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Validation of Models for Analysis of the Flexibility of the Swedish Power System

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Validation of Models for Analysis of the Flexibility of the Swedish Power System

Master thesis project

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Abstract

The Swedish parliament has passed a planning framework to increase wind power production and have the annual production of 30 TWh wind power in 2020. The expansion of a continuously varying generation would result in an increased need for the capability of power system to keep the balance between generation and consumption. Therefore, it is important to study the flexibility of Swedish power system.

Two models of Swedish power system are studied in this thesis work. The first model is a model of Swedish hydro power system which has been developed at KTH. The KTH model is formulated as a large linear optimization problem simulated in GAMS platform. It has a detailed representation of large hydro power plants but presents a simple model of electricity market and trading to other areas. The other model is Apollo which is developed by Sweco Company. Apollo is also formulated as an optimization problem and is a market model which uses a simplified model of hydro power system.

The objective of this thesis work is to exchange data between the two models in order to compare, validate and if possible improve the models. To exchange data, the inputs and some outputs of Apollo are used as the inputs of KTH model and finally the outputs of KTH model is compared with the corresponding outputs of Apollo.

There are some differences between the two models that must be removed in order to exchange data. All of differences except one of them are removed by data adjustment. The different methods that are used to remove those differences are discussed in the report. Due to the remaining difference and different efficiencies in the two models, scenarios cannot be directly transformed from Apollo to the KTH model. Therefore, three methods are introduced as compensation for the remaining differences. After applying those methods the same results can be obtained in the two models.

As a result of the work on the data exchange some improvements are implemented in the KTH model and some improvements are identified and proposed for future work. The improvements are toward removing all the differences between the two models and make the models more similar to the real Swedish hydro power system. It is also concluded from the results that the Apollo hydro power schedules are feasible according to KTH model of hydro power system. This shows that Apollo does not overestimate the flexibility of Swedish hydro power system in the tested scenarios.

Sammanfattning

Riksdagen har beslutat om ett planeringsmål för ökad vindkraftproduktion upp till 30 TWh vindkraft år 2020. En utbygnnad av kontinuerligt varierande produktion skulle medföra ett ökat behov för elsystemets förmåga att balansera produktion och konsumtion. Därför är det viktigt att studera flexibiliteten i det svenska elsystemet.

Två modeller av det svenska elsystemet studeras i detta examensarbete. Den första modellen, som är utvecklad på KTH, är en modell av det svenska vattenkraftsystemet. KTH-modellen är formulerad som ett stort linjärt optimeringsproblem som simuleras i GAMS-plattformen. Modellen har en detaljerad representation av större vattenkraftverk, medan modellen av elmarknaden och handeln med andra områden är mycket förenklad. Den andra modellen heter Apollo och är utvecklad av konsultföretaget Sweco. Apollo är också formulerad som ett optimeringsproblem, och är en marknadsmodell som använder en förenklad modell av vattenkraftsystemet.

Målsättningen med detta arbete är att utbyta data mellan de två modellerna för att jämföra, validera och om möjligt förbättra de två modellerna. För att utbyta data används indata och vissa utdata från Apollo som indata till KTH-modellen och slutligen jämförs utdata från KTH-modellen med motsvarande utdata från Apollo.

Det finns en del skillnader mellan de två modellerna som måste hanteras för att datautbytet ska vara möjligt. Alla skillnader utom en hanteras genom att modifiera data. De olika metoder som används för att hantera dessa skillnader diskuteras i rapporten. På grund av den återstående skillnaden och olika verkningsgrader i de två modellerna så kan inte scenarier överföras direkt från Apollo till KTH-modellen. Därför föreslås tre metoder för att kompensera de återstående skillnaderna. Med hjälp av dessa metoder kan samma resultat erhållas från de två modellerna.

Till följd av arbetet med datautbytet har några förbättringar av KTH-modellen implementerats och ytterligare förbättringar har identifierats och föreslagits som framtida arbete. Dessa förbättringar syftar till att ta bort skillnaderna mellan de två modellerna och att göra de modellerna mer lika det verkliga svenska vattenkraftsystemet. En slutsats från projektet är också att de produktionsplaner för vattenkraften som erhålls från Apollo är genomförbara enligt KTH:s modell av vattenkraften. Detta visar att Apollo i de testade scenarierna inte överskattar flexibiliteten i det svenska vattenkraftsystemet.

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Nomenclature

Sets

i	Hydro power plants
j	Segment
d	Day (24 h)
t	Time (h)
z	Price area
l	Snitt
k	Transmission line
D_i	Set of indices for power plants downstream of reservoir i
U_i	Set of indices for power plants upstream of reservoir i

Variables

$H_{i,t}$	Electricity production of power plant i during hour t (MWh)
$M_{i,t}$	Content of reservoir i at the end of hour t (HE)
$Q_{i,j,t}$	Discharge in power plant i during hour t (HE)
$S_{i,t}$	Spillage past power plant i during hour t (HE)
$Htot_{z,t}$	Electricity production of all hydro power plants in price area z hour t (MWh)
$Snitt_{l,t}$	Transmission through snitt l during hour t (MWh)
$nor_{k,t}$	Transmission to Norway through line k during hour t (MWh)
$fin_{k,t}$	Transmission to Finland through line k during hour t (MWh)
$dan_{k,t}$	Transmission to Denmark through line k during hour t (MWh)
tys_t	Transmission to Germany during hour t (MWh)
pol_t	Transmission to Poland during hour t (MWh)
$DP_{l,t}$	Introducing penalty for internal transmission from north to south (MWh)
$DN_{l,t}$	Introducing penalty for internal transmission from south to north (MWh)
$n_{k,t}$	Introducing penalty for import to Norway (MWh)
$f_{k,t}$	Introducing penalty for import to Finland (MWh)
$d_{k,t}$	Introducing penalty for import to Denmark (MWh)
t_t	Introducing penalty for import to Germany (MWh)
p_t	Introducing penalty for import to Poland (MWh)

Parameters

$\overline{H}_i$	Installed capacity of power plant i (MW)
$\mu_{i,j}$	Marginal production equivalent for power plant i segment j (MWh/HE)
$M_{start,i}$	Content of reservoir i in the beginning of period (HE)
$M_{slut,i}$	Content of reservoir i at the end of period (HE)
$\overline{M}_i$	Maximal content of reservoir i (HE)
$\underline{Q}_{i,t}$	Minimum discharge in power plant i during hour t (HE)
$\overline{Q}_i$	Maximum total discharge in power plant i (HE)
$\overline{Q}_{i,j}$	Maximum discharge in power plant i segment j (HE)
$\underline{S}_i$	Minimum spillage from power plant i (HE)
$Qned_i$	Index of the closest power plant downstream of power plant i for discharge
$Sned_i$	Index of the closest power plant downstream of power plant i for Spillage
Rqh_i	Flow time from power plant i to the closest downstream power plant in whole hours (discharged water)
Rqm_i	Flow time from power plant i to the closest downstream power plant in remaining minutes (discharged water)
Rsh_i	Flow time from power plant i to the closest downstream power plant in whole hours (spilled water)
Rsm_i	Flow time from power plant i to the closest downstream power plant in remaining minutes (spilled water)
V_i	Local inflow power plant i (m3/s)
$Vstart_{i,t}$	Water in the way between two power plants when the week begins in whole hours (m3/s)
$V2start_{i,t}$	Water in the way between two power plants when the week begins in a time less than one hour (m3/s)
w_i	Average annual flow of power plant i (HE)
V_{sf}	Scale factor for average annual flow during a week
$wind_{z,t}$	Wind power production area z hour t (MWh)
$other_{z,t}$	Other production (Thermal power plants production) area z hour t (MWh)
$load_{z,t}$	Load in area z hour t (MWh)
$snittmax_l$	Maximum capacity of transmission toward south through snitt l (MWh)
$snittmin_l$	Maximum capacity of transmission toward north through snitt l (MWh)
$normin_{k,t}$	Maximum export to Norway through line k during hour t (MWh)
$normax_{k,t}$	Maximum import from Norway through line k during hour t (MWh)
$finmin_{k,t}$	Maximum export to Finland through line k during hour t (MWh)
$finmax_{k,t}$	Maximum import from Finland through line k during hour t (MWh)
$danmin_{k,t}$	Maximum export to Denmark through line k during hour t (MWh)
$danmax_{k,t}$	Maximum import from Denmark through line k during hour t (MWh)

$tysmin_t$ Maximum export to Germany during hour t (MWh)

$tysmax_t$ Maximum import from Germany during hour t (MWh)

$polmin_t$ Maximum export to Poland during hour t (MWh)

$polmax_t$ Maximum import from Poland during hour t (MWh)

1. Introduction

1.1 Background

Hydro power is the most important renewable energy source in Sweden and makes a significant part of Sweden's electricity production. In year 2013, 40 percent of total electricity production was provided by hydro power. The other source of renewable energy which is planned to be expanded is wind power. In 2013, about 6,6 percent of total electricity production was supplied by wind power in Sweden [1].

The renewable energy target which is decided by European Union obliged Sweden to have at least 49 percent of its energy consumption provided from renewable energies. The Swedish parliament has increased this amount to 50 percent and passed a planning framework to have 30 TWh wind power per year in 2020 from which 20 TWh is onshore and 10 TWh is offshore [2].

Wind power generation is a continuously varying generation which leads to uncertainty in generation. With the expansion of wind power generation, it is important to increase the flexibility of Swedish power system since the capability of power system to keep the balance between generation and consumption must be increased. In Sweden, hydro power is used as the balancing power because it is able to quickly change the generation when demand is changed.

There are many models that are developed for studying the flexibility of Swedish power system. In this work, two models will be used to analyze the flexibility of Swedish power system. The first model is KTH model which is developed by KTH Electric Power Systems Lab. KTH model is a model of hydropower system in Sweden with detailed representation of large hydro power plants in Sweden and simplified model of demand, other generations, electricity market and trading. The other model is Apollo which is developed by Sweco Company. Apollo is a market model with seasonal planning of hydro power. Apollo has an advanced representation of neighboring areas but its hydro power model uses one aggregated reservoir per price area.

1.2 Objectives and Problem definition

The main objective of this study is to exchange data between Apollo and KTH model. Since two models are discussed in this work, the objectives of data exchange can be divided to two groups. The first group includes the objectives from the perspective of KTH model. The objectives of data exchange from the perspective of KTH model are to run the model on interesting scenarios, identify possible improvements and implement some improvements. The second group of objectives includes the goals of Sweco Company. The objectives of data exchange from the perspective of Sweco are to test the validity of Apollo by investigation of KTH model results and upgrade Apollo.

In order to exchange data, the inputs and some outputs of Apollo must be used as inputs for KTH model. After running KTH model with new inputs, the output of KTH model must be compared to the corresponding output of Apollo. It is expected to get the same outputs in the two models, if all inputs of KTH are exactly the same as Apollo data.

The problem that we encounter in exchanging data is that there are some differences between the two models or between the forms of presenting data in two models. Therefore those differences should be removed to be able to exchange data and use the inputs for KTH that are exactly the same as Apollo data.

Some of the mentioned differences can be removed in different ways; those differences are called “removable differences”. Some examples are updating data, changing the code or changing the unit of KTH data. The different methods that are used for removing those differences will be described in the report. Some differences cannot be removed that are called “remaining differences”. Due to the remaining differences and different efficiencies in the two models, scenarios cannot be directly transformed from Apollo to the KTH model. Therefore three methods will be introduced to compensate for the remaining differences. By using those methods, we can obtain the results and compare the output of the models.

1.3 Report overview

Chapter 2 gives a background about electricity production in Sweden. Chapter 3 introduces KTH model and Apollo. In Chapter 4, the reader can find the updated data of hydro power plants in Sweden. Chapter 5 covers methods that are used to exchange data. Chapter 6 discusses simulation results and Chapter 7 is the conclusions of this thesis work as well as possible improvements that can be implemented in the future.

2. Background

2.1 Electricity production in Sweden

Sweden is part of the Nordic power system. Other countries which are part of Nordic power system are Norway, Finland and Denmark. There are transmission lines between those countries and the generation and consumption of electricity in each country affect the whole Nordic system. Therefore the increasing of wind power production in Sweden will also affect the electricity production in other Nordic countries. In this master thesis, the flexibility of Swedish power system is studied, so in this chapter a background of the Swedish power system will be introduced.

Hydro power and nuclear power make a significant part of electricity production in Sweden. Generally hydro is the source with the most contribution in electricity production in Sweden and it acts as the regulating power in Swedish power system. However in 2013 the share of nuclear power was more than hydro power in electricity production while the total electricity production in 2013 was smaller than total electricity production in 2012.

In year 2013, the total electricity production in Sweden was about 149.2 TWh from which 60.8 TWh was provided by hydro power that is 40 percent of total electricity production in year 2013 [1]. The amount of hydro power production depends on the measure of rain and snow in a year. It means that in a dry year with low rainfall the hydro power production is less than the hydro power production in a wet year with heavy rainfall.

Nuclear power accounted for over 63.6 TWh energy in 2013 which is about 43 percent of electricity production in 2013.The other sources of energy which are used for producing electricity in Sweden are wind power and thermal power . The amount of wind power and thermal power production in 2013 was 9.9 TWh and 14.9 TWh respectively [1].

The following charts show the electricity production per source in years 2012 and 2013. Total production was 162 TWh and 149,2 TWh in years 2012 and 2013 respectively.

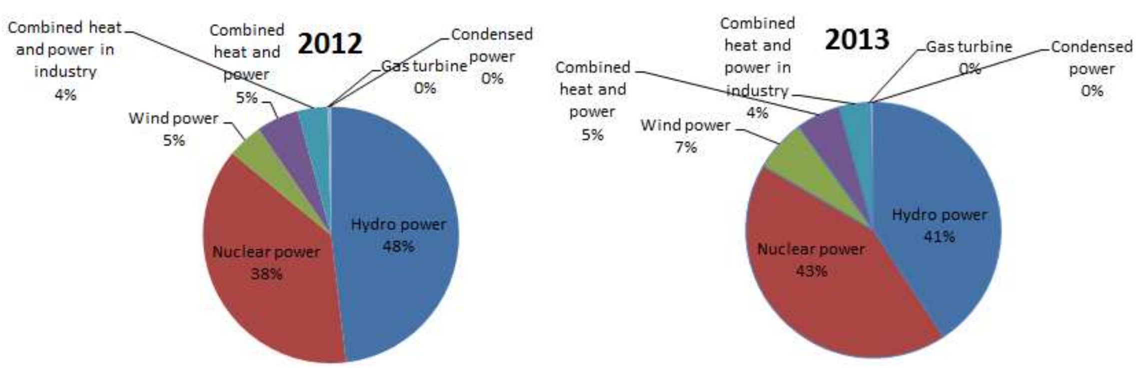

Figure 2.1 Electricity production in Sweden per Source

The following table contains the electricity production per source together with import and export in 2012 and 2013 [1].

Table 2.1 Electricity production, net export and supply in Sweden

Power (TWh)	2012	2013
Total production	162	149.2
Hydropower	78	60.8
Nuclear power	61.4	63.6
Wind power	7.2	9.9
Thermal power	15.5	14.9
Import	11.7	12.7
Export	31.3	22.7
Supply	173.7	161.8

2.1.1 Hydropower

Hydro power has been used for electricity production in Sweden for more than 100 years and is still the most important source for renewable energy in Sweden. The operation of hydro power plants causes no emission of carbon dioxide and water goes back to the river after it leaves the turbine. Hydro power accounts for about 45 percent of Swedish electricity production. Most of Swedish rivers have hydro power plants.

There are more than 1800 hydro power plants in Sweden. Most of them are small power plants with the installed capacity of tens or hundreds of kilowatts. More than 200 hydro power plants are larger power plants with the installed capacity of more than 10 MW while about 50 of them have the installed capacity of more than 100 MW [3].

The good property of hydro power is that it is able to rapidly regulate the production when the demand changes. The electricity cannot be saved so whatever that is produced should be used directly after production, but it is easy to store water in reservoirs and use it later for electricity production. It is possible to regulate the flow of water into turbines and change the production based on the demand [4]. Therefore hydro power is used as the regulating power in Sweden. It can be decreased when the production from other sources like wind is higher, and can be increased when the other productions are not enough to supply the demand.

Reservoirs

Electricity cannot be stored; instead the water that is used for electricity production can be stored in large reservoirs. The large amount of water which is the consequence of snow melting in spring and summer rains is stored in large reservoirs. The reservoirs are drained during times of the year when water inflow is low and electricity demand is high [4]. For example in winter a considerable amount of the water which is stored in reservoirs is used to produce electricity.

How do hydro power plants work?

The sun's heat evaporates water, causes the water in sea and oceans to evaporate and the evaporated water form clouds. The clouds provide snow and rain which will join rivers after arriving to the ground. The water which is in form of rivers and streams flowing back to sea and oceans can be stored in reservoirs and used in hydro power plants [5].

Hydro power plants use the potential energy of water between two levels. With a greater difference between two levels (head), more energy is achieved from water. The water that is flowing from a higher level to the lower level passes through a turbine and causes the turbine blades to rotate. The turbine drives a generator which produces electricity. After water passes the turbine it will go back to sea or oceans but it may pass some other hydro power plants in its way. The water will evaporate again after returning to sea and the stated process will be continued [3].

Environmental impact

The expansion of hydro power plants and dams is an environmental intervention which can change the life condition in that area. The changing of natural water flow can damage some plant and animal species and benefit some others. Large variations in water level harm the beach vegetation. Converting flowing water to still water has bad effect on fishing [6].

The destruction of nature values has negative effect on tourism but on the other hand better roads and services are good aspects.

Agriculture and forestry will be affected by constructing dams as the soil may change thus the conditions of farming on the land will change. In densely populated areas, the construction of large dams causes severe problems because many people have to move from the area [6].

