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Modelling of the Flexibility of the Swedish Power System

YING LI

KTH ROYAL INSTITUTE OF TECHNOLOGY

ELECTRICAL ENGINEERING

Abstract

This master thesis studies the flexibility of Swedish power system. Because of the increase of fuel price and the environmental issues, renewable energy plays an increasingly important role. Sweden parliament has a planning frame of 30 TWh wind power energy per year in 2020. Wind power generation is largely dependent of wind speed. Since wind speed varies all the time and is hard to be predicted, the introduction of wind power will cause variation of power generation which needs to be balanced. Therefore, it is very important to study the regulation capacity of the power system in order to balance wind power. In Sweden, it is hydropower and thermal power that plays the role as balancing power. In earlier studies at Department of Electric Power Systems KTH, a model has been built to examine the flexibility of Swedish hydropower system. The aim of this thesis is to further develop this original model. In the improved model, the flexibility of thermal power in Sweden is included. Moreover, the improved model further considers the future value of stored water and the impact of delayed running water released from the upstream power plants at the end of simulated week.

The whole model is a large short-time planning problem and the objective of this model is to maximize the profits. In this thesis, the profit is expressed as the future value of hydropower minus the generation cost of thermal unit. Besides, the profit also includes the income and the cost for the trading energy. The improved model is built as an optimization problem in GAMS. The time step is one hour and the time span of each simulation is one week. The load consumption and wind power production in each area are given as time series. The constraints considered in this model include the generation limitations, operational constraints of thermal power plants, hydrological coupling of hydropower plants, load balance in each bidding area and transmission capacity. Several case studies are performed in this thesis. Two models, both original model and improved model, will be tested. To find out how large the regulation capacity the Swedish power system has, four different expansion levels of wind power: 0 MW, 4000 MW, 8000 MW and 12000 MW are introduced. The information regarding hydropower is obtained from statistic data in 2009 and the wind power data for each week is coming from scaling the data in earlier studies. The operational constraints of thermal power plants are based on the statistics data from 2008 to 2012. The main finding from these case studies is that spillage will not increase when more wind power is introduced to the system but only increase when the export capacity is reached and the surplus power cannot be exported to other countries. Therefore, it can be concluded that the Swedish power system has good possibilities to balance large amounts of wind power. However, some simplifications and assumptions are made when the model is built, which will give rise to some inaccuracy to the result. Therefore, in the end of this thesis, some future studies are suggested to further improve this model.

Key words: flexibility, short-term planning, hydropower, thermal power

Sammanfattning

I detta examensarbete studeras flexibiliteten i det svenska elsystemet. På grund av ökande bränslepriser och miljöproblem kommer betydelsen av förnybar energi att öka. Den svenska riksdagen har beslutat om ett planeringsmål på 30 TWh vindkraft till år 2020. Elproduktionen från vindkraft beror på vindhastigheten. Eftersom vindhastigheten varierar hela tiden och är svår att förutsäga, medför en ökning av vindkraften variationer i elproduktionen som måste balanseras. Därför är det mycket viktigt att studera elsystemets förmåga att balansera vindkraft. I Sverige sköts denna balansering av vattenkraft och termiska kraftverk. I tidigare studier vid Avdelningen för elektriska energisystem, KTH, har en modell utvecklats för att studera flexibiliteten i det svenska vattenkraftsystemet. Målsättningen med detta arbete är att vidareutveckla den ursprungliga modellen. I den förbättrade modellen inkluderas flexibiliteten i de svenska termiska kraftverken. Dessutom tar den förbättrade modellen hänsyn till värdet av sparat vatten och inverkan av vatten som rinner mellan två kraftverk i slutet av den simulerade veckan.

Hela modellen är att stort kotttidsplaneringsproblem och målfunktionen i denna modell är att maximera vinsten. I det här arbetet uttrycks vinsten som värdet av sparat vatten minus produktionskostnaderna i de termiska kraftverken. Dessutom ingår inkomster och konstnader för elhandel. Den förbättrade modellen är uppbyggd som ett optimeringsproblem i GAMS. Tidssteget är en timme och varje simulering omfattar en vecka. Lasten och vindkraftproduktionen i varje område är givna som tidsserier. De bivillkor som ingår i denna modell är begränsningar i elproduktion, driftbegränsningar i termiska kraftverk, hydrologisk koppling mellan vattenkraftverk, lastbalans i varje område och transmissionsbegränsningar. Flera fallstudier genomförs. Två modeller, den ursprungliga och den förbättrade, testas. För att undersöka hur stor balanseringsförmåga det svenska elsystemet har undersöks fyra olika nivåer på vindkraftsutbyggnad: 0 MW, 4000 MW, 8000 MW och 12000 MW. Data för vattenkraften erhålls från statistik för 2009 och vindkraftsdata är skalade data från tidigare studier. Driftbegränsningarna i termiska kraftverk baseras på statistik från 2008 till 2012. Den viktigaste slutsatsen från dessa studier är att spillet inte ökar då mer vindkraft introduceras i systemet, såvida man inte når gränsen för exportkapaciteten och det inte är möjligt att exportera överskottsproduktion till andra länder. Därför kan man dra slutsatsen att det svenska elsystemet har en god förmåga att balansera stora volymer vindkraft. Modellen bygger dock på vissa förenklingar och antaganden, vilket medför en viss osäkerhet i resultaten. Därför föreslås i slutet av rapporten några framtida studier för att förbättra modellen ytterligare.

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Ying Li

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Nomenclature

Sets

D_i	the set of indices for all power plants downstream of reservoir i, including power plant i itself
d	day within one week, from Monday to Friday
i	hydro power plant
id	unit characteristics
j	segment
k	the transmission line
g	Thermal power unit
U_i	the set of indices for all power plants upstream of reservoir i
w	set for simulated week
z	bidding area

Parameters

DT_g	the minimum down time of unit g
$danmin_{k,t}$	Export capacity to Denmark through line k during hour t
$danmax_{k,t}$	Import capacity from Denmark through line k during hour t
F_g	the initial hours during which the unit g must be offline
$finmin_{k,t}$	Export capacity to Finland through line k during hour t
$finmax_{k,t}$	Import capacity from Finland through line k during hour t
$germin_t$	Export capacity to Germany during hour t
$germax_t$	Import capacity from Germany during hour t
$\overline{H}_i$	The maximum hydropower production for plant i
h	heat contents,

L_g	The initial hours during which the unit *g* must be online
$Load_{z,t}$	Load in area *z* during hour *t*
$\bar{M}_i$	the maximum content of reservoir *i*
$M_{start,i}$	Reservoir content when the week starts i.e. at the beginning of hour 1
$M_{end,i}$	the end content of the reservoir *i*
$\Delta M_{i,d}$	Volume changes of reservoir *i* within day *d*
m_{start}	the start percentage
m_{end}	the end percentage
$normin_{k,t}$	Export capacity to Norway through line *k* during hour *t*
$normax_{k,t}$	Import capacity from Norway through line *k* during hour *t*
$\underline{P}_g$	maximum generation of unit *g*
$\overline{P}_g$	minimum generation of unit *g*
$Penalty_1$	Penalty cost for import from foreign countries
$Penalty_2$	Penalty cost for transmission between bidding area
$polmin_t$	Export capacity to Poland during hour *t*
$polmax_t$	Import capacity from Poland during hour *t*
$\bar{Q}_{i,j}$	The maximum discharge for plant *i* segment *j*
$\bar{Q}_i$	The maximum discharge for plant *i*
$\underline{Q_{i,t}}$	Minimum discharge for plant *i* during hour *t*
$\underline{Q_{i,d}}$	Daily minimum discharge for power plant *i* in day *d*
$\underline{Q_{i,w}}$	Weekly minimum discharge for power plant *i* in week *w*
$\underline{Q_{i,h}}$	Minimum discharge for current hours
$\Delta Q_{i,d}$	Discharge changes within day *d*
RU_g	Ramp-up constraints of unit *g*
RD_g	Ramp-down constraints of unit *g*
Rqh_i	Delay time for discharged water of plant *i* (hour)

Rqm_i	Delay time for discharged water of plant *i* (minute)
Rsh_i	Delay time for spilled water of plant *i* (hour)
Rsm_i	Delay time for spilled water of plant *i* (minute)
$\underline{S_i}$	Minimum spillage for plant *i* in each hour
SU_g	Start-up constraints of unit *g*
SD_g	Shut-down constraints of unit *g*
sf_z	Scale factor of bidding area *z*
T_g^{ini}	the number of hours that unit *g* was on/off before the planning week
$T_{inmin_{k,t}}$	Transmission capacity between different bidding areas from south to north
$T_{inmax_{k,t}}$	Transmission capacity between different bidding areas from north to south
$Thermal_{z,t}$	Thermal power production in area *z* during hour *t* (for original model)
UT_g	the minimum up time of unit *g*
V_i	The local inflow of power plant *i*
V_{sf}	the scale factor which is different for different week
$V_{start_{i,t}}$	the amount of water which flows during the hours before the week starts and runs to the power plant
$V_{2start_{i,t}}$	the water which is dropped to power plant *i* during part of an hour before week begins
v_g^{ini}	Initial condition of thermal unit *g*
w_i	the year average water flow for reservoir *i*
$Wind_{z,t}$	Wind power production in area *z* during hour *t*
$\mu_{i,j}$	the marginal production equivalent of power plant *i* segment *j*
λ_f	The estimated future price
λ_{ex}	Estimated price for export energy
λ_{im}	Estimated cost for import energy
$\gamma_{i''}$	the expected future production equivalent for power plant *i''*
$\tau_{i'}$	water delay time (hours) from power plant *i'* to power plant *i*
ϕ	the fuel price,

η	efficiency at the generation *G* [%],
β_g	the operational cost of unit *g*

Variables

$dan_{k,t}$	Transmission with Denmark through line *k* during hour *t*
$dan_{ex_{k,t}}$	Export to Denmark through line *k* during hour *t*
$dan_{im_{k,t}}$	Import from Denmark through line *k* during hour *t*
$fin_{k,t}$	Transmission with Finland through line *k* during hour *t*
$fin_{ex_{k,t}}$	Export to Finland through line *k* during hour *t*
$fin_{im_{k,t}}$	Import from Finland through line *k* during hour *t*
$F(P_{g,t})$	fuel input as a function of generation,
$Gas_{z,t}$	Power generation from gas turbine in area *z* during hour *t*
ger_t	Transmission with Germany during hour *t*
ger_{ex_t}	Export to Germany during hour *t*
ger_{im_t}	Import from Germany during hour *t*
$H_{i,t}$	Hydropower production in plant i during hour *t*
$H_{tot_{z,t}}$	Total hydropower production in area *z* during hour *t*
$M_{i,t}$	the content of reservoir *i* at the end of hour *t*
$nor_{k,t}$	Transmission with Norway through line *k* during hour *t*
$nor_{ex_{k,t}}$	Export to Norway through line *k* during hour *t*
$nor_{im_{k,t}}$	Import from Norway through line *k* during hour *t*
$Nuclear_{z,t}$	Generation from nuclear power plant in area *z* during hour *t*
$Other_{z,t}$	Other thermal power generation in area *z* during hour *t*
$p_{g,t}$	the output of unit *g* in hour *t*
pol_t	Transmission with Poland during hour *t*

pol_{ex_t}	Export to Poland during hour *t*
pol_{im_t}	Import from Poland during hour *t*
$Q_{i,j,t}$	the discharge of the reservoir *i*, segment *j*, hour *t*
$Qup_{i',t}$	the amount of discharged water from the power plant i’ which directly upstream of power plant *i*
R_i	Running water released from upstream power plant of plant *i* at the end of week
$S_{i,t}$	the spillage of power plant *i* during hour *t*
$Sup_{i',t}$	the amount of spilled water from the power plant *i’* which directly upstream of power plant *i*
$T_{in_{k,t}}$	the transmission between different bidding area
$v_{g,t}$	a binary variable which stands for the unit commitment in power plant *g* during hour *t* (1, if the unit is committed, 0 otherwise).

Chapter 1

Introduction

This chapter introduces the background and the motivation of this project. It also defines the problem and objective of this thesis. The chapter ends with a reading instruction of this thesis.

1.1 Background

The shortage of energy and the climate changes become the greatest issues concerned by many countries in recent years. Due to the increasing price of oil and coal and the environmental issues, renewable energy gains popularity. Figure 1.1 shows the net changes in EU installed power capacity from 2000 to 2013. From this figure, it is obvious that since 2000 the renewable energy has great development. On the contrary, energy produced by nuclear, coal and fuel oil are continuously reduced and replaced by renewable energy instead. Among all the renewable energy, wind power is the most rapidly developing renewable power. In 2000, the annual wind power installation was only 3.2 GW. Until 2013, the annual wind power installation became 11 GW [1].

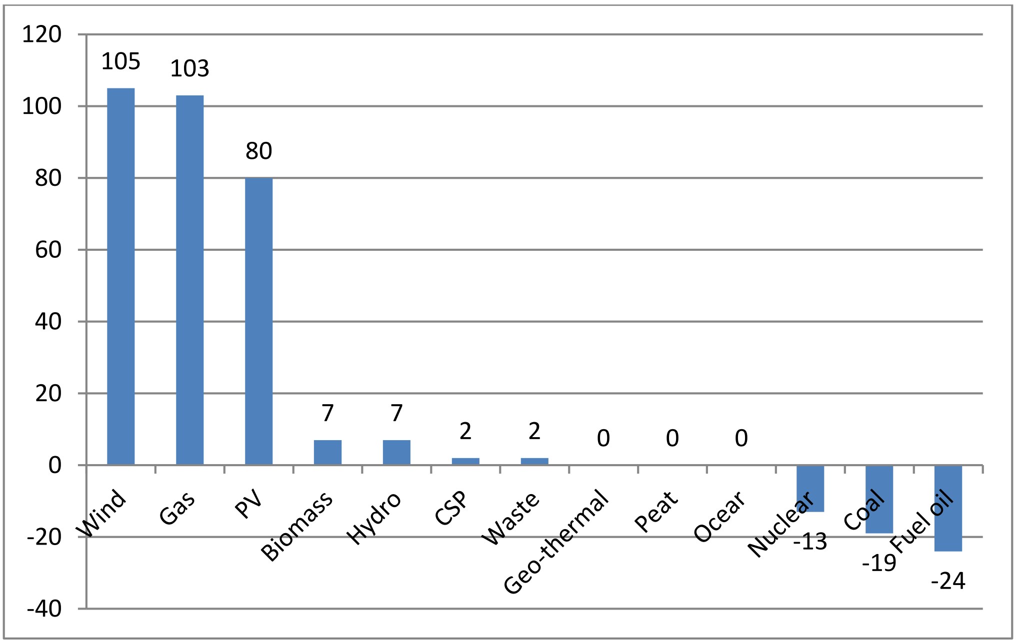

Figure 1.1 Net electricity generating installations in EU 2000-2013 (GW) [2]

In the following years, EU still has the intension and plan to develop renewable energy. By 2020, EU aims to reduce the greenhouse gas by at least 20% compared to 1990 levels [3]. They also aim to increase the share of renewable energy sources in the total energy consumption by 20% [3]. To meet this target, each member country also establishes its own target. For Sweden, 49% energy in final energy consumption should be from renewable sources in 2020 [3].

