instructions. Further development will also take into account user feedback.

The original idea was to create a model that can optimize several years of hydropower production. The created tool uses a free of charge solver called lpSolve which implements a Simplex Method in the optimization and it does not have any limitations on the size of the optimization time-period but typically only a running year will be planned. Optimizing a 365 day time-period with 21900 variables and 17974 constraints takes approximately 80 seconds and it will increase if a longer or a more detailed resolution will be used. The time the model takes to calculate an optimization problem is reasonable and user friendly enough to be used in the actual planning process as long as the time-period is not extremely large. For optimization processes that include several years' worth of data, a commercial solver would be more preferable as they reduce the optimization time radically from the used free software. The results would of course stay identical as a linear programming product would be used. Besides a commercial solver, another possibility would be to modify the resolution of the model to a more inaccurate form. Moreover, the end product, made with the lpSolve, is a robust program that can be adapted to other environments with some minor changes. The model is also easily updateable if there are for example capacity increases in the hydropower plants in the hydro system or the mid-term planners want to update the solver to a commercial one.

As the planning model is created for one co-owner only, the results it produces are not final. The other co-owners produce their own plans and the final plan is a combination of every co-owners plans. The plans of the companies are weighed according to the shares and hence some co-owners have more power than others. The created planning model does not take into account the other companies wishes as they are visible only to the operator. Therefore if other co-owners want to increase the utilization of the reservoirs and be more active in the river operations and others want to continue with the more conservative plans, the final plan is somewhere in between. This will most likely prevent too aggressive final plans and river operation will probably be not as active as what is presented in this thesis.

Another issue that decreases the possible over-dynamic plans of the model is the practice of recreating the mid-term plans every week. Generally the most distant forecasts have the most inaccuracy. By planning the whole system every week and creating the suggestions on how to operate the river with new forecasts, the results stay on a satisfying level and are possible to achieve in the short-term time-period. Basically this process of planning the whole system with fresh data eliminates the biggest miscalculations in the mid-term plans and makes the plans slightly "softer" and hence easier for the operator.

8 CONCLUSIONS

This thesis, together with the mid-term hydro planning tool which was created simultaneously with the thesis, presents a new and a more optimal method for modeling the presented co-owned hydro system. The tool gives the Production Company's mid-term planners an instrument which they can utilize in simulating the said system and hence confirm that the system operator itself is doing an adequate job in hydropower generation scheduling. This is vital because optimal planning of hydro assets is extremely beneficial economically for all the parties involved. It is also good for the environment as, for example, excess flooding can be minimized with good mid-term planning of hydro systems.

The challenges in creating the model were mostly involving the fact that we are not able to operate the system and therefore our plan is just one of the many the system operator takes into account when scheduling the hydropower generation. Another challenge was to model the hydro system as the hydropower plants are owned unequally and to be realistic; every party involved in the hydro system should be satisfied. In this case every co-owner had to be satisfied with the plan and the river must be modeled so that actual river operation is possible without breaking the Governance Rule and the law. Hence, the final model optimizes the river as a whole and does not concentrate on any single reservoir or hydropower plant. Besides making acceptable plans for all parties involved in the system and being realistic for the operator, optimizing the whole river with all the reservoirs and hydropower plants creates accurate plans that model the river's dynamics better. Without all the reservoirs and hydropower plants the results from the model could even be technically unrealistic as the river is operated as a whole. This model does not, as a result, create plans that are financially most beneficial to the Production Company but optimizes the river as a whole instead.

The model's results were extremely promising and it successfully satisfies all the constraints in the optimization. The tool also models the river system well and proves that linear programming is adequate for this kind of optimization. The river system had been previously planned rather conservatively and the assets were not used to their full potential. The new model is more dynamic in the utilization of the reservoirs and creates more value from the system to the co-owners. Depending on the year, comparing the model's results to the actual historical operation, it is clear that a new, more dynamic, way of operation would create more value from the system. If that added value could be achieved in the real world operations that would be a significant amount of money. The requirement for the increased active utilization is to have good quality price and inflow forecasts and understand the challenges in operating a river.

Furthermore, the planning tool's results show that it models the system soundly, it is able to calculate the energy production from the discharges proficiently and it allocates energy production to the most expensive days according to the inflows and reservoir surface levels without breaking the environmental permits or the Governance Rule. The resulting surface level plans that are directed to the actual operator are satisfactory and create more value from the system to the co-owners. Consequently, the tool accomplished the objectives set for it and after minor esthetic modifications it can be included in the actual planning process.

In the future the planning tool can be improved in several different ways. By including weighed plans so that our own plans would be emphasized more could increase our significance in the hydro system. In addition, certain winter restrictions, such as prohibiting reservoir surface levels from rising after the surface of the reservoir freezes, could be added so that the results would be even more realistic. Also, the water in the reservoirs could be valued in a new manner. Some of the improvements can be done immediately but some require changes in the Governance Rule or additional research to acquire necessary information in order to further develop the created tool.

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