Future hydro power plants

The possibility to build new hydro power plants in Sweden is low. The level of electricity production from hydro power plants will be remained unchanged. The future extra need of electricity is expected to be provided by other energy sources so the share of hydro power plants in producing electricity will reduce even if the amount of production does not change [7].

2.1.2 Wind power

Wind power is a renewable energy source that is an important source to help decrease carbon dioxide emissions. The electricity produced from wind power was about 9,9 TWh in year 2013. At the end of year 2013 there were 2663 wind power plants in Sweden with the total capacity of 4382 MW [8].

Wind energy cannot be stored and it is not possible to easily forecast how much wind will blow, so variations of wind power should be balanced by a regulating power. Since there is a large amount of hydro power in Sweden, hydro power is mostly used as the regulating power.

It is important to build wind power plants in places where wind blows a lot. The conditions for wind power are good in Sweden. Sweden is a wind-rich country, especially on the coast. The best windy locations are Gotland and Öland on the west coast and Skåne's coast. In Sweden it is more windy in winter than summer and this is good as the demand is higher in winter [9].

How do wind power plants work?

The wind power plants are operated by sun. The sun's rays provide different temperatures in different places of world. Temperature difference cause different air pressures and this leads to air motion which is the wind. A wind power plant converts the wind's movement to electricity. The wind power is transferred via a shaft and a gearbox to a generator and the generator converts kinetic energy of the wind to electricity [10].

Wind power expansion

EU has imposed Sweden to have at least 49 percent of its energy consumption be produced from renewable energies. The government has increased this to 50 .To reach that goal the Swedish parliament passed a planning framework of 30 TWh wind energy per year in 2020. The planning frame is to produce 20 TWh offshore wind power and 10 TWh onshore wind power in 2020. The planning framework does not mean that this goal will definitely be achieved but the future planning for wind power production should be based on those amounts of wind power.

A modern 2 MW onshore wind turbine produces 6 GWh energy per year, which is enough to provide electricity for about 1200 households each of 5 MWh per year. Therefore more than 1000 wind power plants should be built in Sweden to achieve the planning goal by year 2020 [8].

The wind power plants that currently work in Sweden are mostly onshore power plants. Onshore wind power plants have been built on land while offshore wind power plants are built at sea. Better wind speed is available at sea compared to land but it is more expensive to build and maintain offshore wind power plants. The cost of building offshore wind power plants is about twice as high as building onshore wind power plants which is about 20 - 30 million Swedish kronor per megawatt. A big part of the cost is for connecting to the network. On the other hand the annual production of offshore power plants is much higher; it is about 3300 to 4300 MWh per MW of installed capacity [8]. The power plant "Lillgrund" which is located in

“Öresund” was the third largest offshore power plant in the world when it was built in 2007 with the electricity generation of 0.33 TWh per year [9].

Cost of investment, operation and maintenance

The expansion of wind power in recent years has made the costs to be decreased significantly. The costs are expected to decrease more with further developments. Installation of a wind power plant and preparing it to deliver power to the grid costs about 10 to 13 million kronor per MW. A few years ago it cost 15-17 million kronor per MW. The costs are based on the type of turbine, the distance to grid connection and other infrastructures. Another important parameter is the exchange rate of currency to Euro.

2.1.3 Nuclear power

Nuclear power is an efficient technology for electricity generation. The cost of electricity production is low and the emissions of carbon dioxide are also low. In a nuclear power plant the electricity is produced by splitting the atomic nuclei of uranium. The splitting of atoms generates heat and the heat is used to generate steam. The steam drives a turbine and the turbine drives the generator to produce electricity.

Sweden started using nuclear energy to produce electricity from 1972. Today there are three reactors in “Forsmark”, three reactors at “Oskarshamn” and four reactors in “Ringhals”. Two reactors were closed in “Barsebäck”. Nuclear power accounts for about 40 percent of electricity production in Sweden [11].

The using of nuclear power has some disadvantages. Since nuclear accidents are very dangerous like the disaster that happened in Fukushima, the security management in nuclear power is very important. Safety should always be the first issue in nuclear power plants to protect people from danger. The shipment of nuclear fuel involves risks. The uranium mining and waste from nuclear power plants are dangerous for the environment. The waste from nuclear power plant must be stored for thousands of years to prevent harming humans, animals and nature. SKB is the Swedish nuclear fuel and waste company which is responsible to take care of radioactive waste from nuclear power plants [11].

2.1.4 Combined heat and power

Combined heat and power means that the fuel is used to produce heat and power at the same time, so it is very energy efficient. In CHP power plants only 10 percent of energy will be lost in the flue gas. The environmental impact of CHP is low and the security is high. In year 2013 about 10 percent of electricity production was supplied from combined heat and power.

In combined heat and power plants that are using biomass as the fuel, 30 percent of the fuel is converted to electricity and the rest is converted to heat, while losses are 10 percent. There are also natural gas fired CHP power plants that have the same loss but they produce the same amount of heat and electricity. The examples of such power plants are “Ryaverket” in Göteborg and “Öresundsverket” in Malmö [12].

2.1.5 Condensing power

The condensing power plants give the greatest electricity production relative to the used fuel. Condensing power only produce electricity and no heat is produced. 30-60 % of the used fuel is converted to electricity and the rest is released in flue gas and losses of cooling water.

The Condensing power plants in Sweden are fired by oil and it is expensive to use them for electricity production. Therefore they are used as the backup power when the nuclear and hydro power production is not enough due to failure of some power plants or higher demand [13].

3. Models

3.1 KTH Model

The KTH model refers to a model developed in 2012 and presented in a master thesis report [14]. The model is a promotion of the model described in Elforsk report 09:88 which is the extension of the model used in system planning book [15],[16].

The model is formulated as a large linear optimization problem which is written in GAMS. GAMS is a language which is used to solve advanced optimization problems [17].

The model simulates the whole Sweden's hydropower system under the assumptions of perfect information and perfect competition. 255 hydro power plants with their reservoirs and two reservoirs without power plants are installed in this model. Totally 257 reservoirs are considered in the model. The model is simplified in the way that only power plants with the capacity of more than 5 MW are included in the model; otherwise there should be about 1800 power plants in the model. If enough information is available, the small power plants can also be included to have more precise model. With this simplification, the total installed capacity which is considered to be installed in the existing model of KTH is 15640MW while the total capacity of hydro power in Sweden is about 16200. It means that only 96.5% of the installed capacity of hydro power in Sweden is considered in the model.

3.1.1 Model structure

The objective function is to maximize hydropower production. There are also some punishments considered to minimize import from neighboring counties and internal trading, wind spillage is also minimized. The ability of hydro power to satisfy a given load while power productions from other sources are also given is treated in the model. An important condition is that there must be a certain target level for reservoirs at the end of each week. Moreover there are constraints on produced electricity and hydrological balance for each power plant. If there is not enough electricity produced in an hour, the electricity must be imported. On the other hand if there are surplus of electricity production the electricity must be exported and if there is not enough transmission capacity in the lines, the water will be spilled. There is some water spillage that is planned to exist in the model but extra water spillage is not desired. To spill water is the same as losing money, so an alternative objective function in KTH model is to minimize the spillage.

Objective function:

Maximize: Hydro power production for one week – penalty* import from other countries - penalty*trading between bidding areas - wind spillage

Hydrological balance for each power plant:

Reservoir content at the end of hour t= Reservoir content in the previous hour - discharged water – spilled water + discharged water from previous power plants which flows at hour t + spilled water from previous power plants which flows at hour t+ local inflow

Load balance

Load balance in area z = hydro power production in area z + wind power production in area z + other production in area z + import from other areas- export to other areas

Target level of reservoirs

There are some Requirements for all reservoirs content at the end of the week.

Discharge rules

There are some conditions that affect the discharge in power plant, for example the minimum and maximum discharge is different in different days and for different times of the year.

Inputs

- Wind power production
- Other generation
- Demand
- Transmission capacity of internal and external lines
- Start and end level of reservoirs
- Local inflow

Outputs

- Hydro power production
- Hourly trading in internal and external lines
- Water spillage
- Discharged water

On November 1st, 2011 Sweden was divided to four electricity bidding areas. The model treats each price area separately which means that there will be four different load balances in this model.

Figure 3.2 shows the map of Sweden and its neighboring countries. The map shows all Nordic bidding areas, the transmission lines to other neighboring countries and between bidding areas as well as the capacity of each transmission line [18].

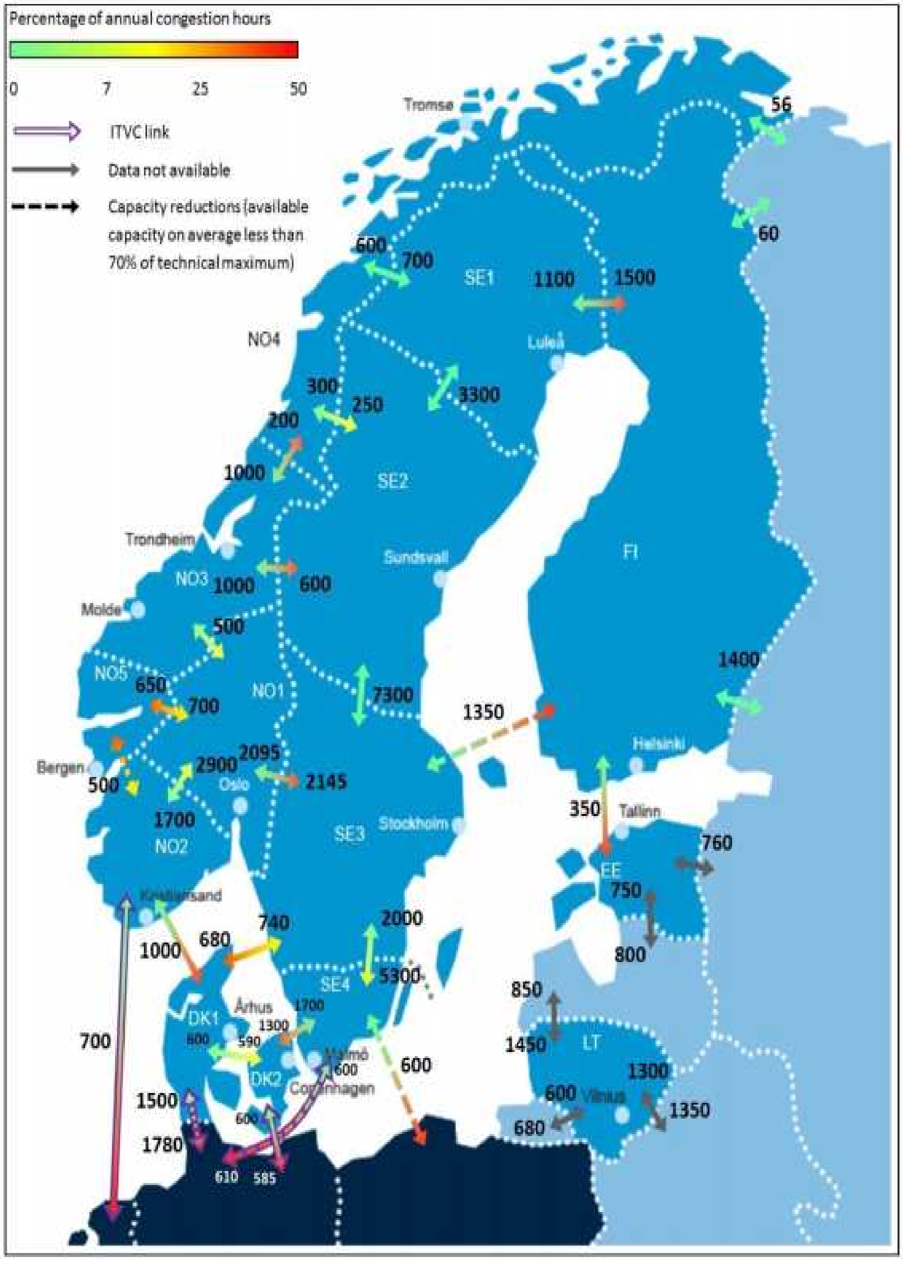

Figure 3.1 Sweden bidding areas and transmission line's capacities in 2012

The model considers the transmission constraints between those four bidding areas and also on transmission lines between Sweden to other countries. The countries that are connected to Sweden through transmission lines are Norway, Denmark, Finland, Germany and Poland.

Tables 3.1 and 3.2 present the transmission lines to other countries and transmission lines between four price areas.

Table 3.1 Transmission lines to neighboring countries

External transmission lines	Line name
SE1→ NO4	Nor1
SE1→ Finland	Fin1
SE2→ NO3	Nor2
SE2→ NO4	Nor3
SE3→ NO1	Nor4
SE3→ DK1	Dan1
SE3→ Finland	Fin2
SE4→ DK2	Dan2
SE4 → Germany	Tys1
SE4 → Poland	Pol1

Table 3.2 Transmission lines between bidding areas inside Sweden

Internal transmission lines	Line name
SE1 → SE2	Snitt 1
SE2 → SE3	Snitt 2
SE3 → SE4	Snitt 4

3.1.2 Equations

In this section the equations which are used in KTH model for objective function and for constraints are presented.

Objective function

$$Max \sum_t Scalefactor1 * Htot_{1,t} + Scalefactor2 * Htot_{2,t} + Scalefactor3 * Htot_{3,t} + Scalefactor4 * Htot_{4,t} \quad (3.1)$$

$$-Penalty * \sum_{k,t} d_{k,t} + n_{k,t} + f_{k,t} + p_t + t_t \tag{3.2}$$

$$-\ penalty * \sum_{l,t} DP_{l,t} + DN_{l,t} \tag{3.3}$$

$$-\sum_{t} Vs_{1,t} + Vs_{2,t} + Vs_{3,t} \tag{3.4}$$

The objective function is to maximize the hydro power production in one week. A penalty is also considered to minimize the import from other countries. The penalty is 1 multiplied by the amount of import which means that the objective function will be decreased for each MWh of import. Another penalty is also used for transmission inside Sweden to prevent the unnecessary internal trading. This penalty is 0,001 multiplied by the amount of internal trading and is much lower than the penalty for import. The last part of objective function is to minimize wind spillage. The penalties that are used for import from other countries and internal trading can change in different situations.

The index *z* stands for bidding area and *t* stands for hour. Since all the power plants in Sweden are not included in the model, a scale factor is scaling up the production to compensate for that amount of production which is not considered in the model. The scale factor was introduced in Obel's report [14] but it was not described there that how these scale factors are calculated. The maximizing of hydro production implies that the model avoids the water spillage if it is possible. The start and end level of the water reservoir gives the energy which is produced from hydro power in a week. The objective function tries to spread the hydro power production such that the water spillage will be as small as possible. In the hours that wind power production is high and the transmission capacity to export the power is not enough, the hydro power production will be decreased by discharging less water. The procedure will be reversed when the wind power production is low.

As it was explained in section 3.1.1 the objective function is to maximize hydro power production. There are also some penalties on import to other countries and internal trading between bidding areas. To include those penalties in objective function some variables are used which are introduced below:

$DP_{l,t}$ and $DN_{l,t}$ are variables that are used to include penalty for internal transmission.

$$DP_{l,t} \geq snitt_{l,t} \tag{3.5}$$

$$DN_{l,t} \geq -snitt_{l,t} \tag{3.6}$$

$d_{k,t}, n_{k,t}, f_{k,t}, p_t$ and t_t are variables that are used to enable including penalty for import.

$$d_{k,t} \geq dan_{k,t} \tag{3.7}$$

$$n_{k,t} \geq nor_{k,t} \tag{3.8}$$

$$f_{k,t} \geq fin_{k,t} \tag{3.9}$$

$$p_t \geq pol_t \tag{3.10}$$

$$t_t \geq tys_t \tag{3.11}$$

The maximizing of hydro power production implies a minimization of spillage. Avoiding water spillage is very important for a hydro power producer who aims to maximize the profit. To spill water is the same as to spill money so there is also an alternative objective function which is to minimize the water spillage.

$$Min \sum_{i,t} S_{i,t} * \mu_{i,t} \tag{3.12}$$

Hydrological balance

The hydrological balance states that the content of the reservoir of a power plant in a specific hour should be equal to the content of that reservoir during the last hour minus the discharged and spilled water from the reservoir in this hour plus the water flow from upstream. The water flow from upstream can be the discharged and spilled water that flows from upstream power plants as well as local inflow. Many rivers have several branches which mean that there can be several power plants located upstream so their discharge and spillage must be added.

$$M_{i,t} = M_{i,t-1} + (M_{start}\ if\ t = 1) - \sum_j Q_{i,j,t} - S_{i,t} \tag{3.13}$$

$$+ \sum_{i' \in U_i} Qrinn_{i',t}$$

$$+ \sum_{i' \in U_i} Srinn_{i',t}$$

$$+V_i + Vstart_{i,t} + V2start_{i,t}$$

$Qrinn$ is the amount of discharged water from the upstream power plant which goes to the downstream power plant where $Srinn$ is the amount of spilled water that flows from the upstream power plant to the downstream power plant. $Qned$ and $Sned$ present indices for the power plants downstream.