Swedish Parliament has set up a planning frame of 30 TWh wind power energy per year in 2020, including 20 TWh onshore and 10 TWh offshore [4]. By the end of 2013, the wind power capacity in Sweden was 4,470 MW [2]. To achieve the target of 30 TWh wind power energy, the wind power installed capacity in Sweden will have to be around 12000 MW [5]. Compared to the installed capacity in 2013, a large amount of wind power will be introduced in Swedish power system. Wind power generation largely depends on the wind speed and wind condition. Due to the variation and unpredictability of wind speed, a large-scale expansion of wind power generation results in an increased need for balancing capacity of the power system. Therefore, it is very important to study the flexibility of the Swedish power system to balance a large-scale integration of wind power generation. This thesis will study the regulation capability of hydropower and thermal power in Sweden.

1.2 Problem definition

Earlier studies have already presented a model, which estimates the flexibility of hydropower in Sweden [6] [7]. The objective of this thesis is to further develop this model and to test the flexibility of Swedish power system. The major improvement includes considering the future value of stored water and the flexibility of thermal power in Sweden.

The improved model proposed in this thesis is a development of the model presented in [7]. The problem is a large planning problem based on the main assumption of perfect information and perfect competition. Both models which are studied in this thesis are using optimization theory to simulate the operation of Swedish power system. The improved model is built as a mixed integer linear optimization problem which aims to maximize the total profit. The constraints considered in the model can be summarized as follows.

- For both hydropower and thermal power plants, the power generation is limited by the maximum and minimum generation level of different plants;
- For hydropower plants located in the same river system, the hydropower coupling between the power plants must be considered in order to avoid spillage;
- For some hydropower plants, specific discharge requirement must be met;
- For thermal power plants, more operational constraints must be fulfilled. For example, the thermal power plants cannot be started up immediately. It may take some time to heat the fuel and increase the temperature to certain level. There may be also limitation on how fast the generation has to be increased or decreased;
- The Swedish electricity market is separated into four bidding areas. Furthermore, the Swedish power system is also connected to other neighboring countries. The transmission limitations are included in this model;
- In each bidding area, the generation plus the import energy must be equal to the consumption and the export.

Based on the above constraints, the optimal solution can be obtained. The detailed information about both models will be presented in chapter 3 and 4.

1.3 Overview of the report

The whole structure of this report is summarized as follows:

In chapter 2, the background knowledge on system planning and electricity market will be presented. This chapter will also describe the general usage of Swedish energy.

In chapter 3, the original model in earlier study will be presented.

In chapter 4, the improved model is described. The formulation of objective function and the constraints used in the optimization problem are explained. This chapter is ended by a discussion about the improved model.

In chapter 5 relevant case studies will be presented. The background of case studies, the results of the simulation and related conclusion will be given in this chapter.

In chapter 6, the summary of the study will be given. Furthermore, some possible further studies are suggested in this chapter.

Chapter 2

Literature study

This chapter describes the general usage of energy in Sweden first. Then background knowledge on electricity markets including market players and trading periods will be presented. Finally, system planning problems and basic consideration for the model of hydropower and thermal power plants in short-term planning problem will be explained.

2.1 Energy in Sweden

In 2012, the total electrical power output was 162.0 TWh: Hydropower was 78.0 TWh (48.1%), Nuclear power was 61.4 TWh (37.9%), wind power was 7.2 TWh (4.4%), and other thermal power was 15.5 TWh (9.6%) [8]. This section will give an overview on the electricity generation and energy source in Sweden.

Hydropower

As a renewable energy, hydropower has low carbon emissions and little impact on environment. In Sweden, since the first large hydropower plant started producing electricity in 1909 [9], hydropower developed considerably and until 2012, half of Swedish electricity is produced by hydropower [10]. Electricity has the characteristic that it cannot be stored in the system. As long as electricity is produced, it must be consumed somewhere immediately. However, thanks to the hydropower plants with reservoirs, water can be stored in the reservoirs. As a result, the hydropower can be used in an optimized way. In Sweden, large quantity of hydropower makes it perfect to cover base load power, which is the amount of electricity always needed [11], by hydropower. Furthermore, hydropower generation can be quickly changed to balance the difference between production and consumption in the system. Therefore, besides supplying base load, hydropower has also another important role as balancing power, which is the electricity output that can quickly be turned on and off to meet variations in demand and supply [11].

Nuclear Power

Nuclear power was started in the 1970's in Sweden [9]. Nuclear power has low carbon emissions and low operation cost. It can provide large-scale electricity generation. Nuclear power plants have high fixed cost, therefore, it is always more profitable to operate nuclear power plants at maximum generation level. Therefore, together with hydropower, nuclear power covers Swedish base load power. However, nuclear power unit cannot be started or stopped easily and quickly. As a result, nuclear power is usually not used as balancing power.

Other thermal power

Since Sweden developed nuclear power, the fossil-based (coal, oil) condensing power is continuously phased out from the system [8]. The combustion of fossil fuel emits CO_2 which has negative impact on environment. Although nowadays the thermal power is reduced, it is still necessary to use thermal power generation to meet the consumption requirement. Natural gas is growing energy which has lower carbon emission than other fossil fuels [11]. Natural gas power provides high degree of flexibility of power system and can be used as balancing power [11]. Sweden also has a large amount of bio-mass fuelled thermal power. For example, in 2013, the net generation from biomass was 10 TWh [12].

Wind Power

Wind power is a renewable energy which has the following advantages 1) due to the decreased usage of fuel, the operational cost of power system can be reduced; 2) wind power has no carbon emission, so introducing wind power will improve the environment. Nowadays wind power is the fastest growing source of energy in EU [11]. Sweden has a target to introduce a large amount of wind power in 2020. However, since wind power generation largely depends on wind condition, the variation and unpredictability of wind power will have negative impact on power system. Large varied wind power integration needs to be balanced by other types of energy. In Sweden, the balancing power is mainly provided by hydropower. Thermal power can also contribute to balancing the whole system.

2.2 Electricity markets

2.2.1 Overview of a general electricity market

Electricity is traded in the electricity market and transferred from the producers to the consumers. Some important players in electricity market will be explained as follows.

- Producers and consumers: Producers are the players who supply electrical power and the consumers are the players who consume electrical power. Both of the producers and consumers are connected to the power system and they need to pay for the connection [13].
- Transmission system operator: Transmission system operator is responsible for maintaining the operation of power system, including maintaining the physical balance between production and consumption, frequency control, etc. [13]. Transmission system operator also often acts as grid owner.
- Balance responsible player: In power system, production and consumption must be in balance at any time. The physical power deviation can be balanced by automatic control systems [13]. However, the imbalanced power must be paid by corresponding players as well. Balance responsible player is responsible for keeping the financial balance between the production and consumption.

- Network owner: The network owner provides the physical trading place for the electricity [14]. It is also the network owner's responsibility to make sure that electricity can be transported from the producers to the consumers [14]. A network owner must have a network permit to build and run high-voltage lines. [14]

To fulfill the balance between the production and the load, the electricity must be consumed instantaneously when it is produced. In power system, the physical power balance is maintained by automatic control systems [13], but the trading of the power cannot finish in real time. Therefore, the electricity trading is generally divided into three phases [13].

- The ahead trading: In this phase, the producers and consumers decide the amount of electricity they need to sell or buy. They also need to submit their purchase and sell bids respectively. Then the electricity price is determined according to the purchase and sale bids. The ahead trading is commonly one day before the real electricity trading.
- Real-time trading: In this phase, the electricity trading really occurs. In real-time market, system operator must maintain the safe operation of power system [13]. Therefore, if necessary, system operator has to change the production and consumption respectively [13].
- Post trading: In this phase, the balance responsible players must handle the deviation between the planned production/consumption and the actual production/consumption, so that all players are paid for the power they have produced and are paying for the power they have extracted [15].

2.2.2 The electricity market in Sweden

In Sweden, the electrical power is mainly provided by hydropower and nuclear power. Due to the natural condition of Sweden, there is more hydropower in North Sweden. Because of the population distribution in Sweden, the major electricity consumption is located in the southern part of Sweden. Svenska Kraftnät runs the national grid and has the role of Transmission System Operator (TSO) [16].

The electricity market in Sweden is managed by four systems: Elspot, Elbas, a real-time balancing market and a balancing settlement [17].

- Elspot: Elspot is a day-ahead market where the contract between seller and buyer for the power in the following day are made [18]. Before 12:00, all the producers need to decide the amount and the hourly price of the power they can deliver. Similarly, all the buyers also have to submit the amount of power they need and at what price they want to buy the power each hour. After calculation, the hourly price will be announced at 12:42 or later, and the dealing will be closed [18]. Form 00:00 of the following day, the power will be delivered hour by hour according to the contract. Currently, Sweden is divided into four bidding areas. North Sweden has surplus power and South Sweden has deficit. Therefore, the transmission within Sweden is normally from north to south.

When large power needs to be transferred and the transmission capacity is reached, the price in different areas will be different [18].

- Elbas (Electricity Balance Adjustment System): Elbas is an intraday trading market where the day-ahead production and consumption can be adjusted continuously [19]. The available capacities of Elbas trading for 24 hours of the following day are published at 14:00 [20]. For most of the trades handled in Elspot, the balance of production and consumption can be kept. However, if incidents such as suddenly decrease of production or strong variation of wind power occurs, Elbas acts as a balancing market to the day-ahead market [20]. At Elbas, the imbalance caused by the incidents will be adjusted. As mentioned before, large amount of wind power is introduced in power system. The variation and unpredictability characteristics of wind power make Elbas play an increasing important role in electricity market. [20]
- A real-time balancing market: In the real-time trading phase, Svenska Kraftnät, who is the system operator and network owner in Sweden, is responsible for keeping the balance between the production and consumption. When the production is not equal to the consumption, the frequency of the whole system will change. Frequency control includes primary frequency control, the secondary frequency control and the tertiary control. For primary frequency control, the system is controlled by automatic control system. When the frequency is deviated from the nominal frequency, 50 Hz in Sweden, the power plants, which participate in the primary control and are sensitive to frequency, will response and change their generation correspondingly. In the Nordic system, the frequency controlled normal operation reserve is at least 600 MW [21]. When the frequency is 49.1 Hz or 50 Hz, the whole reserve will be up-regulated or down-regulated within 2-3 minutes [21]. When the frequency falls under 49.9 Hz, the frequency controlled disturbance reserve will be activated [21]. The frequency controlled disturbance reserve is at least 1000 MW and will be fully activated at 49.5 Hz [22]. After the primary control, the balance will be restored and the frequency will be varied. The tasks of secondary control are to restore the system frequency to the normal value and release the reserve of primary control [13]. Secondary control is performed by manual control. Since 2013, an automatic tertiary control (automatic generation control), has been introduced in the Northern Europe synchronous area [23]. Based on the frequency deviation, Svenska Kraftnät determines how large the imbalance is and does the balance regulation by selling or buying the regulating power [17] [24].
- Balance settlement: The balance settlement takes place the day after the delivery. The cost or income of the Svenska Kraftnät for buying or selling the regulating power is distributed among the balance responsible players [16]. Svenska Kraftnät will summarize the amount of power players planning to produce or consume as well as the amount of power players actually produce or consume. The balance responsible players who have a negative balance need to buy the imbalance power from Svenska Kraftnät. On the contrary, the balance responsible players who have a positive balance get paid by Svenska Kraftnät. [13] [24]

2.3 System planning

2.3.1 Overview of system planning

The purpose of system planning is to utilize all energy sources in an efficient way [13]. According to the planning time horizon, planning problem can be categorized as [25]

- Long-term planning: The time span is several years.
- Mid-term planning: The time span is typically one year.
- Short-term planning: The time horizon is from one day to one week.

This thesis mainly focuses on studying the operation of the Swedish power system by using short-term planning method and optimization theory. Each simulation comprises one week.

The aim of short-term planning is to determine the operational plan of all the power plants which are interested in the study in the closet future [13]. Normally the time step of the planning is chosen as the trading period in the electricity market [13]. A short-term planning problem is generally formulated as an optimization problem. For every player in electricity market, the objective function of the optimization problem is to maximize its own profit [13]. To get an optimized solution, some constraints such as physical or legal limitations need to be considered. The general formulation of short-term planning problem is [13]

$$\begin{aligned} \text{Maximize} \quad & \textit{the income of planning period + future income} \\ & \textit{– the costs during the planning period – the future costs} && (2.1) \\ \text{Subject to} \quad & \textit{physical limitations,} && (2.1a) \\ & \textit{legal limitations.} && (2.1b) \end{aligned}$$

Then the basic consideration of modelling hydropower and thermal power plants in short-term planning problems will be discussed. The main target of this thesis is to build a linear model. Moreover, integer variables should be avoided since binary variables will increase the complexity of simulation, which leads to longer computation time. More detailed technical description will be presented in the chapter 3 and 4.

2.3.2 Hydro power planning

Hydro power plants have quite low variable operation cost and limited volume of reservoirs. In order to use hydropower in a more efficient way, it is more profitable to save water in the reservoirs in the periods when the electricity prices are low and use it in the periods when the electricity prices are high.

Hydropower generation

The hydropower production is a non-linear function of head and discharge. To formulate linear optimization problem, the relation between generation, head and discharge must be simplified. The consideration of head will largely increase the complexity of the model. It is not worth doing so in this study. Therefore, this factor can be neglected. In most of the planning problem, the hydropower generation is often approximated as a piecewise linear function of water discharge. The breakdown points are located at the local maximum efficiency points [13]. For each segment, the marginal production equivalent can either be incremental or decreasing. In order to avoid integer variables, the piecewise linear function should be formulated in such way that the discharge at first segment should be fully utilized before the discharge of next segment is made [13].

Hydrological coupling

In the same river system, the hydropower plants locating at the upstream will have an effect on the hydropower plants locating at down-stream. Considering the hydrological coupling between hydropower plants, the reservoir content should be expressed as [13]:

$$\textit{New reservoir content} = \textit{Old reservoir content} + \textit{water discharged/spilled from upper plant} - \textit{discharged water} - \textit{spilled water} + \textit{water inflow} \qquad (2.2)$$

This hydrological balance must be fulfilled at each hour.

Future value

For the hydropower plants with reservoir, the hydropower should be scheduled in an optimal way so that when the electricity price is low, the water should be saved for the situation when the electricity prices are high. Therefore, when planning the operation of hydro power plants, the value of stored water should also be considered. If the future value is not taken into account, the hydropower plants will generate as much as electricity during the planning period and have no water left in the reservoir [6]. The value of stored water can be included by two methods. The first way is to estimate a future price. Then the future income can be obtained by multiplying the future price and the amount of stored water. The other way is to simply set a target level for each reservoir [6] [7]. At the end of the planning period, all the content of reservoirs must reach their own target level [6] [7].