M_{start} is the content of the reservoir when the week begins in the beginning of hour 1. $Vstart$ and $V2start$ are the amounts of water which flow during the hours before the week starts and reach the power plant. Since the model has a time step of one hour, $V2start$ is the water which flows during a time less than one hour while $Vstart$ is for the whole hour.

$$Qrinn_{i,t} = \frac{Rqm_i}{60}\sum_j Q_{i,j,t-(Rqh_i+1)} + \frac{60 - Rqm_i}{60}\sum_j Q_{i,j,t-Rqh_i} \qquad (3.14)$$

$Qrinn_{i,t}$ is the amount of discharge water which flows from power plant i and reaches downstream power plant during hour t. Rqh_i is the flow time of discharge water from power plant i to the closest downstream power plant in the whole hour. Rqm_i is the same as Rqh_i but it is for the time that is less than one hour.

$$Srinn_{i,t} = \frac{Rsm_i}{60} * S_{i,t-(Rqh_i+1)} + \frac{60 - Rsm_i}{60} * S_{i,t-Rqh_i} \qquad (3.15)$$

$Srinn_{i,t}$ is the amount of spilled water from power plant i that reaches downstream power plant during hour t. Rsh_i is the flow time of spilled water from power plant i to the closest downstream power plant in the whole hour. Rsm_i is the same as Rsh_i but it is for the time that is less than one hour.

$$M_{i,168} = M_{slut,i} \qquad (3.16)$$

A certain target level for reservoirs should be obtained at the end of each week that is the end of hour 168 of a week. To simplify the model, the same target level is considered for all reservoirs except Vänern and Vättern. The actual data is used for Vänern and Vättern due to their size and location in southern Sweden. In week 27 the target level that is used for Letten is also different from the target level which is used for all power plants.

$$ws_i = V_{sf} * w_i \qquad (3.17)$$

In equation 3.17, w_i is the average annual water flow for each reservoir and V_{sf} is the scale factor which is different for different weeks. Scale factor for one week is calculated from dividing the inflow of the week by the annual average inflow. In spring there is a large amount of water goes to reservoirs due to sprig flood so the scale factor is large in the spring. On the other hand the scale factor is small in the winter when there is a little amount of water which goes to reservoirs.

$$V_i = ws_i - \sum_{i' \in U_i} ws_{i'} \qquad (3.18)$$

The local inflow for one week in a power plant is the difference between the average water flow of the power plant and the average water flow of the power plants upstream in that week. The inflow of each power plant is assumed to be equal in all hours of the week.

$$Vstart_{i,t} = \sum_{i' \in U_i \wedge t < Rqh_{i'}} ws_{i'} \tag{3.19}$$

At the beginning of each week it should be considered that there is water that dropped from the power plant upstream during the hours before the week starts. Therefore an extra factor is included in hydrological balance for the water flow before starting the week. For example, if the flow time between two power plants is 5 hours, it is assumed that the released water from the power plant upstream corresponds to the mean annual flow to this power plant during five hours before the week begins. Since the model has a time step of one hour, one equation is considered for the water that is dropped during the times equal to whole hours and a separate equation is used for the water which is released in the time that is less than one hour. Equations 3.19 and 3.20 are the mentioned equations respectively. They are used to include the amount of water which is on the way between two power plants when the week begins.

$$V2start_{i,t} = \sum_{i' \in U_i \wedge t < Rqh_{i'}+1 \wedge Rqm_{i'} < 60} ws_{i'} * \frac{\big(60 - (60 - Rqm)\big)}{60} \tag{3.20}$$

Efficiency

The power that can be taken from a hydro power plant is proportional to the head, gravity, water flow and an efficiency ratio.

*Power = Efficiency ratio * Gravity * Water flow * Head*

In reality the efficiency ratio is different for turbines and generators depending on the production. In this model two different efficiency ratios are considered for two segments. It is a simplification of the model since the efficiency depends on the head of water varying with filling rate. Hydro power plants with high filling rate produce more power than those with lower filling rate. There are many reservoirs in which filling rate have significant effects on the head but it is not considered in this model [21].

In KTH model the efficiency ratio is divided to two segments. First segment is for discharge between 0 and 75% and the second segment is for discharge between 75 % and 100 %.

$$\bar{Q}_{i,1} = 0.75 * \bar{Q}_i \tag{3.21}$$

$$\bar{Q}_{i,2} = \bar{Q}_i - \bar{Q}_{i,1} \tag{3.22}$$

The break point is at 75 % since the hydro power plants usually have their best efficiency around 75% discharge. The efficiency is considered to decrease by 5 % after the break point [16]. The production equivalent for segment 1 and segment 2 are showed by $\mu_{i,1}$ and $\mu_{i,2}$ and can be found from the following equations.

$$\overline{H}_i = \mu_{i,1} * \bar{Q}_{i,1} + \mu_{i,2} * \bar{Q}_{i,2} \tag{3.23}$$

$$\mu_{i,2} = 0.95 * \mu_{i,1} \tag{3.24}$$

$$H_{i,t} = \sum_j \mu_{i,j} * Q_{i,j} \tag{3.25}$$

Equation 3.26 shows the hydro power production in one hour per bidding area.

$$Htot_{z,t} = \sum_i H_{i,t,z} \tag{3.26}$$

Load balance

The load balance implies that demand and supply must be equal in each bidding area and thus the load balance is satisfied all over Sweden. Load in each bidding area is equal to the sum of all power production from different sources plus import from other countries and from other bidding areas minus export to other countries and to other bidding areas. The hourly trading between bidding areas which is from northern to southern Sweden is considered as positive. If the direction of transmission is from south to north it will considered as negative energy in the model. On external lines, the imported electricity is considered positive and exported electricity is considered negative.

$$Load_{1,t} = \sum_i Htot_{1,t} + other_{1,t} + wind_{1,t} - snitt_{1,t} + fin_{1,t} + nor_{1,t} \tag{3.27}$$

$$Load_{2,t} = \sum_i Htot_{2,t} + other_{2,t} + wind_{2,t} - snitt_{2,t} + snitt_{1,t} + nor_{2,t} + nor_{3,t} \tag{3.28}$$

$$Load_{3,t} = \sum_i Htot_{3,t} + other_{3,t} + wind_{3,t} - snitt_{4,t} + snitt_{2,t} + fin_{2,t} + nor_{4,t} + dan_{1,t} \tag{3.29}$$

$$Load_{4,t} = \sum_i Htot_{4,t} + other_{4,t} + wind_{4,t} + snitt_{4,t} + dan_{2,t} + tys_{1,t} + pol_{1,t} \tag{3.30}$$

Variable limits

A limit is considered for the water level in the reservoir. The reservoir level should be between the allowed limits.

$$0 \leq M_{i,t} \leq \overline{M}_i \tag{3.31}$$

Equation 3.32 presents the limit for discharge in each segment of each power plant in each hour. In equation 3.33, another limit for discharge is shown. The sum of discharged water in two segments for each power plant should be higher than the minimum discharge of the power plant in each hour during the simulated week.

$$0 \leq Q_{i,j,t} \leq \bar{Q}_{i,j} \tag{3.32}$$

$$\sum_{j} Q_{i,j,t} \geq \underline{Q}_{i,t} \tag{3.33}$$

For some power plants there are requirements for minimum spillage. A simplification of the model is that there is not any upper limit for spillage.

$$\underline{S}_i \leq S_{i,t} \tag{3.34}$$

There are transmission capacities that are considered in the model for lines between bidding areas. Trading between bidding areas inside Sweden should be in a range between a lower and upper limit. Another solution is to increase production in the areas with a shortage of electricity [14].

$$snittmin_{i,t} \leq snitt_{i,t} \leq snittmax_{i,t} \tag{3.35}$$

There are also some limitations for transmissions to or from neighboring countries.

$$normin_{k,t} \leq nor_{k,t} \leq normax_{k,t} \tag{3.36}$$

Additional discharge rules

For some power plants there are requirements for minimum discharge during a day which is shown in equation 3.37. It means that the amount of discharged water should be more than a specific value during a day. Minimum discharge rules are different between weekdays and holidays. In KTH model, d represent day. For example d=1 corresponds to Monday that is hour 1 to 24.

$$\sum_{j,t} Q_{i,j,t} > daymin \;\; power\ plant\ i \;\; day\ d \quad for\ d = 1\ to\ 7 \qquad (3.37)$$

There is also a requirement for weekly minimum discharge in some power plants. The sum of total discharged water during 168 hours should be greater than the minimum weekly discharge for those power plants.

$$\sum_{j,t} Q_{i,j,t} > weekmin \;\; power\ plant\ i \qquad (3.38)$$

Some power plants have different requirements on minimum discharge for different hours in a day, equation 3.39 present the requirement. For example the average discharge for power plant i should be x m3/s on weekdays between 8:00 to 12:00. The owner of power plants can choose to discharge more water in some hours and less water in some other hours but the requirement for average discharge must be fulfilled [14].

$$\sum_{j,t} Q_{i,j,t} \;\; for\ specific\ hours > minimum\ discharge\ for\ the\ specific\ hours \qquad (3.39)$$

For some reservoirs there are requirements that water level should not change too much during a day. A similar requirement also exists for discharge. Equations 3.40 and 3.41 are used for the mentioned requirements respectively.

$$M_{i,t_2} - M_{i,t_1} \leq Volume\ change\ of\ the\ day\ for\ d = 1\ to\ 7 \qquad (3.40)$$

$$\sum_{j} Q_{i,j,t_2} - \sum_{j} Q_{i,j,t_1} \leq discharge\ change\ of\ a\ day \;\; for\ d = 1\ to\ 7 \qquad (3.41)$$

In two power plants of the model, short time regulation is not allowed. It means that discharged water is the same in all hours and discharge should not be changed during the week.

$$\sum_{j} Q_{i,j,t} = \sum_{j} Q_{i,j,t-1} \qquad (3.42)$$

3.2 Apollo

Apollo is a model developed by Sweco Company to simulate electricity market. Similar to KTH model, Apollo is also formulated as an optimization problem. The model includes seasonal planning of hydro power plants which is divided to long-term planning and short-term planning. The long-term planning is the weekly simulation of hydro power plants and the short-term planning is the hourly simulation of hydro power plants. There is one aggregated reservoir per area in Apollo. The model also presents advanced representation of neighboring areas and variable costs of thermal generation.

The optimization problem in Apollo is formulated as below:

Objective function

- Minimize system cost (or maximize the profit for generators under perfect competition)

Constraints

- Hydrological balance for each reservoir
- Load balance in each bidding area
- Price sensitive demand
- Reservoirs storage bounds at the end of the week
- Ramping constrains for time steps of one hour and four hours for aggregated reservoirs.

The data of inputs and outputs of Apollo that is needed to be used in KTH model is provided in a data file for years 2015 and 2040.

A brief description of different data that is provided in Apollo data file can be found below.

3.2.1 Inputs

Demand

The yearly demand is given per 4 bidding areas. The hourly demand is found by multiplying the yearly demand by a ratio that is given in the model. The ratio for each hour and the hourly demand for one year are given in the Apollo data file.

Wind power production

The data for hourly wind generation is given for onshore wind power plants in SE1 and SE2. In SE3 and SE4 the model gives the data for both onshore and offshore wind power plants. The wind power generation is planned to be increased in the coming years, so the data that is given for wind power production is higher for year 2040.

Wave power production

A time series of data with the time step of one hour is given for wave power production located in area3.

Solar power production

The hourly solar power production is given for four areas in the model.

Inflow

The amount of water inflow is given per week and per area in Apollo data file which is the input of Apollo. The inflow is given in terms of energy.

3.2.2 Outputs

Hydro power production

The model includes seasonal planning of hydro power plants. The weekly hydro power production is given for three bidding areas but the weekly hydro production of area 4 is not given. The hourly hydro production for all areas is also given in Apollo data file.

Reservoirs' content

The model uses just one aggregated reservoir per area, but there is no reservoir considered for SE4. Apollo considers run-of-the-river hydro generation in area4. This means that there are only 3 reservoirs in Apollo model. The reservoir state which is the actual amount of water stored in each reservoir is given per week. For the reservoir's start level in a specific week, the data which is given for that week can be used and for the end level the data which is given for the next week can be used.

Hourly trading

Apollo has an advanced representation of neighboring areas considering 1 percent loss in all transmission lines. The actual values for hourly trading to neighboring countries are given in Apollo data file. There are 11 transmission lines from different price areas in Sweden to other neighboring countries in Apollo. Compared to KTH model, one extra transmission line from Sweden to Lithuania exists in Apollo. The data of hourly trading inside Sweden is also given for three internal lines which are the same lines as KTH model.

Nuclear power production

The hourly nuclear power production is given as one set of data for area 3.

Thermal power production

The hourly data of thermal power generation for different types of thermal power plants is given; there are many types of thermal power plants in the model. The number of the types of thermal power plants varies in different years. In the data for year 2040 there are a fewer number of thermal power plants available in the model. In year 2015 there are 40 series of hourly data given for thermal power generation in all areas, but in year 2040 there are 34 series of hourly data for thermal power generation in Sweden. There are more thermal power plants located in area 3 and 4 than area 1 and 2.

4. Data acquisition

The objective of data acquisition is to update the data of hydro power plants that are used in KTH model. The data of KTH model was achieved from year 2009, so some data of power plants may have been changed since that time. Since KTH model should be compared to Apollo, it is important to use the same data of hydro power plants in the two models. Therefore the data for installed capacity, bidding area, owner and river of hydro power plants that exist in KTH model are updated in this chapter. Another type of data that is collected is the installed capacity and bidding areas of small hydro power plants that are not included in KTH model. The data of those power plants are collected however they are not added to KTH model because for including those in KTH model, other data such as maximum capacity of reservoirs, maximum discharge, delay time between power plants and average annual water flow are also needed. The goal of collecting data of hydro power plants that are not included is that data may be used in future work. If other mentioned data that is needed can be achieved, these acquired data can also be used to add the small power plants to KTH model and have more accurate model.

4.1 Installed capacity

There are 257 reservoirs considered in KTH model out of which 255 reservoirs are those belong to hydro power plants. Two of them are only reservoirs to store water and they do not have power plants, it means that their installed capacity is zero. As it was described in chapter 3, the power plants with installed capacity of less than 5 MW are not considered in KTH model. Therefore total installed capacity of KTH model is lower than the actual total installed capacity of hydro power plants in Sweden and total installed capacity of Apollo. The following table shows the installed capacity of KTH model which was found from data of year 2009, the table also contains the installed capacities from Apollo and Svenska Kraftnät.

Table 4.1 Installed capacities of KTH original model compared to installed capacities of Apollo and SVK

Installed capacity (MW)	KTH (original)	Apollo	Svenska Kraftnät
SE1	5491	5262	5255
SE2	7715	8000	8014
SE3	2184	2709	2593
SE4	250	231	341
Total	15640	16202	16203

It can be seen in the table that the total installed capacity of KTH model is 562 MW lower than Apollo. The installed capacities of area 1 and area 4 are higher while the installed capacities of area 2 and area 3 are less than Apollo. The reason of big difference in area 3 is that there are many small private hydro power plants with installed capacity of less than 5 MW in this area.

On the other hand another reason can be the old data from 2009. Therefore the installed capacities of those 255 hydro power plants which are considered in KTH model are updated.

The data was checked using multiple references. The first source which is used to check installed capacities is the homepage of Leif Kuhlin which provides data of 1505 hydro power plants in Sweden [19]. Another way to find installed capacity of power plants which should be more reliable is to check from the owners' website [20]-[24]. The installed capacities of all 255 hydro power plants except 23 of them were found from owners' website. Some owners like Holmen and Jämtkraft do not provide data of installed capacity in their homepage [25], [26].

Table 4.2 shows some examples of hydro power plants in KTH model with their updated data of installed capacity and owners.

Table 4.2 Examples of power plants with updated installed capacity

Power plant	Owner	Installed capacity original KTH (MW)	Installed capacity Kuhlin (MW)	Installed capacity owners (MW)	Installed capacity updated KTH (MW)
Harsprånget	Vattenfall	1001	977	977	977
Harrsele	Statkraft	203	223	223	223
Stalon	Vattenfall	105	130,2	130	130
Hjälta	E.on	165	178	178	178
Krångede	Fortum	240	248,4	250	250
Norränge	Fortum	44	50	50	50
Vargfors	Vattenfall	131	122,1	120	120
Ligga	Vattenfall	367	326,75	324	324
Gallejaur	Vattenfall	214	219	221	221
Kvistforsen	Statkraft	130	140	140	140

A problem which exists in data acquisition is that data from different sources have some differences, in that case it is important to be able to recognize which source is more reliable. For installed capacity the data from owners' websites should be more reliable so it is used as the updated data. The following table shows the original and updated installed capacities of KTH model per area compared to the installed capacity of Apollo.

Table 4.3 Updated installed capacity of KTH compared to the original data and Apollo

Installed capacity (MW)	KTH (original)	KTH (Updated)	Apollo
SE1	5491	5430	5262
SE2	7715	7874	8000
SE3	2184	2148	2709
SE4	250	253	231
Total	15640	15705	16202

4.2 Bidding area

The bidding area of each hydro power plant of KTH model was checked to ensure that the used data is reliable. For finding bidding areas Leif Kuhlin's website is used again. The other source which was found to check price areas was a list from Svenska Krafnät [27]. This source is the price list of 2014 for the Swedish transmission grid and contains data for some power plants which are not only hydro power plants. The bidding areas of 63 hydro power plants that exist in KTH model were found from the list.

The bidding areas that were found from Kuhlin's homepage are almost the same as KTH original data from 2009 except for 4 hydro power plants. The data from Svenska kraftnät do not provide the bidding areas for all hydro power plants, so among those 4 hydro power plants only one of them is available in that list. That power plant is Vargfors and the price area given by Svenska kraftnät is the same as data from 2009 and different from Kuhlin. Finally the original data which was obtained from year 2009 is used, because one of the differences based on Kuhlin was not correct according to Svenska Kraftnät. Table 4.3 shows those 4 power plants with different bidding area and rivers they are located in.

Table 4.4 Hydro power plants with different bidding area based on Kuhlin

Power plant	River	Price area original KTH (MW)	Price area Kuhlin (MW)	Price area Svenska Kraftnät (MW)	Price area updated KTH (MW)
Vargfors	Skellefteälven	1	2	1	1
Vässinkoski	Oreälven	3	2	-	3
Noppikoski	Oreälven	3	2	-	3
Kvarnholm	Lagan	4	3	-	4

4.3 Hydro power plants which are not included in KTH model

It was mentioned previously that the hydro power plants with the installed capacity of less than 5 MW are not included in KTH model since the data that are needed was not available. There are also a few power plants with installed capacities slightly more than 5 MW that are not considered in KTH model because the data for them was not available as well. The data of hydro power plants which are not included in the model are achieved from Kuhlin's homepage. The data that is found from Kuhlin's homepage include installed capacity and bidding area. As it was explained in the beginning of this chapter some other data are also needed to consider these power plants in KTH model but those data are not available in Kuhlin's homepage. Therefore it is not possible to add these power plants to the model. Table 4.5 shows some examples of these small power plants with their data of installed capacity and bidding area.

Table 4.5 Examples of hydro power plants that are not included in KTH model

Power plant	Area	Installed capacity (MW)
Hednäs	1	2.15
Kvarnforsen	2	4.25
anundsjö	2	5
Brynge	2	5
Sippmikk	2	4
Sundshagsfors	3	5
Tänger	3	4.6
Långed	3	4.97
Älvestorp	3	4.2
Högsby	4	3.5

Table 4.6 contains the total installed capacity and installed capacity per area that are not included in KTH model based on the data from Kuhlin's homepage. There are some power plants with unknown price areas in Kuhlin's homepage.

Table 4.6 Installed capacity that is not included in KTH model based on Kuhlin's data

Area	Installed capacity (MW)
SE1	22,356
SE2	172,789
SE3	442,838
SE4	97,007
Unknown	32,127
Total	767,117

4.4 Conclusions

After updating data, the installed capacity of KTH model was slightly increased and became closer to the installed capacity of Apollo. However there is still a significant difference between total installed capacities of the two models. The difference is due to the small power plants that are not included in KTH model.

By updating data of bidding areas it was found that the bidding areas that were used in original KTH model is almost the same as updated bidding areas. There are only four bidding areas according to Kuhlin's homepage that are different from bidding areas used in original KTH model. However the original KTH bidding areas were used finally because one of those four different areas was checked from Svenska kraftnät and found to be the same as area used in original KTH model.

By collecting the data of power plants that are not included in KTH model it was found that the total installed capacity that is not included in KTH model based on Kuhlin's data is 767 MW. The installed capacity that is not included in KTH model is more significant in area 3 compared to other areas. The reason is that there are many private power plants in area 3 with small installed capacities that are not included in KTH model.

5. Data exchange between Apollo and KTH model

The main goal in this work is to exchange data between KTH model and Apollo. The models were presented in previous sections. The inputs and outputs of Apollo model are presented in the form of an excel file containing all hourly and weekly data of Apollo's inputs and output. The data for Apollo is given for the whole year but in forms of hourly and weekly data which are dedicated to short-term and long-term planning respectively. On the other hand, in KTH model the simulation is done for the period of one week. Some specific weeks are simulated in KTH model since data is available only for those weeks and all weeks of the year are not simulated. The data of hydro power plants in KTH model are based on the actual scenario of year 2009.

5.1 Objectives of data exchange

As it was explained in the introduction section, the objectives of this master thesis or particularly the objectives of data exchange which is the main task in this work can be divided into two parts. As two models are discussed in this report, the specific objectives for each model must be considered. The objectives of data exchange from the perspective of KTH model are to run the model on interesting scenarios, identify improvements and implement some of them if implementation was possible in the time frame of project. The objective of data exchange from the perspective of Sweco Company is to test the validity of Apollo by investigation of the results from KTH model as well as upgrading Apollo.

5.2 Data exchange procedure

The inputs and outputs of each model were discussed before in chapter 3. The goal in the starting point of data exchange was to use the following instructions:

1. All of the inputs of Apollo and all outputs except hourly hydro generation should be used as input for KTH model.

2. The output of KTH model which is hydro generation will be compared to hydro generation of Apollo.

Some kinds of data can easily be exchanged, as there are no differences between the forms that they are presented in the two models. They are time series of data for one week with time step of one hour:

- Hourly wind generation
- Hourly other generations
- Hourly demand

Hourly wind generation and hourly demand are inputs of Apollo and hourly other generation is an output of Apollo, but all of them are used as inputs for KTH model. For hourly other generation, all data of hourly generation that is taken from Apollo except for hydro generation and wind generation are added and used as one time series of input in each area for KTH model.

It is expected to get exactly the same hourly hydro generation if we could use inputs for KTH model that were exactly the same as Apollo data, but the problem is that there are some differences between the two models or between the forms of presenting data in two models. For example the unit of given data may be different in the two models or the data is old and needs to be updated. To be able to exchange data, the mentioned differences which are called preliminary differences should be found and some adjustments should be done to remove differences. Despite of some adjustments, some of the differences cannot be removed and will remain at the end. The preliminary differences are divided to two types; the differences that are removed are called "Removable differences" and the differences that cannot be removed are called "Remaining differences" in this report. Finally it is not possible to run the simulation with remaining differences and the solution will be infeasible, so some compensation are needed to get the result.

The different steps of the procedure of exchanging data until reaching the results are shown below:

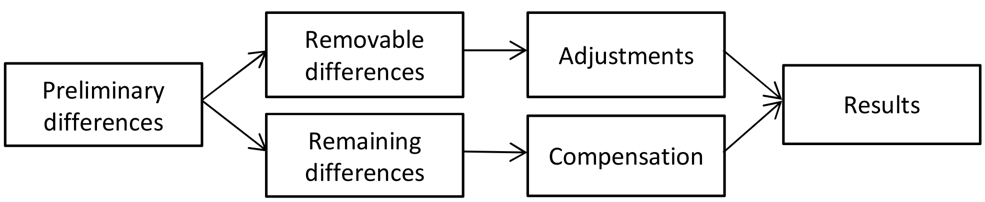

Figure 5.1 Different steps of data exchange

5.2.1 Preliminary differences

There are some differences between these two models before starting data exchange. These differences can be between the pre-assumed data about power plants or between the form of presenting data of inputs and outputs in the two models. To be able to exchange data and use Apollo data in KTH model, it is necessary to remove those differences. If we can remove all the differences and use exactly the same data as Apollo for KTH model, we can expect to get same results. But we are not able to remove all the differences, so we classified differences to two types which are removable and remaining differences.

The preliminary differences between the two models appear in the following cases:

- Hourly trading
- Installed capacity
- Loss in external transmission lines

- Loss in internal transmission lines
- Maximum capacity of reservoirs
- Reservoir levels at start and end of the week
- Inflow data

In data adjustment, I will try to remove the differences that are possible to remove but some differences are not possible to remove and will remain. After the part for data adjustment, in section 5.2.3 the above mentioned differences will be categorized and it is determined either they belong to removable differences or remaining differences.

5.2.2 Data adjustment

Some data adjustments are needed to remove the differences. In this section, the methods that are applied to eliminate removable differences will be explained. Moreover remaining differences will be determined and the reasons that remaining differences cannot be removed are discussed.

5.2.2.1 Hourly trading

The actual hourly trading is the output of Apollo, which should be used as input for KTH model. In KTH model the capacity of internal and external transmission lines are given to the model as input and the actual trading will be taken from the results of simulation so similar to Apollo actual trading is an output in KTH model.

The problem that occurs and should be resolved in data adjustment is that the output of Apollo which is actual trading should be used as the input for KTH but the input for KTH is the capacities of transmission lines. Therefore the model should be changed so that the actual trading can be used as input for KTH model instead of transmission capacities.

In KTH model there are two sets of data which gives the lower and upper limit of trading for each transmission line that specify the transmission capacity. These times series of data for each line are given for 168 hours corresponding to one week. The first series of data provides the lower limit or the minimum value and the second series of data provides the upper limit or maximum value. For external transmission lines, the transmitted energy is negative if it is export from Sweden and is positive if it is import to Sweden. For internal transmission lines the transmitted energy is positive if the transmission direction is from north to south of Sweden, and is negative if it is from south to north of Sweden.

Trading in each line and for each hour should be between the lower and upper limit. For example for the line nor1 which is the line between SE1 and NO4, the trading is defined as following:

$$nor1min \leq Tr \leq nor1\max \qquad (5.1)$$

To have the actual trading of Apollo as input for KTH model instead of line capacities, the lower and upper limits should be replaced with the value of actual trading in the input file for each hour and each line. This means that the lower and upper limits will be the same and equal to the value of transmitted energy in each hour that is taken from Apollo. Now the lines capacities are not inputs anymore and hourly trading is a fixed value given as input for KTH model.

Example:

The capacity of line “nor1”, in KTH model before data adjustment which is given as input is shown below:

$$-405^{MWh} \leq Tr \leq 421^{MWh} \tag{5.2}$$

The actual trading in hour 1009 which is the first hour of week 7 of year 2015 is taken from Apollo, it is 600 MWh export. Now the lower and upper limits of above inequality should be changed to 600 MWh but with a minus sign as it is export. Therefore the trading in hour 1009 will be fixed on 600 MWh export and the actual trading is used as input for KTH model.

$$-600^{MWh} \leq Tr \leq -600^{MWh} \tag{5.3}$$

In section 5.2.2.3, I will explain that this amount will slightly be changed due to some further data adjustments.

As an example for internal lines is the line snitt1 between SE1 and SE2, the trading is defined as following:

$$snitt1min \leq Tr \leq snitt1\max \tag{5.4}$$

The actual trading of this line in the first hour of week 7, year 2015 is taken from Apollo. It is 1243,6 MWh from SE1 to SE2. Now the lower and upper limits of above inequality should be changed to 1243,6 MWh .

$$1243{,}6^{MWh} \leq Tr \leq 1243{,}6^{MWh} \tag{5.5}$$

This amount will also be changed due to some further data adjustments that will be explained later in section 5.2.2.4.

As a result, the difference in hourly trading is a “removable difference” because it has been removed by data adjustment.

5.2.2.2 Installed capacity

In KTH model, the whole Swedish hydropower system is simulated. Therefore all the hydro power plants of Sweden must be considered in the model. But as previously mentioned, some small power plants with installed capacity of less than 5 MW are not considered in KTH model because the data for them were not available at the time of collecting data. On the other hand, most of those power plants that are not included in KTH model are considered in Apollo and this causes the total installed capacity of Apollo to be greater than KTH model.

In chapter 4, the data collection was explained. The data for installed capacities and bidding zones of existing power plants was updated and the data of small power plants which are not considered in KTH model was collected but not added to the model. Those small power plants cannot be added to the model, since all the required data for those power plants to be used in KTH model are not available. The only data that was collected for those power plants was their names, installed capacities and bidding zones. Some other data such as maximum total discharge, maximum capacity of reservoir and delay time of those power plants are also needed to be able to add them to KTH model.

The objective function of KTH model is to maximize hydro power production. In objective function of original KTH model, some scale factors were considered for hydro power production in each area to compensate for hydro generation of power plants that are not included. The scale factors are removed in the updated KTH model because we want to see the difference between results of the two models considering installed capacity as a difference and later in section 5.2.4.2 the data of installed capacities will be changed to be exactly the same as Apollo by calculating new scale factors for each area.

Since the installed capacities of existing power plants were updated and changed in input files of KTH model, we can say that some data adjustments related to installed capacities of existing power plants was done before. The following table shows the installed capacities of KTH original model compared to updated installed capacities of KTH model and installed capacities of Apollo.

Table 5.1 Updated installed capacities of KTH compared to Apollo

Installed capacity (MW)	KTH (original)	KTH (Updated)	Apollo
SE1	5491	5430	5262
SE2	7715	7874	8000
SE3	2184	2148	2709
SE4	250	253	231
Total	15640	15705	16202

It can be seen in the table that the updated capacities are closer to the capacities of Apollo, but the difference between updated capacities of KTH and Apollo still exists. This difference is due to not considering power plants with the capacity of less than 5 MW in KTH model. Especially in area 3 we can see a significant difference, because there are many private power plants in that area with small installed capacities. In area 1 the installed capacity of KTH model is larger than Apollo which is not the result of not considering small power plants. This difference became smaller but was not eliminated after updating installed capacity.

As a result, the total installed capacity of power plants in KTH model is lower than the total installed capacity of Apollo and the difference can be removed if we add all small power plants that are not included in KTH model. It is not possible to add those power plants as all needed data for adding them are not available. Therefore the total installed capacity and installed capacities in each area will remain different in the two models. The difference in total installed capacity of power plants is a “remaining difference” as it cannot be removed.

5.2.2.3 Loss in external transmission lines

In Apollo, 1 percent loss is considered in the transmission lines. This means that 1 percent of transmitted energy is lost in the transmission lines. Assume that it is intended to receive “Y” MWh energy from Sweden in another country, then “$\frac{100}{99} \times Y$” MWh must be sent on the transmission line. The arrived energy will be “Y” MWh while “$\frac{1}{99} \times Y$” MWh is lost in the line.

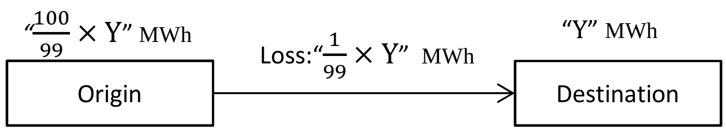

Figure 5.2 Loss in transmission lines

In KTH model there is no loss in transmission lines. It means that exactly the same amount of energy that is sent from the origin will be arrived to the destination. Now the difference is obvious, we cannot use exactly the same data that is taken from Apollo for external hourly trading as the data that is taken from Apollo is after considering 1 percent loss in the transmission lines.

It was previously explained in the section for hourly trading that there are two sets of data in KTH model for 168 hours in each line that specifies the minimum and maximum amount of trading. Those two values (maximum and minimum) should be set the same to have exactly the same number that is taken from Apollo. Therefore the data that is given to KTH input for hourly trading is the energy that is intended to be sent on lines (data in origin) while the data that is taken from Apollo is the energy that is arrived to destination.

The model or data should be changed so that 1 percent loss is also included in KTH model. The solution to remove this difference is to change data so that 1 percent loss is taken into account in the input data of KTH model.

It is worth to mention that the energy which exists in bidding zones inside Sweden is important to us for KTH model. The load balances for each price area inside Sweden should be satisfied and the energy which is received in other countries or sent to other countries is not important for satisfying load balances in KTH model. Therefore the amount of import after arriving to Sweden and the amount of export before sending to other countries must be calculated and used as input for KTH model.

As it was mentioned, the data taken from Apollo is after arriving to destination. Moreover the energy inside Sweden is important, so the data that determines import must be kept unchanged. The positive value in an hour is the imported energy that will be used as input for KTH model without change.

As an example consider the line "fin1" which is the line from SE1 to Finland. In hour 1009 which is the first hour of week 7, the value of transmitted energy is 1100 MWh. Since the value is positive, it shows that the trading is import from Finland to Sweden.

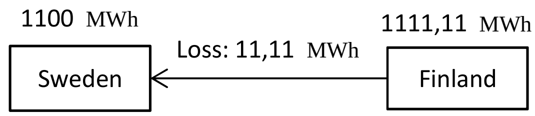

Figure 5.3 Example of loss in transmission lines for imported energy

The value that is taken from Apollo is 1100 MWh, considering 1 percent loss the value in the origin must be 1111,11 MWh. But the energy in Sweden is important for us and should be used as input which is the value that is taken from Apollo for import. The imported energy has plus sign in KTH input data, so the values that are positive should be kept unchanged.

For exported energy, the value that is taken from Apollo must be increased by one percent and be used as the input for KTH model. Since the value that is taken from Apollo is the energy after arriving to destination so the value should be increased by 1 percent to achieve the energy that was sent from the origin. The value that should be considered in the load balance of the related bidding zone or the total load balance in Sweden should be the amount that is increased by one percent. The negative value in an hour is the exported energy, so the negative values that are taken from Apollo should be increased by one percent.

The following example assumes the first hour of week 7 which is hour 1009 and the line is "nor1" which is from SE1 to Norway. The transmitted energy is -600 MWh, the negative value shows that it is export from Sweden to Norway.

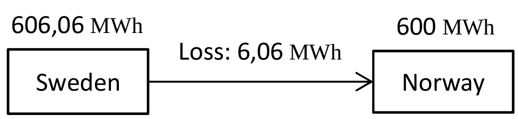

Figure 5.4 Example of loss in transmission lines for exported energy

The value that is taken from Apollo is -600 MWh. Considering 1 percent loss, the value in the origin must be -606,06 MWh. As the energy in Sweden is important for us and will be used as input, the value that is increased by one percent should be used for export. The exported energy has minus sign in KTH input data, so the values that are negative should be increased by one percent.

The difference is removed by changing the data of hourly external transmission that is taken from Apollo. All positive values which represent import are kept unchanged and all negative values which represent export are increased by one percent. A simple MATLAB code was written to apply the stated changes. Changed values are used as the inputs for KTH model.

The difference caused by not considering loss in external transmission lines in KTH model is removed by data adjustment, so this difference is a "removable difference".

5.2.2.4 Loss in internal transmission lines

In the previous section, it was explained that 1 percent loss is considered in transmission lines in Apollo but there is no loss in the lines in KTH model. The previous section described that it is possible to adjust the data in order to consider loss in external transmission lines. In this section, loss in internal transmission lines will be discussed and it will be shown that the data can be adjusted for considering loss in internal transmission lines.

The difference between this case and the previous case for external lines is that here, both of areas are located inside Sweden. Both of origin and destination are bidding zones inside Sweden, so export for one area is import to another area when considering load balances. Since the amount of energy inside Sweden is important for us to be used as input in KTH model, both of the values that we have in origin and in destination must be used correctly.