Physical/legal limitations

For each hydropower plant, the content of the reservoir must be less than the maximum reservoir capacity. During the operation of the hydropower plants, some special rules may also need to be considered. For example, for some power plants, the minimum discharge will differ in different days or hours; there are some requirements on how fast the level of water can change; sometimes the minimum content level for the reservoirs must be met, etc.

2.3.3 Thermal power planning

The variable operation costs of thermal power plants must be taken into account when planning the behavior of thermal power plants. The commitment of thermal power plants should be scheduled optimally in order to operate the system in the most profitable way.

Operation cost

The operation cost depends on the fuel price, the heat contents of the used fuel and the efficiency of the generation. If the efficiency of the power plant is constant, then the operation cost will also be constant. However, if the efficiency is varying with the amount of generation, the operation cost will become a non-linear function [13]. To solve thermal power scheduling problem, the most useful tool is linear programming. Therefore, the operation cost must be approximated by piecewise linear function or stair function [26].

Start-up cost

When starting up a thermal power plant, certain amount of fuel is needed in order to heat the boiler to required temperature, which will result in start-up cost. The start-up cost can vary from a maximum "cold-start" value to a much smaller value if the unit was only turned off recently and is still relatively close to operating temperature [26]. Usually, three types of start-up costs are provided by the manufacturer, which are cold start-up, warm start-up and hot start-up [27]. To take start-up cost into consideration, binary variables must be introduced in the planning problem. The introduction of binary variables will give rise to longer computation time.

Generation constraints

The power output can never be higher than the installed capacity. Particularly, for some power plants, there exist minimum generation constraints. During the operation, thermal power plants cannot change their power generation at any rate [13]. Therefore, in a planning problem, it is also necessary to consider the ramping constraints, which limit how much the generation can change from one hour to another [13]. Furthermore, in this thesis, since the thermal power is modelled as aggregated units, it is difficult to consider start-up cost. Therefore, in order to minimize the start-up cost of thermal power plants, the minimum up and down time constraints should be included in this model.

Mixed-Integer Linear Programming method has been widely applied to solve the optimization problems for scheduling thermal power units [28]. However, as mentioned before, due to the introduction of binary variables, the time required to solve thermal unit commitment problem is a critical limitation that restricts the size and scope of the models [29]. Therefore, it is important to create a model which contains as few binary variables as possible, so that the computation complexity and time can be reduced.

Chapter 3

The original model in earlier studies

This chapter starts with an overview of the original model presented in the earlier studies [6] [7].*Then the objective function and the constraints will be explained.*

3.1 Overview of the original model

Earlier studies [6] [7] have already built a model to study the hydropower system in Sweden and its regulation capacity to balance the wind power. The model is built as a linear optimization problem in GAMS, where the input data are imported from Excel sheets and the output data are also exported to Excel sheets. The model uses a time step of one hour and each simulation comprises one week. The main purpose of this model is to use the simulation to study the behavior of Swedish hydropower system based on the assumptions of perfect information and perfect competition. The results of the simulation only study the possibility of the system to balance the power variation. The actual schedule of each power plant in Swedish power system won't be determined based on the simulated results.

The original model does not cover all the power plants in Sweden. It only includes hydro power plants with the installed capacity larger than 5 MW. Therefore, there are in total 256 hydropower plants in the model and about 96.5% of all installed hydropower is included. The overall installed capacity of hydropower in Sweden is about 16 200 MW and the total capacity of hydropower plants in this model is 15 640MW [7]. In order to cover the entire Swedish hydropower production, the output hydropower generation of the model will be scaled up by a scale factor.

In the following sections, the original model will be presented. All the equations and constraints refer to Fredrik Obel's report [7].

3.2 Description of the original model

The original model used in [7] is formulated as

Maximize *the hydro power production for one week* (3.1)

Subject to *Hydrological balance for each hydropower plant* (3.1a)

Load balance for each bidding area (3.1b)

Physical limitations (3.1c)

Economic/legal limitations (3.1d)

3.2.1 Objective function:

$$Max \qquad \sum_{z,t} sf_z \times H_{tot_{z,t}} \tag{3.2}$$

Where

sf_z =Scale factor of bidding area *z,*

$H_{tot_{z,t}}$=Total hydropower production in area *z* during hour *t.*

In this model, the hydropower is assumed to operate in such a way that the hydropower generation of planning week is maximized. The model contains 256 hydropower plants, which means that about 96.5% of installed capacity of hydropower in Sweden is included in the model. To cover the entire Swedish installed capacity of hydropower, the output of the model in each electricity area needs to be scaled by a certain scale factor. The scale factor can be obtained by the ratio between the actual total installed capacity of hydropower and the total installed capacity of hydropower considered in the model in each area.

Basically, to maximize hydropower production is to operate the hydropower plants in an optimized way so that the water can be spilled as little as possible. In reality, maximization of hydropower production is not exactly the same as minimization of spillage, but the difference is small. Therefore, an alternative objective function can be obtained by minimizing spilled energy.

$$Min \qquad \sum_{i,t} S_{i,t} \times \mu_{i,1} \tag{3.3}$$

Where

$S_{i,t}$ = the spillage of power plant *i* during hour *t*,

$\mu_{i,1}$ = the marginal production equivalent of power plant *i*. Here it is assumed that the spilled energy is obtained at the best efficiency.

In order to make sure hydropower can be used to regulate in the first place instead of imports of electricity, penalty is introduced to the objective function. As a result, the imports from other countries and the unnecessary transmission between bidding areas can be minimized.

$$Penalty_1 \times \sum_{k,t}(dan_{k,t} + nor_{k,t} + fin_{k,t} + pol_t + ger_t) \tag{3.4}$$

$$Penalty_2 \times \sum_t(T_{in_{1,t}} + T_{in_{2,t}} + T_{in_{3,t}}) \tag{3.5}$$

Where

$T_{in_{k,t}}$= the transmission between different bidding areas, $Tin_{1,t}$ is the transmission between area 1 and 2, $Tin_{2,t}$ is the transmission between area 2 and 3, $Tin_{3,t}$ is the transmission between area 3 and 4.

The model presented in [7] designs different penalties for imports from other countries and transmission between bidding areas respectively. A penalty equal to 1 is used to reduce imports and a far less punishment (0.001) is used to avoid unnecessary transmission between electricity bidding areas in Sweden.

3.2.2 Hydrological balance

$$M_{i,t} = M_{i,t-1} - \sum_j Q_{i,j,t} - S_{i,t} + \sum_{i'} Qup_{i',t} + \sum_{i'} Sup_{i',t} + V_i + V_{start_{i,t}} + V_{2start_{i,t}}$$

$$\text{for } t>1 \qquad (3.6a)$$

$$M_{i,t} = M_{start,i} - \sum_j Q_{i,j,t} - S_{i,t} + \sum_{i'} Qup_{i',t} + \sum_{i'} Sup_{i',t} + V_i + V_{start_{i,t}} + V_{2start_{i,t}}$$

$$\text{for } t=1 \qquad (3.6b)$$

Where

$M_{i,t}$ = the content of reservoir *i* at the end of hour *t,*

$M_{start,i}$ = reservoir content when the week starts i.e. at the beginning of hour 1,

$Q_{i,j,t}$ = the discharge of the reservoir *i*, segment *j*, hour *t*,

$S_{i,t}$ = the spilled water of reservoir *i* during hour *t*,

$Qup_{i',t}$ = the amount of discharged water from the power plant *i'* which directly upstream of power plant *i*,

$Sup_{i',t}$ = the amount of spilled water from the power plant *i'* which directly upstream of power plant *i*,

V_i = the local inflow of power plant *i*,

$V_{start_{i,t}}$ = the amount of water which flows during the hours before the week starts and runs to the power plant *i*,

$V_{2start_{i,t}}$ = the water which is dropped to power plant *i* during part of an hour before the week begins.

When hydropower plants are located in the same river system, the water released from the upstream power plant can also be used to generate electricity in the downstream power plant. Therefore, hydropower coupling must be taken into account. Hydrological balance for each power plant is formulated as the reservoir content at the end of hour *t* is equal to the reservoir content of previous hour minus discharged water and spilled water during this hour plus released water from power plants directly upstream and plus the local inflow.

Since the time step is one hour and each simulation is for one week, some of the variables shown in the (3.6a) and (3.6b) need to be calculated or scaled.

Discharge and spillage

To simplify, the delay time between two power plants is regarded as a constant value. Assuming the delay time for discharged water between upstream power plant *i’* and the power plant *i* is $Rqh_{i'}$, hours and $Rqm_{i'}$ minutes, $Qup_{i',t}$, the amount of water from upstream power plant *i’* during the hour *t* can be obtained by

$$Qup_{i',t} = \frac{Rqm_{i'}}{60} \sum_j Q_{i',j,t-(Rqh_{i'}+1)} + \frac{60-Rqm_{i'}}{60} \sum_j Q_{i',j,t-Rqh_{i'}} \tag{3.7}$$

A similar expression can be formulated for the spilled water $Sup_{i',t}$.

Reservoir contents

At the beginning of the week, the initial content is designed as a certain percentage, which is the same for all the reservoirs except for Vänern and Vättern, of the reservoir’s maximum content.

$$M_{start,i} = m_{start} \times \overline{M}_i \tag{3.8}$$

Where

$M_{start,i}$ = the content of reservoir *i* at the beginning of planning period,

m_{start} = the start percentage,

$\overline{M}_i$ = the maximum content of reservoir *i*.

In this model, the stored water is considered by setting a certain final reservoir level at the end of each week. Similar to the initial content levels of reservoirs, the end content level is also chosen as a certain percentage of the reservoir’s maximum content and this percentage is the same for all the reservoirs except for Vänern and Vättern. Hour 168 is the last hour of each simulated week, therefore

$$M_{t,168} = M_{end,i} = m_{end} \times \overline{M}_i \tag{3.9}$$

Where

$M_{end,i}$ = the end content of the reservoir *i*,

m_{end} = the end percentage.

For Vänern and Vättern, the actual data are used due to their size and location.

Inflow

The water flow for each week can be obtained by scaling the average water flow of the year.

$$ws_i = V_{sf} \times w_i \tag{3.10}$$

Where

w_i = the year average water flow for reservoir *i*,

V_{sf} = the scale factor for water inflow which is different for different week.

The scale factors for different weeks come from the Swedish Energy's weekly statistics. Apparently, the scale factor will be large during the spring flood and small during the winter since little inflow runs to reservoirs.

The local inflow for reservoir *i* is the difference between the average water flow for this power plant for the week and the water flow coming from the power plants upstream. The inflow is assumed to be equal in every hour during the week for each power plant. The expression of local inflow can be given as

$$V_i = ws_i - \sum_{i'} ws_{i'} \qquad (3.11)$$

Where

$ws_{i'}$= the water flow from power plant *i'* which is upstream of power plant *i*.

At the beginning of each week, it is assumed that the water is drained from the power plants upstream during the hours before the simulated week begins. As mentioned in Fredrik Obel's report [7], the assumption is that before the simulation, the water dropped from the upstream power plant is corresponding to the yearly average water flow. If the delay time between the power plant *i* and the power plant *i'* upstream is $Rqh_{i'}$, the starting inflow of power plant *i* can be obtained by

$$V_{start_{i,t}} = \sum_{i'} ws_{i'} \qquad if\ t < Rqh_{i'} \qquad (3.12)$$

Since the model has a time step of one hour, a separate equation is used for the water which is dropped to power plant *i* during part of an hour before the week begins.

$$V_{2start_{i,t}} = \sum_{i'} ws_{i'} \times \frac{60 - (60 - Rqm_{i'})}{60}$$

$$if\ t < Rqh_{i'} + 1\ and\ \ Rqm_{i'} < 60 \qquad (3.13)$$

3.2.3 Load Balance for each bidding area

Hydropower production

The electricity production of a hydropower plant depends on head and the amount of water flowing through the power plant's turbines [13]. The relation between the production, discharge and the head is a complex nonlinear function. In this model, to make the model be linear, the power output is approximated as a function of the amount of water that flows through the turbines and the impact of the head is ignored.

The ratio between the energy generation and the discharge through the turbines (*γ(Q)=H(Q)/Q*) is defined as the production equivalent. The production equivalent is different for different discharges. Here, a piecewise linear function can be used to describe the relationship between power generation in a hydropower plant and the discharge flowing through turbine. The breakpoints between the segments are preferably located at the discharge where the efficiency is local maximum. The original model in [7] divides the discharge into two segments. The breakpoint is at 75% because hydropower plants generally have their best efficiency at 75% of the maximum discharge [7]. Therefore, the maximum discharge for each segment will be

$$\bar{Q}_{i,1} = \bar{Q}_i \times 0.75 \tag{3.14}$$

$$\bar{Q}_{i,2} = \bar{Q}_i - \bar{Q}_{i,1} \tag{3.15}$$

To make sure that the first segment should be fully utilized before the second one begins, after the breakpoint, the efficiency is assumed to decrease by 5%. Based on these assumptions, the following expressions can be obtained.

$$\mu_{i,2} = 0.95 \times \mu_{i,1} \tag{3.16}$$

$$\mu_{i,1}\bar{Q}_{i,1} + \mu_{i,2}\bar{Q}_{i,2} = \bar{H}_i \tag{3.17}$$

Where

$\mu_{i,j}$ = the marginal production equivalent for segment *j*, power plant *i*

According to the above two equations, the marginal production equivalent $\mu_{i,j}$ can be solved by

$$\mu_{i,1} = \frac{\bar{H}_i}{\bar{Q}_{i,1}+0.95\bar{Q}_{i,2}} = \frac{\bar{H}_i}{0.75\bar{Q}_i+0.95\times0.25\bar{Q}_i} \tag{3.18}$$

$$\mu_{i,2} = 0.95 \times \mu_{i,1} \tag{3.19}$$

The total production from hydropower plant *i* is

$$H_{i,t} = \sum_j \mu_{i,j} Q_{i,j} \tag{3.20}$$

If power plants are located in the same electricity area, the total hydropower production in area *z* can be obtained as

$$H_{tot_{z,t}} = \sum_{i\in z} H_{i,t} \tag{3.21}$$

Load balance

$$Load_{1,t} = sf_1 \times Htot_{1,t} + Thermal_{1,t} + Wind_{1,t} - T_{in_{1,t}} + fin_{1,t} + nor_{1,t} \tag{3.22}$$

$$Load_{2,t} = sf_2 \times Htot_{2,t} + Thermal_{2,t} + Wind_{2,t} - T_{in_{2,t}} + T_{in_{1,t}} + nor_{2,t} + nor_{3,t} \tag{3.23}$$

$$Load_{3,t} = sf_3 \times Htot_{3,t} + Thermal_{3,t} + Wind_{3,t} + T_{in_{2,t}} - T_{in_{3,t}} + fin_{2,t} + nor_{4,t} + dan_{1,t} \tag{3.24}$$

$$Load_{4,t} = sf_4 \times Htot_{4,t} + Thermal_{4,t} + Wind_{4,t} + T_{in_{3,t}} + dan_{2,t} + tys_t + pol_t \tag{3.25}$$

Where

sf_z = Scale factor of hydropower production in area *z*

Sweden has been divided into 4 bidding areas. In each area, the load is equal to the total power generation in this area plus trading of other bidding areas and other countries. Electricity transferred from north Sweden to south Sweden, i.e. the transmission from area 1 to area 2, from area 2 to area 3 and from area 3 to area 4 is assumed as positive. On the contrary, electricity transported from the south to north is regarded as negative. What's more, imported electricity is assumed as positive and exported electricity is regarded as negative.

3.2.4 Variable limitations

Discharge

For all hydropower plants, the discharge in each segment must be less than the maximum discharge in this segment.

$$0 \le Q_{i,j,t} \le \bar{Q}_{i,j} \tag{3.26}$$

The sum of the discharge of two segments of each power plant must be larger than the minimum discharge for this power plant per hour during the week.

$$\sum_j Q_{i,j,t} \ge \underline{Q_{i,t}} \tag{3.27}$$

Besides above basic rules for discharge, report [7] also states some other special discharge rules which are used to limit the discharge for some power plants.

For some power plants, a daily minimum discharge must be met. That means a certain amount of water must be discharged during the whole day of 24 hours. In this model, *d* represents day and *t* represents the simulation hour. Therefore, *d*=1 corresponds to *t*=1 to 24, *d*=2 corresponds to *t* =25 to 48, etc.

$$\sum_{j,t} Q_{i,j,t} > \underline{Q_{i,d}} \qquad for\ d = 1\ to\ 7 \tag{3.28}$$

Where

$\underline{Q_{i,d}}$= Daily minimum discharge for power plant *i* in day *d*.

For some power plants, a weekly minimum discharge must be met. In this situation, the total discharges during the 168 hours for each power plant must be larger than the weekly minimum discharge for that particular power plant.

$$\sum_{j,t} Q_{i,j,t} > \underline{Q_{i,w}} \tag{3.29}$$

Where

$\underline{Q_{i,w}}$ = Weekly minimum discharge for power plant *i*.

Some power plants have the requirement that the discharge during a certain hours must be larger than the minimum discharge for these hours.

$$\sum_{j,t} Q_{i,j,t} > \underline{Q_{i,h}} \tag{3.30}$$

Where

$\underline{Q_{i,h}}$= minimum discharge for current hours

Some plants may also have a requirement that the discharge should not change too much during one day (24 hours).

$$\sum_j Q_{i,j,t} - \sum_j Q_{i,j,t'} \leq \Delta Q_{i,d} \qquad for\ d = 1\ to\ 7 \tag{3.31}$$

Where

$\Delta Q_{i,d}$ = Discharge changes within day *d*.

At some power plants, there are water permits that limit how quickly discharge can be changed. Here, the requirement is that it should take one hour to discharge water from zero to 100 m^3/s. As mentioned in Fredrik's report [7], the following expression is used to avoid binary variable. The value of C should be a relatively small number. If C is too large, it is possible that in hour t-1 some water is discharged and in hour t no water will be discharged. In this original model, the value of *C* is chosen as 5.

$$\sum_j Q_{i,j,t} \leq 100 + C \times \sum_j Q_{i,j,t-1} \tag{3.32}$$

In a few plants, short-term regulation is not allowed, i.e. the discharge for each hour is constant. In the two power plants in the model, the discharge does not change during the week, which means that the generation must be the same at all hours of the week.

$$\sum_j Q_{i,j,t} = \sum_j Q_{i,j,t-1} \qquad for\ t > 0 \tag{3.33}$$

Spillage

For some hydropower plants, the minimum spillage must be fulfilled during each hour. There's no upper limit of spilled water.

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

Reservoir content

Reservoir content must be less than the maximum reservoir capacity.

$$0 \leq M_{i,t} \leq \overline{M}_i \tag{3.35}$$

Some power reservoirs have the requirement that the reservoir level should not change too much during one day. This requirement is modelled based on the simplification that the water area in the reservoirs is constant regardless of the water level.

$$M_{i,t} - M_{i,t'} \leq \ \Delta M_{i,d} \qquad for\ d = 1\ to\ 7 \tag{3.36}$$

Where

$\Delta M_{i,d}$ = Volume changes of reservoir *i* within day *d*

Transmission limits

The transmission between different bidding areas must be within maximum and minimum transmission limits.

$$T_{inmin_{1,t}} \leq T_{in_{1,t}} \leq T_{inmax_{1,t}} \tag{3.37}$$

For the transmission between Sweden and foreign countries, the imported and exported electricity must be within the transmission limitations. The transmission limits come from Swedish Kraftnät statistics. E.g.

$$normin_{k,t} \leq nor_{k,t} \leq normax_{k,t} \tag{3.38}$$

3.2.5 Input and output data

Input data

Other production, wind power generation, load, import and export capabilities with other neighboring countries, start level and target level of the reservoirs, inflow, the transmission capacity between different bidding areas

Output data

Hydropower production, spills from hydropower, electricity trade between areas, electricity trade between Sweden and neighboring countries.

Chapter 4

The improved model

On the basis of the original model presented in the previous chapter, an improved model will be presented in this chapter. Three major improvements which are the future value of stored water, the impact on the water delay time and the flexibility of Swedish thermal power plants are considered.

4.1 Overview of the improved model

The model is the improvement and development of the original model which is described in chapter 3. The previous chapter mentioned that the original model only studies the hydropower system in Sweden. The thermal power generation is given by time series, which is deterministic and known at the beginning of the simulation. The balancing power is only provided by hydropower. However, in reality, some balancing power in Sweden is also provided by thermal power. Therefore, the flexibility of thermal power plants will be considered in the improved model. The improved model is built as a mixed-integer linear optimization problem in GAMS. The model still uses a time step of one hour and each simulation comprises one week. The input data will be imported into GAMS from Excel sheets and the main results will also be exported to Excel sheets.

Similar to the original model, the model proposed in this chapter is mainly used to simulate the operation of the system based on the assumptions of perfect information and perfect competition. A simulation is to study the behavior of the power system based on a series of assumptions and conditions. However, for a real short-term planning problem, some conditions cannot be fulfilled, for example it is really difficult to have accurate forecast of the wind power generation at the beginning of the planning period. Therefore, the results of the simulation in this thesis only provide the possibility of the system of balancing the power variation. The actual planning schedule of the system should not be based on the simulated results since in reality some required conditions of the simulation can hardly be fulfilled.

The model covers both hydropower and thermal power generation. 256 hydropower plants are already included in the original model. Additionally, in each bidding area, the thermal power is modeled by three aggregated units, namely gas turbine, nuclear power plant and other thermal power plant. The improved model can be formulated as follows:

Maximize *the value of stored water + value of export - the operational cost of*

thermal power plant – cost of import (4.1)

Subject to *Hydrological balance for each hydropower plant* (4.1a)

Load balance for each bidding area (4.1b)

Court decision for hydropower (4.1c)

Flexibility of thermal power plants (4.1d)

4.2 Objective function

The objective of this optimization problem is to maximize the profit. Since the load during the planning period is deterministic, the income of sold energy is determined in advance. As a result, the income of sold energy can be omitted from the objective function.

4.2.1 Hydropower

The value of stored water

When planning the operation of hydropower plants, it is very important to consider the value of stored water, otherwise, the hydropower plant will produce as much as possible during the planning period. Here, the value of stored water is obtained by the estimated future prices multiplying the amount electricity which is produced by the stored water, which can be expressed by

$$\lambda_f \times \sum_i (M_{i,168} * \sum_{i'' \in D_i} \gamma_{i''}) \tag{4.2}$$

Where

λ_f = the estimated future price,

$M_{i,168}$ = the content of reservoir *i* at the end of simulated week,

$\gamma_{i''}$ = the expected future production equivalent for power plant *i''*

D_i = the set of indices for all power plants downstream of reservoir *i*, including power plant *i* itself.

Furthermore, to make sure that there will be certain amount of water which can be saved for the next week, the same target level is used in the improved model, but this target level is regarded as a minimum value, i.e.

$$M_{i,168} \geq M_{end,i} \tag{4.3}$$

Where

$M_{end,i}$ = the target content of reservoir *i*.

The target level is obtained by the target percent multiplying the maximum content of each reservoir. The choice of the percent of each reservoir is the same as the original model.

The impact of water delay time

Water delay time is a complex function which is related to the season, water flow and the reservoir levels [13]. In the original model, for simplification, the water delay time is given by the input data which is constant and known in the beginning of the simulated week. However, the model which is presented in the earlier study does not consider the water discharged or spilled from the upstream power plants in the last time steps, because this amount of water will reach the downstream power plant beyond the simulation time [30]. In this improved model, the impact of the delayed water will be taken in account. Only the amount of water, which has been released from the upstream power plants during the hours before the week ends, is considered and regarded as future stored water. Furthermore, it is assumed that the reservoir of downstream power plant has space to store this amount of running water. This assumption is acceptable since this running water will definitely reach the downstream power plant in the future time and in reality, the players will know if there will be water running to the reservoir and they will make room for this amount of water. The running water which is discharged or spilled at the end of the planning period is formulated as the following equation.

$$R_i = \sum_{k=1}^{\tau_{i'}} \left(\sum_{i' \in U_i} \left(Q_{i',T+1-k} + S_{i',T+1-k} \right) \right) \tag{4.4}$$

Where

$Q_{i',T+1-k}$ = the water discharged from upstream power plant *i'*,

$S_{i',T+1-k}$ = the water spilled from upstream power *i'*,

$\tau_{i'}$ = water delay time (hours) from power plant *i'* to power plant *i*.

U_i = the set of indices for all power plants upstream of reservoir *i*.

The water value of upstream power plant is higher than the water value of downstream power plant, since the water in upstream reservoir can be used to generate electricity in both upstream and downstream power plants. If the water is released to the downstream power plant, the power generation which can be obtained from this amount of water will decrease. When the running water is considered as stored water and included in the objective function, in order to maximize water value, it is more profitable to save the water in the upstream reservoir than to spill. As a result, the spillage in the last time steps will be limited.

Therefore, the value of stored water can be summarized as follows.

$$\lambda_f \times \sum_i \left((R_i + M_{i,168}) * \sum_{i'' \in \mathcal{M}_i} \gamma_{i''} \right) \tag{4.5}$$

4.2.2 The value of export and the cost of import

When the generation cannot meet the consumption in Sweden, electricity should be imported from other neighboring countries. On the contrary, when there is surplus, electricity should be exported to other countries.

Let λ_{ex} represents the price of export and λ_{im} stands for the cost of the import. The cost or the income from the transmission can be formulated as

$$\lambda_{ex} \times \sum_{k,t}(nor_{ex_{k,t}} + fin_{ex_{k,t}} + dan_{ex_{k,t}} + ger_{ex_{k,t}} + pol_{ex_{k,t}})$$

$$-\lambda_{im} \times \textstyle\sum_{k,t}(nor_{im_{k,t}} + fin_{im_{k,t}} + dan_{im_{k,t}} + ger_{im_{k,t}} + pol_{im_{k,t}}) \qquad (4.6)$$

The selection of λ_{ex} and λ_{im} will have impacts on the optimal solution. The impacts are discussed as follows.

(1) If $\lambda_{ex} > \lambda_f$, it is more profitable to produce energy to export rather than store water. Therefore, the amount of stored water will decrease, the export will increase. Otherwise, export will be limited and more water can be stored.

(2) If $\lambda_{im} > \lambda_f$, it is more profitable to use hydropower power for regulation. As a result, the import will be limited and the stored water will decrease.

4.2.3 Thermal power

Thermal power in Sweden

In order to build a model which is more realistic to Swedish power system, statistics of thermal power generation should be analyzed.

The analysis is based on the hourly generation of thermal power per area from 2008 to 2012. The data can be accessed from the SvK website.

From the data analysis of Swedish thermal power generation, this model considers three types of thermal power: Gas turbine/diesel unit, Nuclear power and other thermal power. Other thermal power includes power generated by oil, coal, biomass, etc. It is further assumed that each bidding area has one gas turbine/diesel unit, one nuclear power plant and one unit of other thermal power.

The detailed data for each unit is summarized in the following tables. All these values are used in the simulation.

✓ Generation of Gas turbine

According to the statistics, in each area the maximum hourly generation, the minimum hourly generation, maximum ramp-up rate, maximum ramp-down rate, minimum up time, minimum down time, maximum startup ramp rate and maximum shutdown ramp rate can be summarized in the following table.

Table 4.1 Summary of gas turbine/diesel generation in Sweden

Gas turbine/diesel				
Bidding area	SN1	SN2	SN3	SN4
Max Gen [MWh/h]	0,64	6,953426	330,15	672,16
Min Gen[MWh/h]	0	0	0,3254	0
Max Ramp-up[MWh/h]	0,52	3,735892	252,6	320,6
Max Ramp-down[MWh/h]	0,58	3,86683	276,2	390,7
Min Up [h]	1	1	8760	1
Min Down [h]	1	1	0	1
Start-up [MWh/h]	0,481	3,067417	0	139,2
Shut-down [MWh/h]	0,58	2,354578	0	119,04

Note: In area 3, the minimum generation of gas turbine is larger than zero, which means gas turbine of area 3 is always on-line. Therefore, the minimum down time is 0 and there is no start-up and shut down process.

- ✓ Other thermal power generation

According to the statistics from 2008 to 2012, in each area the maximum hourly generation, the minimum hourly generation, maximum ramp-up rate, maximum ramp-down rate, minimum up time, minimum down time, maximum startup ramp rate and maximum shutdown ramp rate can be summarized in the following table.

Table 4.2 Summary of other thermal power generation in Sweden

Other thermal				
Bidding area	SN1	SN2	SN3	SN4
Max Gen [MWh/h]	67,041	227,828042	2122,9	1651,21
Min Gen[MWh/h]	1,488	17,474777	172,32	15,11
Max Ramp-up[MWh/h]	30,27	27,78	244,91	384,85
Max Ramp-down[MWh/h]	28,32	38,34	273,44	464,72
Min Up [h]	8760	8760	8760	8760
Min Down [h]	1	1	0	0
Start-up [MWh/h]	2,36	3,77	0	0
Shut-down [MWh/h]	2,63	13,17	0	0

Note: For other thermal generation, the minimum generation in area 3 and 4 is larger than 0, which means other thermal power units in area 3 and 4 are committed all the time. As a result, the minimum down time is 0 and there is no start-up and shut-down process.

- ✓ Generation of Nuclear power

According to the statistics, in each area the maximum hourly generation, the minimum hourly generation, maximum ramp-up rate, maximum ramp-down rate, minimum up time, minimum down time, maximum startup ramp rate and maximum shutdown ramp rate can be summarized in the following table.