As an example, assume hour 1009 which is the first hour of week 7. In this hour there is 1243,6 MWh energy trading from SE1 to SE2. The data that is taken from Apollo is after arriving to destination.

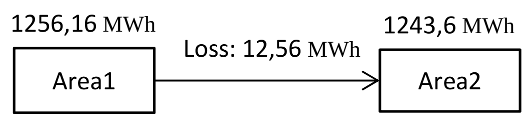

Figure 5.5 Example of loss in internal transmission lines

The value that is taken from Apollo is 1243,6 MWh. Considering 1 percent loss. The value in the origin must be 1256,16 MWh. If the transmission is from north to south the value will be positive and if it is from south to north of Sweden it will be negative. Thus the value is positive in this example.

The problem is that only one set of data is considered in KTH model for both of the values before and after transmission. It means that when we want to give the input to KTH model for internal trading, we can give only one value that should specifies export from area of origin as well as import to destination area. It does not make any problem for the original model of KTH because there is no loss in lines and the values are the same. On the other hand, when we want to use Apollo data as input, loss must be considered and the problem occurs here. Two values are different but we can only give one value as input which should specify both of them.

However it is possible to remove the differences by data adjustment in another way. The internal transmission must be kept the same as Apollo in KTH input files, instead the load in each hour must be increased by the amount of loss in the corresponding transmission line in that hour. For the example that was showed in figure 5.5 in hour 1009, the load in area 1 must be increased by the amount of loss in line from SE1 to SE2. The original load in area 1 is 976.3 MWh in hour 1009 and it should be increased by 12,56 MWh. Therefore the load which must be used as input in updated KTH model for area 1 will be 988.86 MWh. The load changing should be done for all hours in areas 1, 2 and 3 because they are the origins of internal trading.

The difference that was caused by not considering loss in internal lines in KTH model, was removed by data adjustment. Therefore it is a “removable difference”.

5.2.2.5 Reservoir level at start and end of the week

There are 3 reservoirs considered in Apollo for area 1 to 3, area 4 is assumed to be run-of-the-river, so no reservoir exists for area 4. The content of each reservoir in each week is the output of Apollo and is given in Apollo data file. The maximum capacities of reservoirs in Apollo model are also given.

In KTH model there is one reservoir per each power plant. It is assumed that all reservoirs except Vänern (Vargön) and Vättern (Motala) have the same start and end levels. In KTH model two ratios that show the level of water in reservoirs at start and end of the week are given as input. For calculating those ratios the content of a reservoir at start and end of the week must be divided by the maximum capacity of that reservoir.

Therefore in Apollo we should give three different start and end levels for three reservoirs in three areas. In KTH model we have also three start and end levels but one of them in for Vänern, one for Vättern and one for all other power plants. This is one of the differences that exist between the two models that can be removed. The model should be changed so that similar to Apollo, start and end levels of reservoirs are given based on their bidding area. Thus the code is changed such that we have four start and end levels for reservoirs in four areas. In Apollo there is no reservoir in area 4 but in KTH model there are some reservoirs in area 4, so the code was changed based on four areas. To have the same condition as Apollo, the start and end levels of reservoirs in area 4 was set to be the same as each other. Therefore no water is considered in reservoirs of area 4.

To exchange data and use Apollo data in KTH model, the values for reservoirs contents at start and end of the week must be taken from Apollo. The reservoir content of each week is used as the start content of that week and the reservoir content of the next week is used as the end content for the week. To obtain the ratios that are needed in KTH model, those values should be divided by maximum capacity of reservoirs.

The difference was removed by changing the code, so it is a “removable difference”.

5.2.2.6 Maximum capacity of reservoirs

The maximum capacity of reservoirs in KTH model should be used to calculate the ratios for start and end levels that were described in previous section. We may get wrong result if we use the maximum capacity of reservoirs given in Apollo as the maximum capacities may be different in the two models.

The difference that exists between the two models is that the start and end contents of reservoirs are given in terms of energy in Apollo. The unit is MWh (Mega Watt hour) in Apollo. But in KTH model the maximum capacities of reservoirs are given in HE (Hour Equivalent). To calculate start and end levels of reservoirs based on Apollo data, the maximum capacities of reservoirs in KTH model should be converted to MWh.

The following formula is used to calculate maximum capacities of KTH model in MWh, This is the same formula that is used to calculate stored water in [15].

$$M_{i(MWh)} = (\gamma_{i,1} + \sum_{i' \in D_i} \gamma_{i',1}) \times M_{i(HE)} \tag{5.6}$$

D_i: The set of indices for all power plants downstream for reservoir i

The important point for calculating maximum reservoir capacities is the location of power plants in relation to each other which is shown in figure 5.6. We should know which power plants are located downstream to power plant i. The sum of production equivalent of the power plant itself and the production equivalents of downstream power plants should be multiplied by the maximum capacity in hour equivalent. The production equivalent of downstream reservoirs should also be considered because we have to consider that the water in a reservoir will finally reach the downstream reservoirs and will be used in downstream power plants to generate power [15]. The obtained value is the maximum capacity of reservoir in terms of energy (MWh).

The maximum capacities of reservoirs in KTH model calculated in MWh are shown in the table below. The maximum capacities of Apollo are also presented in the table. It is possible to compare the two models in this context.

Table 5.2 Maximum capacity of reservoirs of KTH and Apollo in TWh

M_{max}, Maximum reservoir capacity (TWh)	KTH	Apollo
SE1	14,556371	14,81379
SE2	12,920077	15,73691
SE3	2,705975	3,13535
SE4	0,1593319	-

It can be seen in the table that the maximum capacities of reservoirs are different in the two models, especially in area 2 there is a significant difference. The capacities that are used in Apollo are more close to what exists in the real hydropower system of Sweden. The calculations for converting maximum capacity of reservoirs from HE to MWh were checked 4 times to make sure that this difference is not due to calculation mistakes. A part of the difference between the reservoir capacities in the two models can be due to not considering small power plants in KTH model. It was explained before that in KTH model the power plants with the installed capacities of less than 5 MW are not considered. The small power plants that are not considered affect the KTH reservoir capacity in two ways: First, the reservoir capacity of these hydro power plants is not included. Second, the production equivalent of the small hydro power plants is not included when the content of the reservoirs in the model is converted from HE to MWh. Therefore, the size of the reservoirs might be accurate but the energy content of the reservoirs can be underestimated. Another reason for different reservoir capacities can be possible errors in the input data of KTH model.

The figure below shows the location of power plants in relation to each other. They are represented by the numbers assigned to each power plant in KTH model.

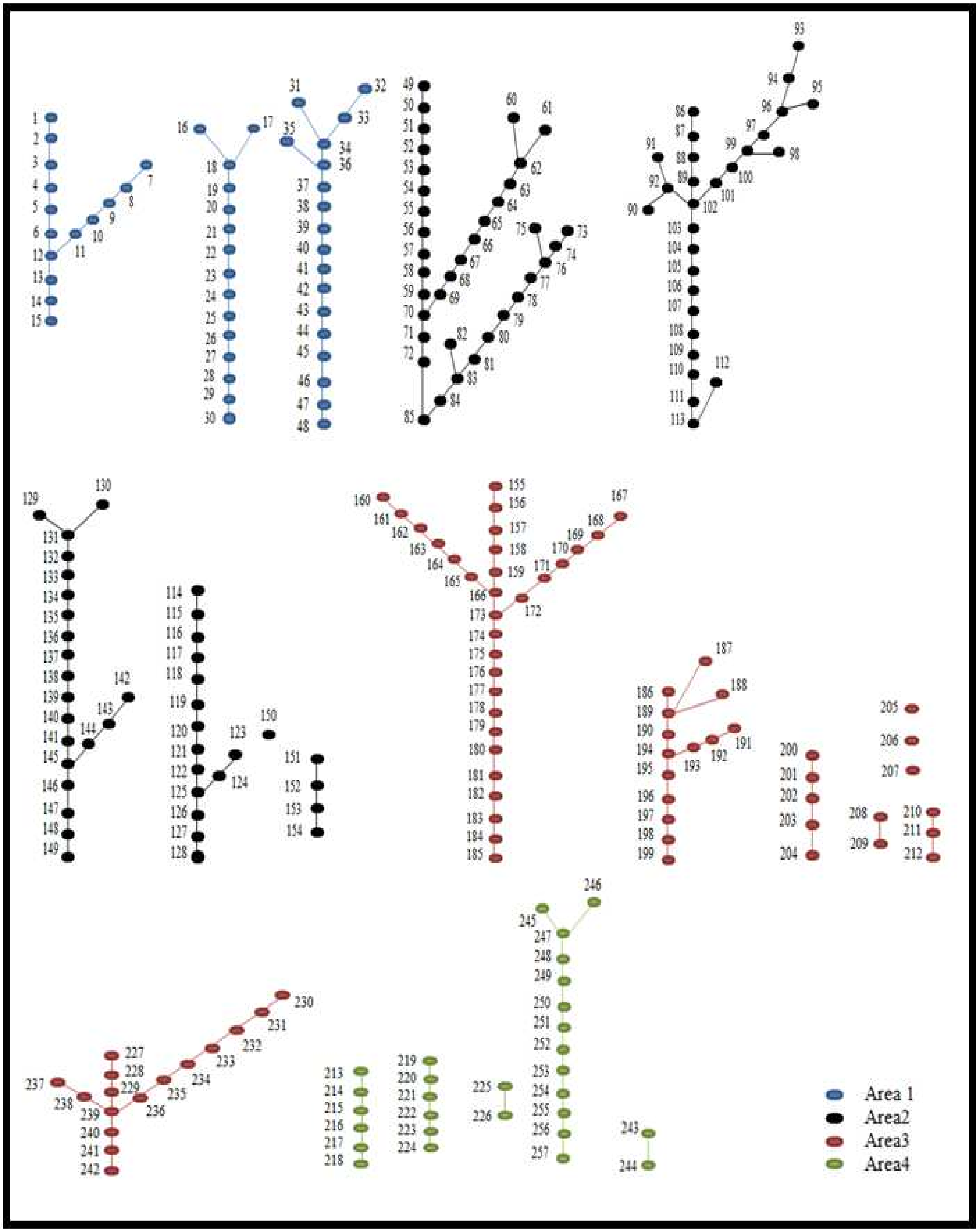

Figure 5.6 Position of hydro power plants in Sweden relative to each other

The following table is an example of calculating the reservoir level at start and end of week 7. The start and end content of reservoirs are taken from Apollo and divided by the maximum reservoirs capacities of KTH model to obtain the ratios for start and end level.

Table 5.3 Calculation of start and end levels of reservoirs in week 7

Area (2015)	M_{max}, Maximum capacity of reservoirs in KTH model (TWh)	Apollo's reservoir content at the start of week 7	Apollo's reservoir content at the end of week 7	Start level	End level
SE1	14,556371	7,074074	6,664830	0,485978	0,457863
SE2	12,920077	6,162668	5,485406	0,476984	0,424564
SE3	2,705975	1,261002	1,124917	0,466007	0,415716
SE4	0,1593319	-	-	-	-

Since the start and end levels are calculated based on maximum capacity of reservoirs in KTH model, the difference between capacities of reservoirs in the two models has no impact on the results. It was tested such that the capacity of reservoirs in KTH model in each area was calculated by a scale factor to become the same as Apollo's capacity of reservoirs in that area. Then the results of simulation after the capacities were changed found to be the same as previous results when KTH capacities were used. It shows that the different capacity of reservoirs in KTH model has no impact on results when the start and end levels are changed based on KTH capacities. Therefore it is considered as "removable difference".

5.2.2.7 Inflow data

The actual inflow data is given per week per area in Apollo. The data in Apollo is given in Mega Watt hour (MWh). In KTH model, The local inflow (V_i) for one week in power plant *i* is the difference between the average water flow of power plant *i* and the average water flow of the power plants upstream in that week. The average water flow of each week for each power plant (ws_i) is calculated by multiplying the average annual flow of the power plant by a scale factor (V_{sf}) which is particular for that week. The scale factor of each week can be changed in the input file of KTH model. The following equations which were introduced in chapter 3 are used in KTH model to acquire local inflow.

$$ws_i = V_{sf} * w_i \tag{5.7}$$

$$V_i = ws_i - \sum_{i' \in U_i} ws_{i'} \tag{5.8}$$

The average annual flow for each power plant (w_i), is given in the input file of KTH model. The unit of average annual flow is HE (Hour Equivalent) which leads the local inflow to be in Hour Equivalent as well. The difference between the two models is the unit of inflow data, which is "MWh" in Apollo and "HE" in KTH model. In order to remove the difference and exchange data, the unit of average annual flow should be changed to MWh to obtain the local inflow in MWh.

We can use the following formula to convert the unit of local inflow in KTH model to MWh.

$$W_{i-i'\,(MWh)} = (w_{i(HE)} - \sum_{i' \in U_i} w_{i'(HE)}) \times (\gamma_{i,1} + \sum_{i' \in D_i} \gamma_{i',1}) \qquad (5.9)$$

To find the weekly scale factor (V_{sf}) of each area, all water flow differences that is calculated in MWh must be added, then the inflow data that is given in Apollo data file for each week and each area should be divided by the sum of water flow differences in KTH model that is found from (5.9). Then new V_{sf} should be used in new input file of KTH model.

$$V_{sf}(z) = \frac{Apollo\ inflow\ in\ area\ z}{\sum_{i \in z} W_{i-i'\,(MWh)}}$$

The difference in inflow data is removed by data adjustment, so this difference is a "removable difference".

5.2.3 Categorizing differences

The differences were introduced in previous sections and the methods that were used to remove differences were introduced. However one of those differences is still remained and cannot be removed. To summarize the result of previous sections, the differences which belong to each group are listed below.

Removable differences

- Hourly trading
- Loss in external transmission lines
- Loss in internal transmission lines
- Maximum capacity of reservoirs
- Reservoir levels at start and end of the week
- Inflow data

Remaining difference

- Installed capacity

Although most of the differences were removed by data adjustment, still it is not possible to obtain the solution after running the simulation and the solution of the optimization problem will be infeasible because in data adjustment more constraints were considered in KTH model so we are limiting the flexibility of KTH model. Thus compensations are needed to be able to run the model and obtain results.

5.2.4 Compensation methods

It had been mentioned that despite of removing some differences by data adjustment, we get infeasible solution after running the simulation. The results that should be compared are the hourly hydropower production of the two models which is the output in both models. The reason of getting infeasible solution is that by adjusting data to have the same inputs as Apollo we are limiting the flexibility of KTH model so the hydropower production is not enough to satisfy load balance. To solve this problem, the flexibility of model should be increased in another way to compensate the lack of hydro generation or eliminate the remaining difference. There are three methods of compensation for lacking hydro power generation that will be introduced in the next sections. The results of simulations that are obtained by using three methods will be presented in chapter 6.

5.2.4.1 Method 1: Considering transmission limits

The first method that is used to compensate for the lack of hydro generation is allowing the model to have more import from other countries and less transmission between price areas. In this method the flexibility of model is increased.

The hydro generation is not enough to satisfy total load balance. By increasing import (or decreasing export), the power deficit will be supplied and the load balance is satisfied. Moreover to satisfy the load balance in each bidding area, the internal trading should also be flexible.

It was explained previously that in KTH model there are two sets of data which gives the lower and upper limits of trading for each transmission line that specify the transmission capacity. Those limits were set to be the same to have exactly the same trading as Apollo. In this step, to increase import a 40 MWh range is added to the upper limit of external transmission lines in week 7 of 2015. It means that the trading in a specific hour can be increased in the range of 40 MWh.

The example in hourly trading section was the first hour of week 7, year 2015 in line “nor1”:

$$-600^{MWh} \leq Tr \leq -600^{MWh} \quad (5.9)$$

Then, due to external transmission losses it was changed to:

$$-606{,}06^{MWh} \leq Tr \leq -606{,}06^{MWh} \quad (5.10)$$

In this step 40 MWh range is added to upper limit for external lines:

$$-606{,}06^{MWh} \leq Tr \leq -566{,}06^{MWh} \quad (5.11)$$

It is worth to mention here that the value which is added to the upper limit can be any number higher than 40 MWh. As the objective function of KTH is to minimize import from other countries, the minimum import that is needed to satisfy load balance will be used. 40 MWh is the minimum import that is needed in each line and each hour for week 7 of 2015. This number was found by trial and error; different values were tested until reaching this minimum value. Therefore even if the range is more than 40 MWh, more import than necessary will not be used by the model.

Another range is also considered in internal transmission lines. For internal transmission the lower limit is decreased by 300 MWh in week 7 of 2015. This number is also obtained by trial and error. This allows the model to have less internal trading which is more desirable in the model as a punishment is considered in objective function for internal trading. The ranges which are considered for internal and external transmission lines are particularly for week 7, for other weeks and years the limits can be different.

Example for hourly trading from SE1 to SE2, first hour of week 7, year 2015:

$$1243{,}6^{MWh} \leq Tr \leq 1243{,}6^{MWh} \tag{5.12}$$

The internal transmission in this hour was set to be fixed on 1243,6 MWh which is the value that is taken from Apollo. But in this step the lower limit is decreased by 300 MWh.

$$943{,}6^{MWh} \leq Tr \leq 1243{,}6^{MWh} \tag{5.13}$$

Hydro generation is the output of the two models that will be compared in the result section. The advantage with this method is that we can see the difference between results that is caused by remaining differences, because increasing import or decreasing internal trading has no impact on hydro generation.

5.2.4.2 Method 2: Increasing installed capacity

In this method the total installed capacity of KTH model and the total installed capacity of each area are changed to be the same as Apollo. This method is trying to eliminate the remaining difference in installed capacity.