Table 4.3 Summary of nuclear power generation in Sweden

Nuclear power	
Bidding area	SN3
Max Gen [MWh/h]	9161,579
Min Gen[MWh/h]	3713,21
Max Ramp-up[MWh/h]	617,79
Max Ramp-down[MWh/h]	1362,034
Min Up [h]	8760
Min Down [h]	0
Start-up [MWh/h]	0
Shut-down [MWh/h]	0

Note: In area 1, 2 and 4, there is no nuclear power generation. In area 3, nuclear power is always committed.

Since in reality, the nuclear power plants will be down-regulated during summer, the maximum generation level of nuclear power unit in each bidding area during summer (from week 19 to week 38) is set based on the following table.

Table 4.4 Maximum generation level for Nuclear power unit in each area during summer

Week	19	27	32	35	38
Max for Nuclear 3 [MWh/h]	5950,13	4951,65	4107,08	5300	4350,13

Operational cost:

The operational cost can be calculated by: [13]

$$C(p_{g,t}) = \phi F(p_{g,t}) = \phi \frac{p_{g,t}}{h \cdot \eta(p_{g,t})} \approx \beta_g p_{g,t} \qquad (4.7)$$

Where

ϕ = the fuel price,

$F(p_{g,t})$ = fuel input as a function of generation,

h = heat contents,

$\eta(p_{g,t})$ = efficiency at the generation $p_{g,t}$ [%],

β_g = the operational cost.

Here four fossil fuels are considered: fossil gas, coal, oil and uranium.

The data of fossil fuels is shown in the following table.

Table 4.5 The data of fossil fuels

Fossil Fuel	Gas	Uranium	Coal	Oil
Fuel price[1]	7.97 ($/mmbtu)	55 $/lb	100$/ton	80 $/bbl
Heat contents[2] (kWh/kg)	14.4	880 000 (3%-5%)[4]	4.5-9.0	11.9
Density[2](kg/m^3)	0.75	18680	450-800	840
Efficiency[3](%)	Up to 39	33-36	39-47	38-44

Note:

[1] Price is obtained from source [31] and [32]

[2] Heat contents is coming from [13]

[3] The efficiency is coming from source [33]

[4] The percentage of uranium comes from [34]

According to (4.7) and table 4.5, the merit order of thermal power plants can be estimated as

Gas:

$$C_{gas}(p_{g,t}) = \frac{7.97\$}{27.9m^3} \times \frac{1}{14.4kWh/kg \times 0.75kg/m^3 \times 0.35} \times p_{g,t} = 75.57\$/MWh \times p_{g,t}$$

Uranium:

$$C_{uranium}(p_{g,t}) = \frac{55\$}{2.205kg} \times \frac{1}{5\% \times 880MWh/kg \times 0.35} \times p_{g,t} = 1.620\$/MWh \times p_{g,t}$$

Coal:

$$C_{coal}(p_{g,t}) = \frac{100\$}{1ton} \times \frac{1}{8MWh/ton \times 0.47} \times p_{g,t} = 26.60\$/MWh \times p_{g,t}$$

Oil:

$$C_{oil}(p_{g,t}) \quad = \frac{80\$}{0.1590m^3} \times \frac{1}{\frac{0.012MWh}{kg} \times \frac{840kg}{m^3} \times 0.44} \times p_{g,t}$$

$$= 114.5\$/MWh \times p_{g,t}$$

Therefore, converting US dollar to Swedish kronor, the operational cost order used in this model will be assumed as

Table 4.6 The merit order of operational cost for different thermal power plants

Thermal power	Gas	Nuclear	Other
Cost order	495	11	500

Specially, for other thermal power units, the merit order is a random value between the operational cost for the units with coal and the operational cost of the units with oil. Compared the value shown in table 4.6, in reality, the operational cost of nuclear power plant and gas turbine is much higher in reality and the operational cost of other thermal power plant should be lower than the operational cost of gas turbine.

Then the operational cost of the thermal power can be calculated by

$$\sum_{g,t} \beta_g \times p_{g,t} \tag{4.8}$$

Where

β_g = the operational cost of unit *g*,

$p_{g,t}$ = the power generation of unit *g* during hour *t*.

Therefore, the objective function can be written as

Max

$$\sum_i (\lambda_f \times (R_i + M_{i,168}) \times \sum_{i'' \in \mathcal{M}_i} \gamma_{i''}) - \sum_{g,t} \beta_g \times p_{g,t}$$
$$+\lambda_{ex} \times \sum_{k,t} (nor_{ex_{k,t}} + fin_{ex_{k,t}} + dan_{ex_{k,t}} + ger_{ex_{k,t}} + pol_{ex_{k,t}})$$
$$-\lambda_{im} \times \sum_{k,t} (nor_{im_{k,t}} + fin_{im_{k,t}} + dan_{im_{k,t}} + ger_{im_{k,t}} + pol_{im_{k,t}}) \tag{4.9}$$

4.3 Constraints

In this section, the constraints regarding to hydropower and load balance refer to Fredrik Obel's report [7]. The main difference between original model and improved model is that this model includes the operation constraints of thermal power plants.

Hydrological balance for each hydropower plant

$$M_{i,t} = M_{i,t-1} - \sum_j Q_{i,j,t} - S_{i,t} + \sum_{i'} Qup_{i',t} + \sum_{i'} Sup_{i',t} + V_i + V_{start_{i,t}} + V_{2start_{i,t}}$$

$$\text{for } t>1 \tag{4.10a}$$

$$M_{i,t} = M_{start,i} - \sum_j Q_{i,j,t} - S_{i,t} + \sum_{i'} Qup_{i',t} + \sum_{i'} Sup_{i',t} + V_i + V_{start\,i,t} + V_{2start\,i,t}$$

for t=1 (4.10b)

Where

$M_{i,t}$ = the content of reservoir *i* at the end of hour *t*,

$M_{start,i}$ = reservoir content when the week starts i.e. at the beginning of hour 1,

$Q_{i,j,t}$ = the discharge of the reservoir *i*, segment *j*, hour *t*,

$S_{i,t}$ = the spilled water of reservoir *i* during hour *t*,

$Qup_{i',t}$ = the amount of discharged water from the power plant *i'* which directly upstream of power plant *i*,

$Sup_{i',t}$ = the amount of spilled water from the power plant *i'* which directly upstream of power plant *i*,

V_i = the local inflow of power plant *i*,

$V_{start\,i,t}$ = the amount of water which flows during the hours before the week starts and runs to the power plant.

$V_{2start\,i,t}$= the water which is dropped to power plant *i* during part of an hour before the week begins.

Hydrological balance for each hydropower plant used in this model is the same as the original model, which is described in chapter 3.

In the improved model, at the beginning of the simulated week, the start content of each reservoir is determined. The start level of reservoir can be obtained by the maximum content multiplying a certain percentage. The percentage is the same for all the reservoirs except for Vättern and Vänern.

$$M_{start,i} = m_{start} \times \overline{M}_i \tag{4.11}$$

Where

$M_{start,i}$= the content of reservoir *i* at the beginning of planning period,

m_{start}= the start percentage,

$\overline{M}_i$ = the maximum content of reservoir *i*.

The time step of this model is one hour, so the discharged water from the upstream power plant *i'* during hour t needs to be scaled. [7]

$$Qup_{i',t} = \frac{Rqm_{i'}}{60}\sum_j Q_{i',j,t-(Rqh_{i'}+1)} + \frac{60-Rqm_{i'}}{60}\sum_j Q_{i',j,t-Rqh_{i'}} \tag{4.12}$$

Where

$Rqh_{i'}$= the delay time for discharged water between upstream power plant *i′* and the power plant *i* (hour),

$Rqm_{i'}$= the delay time for discharged water between upstream power plant *i′* and the power plant *i* (minute).

The similar expression for the spillage from the upstream power plant *i′* during hour *t* can be obtained.

$$Sup_{i',t} = \frac{Rsm_{i'}}{60}\sum_j S_{i',j,t-(Rsh_{i'}+1)} + \frac{60-Rsm_{i'}}{60}\sum_j S_{i',j,t-Rsh_{i'}} \tag{4.13}$$

Where

$Rsh_{i'}$ = the delay time for spilled water between upstream power plant *i′* and the power plant *i* (hour),

$Rsm_{i'}$= the delay time for spilled water between upstream power plant *i′* and the power plant *i* (minute).

In the improved model, the water flow for each week of power plant *i* can be obtained by scaling the yearly average water flow.

$$ws_i = V_{sf} \times w_i \tag{4.14}$$

Where

w_i = the year average water flow for reservoir *i*;

V_{sf} = the scale factor which is different for different week.

The expression of local inflow can be given as

$$V_i = ws_i - \sum_{i'} ws_{i'} \tag{4.15}$$

Where

$ws_{i'}$= the water flow from power plant *i′* which is upstream of power plant *i*.

At the beginning of each week, the local inflow can be expressed by

$$V_{start_{i,t}} = \sum_{i'} ws_{i'} \qquad if\ t < Rqh_{i'} \tag{4.16}$$

Since the model has a time step of one hour, a separate equation is used for the water which is dropped to power plant *i* during part of an hour before the week begins.

$$V_{2start_{i,t}} = \sum_{i'} ws_{i'} \times \frac{60-(60-Rqm_{i'})}{60}$$

$$if\ t < Rqh_{i'} + 1\ and\ \ Rqm_{i'} < 60 \quad (4.17)$$

Load balance for each bidding area

In this model, load balance in each area still needs to be fulfilled. Unlike the original model, the export and import are represented by different positive variables.

$$Load_{1,t} = sf_1 \times Htot_{1,t} + Gas_{1,t} + Other_{1,t} + Nuclear_{1,t} + Wind_{1,t} - T_{in_{1,t}}$$

$$+fin_{im_{1,t}} + nor_{im_{1,t}} - fin_{ex_{1,t}} - nor_{ex_{1,t}} \quad (4.18)$$

$$Load_{2,t} = sf_2 \times Htot_{2,t} + Gas_{2,t} + Other_{2,t} + Nuclear_{2,t} + Wind_{2,t} - T_{in_{2,t}} + T_{in_{1,t}}$$

$$+nor_{im_{2,t}} + nor_{im_{3,t}} - nor_{ex_{2,t}} - nor_{ex_{3,t}} \quad (4.19)$$

$$Load_{3,t} = sf_3 \times Htot_{3,t} + Gas_{3,t} + Other_{3,t} + Nuclear_{3,t} + Wind_{3,t} + T_{in_{2,t}} - T_{in_{3,t}}$$

$$+fin_{im_{2,t}} + nor_{im_{4,t}} + dan_{im_{1,t}} - fin_{ex_{2,t}} - nor_{ex_{4,t}} - dan_{ex_{1,t}} \quad (4.20)$$

$$Load_{4,t} = sf_4 \times Htot_{4,t} + Gas_{4,t} + Other_{4,t} + Nuclear_{4,t} + Wind_{4,t} + T_{in_{3,t}}$$

$$+dan_{im_{2,t}} + tys_{im_t} + pol_{im_t} - dan_{ex_{2,t}} - tys_{ex_t} - pol_{ex_t} \quad (4.21)$$

Where

sf_z = Scale factor of hydropower production in area *z*

Hydropower production

The hydropower production is approximated as a piecewise function of discharge. The generation is divided into two segments and the breakpoint between these two segments is located at the 75% maximum discharge. Moreover, to make sure that the first segment will be fully used before the second segment starts, the marginal production equivalent of the second segment is 5% lower than the marginal production equivalent of the first segment [7].

Therefore, the total production from hydropower plant *i* is

$$H_{i,t} = \sum_j \mu_{i,j} Q_{i,j} \quad (4.22)$$

Where

$Q_{i,j}$ = the discharge for segment *j*, unit *i*,

$\mu_{i,j}$ = the marginal production equivalent for segment *j*, power plant *i*.

If power plants are located in the same electricity area, the total hydropower production in area *z* can be obtained as

$$H_{tot_{z,t}} = \sum_{i \in z} H_{i,t} \tag{4.23}$$

Court decision for hydropower

The new model keeps the court decisions for hydropower used in the original model.

The discharge in each segment must be less than the maximum discharge in this segment.

$$0 \leq Q_{i,j,t} \leq \bar{Q}_{i,j} \tag{4.24}$$

The sum of the discharge of two segments of each power plant must be larger than the minimum discharge for this power plant per hour during the week.

$$\sum_j Q_{i,j,t} \geq \underline{Q_{i,t}} \tag{4.25}$$

For some power plants, a daily minimum discharge must be met.

$$\sum_{j,t} Q_{i,j,t} > \underline{Q_{i,d}} \qquad for\ d = 1\ to\ 7 \tag{4.26}$$

Where

$\underline{Q_{i,d}}$= Daily minimum discharge for power plant *i* in day *d*.

For some power plants, a weekly minimum discharge must be met.

$$\sum_{j,t} Q_{i,j,t} > \underline{Q_{i,w}} \tag{4.27}$$

Where

$\underline{Q_{i,w}}$ = Weekly minimum discharge for power plant *i*.

Some power plants have the requirement that the discharge during a certain hours must be larger than the minimum discharge for these hours.

$$\sum_{j,t} Q_{i,j,t} > \underline{Q_{i,h}} \tag{4.28}$$

Where

$\underline{Q_{i,h}}$= minimum discharge for current hours

Some plants have a requirement that the discharge should not change too much during one day (24 hours).

$$\sum_j Q_{i,j,t} - \sum_j Q_{i,j,t'} \leq \Delta Q_{i,d} \qquad for\ d = 1\ to\ 7 \tag{4.29}$$

Where

$\Delta Q_{i,d}$ = Discharge changes within day *d*.

At some power plants, there are water permits that limit how quickly discharge must be changed.

$$\sum_j Q_{i,j,t} \leq 100 + C \times \sum_j Q_{i,j,t-1} \tag{4.30}$$

In a few plants short-term regulation is not allowed, i.e. the discharge for each hour is constant. In the two power plants in the model, the discharge does not change during the week, which means that the product must be the same at all hours of the week.

$$\sum_j Q_{i,j,t} = \sum_j Q_{i,j,t-1} \quad if\ t > 0 \tag{4.31}$$

In this model, there's no upper limit of spilled water for each hour.

$$\underline{S_i} \leq S_{i,t} \tag{4.32}$$

Reservoir content must be less than the maximum reservoir capacity.

$$0 \leq M_{i,t} \leq \overline{M}_i \tag{4.33}$$

Some power reservoirs have the requirement that the reservoir level should not change too much during one day. In this model, it is simplified that the water area of reservoir will keep constant regardless of the water level [7].

$$M_{i,t} - M_{i,t'} \leq \ \Delta M_{i,d} \qquad for\ d = 1\ to\ 7 \tag{4.34}$$

Where

$\Delta M_{i,d}$ = Volume changes of reservoir *i* within day *d*

The transmission between different bidding areas must be within maximum and minimum transmission limits.

$$T_{inmin_{1,t}} \leq T_{in_{1,t}} \leq T_{inmax_{1,t}} \tag{4.35}$$

For the transmission between Sweden and foreign countries, the imported and exported electricity must be within the transmission limitations, e.g.

$$0 \leq nor_{ex_{k,t}} \leq -normin_{k,t} \tag{4.36}$$

$$0 \leq nor_{im_{k,t}} \leq normax_{k,t} \tag{4.37}$$

Flexibility of aggregated thermal power plants

When planning thermal power generation, the operation constraints of thermal power plants should be considered. The limitations and constraints are considered based on the statistics of hourly generation of Swedish thermal power, which is shown in the table 4.1 to table 4.4.

In this thesis, the following method, referring to [35], is used to model the flexibility of thermal power plants.

✓ Generation limits

The generation limits of each thermal power plant is set as [35]

$$\underline{P}_g v_{g,t} \leq p_{g,t} \leq \overline{P}_g v_{g,t} \tag{4.38}$$

Where

$\underline{P}_g$ = maximum generation of unit *g*,

$\overline{P}_g$ = minimum generation of unit *g*,

$p_{g,t}$ = the output of unit *g* in hour *t*,

$v_{g,t}$ = a binary variable which stands for the unit commitment in power plant *g* during hour *t* (1, if the unit is committed, 0 otherwise).

It is obvious when the power plant *g* is online, the generated power is limited by the minimum power generation limitation and the maximum available generation. When the power plant *g* is offline, the power output will be forced to 0.

✓ Minimum Up and Down Time Constraints

The minimum up and down time constraints is used for the requirement that as long as the power plant is started or stopped, the state must be kept for some required hours. The minimum up constraints can be discussed by three conditions.

a. At the beginning of the planning period:

At the beginning of the planning week, the initial condition can be assumed as v_g^{ini}, the number of hours that unit *g* was on/off before the planning week can be assumed as T_g^{ini}. If the unit *g* was online before planning, v_g^{ini}=1, T_g^{ini}>0. Then the unit *g* must be online during the initial hours L_g. On the contrary, if the unit *g* was offline before planning, v_g^{ini}=0, T_g^{ini}<0. Then the unit *g* must be offline during the initial hours F_g. The expression of L_g and $F_g$can be formulated as [35]

$$L_g = min\left(T, \left(UT_g - T_g^{ini}\right) \cdot v_g^{ini}\right) \tag{4.39}$$

$$F_g = min\left(T, \left(DT_g + T_g^{ini}\right) \cdot (1 - v_g^{ini})\right) \tag{4.40}$$

b. During the planning period [35]:

$$\sum_{n=t}^{t+UT_g-1} v_{g,n} \geq UT_g(v_{g,t} - v_{g,t-1}), \forall t = \left(L_g + 1\right) \dots (T - UT_g + 1) \tag{4.41}$$

Where

UT_g = the minimum up time of unit g.

The expression shown above is used to fulfill the minimum up time constraint during the planning period.

To test if the above constraint works or not, it can be assumed that unit g is started at hour t and the minimum up time of unit g is UT_g=3. Therefore, the value of the right side of the constraint (4.41) is equal to 3. As a result, to make sure the constraint (4.41) can be fulfilled, the value of the left side of (4.41) must be equal or larger than 3, which means the unit g must keep online at least during hour t, hour t+1 and hour t+2, i.e. the minimum up time of unit g is 3 hours.

Similarly, the minimum down time constraints during the planning period can be formulated as [35]

$$\sum_{n=t}^{t+DT_g-1}(1 - v_{g,n}) \geq DT_g(v_{g,t-1} - v_{g,t}), \forall t = \left(F_g + 1\right) \dots (T - DT_g + 1) \tag{4.42}$$

Where

DT_g = the minimum down time of unit g.

c. At the end of the planning period [35]:

$$\sum_{n=t}^{T}[v_{g,n} - \left(v_{g,t} - v_{g,t-1}\right)] \geq 0, \forall t = \left(T - UT_g + 2\right) \dots T \tag{4.43}$$

This constraint is used to make sure that if the unit is started during the final UT_g-1 period, the unit will be maintain in online state until the end of the planning week.

Similarly, the down time constraint at the end of the planning period is expressed as [35]

$$\sum_{n=t}^{T}[1 - v_{g,n} - (v_{g,t-1} - v_{g,t})] \geq 0, \forall t = \left(T - DT_j + 2\right) \dots T \tag{4.44}$$

✓ Ramping constraints

For large thermal power plants, it is impossible to increase or decrease generation at any rate [13]. It takes some time to either supply more thermal power or cool down the boiler. Furthermore, if the stream flow is interrupted suddenly, the boiler may be damaged. [13] Therefore, when planning the operation of thermal power plant, it is necessary to consider the ramping constraints which limit the change of power generation from one hour to another. In this model, the ramping constraints is described as [35]

$$p_{g,t} \le p_{g,t-1} + RU_g v_{g,t-1} + SU_g (v_{g,t} - v_{g,t-1}) + \bar{P}_g (1 - v_{g,t}) \tag{4.45}$$

$$p_{g,t} \le \bar{P}_g v_{g,t+1} + SD_g (v_{g,t} - v_{g,t+1}), \forall t \in 1 \ldots T-1. \tag{4.46}$$

$$\begin{aligned} p_{g,t-1} - p_{g,t} \le RD_g v_{g,t} + SD_g (v_{g,t-1} - v_{g,t}) \\ + \bar{P}_g (1 - v_{g,t-1}) \end{aligned} \tag{4.47}$$

Constraint (4.45) is ramp-up constraint, (4.46) is the ramp-down constraint for shut-down. (4.47) is ramp-down constraint.

To test the above ramping constraints is reasonable or not, following discussion is made. The state changes from one hour to another can be summarized into four cases:

From $v_{g,t-1} = 0$ to $v_{g,t} = 0$
From $v_{g,t-1} = 0$ to $v_{g,t} = 1$
From $v_{g,t-1} = 1$ to $v_{g,t} = 1$
From $v_{g,t-1} = 1$ to $v_{g,t} = 0$

The ramping constraints (4.45) and (4.47) can be discussed from these four situations.

a. From $v_{g,t-1} = 0$ to $v_{g,t} = 0$

In this case, the thermal power plant *g* is offline in both two hours, i.e.$p_{g,t-1} = 0, p_{g,t} = 0$.

b. From $v_{g,t-1} = 0$ to $v_{g,t} = 1$

In this case, the unit *g* was offline at hour *t*-1, i.e. $p_{g,t-1} = 0$. At hour *t*, the unit is starting.

$$p_{g,t} \le SU_g \tag{4.48}$$

$$0 \le p_{g,t} + RD_g - SD_g + \bar{P}_g \tag{4.49}$$

The maximum power output of unit *g* should not be larger than the startup ramp.

c. From $v_{g,t-1} = 1$ to $v_{g,t} = 1$

In this case, the unit *g* is online at both hour *t*-1 and hour *t*. Constraints (4.45) and (4.47) become

$$p_{g,t} - p_{g,t-1} \le RU_g \tag{4.50}$$

$$p_{g,t-1} - p_{g,t} \le RD_g \tag{4.51}$$

According to the expressions shown above, if the output is increasing at hour t, the maximum generation at hour t should not be larger than the sum of the output during previous hour and the ramp-up limit. If the output is decreasing at hour t, the difference between the power output from hour t-1 to hour t must be less than the ramp-down limit. This is the major function of ramping constraints.

d. From$v_{g,t-1} = 1$ to $v_{g,t} = 0$

In this case, the unit g was online at hour t-1. At hour t, it is stopped, i.e. $p_{g,t}$=0. The ramping constraints become

$$p_{g,t-1} \leq SD_g \tag{4.52}$$

Expression (4.52) shows that the unit g can only be stopped when the power output during the previous hour is less than shutdown limit SD_g.

Similarly, ramping constraint (4.46) can also be discussed according to the following four categories.

a. From $v_{g,t} = 0$ to $v_{g,t+1} = 0$

In this case, the thermal power plant g is offline during hour t, $p_{g,t}$ =0.

b. From $v_{g,t} = 0$ to $v_{g,t+1} = 1$

In this case, the thermal power plant g is offline during hour t, $p_{g,t}$ =0.

c. From $v_{g,t} = 1$ to $v_{g,t+1} = 0$

The constraint becomes

$$p_{g,t} \ \leq SD_g \tag{4.53}$$

From the expression shown above, if the unit g will be offline during next hour t+1, the maximum power output during hour t should be less than shut-down limit.

d. From $v_{g,t} = 1$ to $v_{g,t+1} = 1$

The constraint can be rewritten as

$$p_{g,t} \ \leq \overline{P}_g \tag{4.54}$$

which is obviously fulfilled.

4.4 Discussion of the model

This section will give discussion on this improved model.

4.4.1 Hydropower

In reality, at different discharge the efficiency will be different. The hydropower production is not only dependent on discharge but also influenced by the height of fall. However, in this model, the hydropower production is assumed only depending on the discharge. Furthermore, the relationship between the hydropower production and the discharge is approximated as a piecewise linear function. This simplification will result in overestimation of hydropower regulation capacity.

In this model the water delay time between two hydropower plants is considered constant. However, in reality, water delay time differs due to the stream flow routing constraints along the river channels [30]. This simplification can also overestimate the regulation capacity.

What's more, the model only includes the hydropower plants with installed capacity larger than 5MW. To cover entire Swedish hydropower, the output hydropower production of the model is scaled up by certain scaling factors. However, in real power system, many hydropower plants with small installed capacity cannot be regulated. As a result, this simplification may underestimate the regulation capacity.

Furthermore, the simulation time is one week. Therefore, it is impossible to use the water during one windy week in another less windy week. Longer simulations that allow seasonal planning of the hydropower should also be included. What's more, there are requirements on the beginning level and the end level of the reservoirs. Actually, for small regulation reservoirs, a greater flexibility is allowed.

In the improved model, the percentage of target level of the reservoir at the end of the planning period is the same for all reservoirs. In reality, for different reservoir, the amount of stored water may vary. This simplification will cause underestimation of the regulation capacity.

4.4.2 Power system

At the beginning of simulation, it is assumed that all the information about wind power generation is deterministic and known. However, in reality, it is difficult to have accuracy prediction of wind power generation for the whole week. The forecast of the wind power generation should be made continuously during the week from the beginning to the end. This simplification will result in the overestimation of the regulation capacity. Similarly, the data of the local inflow is determined by the Swedish yearly average water flow which is known before the simulation starts, which can also overestimate the regulation capacity.

The model only considers the transmission limitation between the different bidding areas and between Sweden and other countries. Transmission limitation within each area and transmission losses are not included, which will lead to overestimation of regulation capacity. Moreover, the price for trading energy is the same during the whole planning period and the same for all countries. As a result, power generation will not vary with the trading price, which results in underestimation of regulation capacity.

4.4.3 Thermal power

In this model, all the thermal power plants in each area are simplified as three different units: one gas turbine, one nuclear power plant and one other thermal power plant. In reality, different thermal power plants have different regulation capacity. This simplification will result in underestimation of the estimation.

When modeling thermal power plants, it is assuming that the operational cost for each unit is constant and the start-up cost is also neglected. However, in reality, the operational cost is a complex function of power production. Moreover, the start-up cost is varied based on different boiler temperature. As a result, these simplified factors may introduce overestimation into the estimated result.

Chapter 5

Case Study

In this chapter, both the original model presented in chapter 3 and the improved model described in chapter 4 will be applied to some particular case studies. Relevant cases will be investigated and then the corresponding results will be provided. Moreover, the results obtained from both models will be compared and analyzed.

5.1 Background description

The model provided in chapter 4 is developed based on the original model which is described in chapter 3. In this chapter, two models will simulate power production during 12 weeks in 2009 which is a normal year in terms of the hydropower production in Sweden. In order to find out how large the regulation capacity the Swedish power system has, four different expansion levels of wind power are introduced: without wind power, 4000 MW installed capacity, 8000 MW installed capacity and 12000 MW installed capacity. What's more, in all case studies, the distribution of wind power is 22% wind power in bidding area 1, 41% wind power in area 2, 29% wind power in area 3 and 9% in area 4 [7]. The information regarding hydropower, including local inflow and reservoir levels, is obtained from statistics of Svensk Energi. Wind power data for each week is obtained from the data in the report [6]. The thermal power production used in the original model and load used in both models during each week comes from statistics of Svenska Kraftnät.

To study the regulation capacity of Swedish power system, what is really of interest is to study how much the spillage will occur.

Spillage always means lost income. Therefore, the optimization problem will always minimize spillage. Spillage will occur when

- ✓ Reservoir is fully filled (or the target reservoir level is reached) at the end of the planning period and the export capacity is reached [13];
- ✓ If the capacity of turbines and spillways is not large enough (the maximum discharge is reached) [13];
- ✓ Due to environmental reasons, it is also possible that some water or environment courts have special requirements on the minimum spillage for hydropower plants. [37]

In this chapter, different cases with varied condition will be studied. To limit the contribution of export and import, in all case studies, the value of export energy is set as $\lambda_{ex} = 70$, the cost of import energy is selected as $\lambda_{im} = 100$. As discussed in chapter 4, since $\lambda_{ex} < \lambda_f$ and $\lambda_{im} > \lambda_f$ the import energy and export energy will be minimized.

5.2 Base case-without wind

First of all, the case without wind power is studied. The following figure shows the hydropower production obtained from both the original model and the improved model. The actual hydropower production of the simulated weeks in 2009 is presented in this figure as well. The data comes from the statistics of Svenska kraftnät.