By dividing Apollo’s total installed capacity of each area by KTH’s total installed capacity of that area a scale factor will be obtained. The installed capacity of each power plant in KTH model will be multiplied by the scale factor that was calculated for the power plant’s bidding area. With this method the installed capacity of each area and the total installed capacity of KTH model will be the same as Apollo. The range that was considered in the first method will be still remained to have more flexibility in the model although we may not need it thanks to increased installed capacity.

However if we want to have the realistic condition that exists in Apollo, all power plants that are considered in Apollo must be added to KTH model and the installed capacity must be increased by adding the installed capacities of those power plants. If those power plants are added their reservoirs will also be added and some other data will be changed as well. As it was described before, it is not possible to add the small power plants that are not included since the data for them is not available. Therefore, with this method we can get the same installed capacity in each area but the condition is not exactly the same as Apollo and this method is not very accurate.

After using this method all differences that existed between input data of KTH model and Apollo data are removed. Therefore we expect to get almost the same hydro generation in the two models. However it will be shown later in chapter 6, that after using method 2 the results will not be the same. The reason for getting different results after using same input data will be explained in chapter 6.

5.2.4.3 Method 3: Increasing water

The last method is to increase water. It was mentioned in section 5.2.4.2 that although all differences between the data which was used in the two models were removed, the results will not be the same. Therefore another compensation method should be used to get the same results. The water can be increased by increasing the water in the reservoirs. By increasing water, the hydropower production will also be increased; thus there is enough hydro generation to satisfy load balance. We should only increase water in the areas that we have lack of hydro generation. The increase of water is done by decreasing the water level in reservoirs at the end of the week. Different amounts of decrement must be tested to find the best amount which gives the hydro generation that is close to Apollo and at the same time does not spill too much water. In this method, the internal trading is set to be the same as Apollo, there is no limit which allows different internal trading. However, the limit for external trading is kept as before, because when we test different amounts to find the best amount the water may not be enough to satisfy load balance and it must be compensated by more import. Method 3 is used after applying method2, which means that the installed capacities are set to be the same in the two models in this method.

6. Results and Discussions

The results are obtained after running the simulation using the three compensation methods that were introduced in chapter 5 section 5.2.4. The objective is to get the same results in the two models. In the first method there is one remaining difference between the input data of the two models therefore it is expected to see dissimilarities between the results of the two models. In the second method it is expected to see results in KTH model that are very similar to Apollo as the compensation method is toward eliminating the only remaining difference in input data. However the results after using method 2 will not be similar due to another reason. The reason for different results after using method 2 is that in higher discharge levels, the production equivalent of KTH model is lower (see section 3.1.2 equations 3.21 to 3.25). Therefore we get a lower hydropower production in KTH model compared to Apollo in area 2. In method 3, we will try to remove this difference by increasing water in the reservoirs of area 2, and then we will get almost the same results in the two models.

In this section the hourly total hydropower production and hydropower production in each bidding area are presented for each method. The figures that compare the hydropower production in the two models will also be shown. Moreover the exported energy and internal trading in each model will be presented in tables. The simulation has been done for all the weeks that are available in KTH model and for years 2015 and 2040 using the data from Apollo. The analysis of the results and the conclusions that are derived from all weeks are the same so this report will only present the results from simulation of week 7, year 2015.

6.1. Results obtained by using method 1

The purpose of using method 1 is to prevent getting infeasible solution and being able to compare hydropower productions of the two models. Due to adding more constraints to KTH model after data adjustment, we get infeasible solution in optimization problem because the hydro generation is not enough to satisfy load balances. Therefore we need to consider compensation for lower hydro generation. In method 1, a range is considered for external trading which allows the model to have more import than Apollo. Another range is also considered for internal trading which allows lower internal trading than Apollo between bidding areas and help to satisfy the load balances in bidding areas. Tables 6.1 to 6.3 show the results of week 7 simulations in comparison to corresponding data available from Apollo. Hydro power production, internal trading and exported energy to other countries are the outputs of KTH model.

Table 6.1 Hydro power production of week 7, 2015 using method 1

Hydro power production (MWh)	KTH	Apollo
SE1	496713	496698
SE2	861643	905585
SE3	181934	211821
SE4	4353	3800
Total	1544643	1617904

Table 6.2 Internal trading of week 7, 2015 using method 1

Internal trading (MWh)	KTH	Apollo
Snitt1 (SE1 to SE2)	214384	214384
Snitt2 (SE2 to SE3)	669170	693801
Snitt4 (SE3 to SE4)	572099	603775
Total	1455653	1511960

Table 6.3 Exported energy of week 7, 2015 using method 1

Exported Energy (MWh)	KTH	Apollo
SE1	131364	131350
SE2	124130	143426
SE3	103621	126467
SE4	84140	115265
Total	443255	516508

The lower total hydropower production in KTH model is compensated by allowing the model to have more import or less export. It is shown in the tables 6.1 and 6.3 that the total hydropower production is higher in Apollo; instead the exported energy is less in KTH model. In table 6.2, the internal trading is given. It should be noted that the trading is from north to south of Sweden when it is positive. The different hydropower production in each area is also compensated by external or internal trading. For example in area 2, the hydropower production of KTH model is less than Apollo which is compensated by less export to other countries as well as less internal trading to area 3.

Figures 6.1 to 6.5 show the comparison between hourly hydropower production in the two models and in different areas for week 7, year 2015 when method 1 is used.

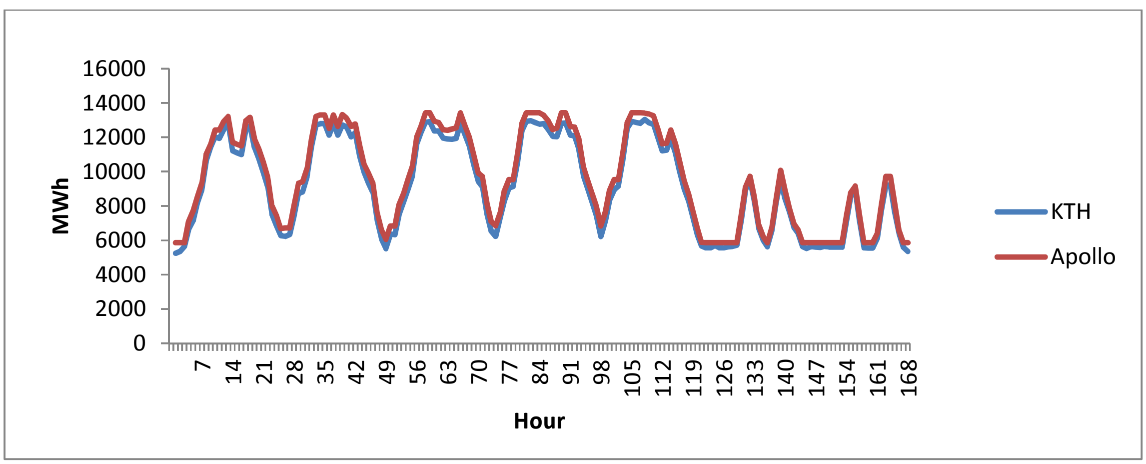

Figure 6.1 Total hydropower productions of KTH and Apollo– week7, 2015 with method 1

It is shown in figure 6.1 that the total hydropower production of KTH is lower than Apollo; the first reason is the remaining difference in exchanged data that were described in chapter 5. The lower installed capacity in KTH model which is due to not considering small power plants leads KTH model to have less hydro power production than Apollo. At lower installed capacity, the production equivalent is also lower therefore less water can be used at best efficiency to produce power and the hydro power production will be lower. The other reason is that in KTH model, at higher discharge levels the water from segment 2 is used which has a lower production equivalent. Therefore in area2, KTH has lower hydropower production than Apollo. As a result the total hydropower production of KTH becomes lower than Apollo after using method 1. In table 6.3 it was shown that the lower hydropower production in KTH model is compensated by less export to other countries.

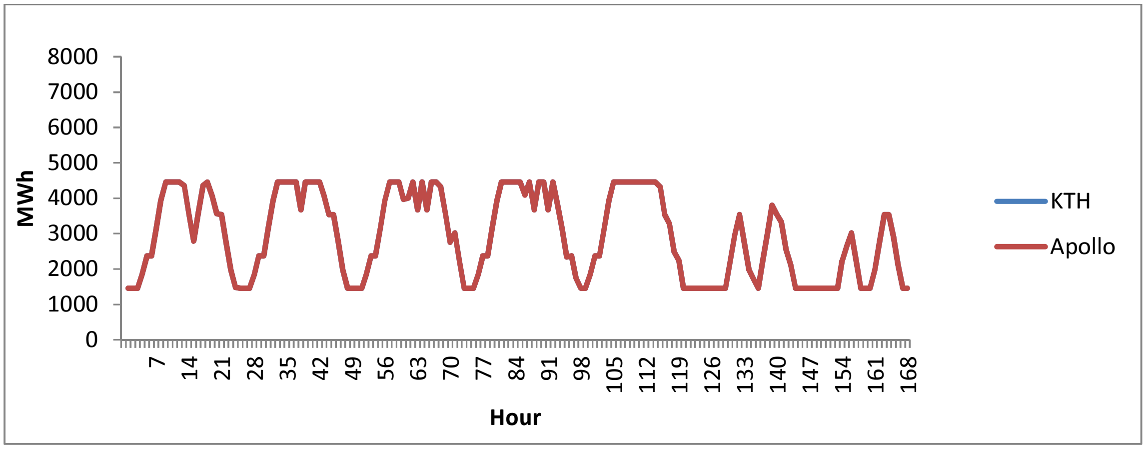

Figure 6.2 Hydropower productions of KTH and Apollo in area 1 – week7, 2015 with method 1

From figure 6.2 it can be seen that the hydropower productions of area 1 are almost the same in the two models. Due to higher installed capacity in KTH model in area 1 we expect to get higher production in KTH models, but we can see that area 1 productions are almost the same in the two models. The reason that we get lower production than expected in KTH model is also due to lower hydro production at high discharge levels, it was described before that the production equivalent is lower at higher discharge levels.

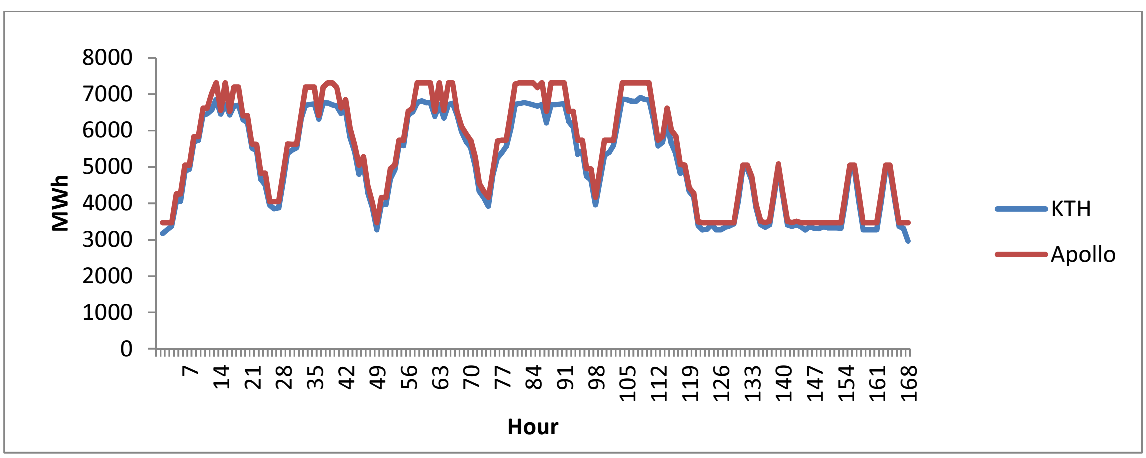

Figure 6.3 Hydropower productions of KTH and Apollo in area 2 – week7, 2015 with method 1

In figure 6.3, it can be seen that the hydropower production of Apollo is much more than KTH in most of hours especially from hour 12 to 118. At the end of the week, the difference between hydro productions of the two models is small when the production is much lower than previous hours. A significant difference appears in the hours when higher electricity production is needed. One reason for different hydro productions as stated before is lower installed capacity in KTH model. The other reason which causes a very remarkable difference between productions of the two models is that in area 2 the discharge level is very high and because the production equivalent is lower at higher discharge levels, thus the hydropower production is lower than Apollo. The lower hydropower production in area 2 in KTH model is compensated by less export to other countries or less internal trading to other areas which is shown in tables 6.2 and 6.3.

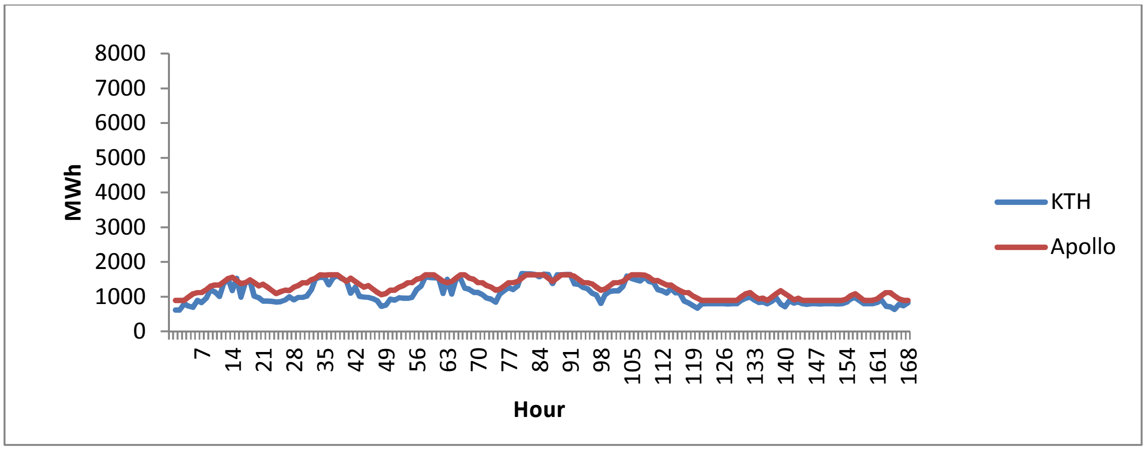

Figure 6.4 Hydro power production of KTH and Apollo in area 3 – week7, 2015 with method 1

The hydro power productions of the two models in area 3 are shown in figure 6.4. It can be seen that the hydropower production of Apollo is more than KTH model in this area. The installed capacity of KTH is much lower than Apollo in area 3 which leads to lower hydropower production in KTH model. The installed capacity is the only reason which makes the difference in area 3 because in this area the discharge level is not high so the other reason for difference in area 2 which was due to lower production equivalent in higher discharge levels does not apply here. The lower production in KTH model is compensated by less export to other countries or less internal trading to other areas.

In figure 6.5, it is shown that the hydropower production of KTH model is higher than Apollo. It can also be checked from table 6.1. The hydropower production of area 4 is much lower compared to other areas because the total installed capacity of power plants which are located in this area is much lower compared to other areas. The installed capacity of power plants in KTH model is more than Apollo in area 4 and this causes the hydropower production of KTH to be higher than Apollo. The other reason can be due to more internal trading to other areas because the higher power generation can be transmitted to other areas when there are power deficit in those areas

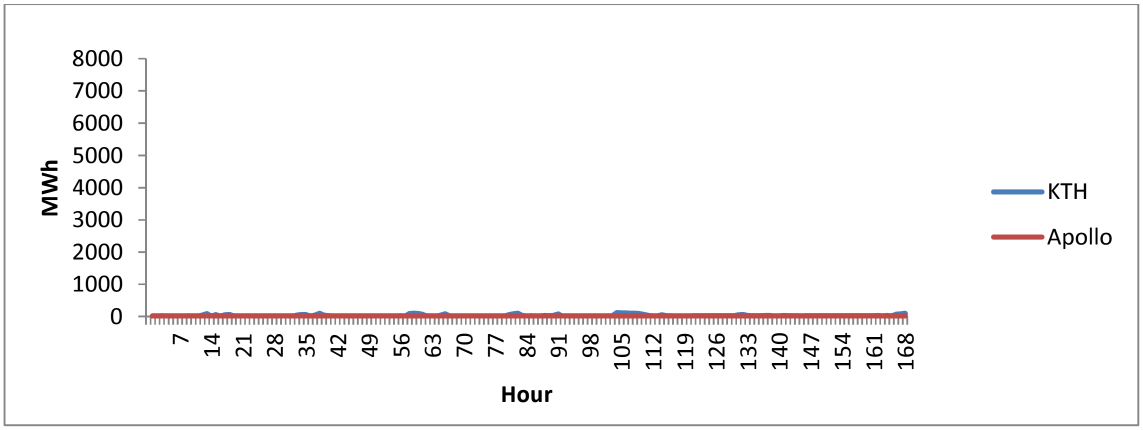

Figure 6.5 Hydropower productions of KTH and Apollo in area 4 – week7, 2015 with method 1

6.2 Results obtained by using method 2

In this section the results of simulation in week 7 of year 2015 when the installed capacity of hydro power plants in KTH model is increased to be the same as Apollo in each area will be shown. In this step the only difference that was remained between KTH input data and Apollo data is eliminated. To eliminate this difference, the installed capacity of each area in Apollo is divided by the installed capacity of each area in KTH model. Therefore a scale factor is found for each area then the installed capacity of each power plant is multiplied by the scale factor of its area. However this elimination is different from removing the difference. If we want to remove the difference in installed capacity, all power plants that are not included in KTH model should be added but it was explained before that it is not possible. In this step we only increase the installed capacity of existing power plants to obtain the same installed capacity as Apollo in each area, so it is not the same as the realistic condition in Swedish hydro power system. Therefore it is called the elimination of the difference and was not introduced as the removable difference.