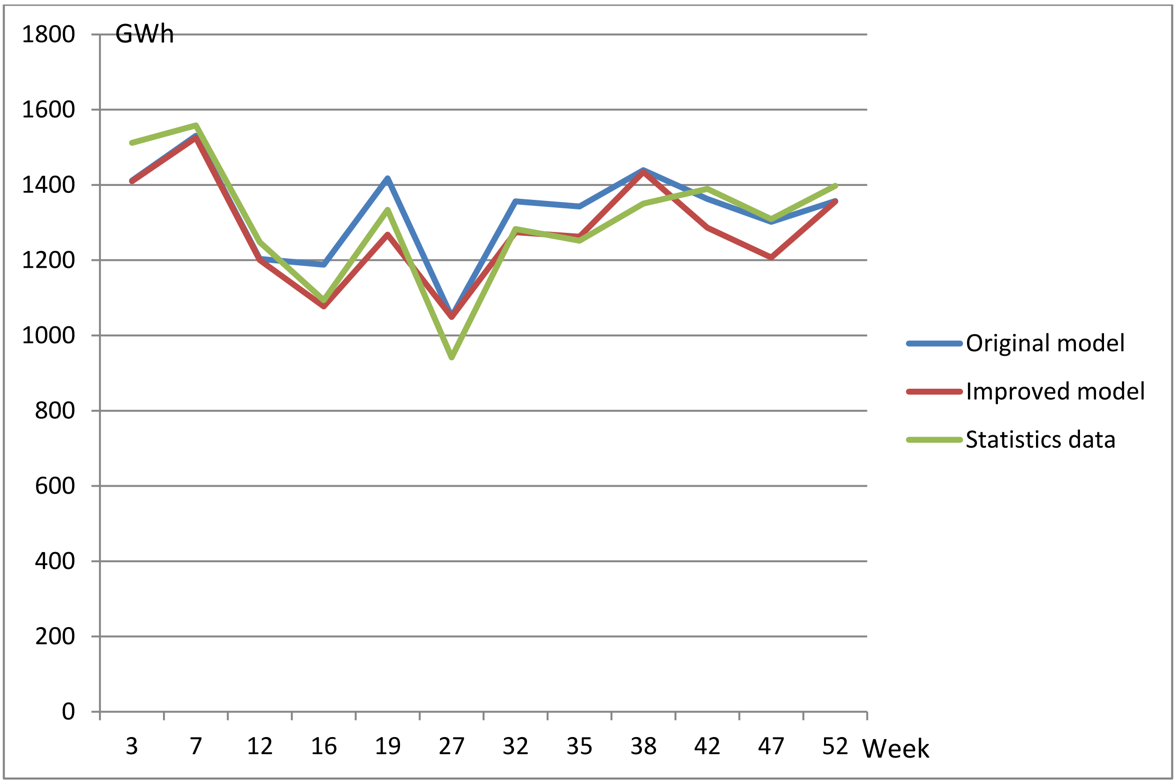

Figure 5.1 Hydropower production in 2009

Generally, the simulated hydropower production from both models can follow the actual production variation quite well. The differences between the outcome of models and the real data are expected since both models have several simplifications. For example, as discussed in section 4.4, the overestimation is introduced by the simplification of relationship between hydropower production and discharge, the simplification of water delay time, deterministic and known data of wind power and water inflow, etc. The underestimation is due to the ignoring small hydropower plant with very little regulation capacity, three aggregated thermal power units and so on. From the figure, it can be noticed that the difference between the model results and the statistics is not larger than about 10%. Therefore, it can be concluded that both the original model and improved model is realistic.

Generally speaking, the hydropower production obtained from the improved model is lower than the hydropower production obtained from the original. It is reasonable since the overall objective of the original model is to maximize the hydropower production during the simulated week, however, for the improved model, it will be more profitable if more water can be stored in the reservoirs at the end of planning period.

5.3 Normal year

In this section, the condition of normal year is examined. In the original model, a penalty of import is introduced in order to limit the contribution of import on the regulation capacity. In the improved model, due to the selection of the price for import energy, the contribution of import on the regulation capacity is also limited. The export capacity is 1244.46 GWh which comes from the statistics of Svenska Kraftnät. To study the ability of Swedish power system to balance variation of wind power, four different installed capacity levels of wind power are studied: 0 MW, 4000 MW, 8000 MW and 12000 MW. The spillage and the export at different expansion levels will be studied after simulation.

The original model:

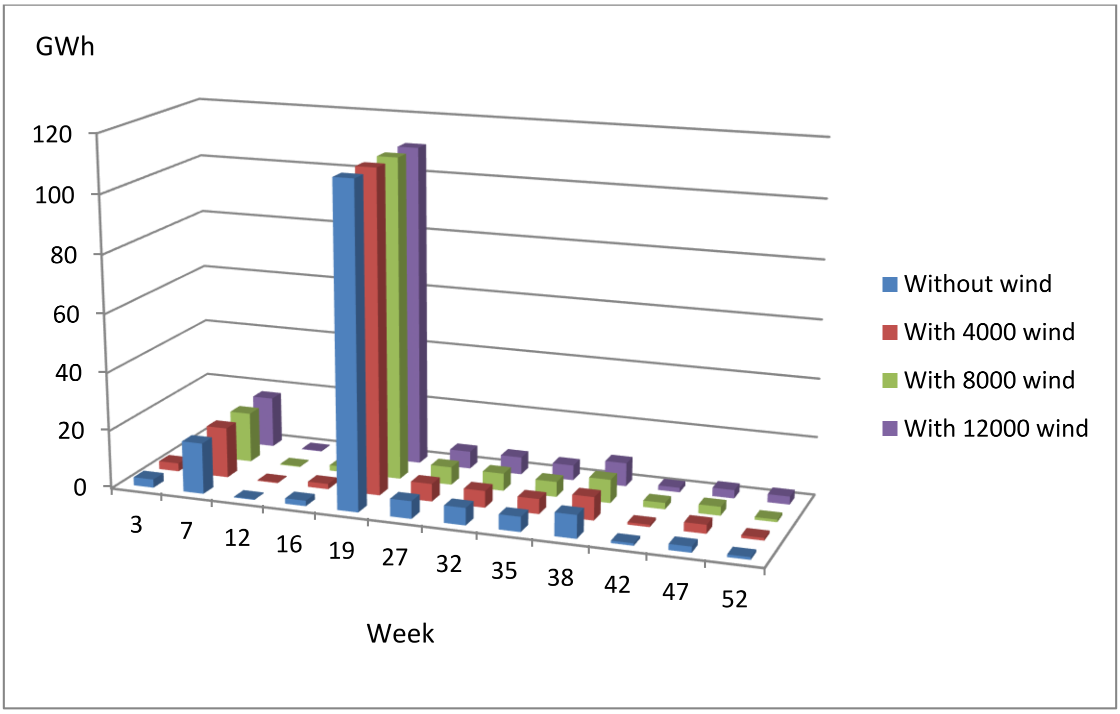

Figure 5.2 Spillage in different weeks at four wind expansion level, original model

The above figure presents the spillage during each simulated week at different expansion level of wind power, which is obtained by the original model. For week 42, the spillage increases from about 0.83 GWh at 4000 MW wind power level to 2.22 GWh at 8000 MW. In week 47, when wind power is introduced into the system, the spillage is increased by 1 GWh. For week 52, the spillage increases from 0.9 GWh to 2.8 GWh between 8000 and 12000 MW installed capacity of wind power. For other simulated weeks, the spillage doesn't increase with the increase of wind power. The spillage during week 19 is significant because of the spring flood inflow. Since the strong inflow during week 19 cannot be discharged entirely, large amount of water needs to be spilled. It can be noticed that in different weeks, the spillage is different. However, for most of the weeks, the spillage will stay constant when different installed capacity of wind power is introduced. The result shows that the spillage varies because of the different local inflow and the selection of final reservoir content level. The expansion of wind power doesn't have significant impact on the spillage. Therefore, the Swedish power system has the capability of balancing power variation.

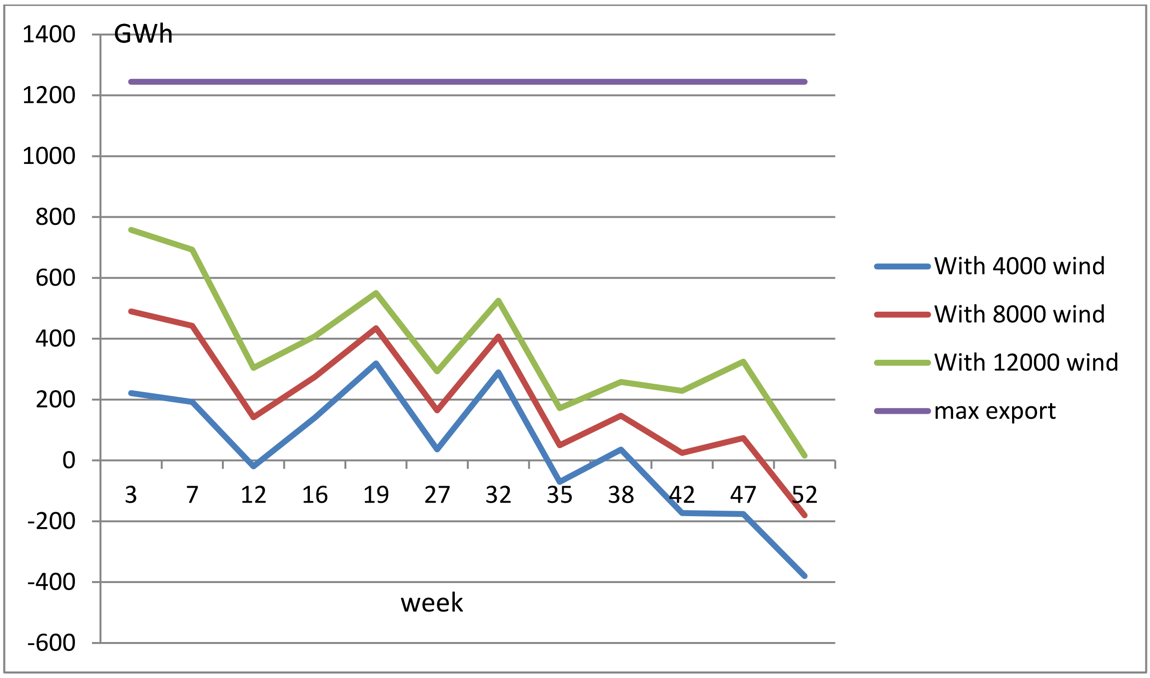

Figure 5.3 Export in different weeks at three expansion level, normal year

The export during each week is presented in figure 5.3. It shows that when more wind is introduced into system, the export will increase. In normal years, the total export capacity is always sufficient regardless the expansion level of wind power. Large export capacity has positive impact on the regulation since surplus power can be exported to other countries instead of being spilled. During week 3, the export reaches the highest value. It is because that more wind power can be produced during the winter. In week 19, export also peaks. The reason is that more hydropower needs to be produced to avoid spillage due to the strong spring flood inflow.

The improved model:

Figure 5.4 shows the spillage during each simulated week at different expansion level of wind power, which is obtained by the improved model. Similarly to results from the original model, for most of weeks, the spillage in each week is almost the same at different expansion level of wind power. In week 52, the spillage increases from 0.9 GWh to 1.4 GWh between 4000 MW and 8000 MW installed capacity of wind power. The highest amount of spillage occurs during week 19 due to the spring flood inflow. For the improved model, same conclusion can also be made that the expansion of wind power will not have significant impact on the spillage.

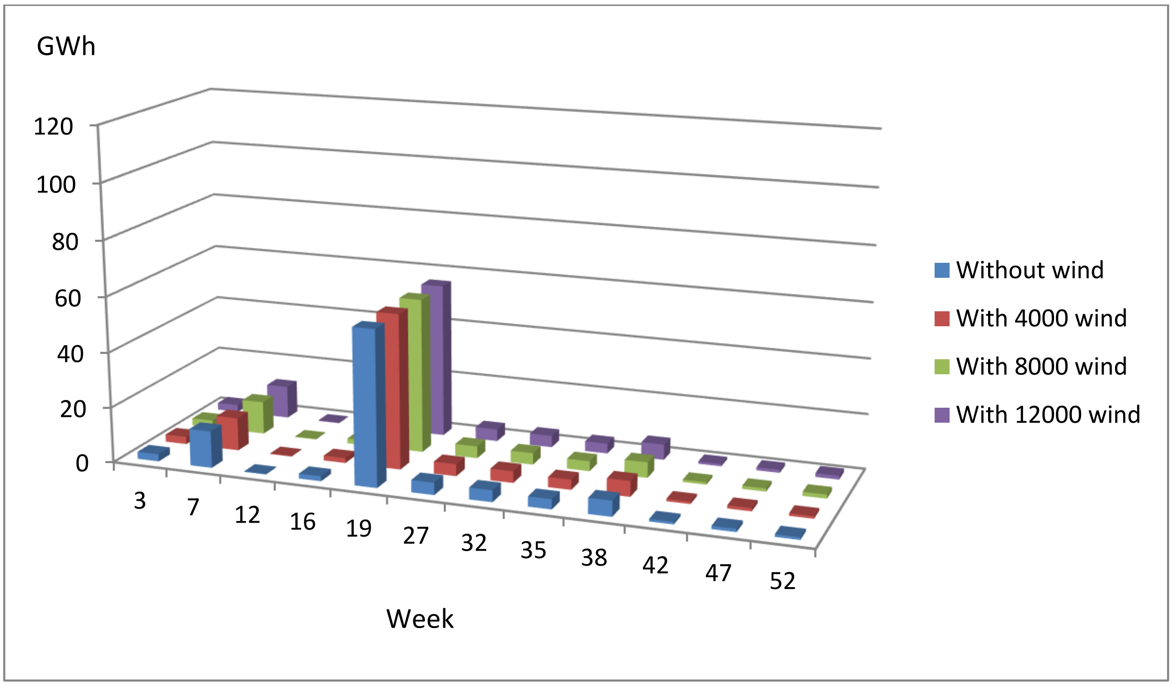

Figure 5.4 Spillage in different weeks at different expansion levels, improved model

Comparing the results of original model and the improved model which are shown in figure 5.2 and 5.4, it can be observed that the spillage of improved model is much lower than the spillage of original model. For example, the spillage in week 19 is much lower when improved model is simulated, since the more water can be stored in the reservoir at the ending of the simulated week. In week 42 and 47, the spillage obtained from improved model is unchanged when the installed capacity of wind power is increasing. In week 52, the difference of spillage between 4000 MW and 8000 MW installed capacity of wind power becomes 0.5 GWh, which is much lower than the difference in original model. Therefore, the improved model presents a better regulation capacity than the original model.

The following figure shows the export obtained by the improved model. From the figure 5.5, it can be noticed that when more wind power is introduced to the system, more energy will be forced to export to other countries. In the middle of the year, since the nuclear power is down-regulated, the export is lower. On the contrary, in winter, the export is higher in accordance to the higher thermal power generation. In normal year, the export capacity is sufficient even for the highest expansion level of wind power.

To summarize, in normal years, the spillage won’t increase with the increase expansion level of wind power. Therefore, wind power can be balanced by power system.

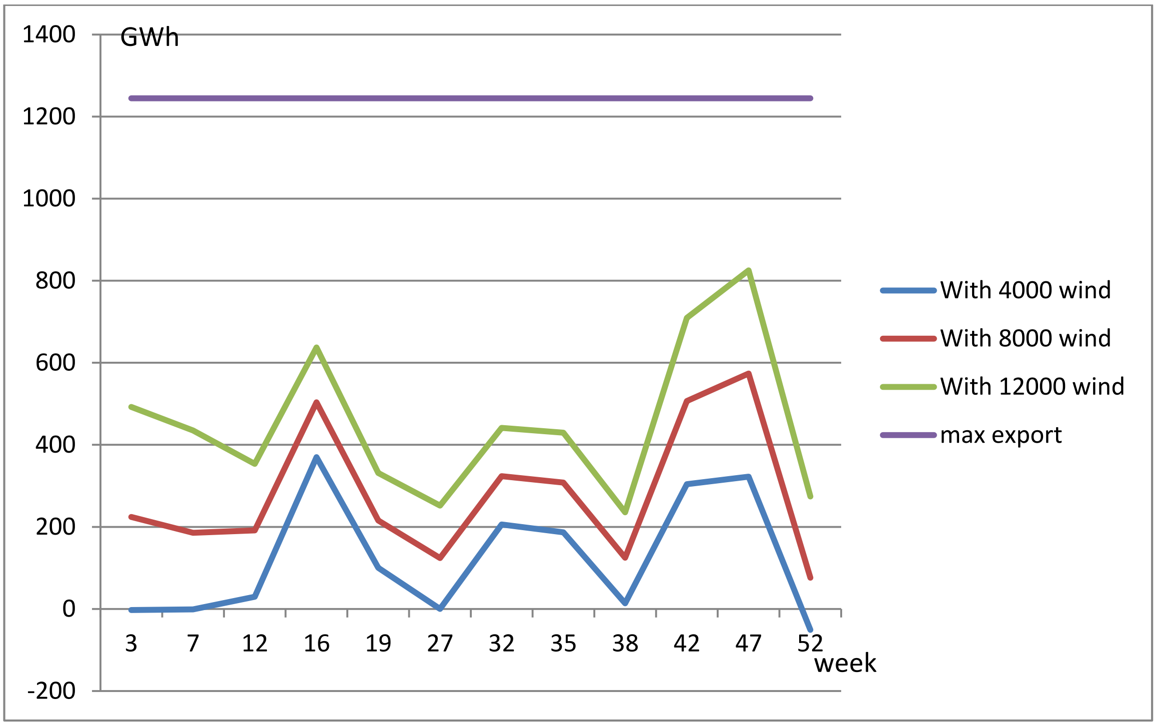

Figure 5.5 Export in different weeks at different expansion levels, improved model

The simulation time for each week is summarized in the following table.