By increasing installed capacity, we expect to get a result in KTH model that is more close to the result of Apollo. However we still need some flexibility in the model to get feasible solution because we still have the problem of getting lower production in high discharge levels due to low production equivalent. Therefore we allow the ranges that were considered in the first method for more import (less export) and for internal trading to be remained. The results of hydropower production, exported energy and internal trading in KTH model are presented in tables 6.4 to 6.6. The results of KTH model are compared to corresponding data of Apollo in the tables.

Table 6.4 Hydro power production of week 7, 2015 using method 2

Hydro power production (MWh)	KTH	Apollo
SE1	495041	496698
SE2	875361	905585
SE3	229466	211821
SE4	3977	3800
Total	1603845	1617904

Table 6.5 Internal trading of week 7, 2015 using method 2

Internal trading (MWh)	KTH	Apollo
Snitt1 (SE1 to SE2)	212751	214384
Snitt2 (SE2 to SE3)	663469	693801
Snitt4 (SE3 to SE4)	591576	603775
Total	1467796	1511960

Table 6.6 Exported energy of week 7, 2015 using method 2

Exported Energy (MWh)	KTH	Apollo
SE1	131324	131350
SE2	141915	143426
SE3	125976	126467
SE4	103241	115265
Total	502456	516508

It can be seen in the tables that the total hydro production of the two models became closer to each other after increasing installed capacity. The lower total hydropower production in KTH model is compensated by more import or less export in KTH model which can be seen in tables 6.4 and 6.6. In table 6.6, the internal trading is given. The different hydropower production in each area is also compensated by external or internal trading. For example in area 2, the hydropower production of KTH model is less than Apollo which is compensated by less export to other countries as well as less internal trading to area 3.

Figures 6.6 to 6.10 show the comparison between hourly hydropower production in the two models and in different areas for week7, 2015 using method 2.

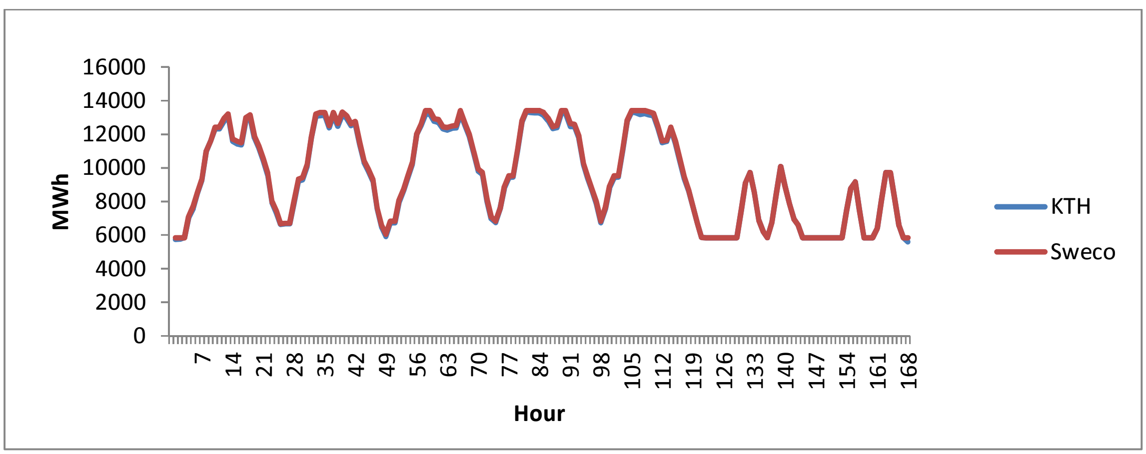

Figure 6.6 Total hydropower production of KTH and Apollo– week7, 2015 with method 2

It is shown in figure 6.6 that the total hydropower production of KTH is very close to the hydropower production of Apollo after using method 2. However the total hydropower production of KTH model is still lower than Apollo. The reason for this lower production is the lower hydro production in area 2 which is due to having lower production equivalent at higher discharge levels in KTH model. Although a part of lower generation in area 2 is compensated by more generation in area 3, but there is still a difference between total hydropower productions of the two models. In table 6.6 it was shown that the lower total hydropower production in KTH model is compensated by less export to other countries.

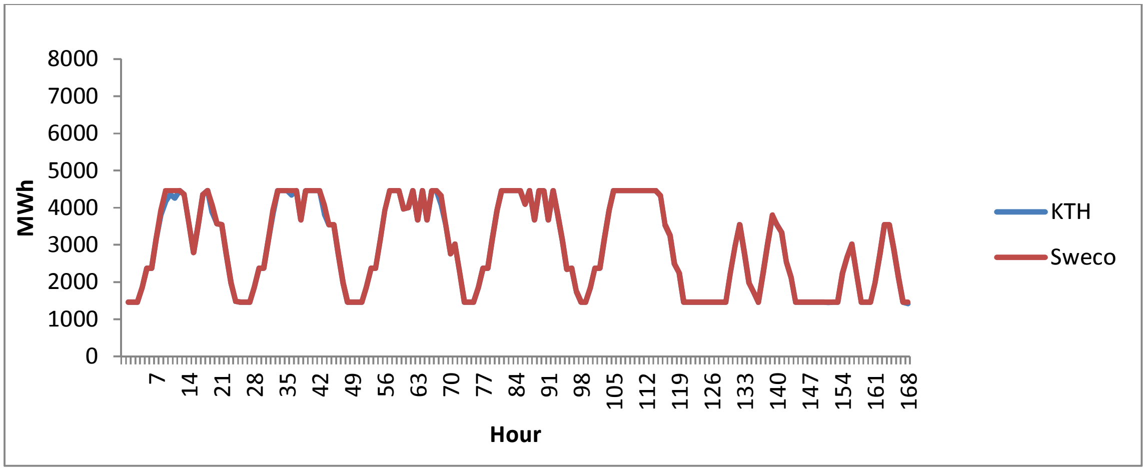

Figure 6.7 Hydro power production of KTH and Apollo in area 1 – week7, 2015 with method 2

In figure 6.7 it can be seen that the hydropower productions of area 1 in the two models are very close to each other. The installed capacity of power plants in each area is set to be the same as Apollo in this method therefore the generation in area 1 become lower compared to method 1 where the installed capacity of KTH model was higher. However it can be determined that the production in KTH model is lower than Apollo as it was shown in table 6.4 as well. The small difference that exists between KTH and Apollo hydro production in area1 is due to lower production equivalent at higher discharge levels in KTH model. However this difference is very insignificant compared to the total generation in area 1.

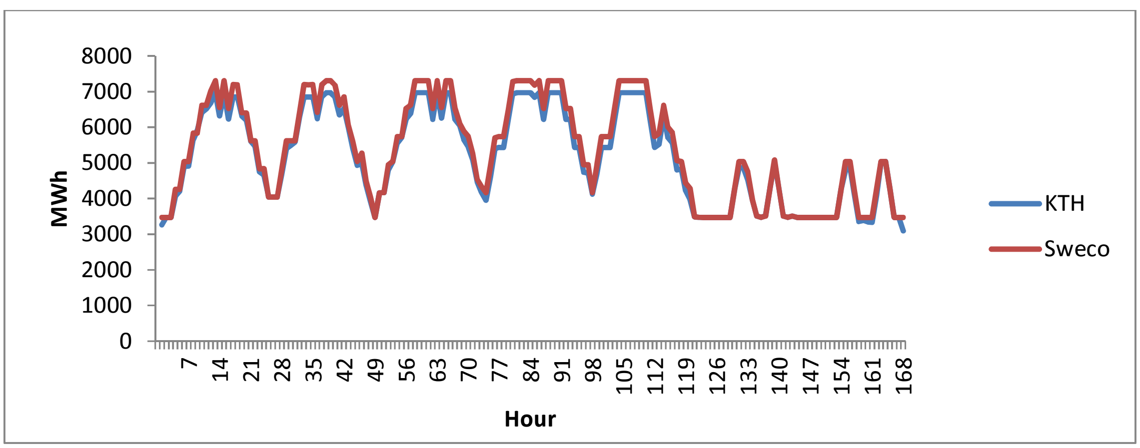

Figure 6.8 Hydro power production of KTH and Apollo in area 2 – week7, 2015 with method 2

In figure 6.8, it can be seen that the hydropower production of Apollo in area 2 is more than KTH in most of hours. A significant difference appears in the hours when higher electricity production is needed. The reason is that in KTH model due to lower production equivalent at higher discharge levels, we get lower hydropower production in area2. However the difference is decreased compared to method 1 because the installed capacity of power plants of KTH model in this area set to be the same as Apollo. The lower hydropower production in area 2 in KTH model is compensated by less export to other countries and less internal trading to area 3 which can be seen in tables 6.5 and 6.6.

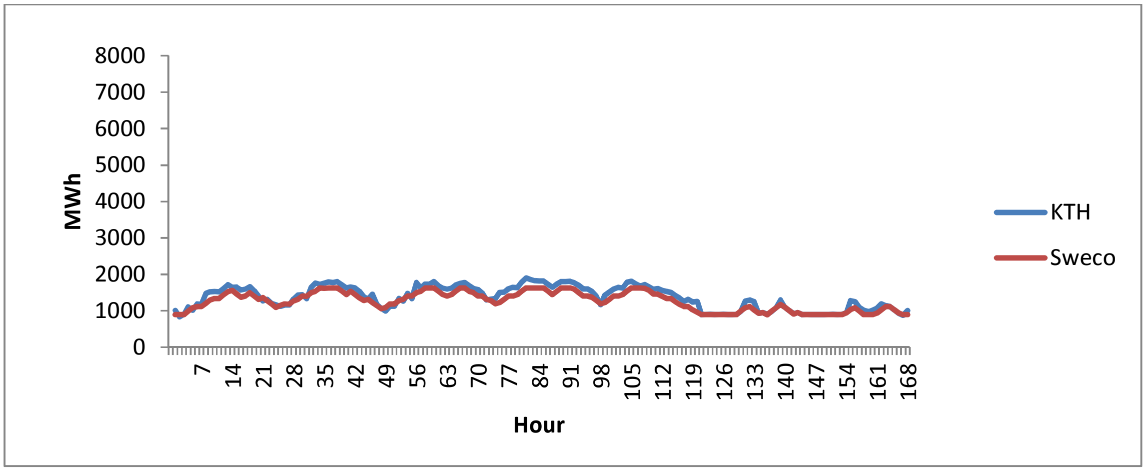

Figure 6.9 Hydropower production of KTH and Apollo in area 3 – week7, 2015 with method 2

The hydro power productions of the two models in area 3 are shown in figure 6.9. It can be seen that the hydropower production of KTH model becomes more than Apollo after using method 2 although in method 1 KTH production in area 3 was lower than Apollo. The installed capacity of the two models are the same in method 2, therefore we expect to get the same production as the discharge level is not high in this area. The reason that we get higher production in area 3 is that area 3 produces more power to compensate for the lack of production in area 2; however it can only compensate a part of the production deficit.

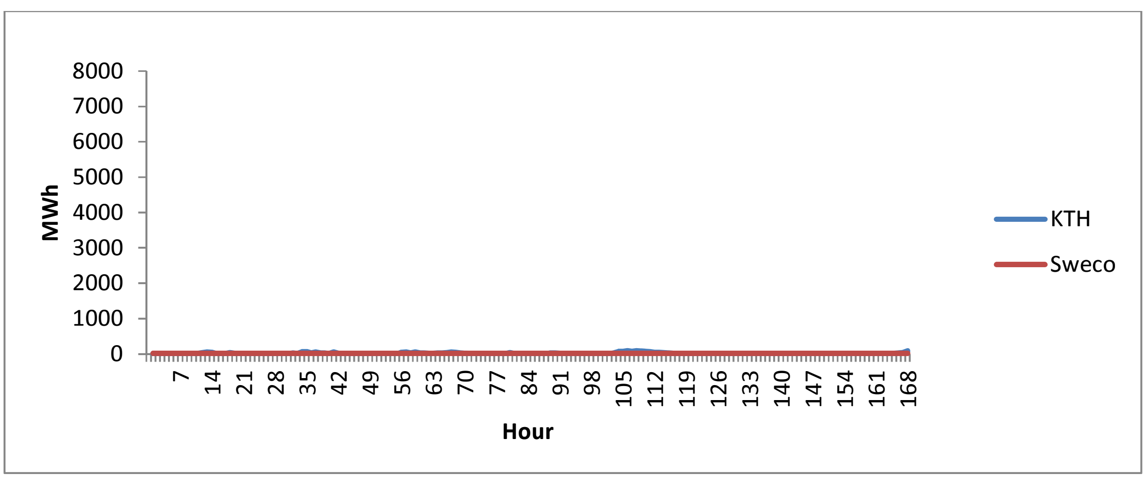

Figure 6.10 Hydro power production of KTH and Apollo in area 4 – week7, 2015 with method 2

In figure 6.10, the hydropower production in area 4 in shown. The hydropower production of area 4 is much lower compared to other areas and the scales of all figures set to be the same to facilitate comparing figures. Therefore it is hard to find out the difference between productions in area 4. However it can be seen in table 6.4 that the hydro production of KTH model is slightly higher than Apollo in this area, even in figure 6.10 it can be determined that KTH production is more in some hours. The difference between productions in the two models becomes lower in method 2 as the installed capacities of the two models are the same. However the slightly higher production in KTH model is used to compensate for lack of production in other areas.

6.3 Results obtained by using method 3

In method 3, the water in reservoirs of area 1 and 2 is increased until the hydro production of KTH model becomes close to Apollo. We increase the water in reservoirs of area 1 and area 2 because the difference in results of method 2 was in areas 1 and 2. Increasing water is done by decreasing the reservoir level at the end of the week. To find the best amount of water in reservoir we should test many alternatives. The best amount is obtained when we get a hydro production which is close to Apollo without too much spillage. In this method the range that was considered for internal trading in method 1 is removed to have the same internal trading as Apollo. However the range for external trading is kept unchanged because we need some compensation for lack of water when different amounts are tested for reservoirs end level. After testing different scenarios the best scenario were found which will be presented in following tables and figures.

Tables 6.7 to 6.9 show the results of hydropower production, internal trading and exported energy to other countries after increasing water.

Table 6.7 Hydro power production of week 7, 2015 using method 3

Hydro power production (MWh)	KTH	Apollo
SE1	496691	496698
SE2	905579	905585
SE3	211893	211821
SE4	3889	3800
Total	1618052	1617904

Table 6.8 Internal trading of week 7, 2015 using method 3

Internal trading (MWh)	KTH	Apollo
Snitt1 (SE1 to SE2)	214384	214384
Snitt2 (SE2 to SE3)	693801	693801
Snitt4 (SE3 to SE4)	603775	603775
Total	1511960	1511960

Table 6.9 Exported energy of week 7, 2015 using method 3

Exported Energy (MWh)	KTH	Apollo
SE1	131342	131350
SE2	143418	143426
SE3	126537	126467
SE4	115353	115265
Total	516650	516508

It was mentioned that the internal trading is fixed to be the same as Apollo which can be seen in table 6.8. In table 6.7 it is shown that the total hydro production of the two models become very close to each other. The hydro productions of all areas are almost the same as Apollo. Moreover the exported energies in the two models are almost the same as each other.

Figures 6.11 to 6.15 show the comparison between hourly hydropower production in the two models and in different areas for week 7, year 2015 when method 3 is used.

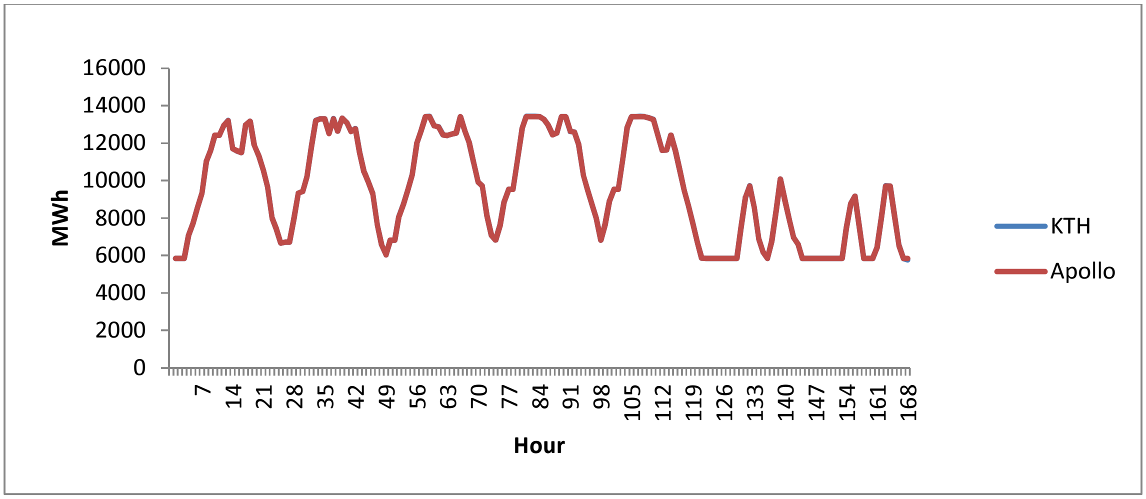

Figure 6.11 Total hydro power production of KTH and Apollo– week7, 2015 with method 3

The total hydro power production of the two models after using method 3 is shown in figure 6.11. It can be seen that the total production of the two models are almost the same in the two models after increasing the water in areas 1 and 2. The difference in area 1, area 2 and in total production that was caused by having lower production equivalent for higher discharge levels in KTH model is removed after increasing water.

Figure 6.12 presents the hydro power production of area 1 with method 3. The hydro power production of area 1 in method 3 is increased after increasing water. The hydro power production of KTH model was slightly lower than Apollo in area 1 in method 2. This difference was also due to lower production equivalent for high discharge levels, thus the difference is removed when the water in area 1 is increased.

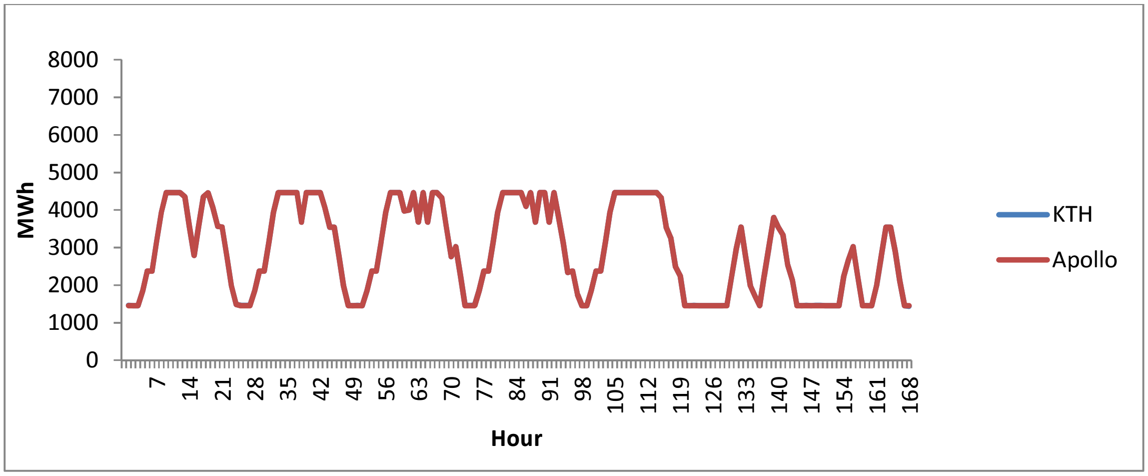

Figure 6.12 Hydropower production of KTH and Apollo in area 1 – week7, 2015 with method 3

It is shown in figure 6.13 that the hydropower production of area 2 in KTH model became the same as Apollo after increasing water. The water was increased by an amount that gave the same hydro production in KTH model as Apollo. The reason for the different hydropower production in method 2 was lower production equivalent at higher discharge levels which led to lower hydro generation. Therefore the difference can be removed by increasing water in reservoirs which leads to more hydropower production.

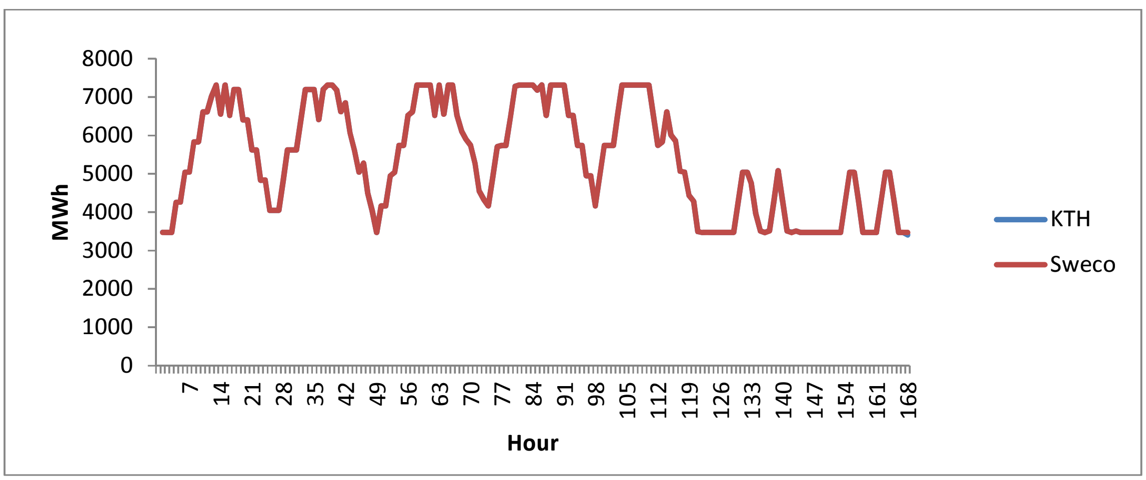

Figure 6.13 Hydro power production of KTH and Apollo in area 2 – week7, 2015 with method 3

The hydropower production of area 3 is shown in figure 6.14. It can be seen from the figure and also from table 6.7 that hydro productions of the two models in area 3 are the same with method 3. The hydro production of KTH model in area 3 was more than Apollo after using method 2. The reason was that more power was produced in this area to compensate for the lack of generation in area 2. After using method 3, more water in area 2 caused the production to be increased and be the same as Apollo, therefore there is no need for more production in area 3 and the hydropower production of area 3 becomes the same as Apollo.

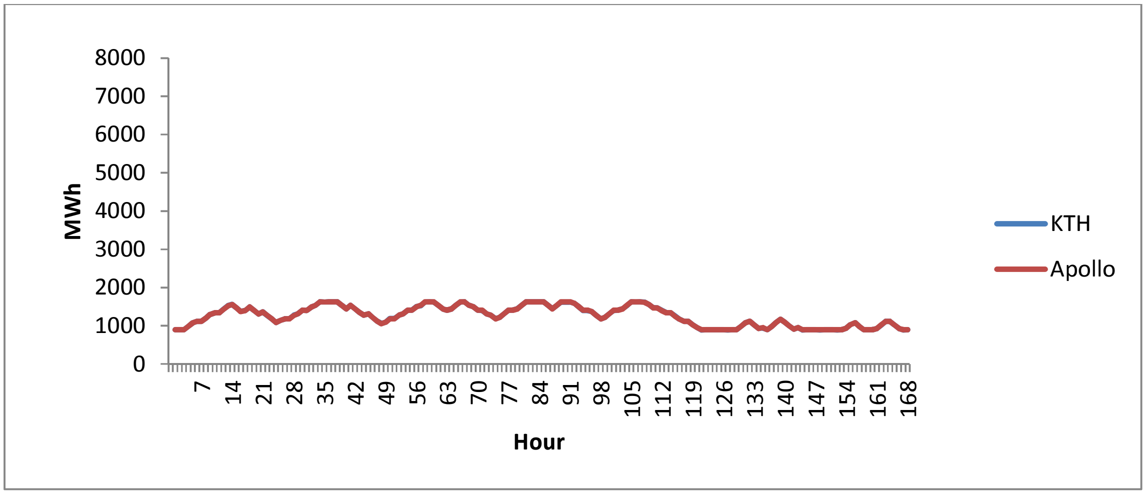

Figure 6.14 Hydro power production of KTH and Apollo in area 3 – week7, 2015 with method 3

In figure 6.15, the hydropower production in area 4 after using method 3 in shown. As it can also be seen in table 6.7, the hydro power production of KTH becomes the same as Apollo after using method 3 because there is no need of more generation in this area to compensate for the lack of generation in other areas in this method.

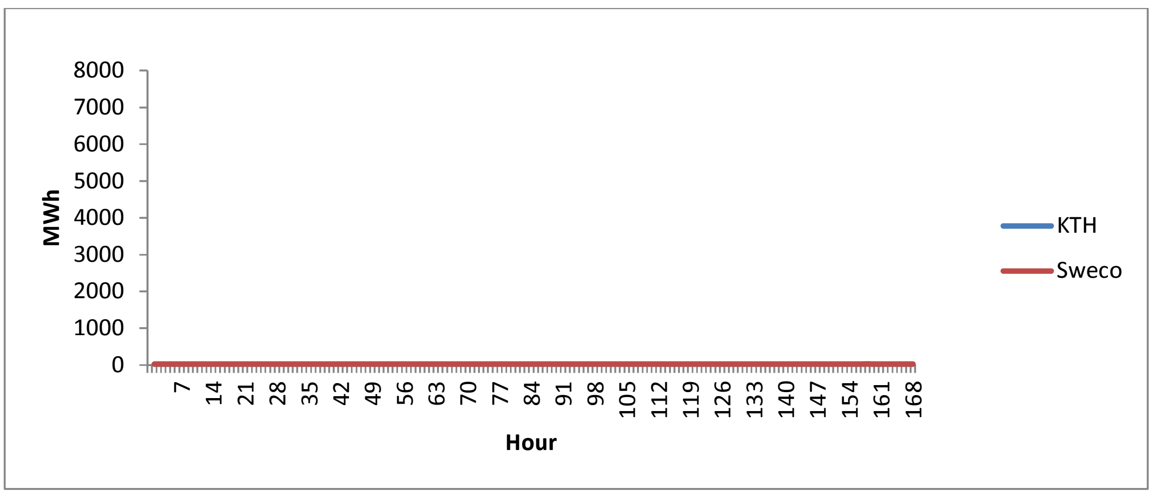

Figure 6.15 Hydro power production of KTH and Apollo in area 4 – week7, 2015 with method 3

6.4 Checking the load balance for a specific hour

In this section, generations from different sources including hydro power as well as demand and trading in transmission lines are presented for hour 105 of week 7, 2015. Tables 6.10 to 6.13 present mentioned data for three methods that were used in KTH model and also for Apollo. Load, wind generation and other generation are input data for KTH model which were taken from Apollo. Hydro generation and trading in internal and external transmission lines are the outputs of KTH model which should be compared to Apollo in method 1 and 2 but for method 3 internal trading is also an input for KTH model. It can be seen from tables how the hydro production and trading changes in different methods and see that when the hydro production is different from Apollo, external or internal trading will also change to satisfy load balance. It should be noted that negative sign of trading represents export and positive sign represents import.

Load = Wind generation+ Hydro generation+ Other generations- Export+ Import

Table 6.10 Hour 105 of week7, 2015 in KTH model-method 1

Area	Load (MWh)	Wind generation (MWh)	Hydro generation (MWh)	Other generation (MWh)	Internal trading (MWh)	External trading (MWh)
SE1	1312	12.6	4456.7	163.2	-1805.5	-1515
SE2	2660.8	39.8	6845.2	356.3	-4557.1	-23.5
SE3	15275.9	91	1528.3	12355.6	2203.1	-902.1
SE4	4610.9	97.8	108.9	760.8	4159.5	-516.1

Table 6.11 Hour 105 of week7, 2015 in KTH model-method 2

Area	Load (MWh)	Wind generation (MWh)	Hydro generation (MWh)	Other generation (MWh)	Internal trading (MWh)	External trading (MWh)
SE1	1312	12.6	4445	163.2	-1805.5	-1503
SE2	2660.8	39.8	6971.2	356.3	-4623.8	-83.5
SE3	15275.9	91	1810.3	12355.6	2174.6	-1155.5
SE4	4610.9	97.8	73.7	760.8	4254.7	-576.1

Table 6.12 Hour 105 of week7, 2015 in KTH model-method 3

Area	Load (MWh)	Wind generation (MWh)	Hydro generation (MWh)	Other generation (MWh)	Internal trading (MWh)	External trading (MWh)
SE1	1312	12.6	4456.2	163.2	-1805.5	-1515
SE2	2660.8	39.8	7311.8	356.3	-4923.7	-123.5
SE3	15275.9	91	1627.2	12355.6	2384.1	-1182
SE4	4610.9	97.8	23.2	760.8	4345.2	-616.1

Table 6.13 Hour 105 of week7, 2015 in Apollo

Area	Load (MWh)	Wind generation (MWh)	Hydro generation (MWh)	Other generation (MWh)	Internal trading (MWh)	External trading (MWh)
SE1	1312	12.6	4456.2	163.2	-1805.5	-1515
SE2	2660.8	39.8	7310.4	356.3	-4923.7	-122
SE3	15275.9	91	1626.5	12355.6	2384.1	-1182
SE4	4610.9	97.8	22.6	760.8	4345.2	-616

6.5 Conclusions

In the first method the lower installed capacity of KTH model leads to lower hydro production in this model. Moreover lower production equivalent in higher discharge level make the hydro production of area 2 to be much lower than Apollo. Instead compensation is considered to for the lack of hydro generation. The compensation is considering limits for external and internal transmission lines instead of using fixed amounts. Therefore the internal and external trading can change in a range and compensate for lack of generation.

In method 2, the installed capacity of KTH model was increased to be the same as Apollo. It was explained in section 6.2 why we do not consider installed capacity as a removable difference although we set it to be the same as Apollo in this method. The difference between total hydro power productions of the two models was essentially reduced by increasing installed capacity. However the difference that is caused by lower production equivalent in higher discharge levels still exists. In this method, the compensation methods that were used in method 1 should also be used to compensate for lower generation.

In the third method, water in reservoirs of area 1 and 2 was increased to compensate for the lower production which is due to low production equivalent at high discharge levels in KTH model. In this method all previous compensation methods except the range that was considered for internal trading are still present. Therefore the hydro generations in area 1 and 2 become the same as Apollo and the total hydro production of KTH model will also become the same as Apollo.

7. Closure

7.1 Summary

The main objective in this thesis was to exchange data between the two models of Swedish hydropower system named KTH and Apollo. The procedure was to use the inputs and some outputs of Apollo as the inputs for KTH model and compare the output of KTH model with corresponding output of Apollo.

In order to exchange data, the differences between input data of the two models were found and analyzed. It was tried to remove all the differences but one of the differences could not be removed. The differences that have been removed by data adjustment are called “removable differences” and the difference that has not been removed is called “remaining difference” which was lower installed capacity of KTH model.

Although most of the differences were removed, the solution of optimization problem was not feasible due to limiting the flexibility of KTH model and hydro generation was not enough to satisfy load balance. The reasons for lower generation in KTH model were lower installed capacity as well as lower production equivalent in the hours with higher discharge levels. Therefore three methods were introduced to compensate for lower hydro generation in KTH model.

Three compensation methods:

Method 1. Considering transmission limits

Method 2. Increasing installed capacity

Method 3. Increasing water

The results obtained by using three methods have been presented and the hydropower production of KTH was compared to hydropower production of Apollo.

7.2 Conclusions

After using method 1, the differences between hydro power productions of the two models were observed. It was discussed and concluded that the differences between hydro power productions in the two models are due to lower installed capacity of KTH model and also lower production equivalent of KTH model when the discharge level is high. By using method 2 and increasing the installed capacity of KTH model, the difference between total hydro power productions of the two models was essentially decreased. In method 3 the water was increased in area 1 and area 2 to compensate for the lower generation caused by lower production equivalent in higher discharge levels. Therefore we got the same hydro productions in the two models after using method 3.

In order to exchange data, some improvements were implemented on KTH model and some improvements are identified and proposed for future work. The improvements are toward removing all the differences between the two models and make the models more similar to the real model of Swedish hydropower system. It is also concluded from the final results that Apollo hydro power schedules are feasible according to KTH model of hydropower system and it shows that Apollo does not overestimate the flexibility of Swedish hydropower system.

7.3 Future work

Improvements which are proposed for future work are listed below.

1. Installed capacity of KTH model is much less than installed capacity of Apollo. The reason is that in KTH model the power plants with installed capacity of less than 5 MW are not considered. To be able to include those power plants in KTH model we should have some other data such as maximum discharge, delay time between power plants and maximum capacity of reservoirs. One of the further improvements can be to find the data for those small power plants and add them to KTH model.

2. The total capacity of KTH reservoirs calculated in MWh is different from the capacity of reservoirs which is given by Swedish energy and Apollo. As it was mentioned in 5.2.2.6 the small power plants that are not included affect the KTH reservoir capacity in two ways. By applying the previously mentioned improvement which is adding smaller power plants, their reservoirs will also be added and the production equivalent of small power plants will also be included in converting reservoirs units. Therefore the impact of not considering small power plants on reservoir capacity of KTH model will be vanished.

3. The start and end levels of reservoirs in KTH model is the same for all reservoirs except for Vänern and Vättern. In this master thesis the model was changed in a way to be able to give different start and end levels for different areas. However the model could be more precise and improved if each power plant could have its own start and end levels.

4. It is also a suggestion for future work to run tougher scenarios from Apollo resulting in higher variation of the hydro generation.

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Appendix

Optimization Theory

Optimization theory or mathematical programming in Mathematics is to solve a problem in the best way. Examples for an optimization problem are finding the shortest path to reach destination, maximizing the profit or finding the cheapest ticket price for a trip. An optimization problem concerns with maximizing or minimizing a function. That function is called the objective function. The variables which can be controlled are called optimization or decision variables [28], [29]. A standard optimization problem can be expressed as:

$$\textbf{minimize} \quad \boldsymbol{f}(\boldsymbol{x}), \qquad (A.1)$$

$$\textbf{subject to} \quad \boldsymbol{x} \in \boldsymbol{X}$$

According to above general formulation, the objective function is *f(x)* and vector *x* represents optimization variables. Usually there are some limitations on how the variables should be chosen represented by *X*. There are two types of such limitations which are constraints and variable limits. Constraints consist of more than one optimization variables while variable limits include just one variable [15].

Constraints $\quad g(x) \leq b \qquad (A.2)$

Variable limits $\quad \underline{x} \leq x \leq \overline{x} \qquad (A.3)$

An optimization problem is divided into two main categories which are linear problems and nonlinear problems [30], [31]. If objective function and constraints are linear functions then the optimization problem is a linear programming problem (LP problem). In general an LP problem is formulated as below:

$$\textbf{minimize} \quad \boldsymbol{C^T x} \qquad (A.4)$$

$$\textbf{subject to} \quad \boldsymbol{Ax} \geq \boldsymbol{b}$$

$$\boldsymbol{x} \geq \boldsymbol{0}$$

If any variable is an integer variable, then the optimization problems is called MILP which accounts for “Mixed Integer Linear Programming” [32].

The linear programming problem can be a stochastic problem or deterministic problem. Deterministic problems are formulated with known parameters while in stochastic programming some of the data that can include the objective or constraints is uncertain. Stochastic optimization problems are divided to different categories that can be found in [33].