Table5.1 Simulation time for each week (Both models)

Week	Original model (min)	Improved model (min)
3	6	5
7	6	10
12	7	6
16	6	5
19	3	4
27	4	5
32	9	4
35	4	11
38	5	7
42	6	3
47	3	2
52	5	5

From above table, it can be seen that for most of the weeks, the difference of simulation time of both models is small.

5.4 Wet year

The local inflow largely depends on the natural condition which is varied year from year. In wet years, hydropower production will increase due to a large amount of inflow, as a result, the electricity price will decrease. In this section, two models will simulate the power production of Swedish power system during wet years. The inflow is assumed 20% higher than the inflow during normal years. The wind power production and the maximum export capacity are unchanged.

The original model:

Original model will be first simulated. Compared to figure 5.2, it can be seen from figure 5.6 that during all the simulated weeks, the spillage in wet year is much higher than the spillage in normal years. Especially in week 19, the spillage in normal year is around 110 GW, however, in wet year, the spillage is increased to almost 300 GW because of the increased inflow. In week 42 and 47, spillage is increased when wind power is introduced. In week 52, the spillage is changed from 3 GW to 5 GW between 4000 MWh and 8000 MWh installed capacity of wind power. For other weeks, the increase of expansion level of wind power doesn't have much impact on the spillage.

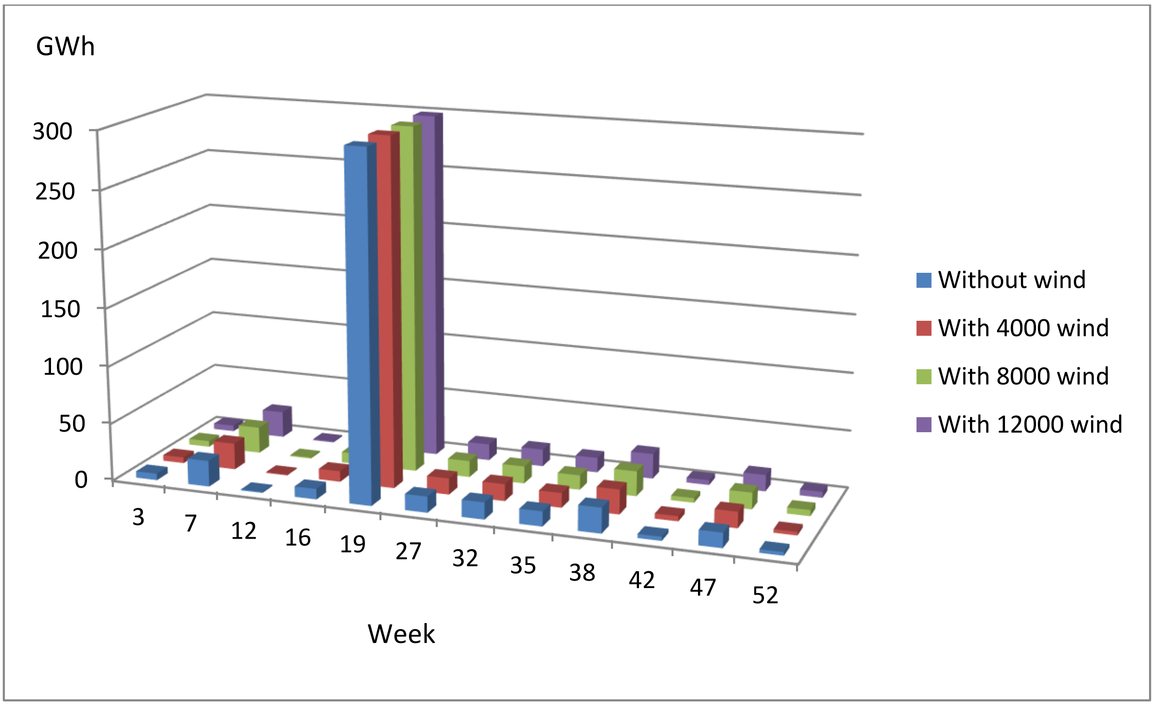

Figure 5.6 Spillage in different weeks at four wind expansion level, original model

The following figure shows the export in different weeks and different expansion levels in wet year. From this figure, it can be seen that due to higher inflow during wet years, the export in all weeks increases. Similarly to the result of normal year, the export energy will increase when the installed capacity of wind power is higher. Moreover, it is obvious that in wet years, there is still sufficient export capacity which can be utilized.

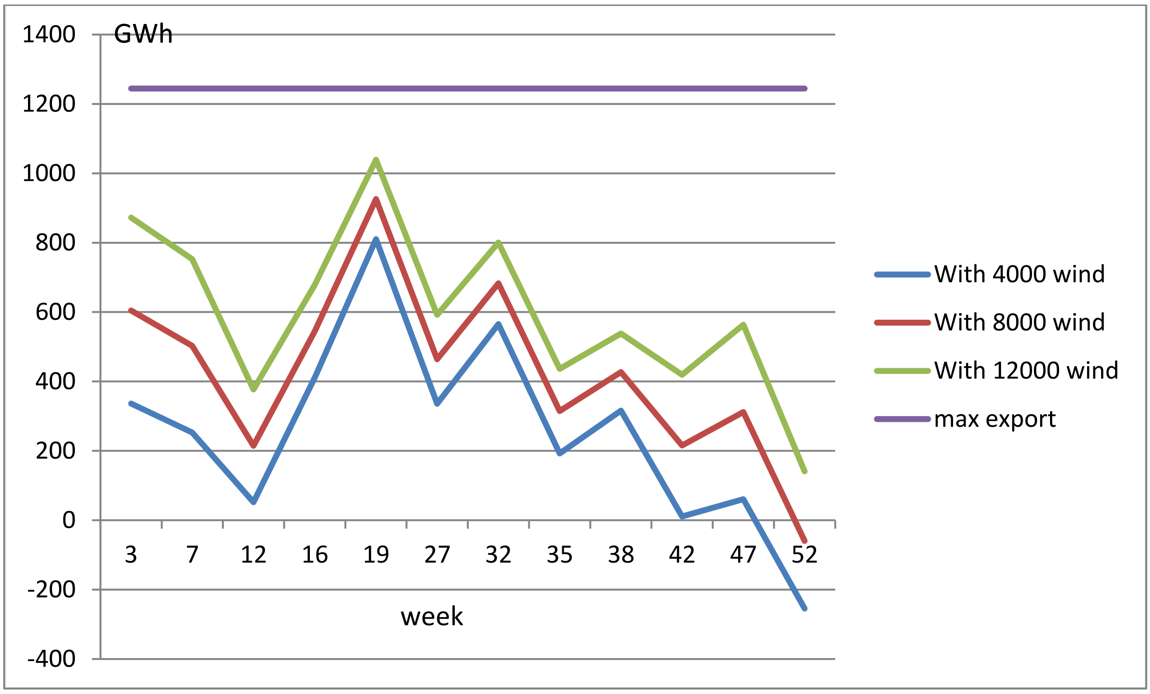

Figure 5.7 Export in different weeks at three expansion level, wet year, original model

Improved model:

The results of spillage and export obtained from improved model during wet years are shown in the following figures.

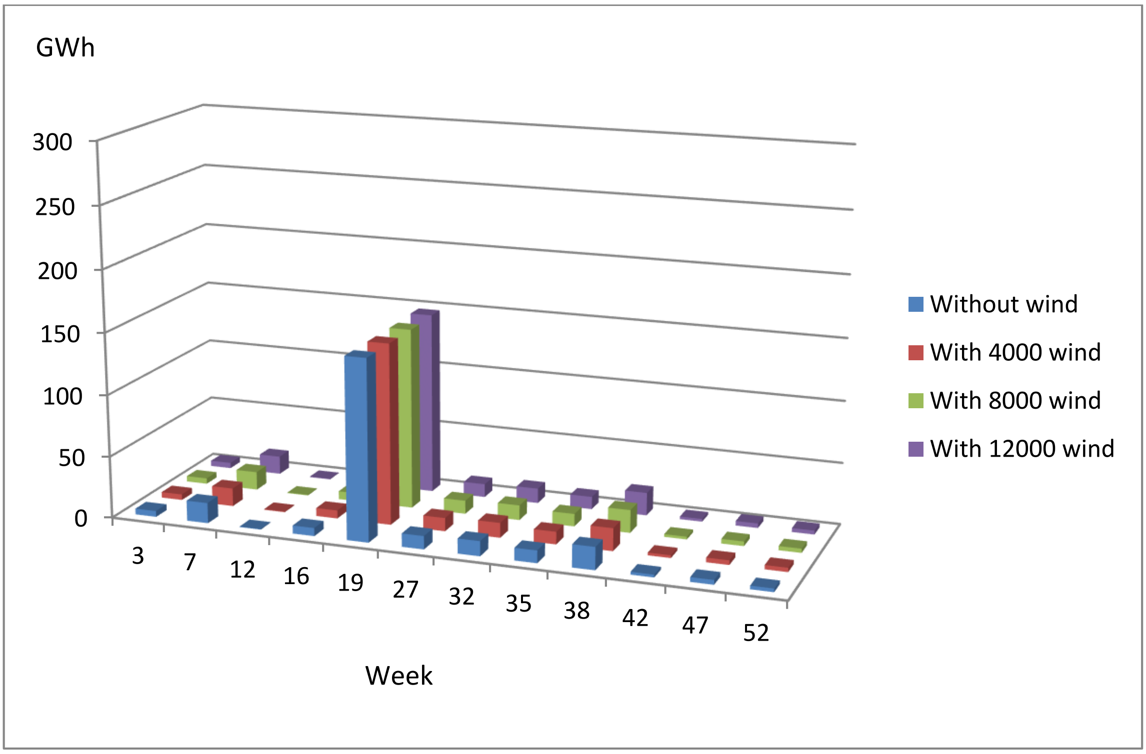

Figure 5.8 Spillage in different weeks at four wind expansion level, improved model

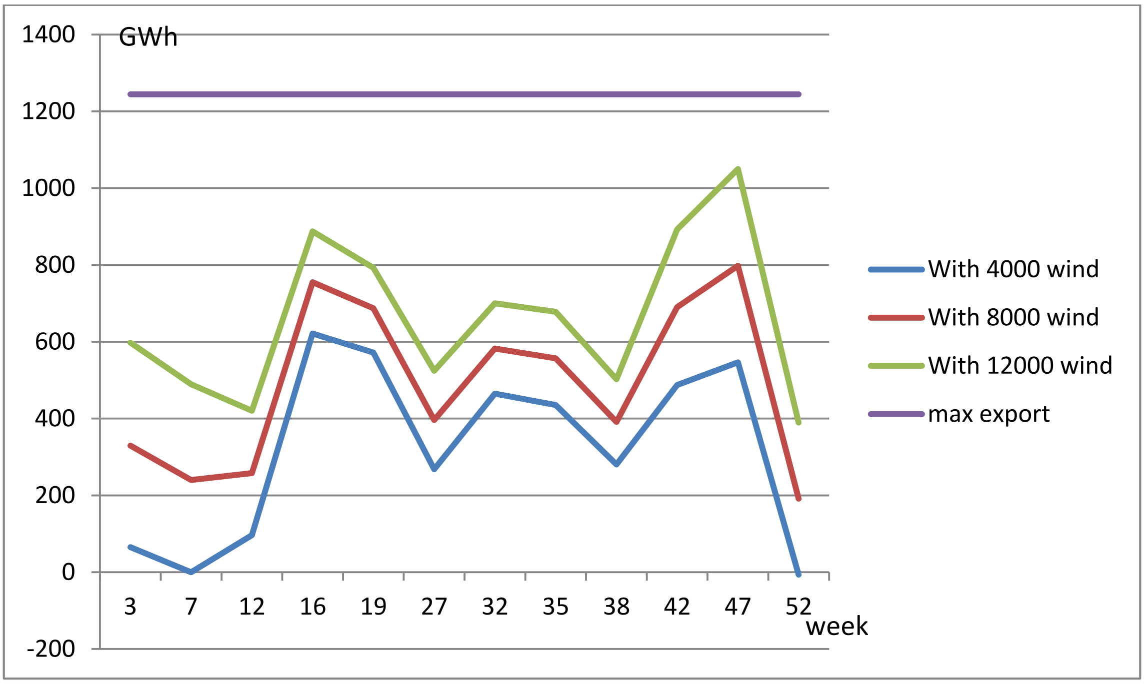

Figure 5.9 Export in different weeks at three expansion level, wet year, improved model

Comparing figure 5.4 and figure 5.8, the results show that due to the higher inflow in wet years, the spillage during all the simulated weeks is significantly increased. For example, in week 19, the spillage is almost three times higher than the spillage in normal years. For most of the simulated weeks, the spillage will not increase with the increase of expansion level of wind power. In week 52, the spillage is slightly increased when wind power is introduced to the system.

The export during wet years is presented in the figure5.9. From the figure, it can be noticed that more power is exported to other countries during wet years since the inflow is higher. When the introduced wind power is increasing, more power will be exported to other countries due to the power surplus.

Comparing the results from both models, it can be noticed that the spillage obtained from the improved model, shown in figure 5.8, is much lower than the spillage got from the original model, shown in figure 5.6. This is expected since the improved model considered the value of stored water and the flexibility of thermal power.

5.5 Reducing export capacity

In the previous case studies, it can be noticed that with the increase of wind power production in the system, more power needs to be exported to other countries. Sufficient export capacity has positive influence on balancing power variation. From previous case studies, it can be seen that when the export capacity is sufficient, the spillage will not increase when more wind power is introduced to the system. In this case, in order to study whether the decrease of the export capacity will have impact on the behavior of power system, the export capacity will be scaled down (20% lower). The situation of wet year with 12000 MW installed capacity of wind power is studied.

Original model

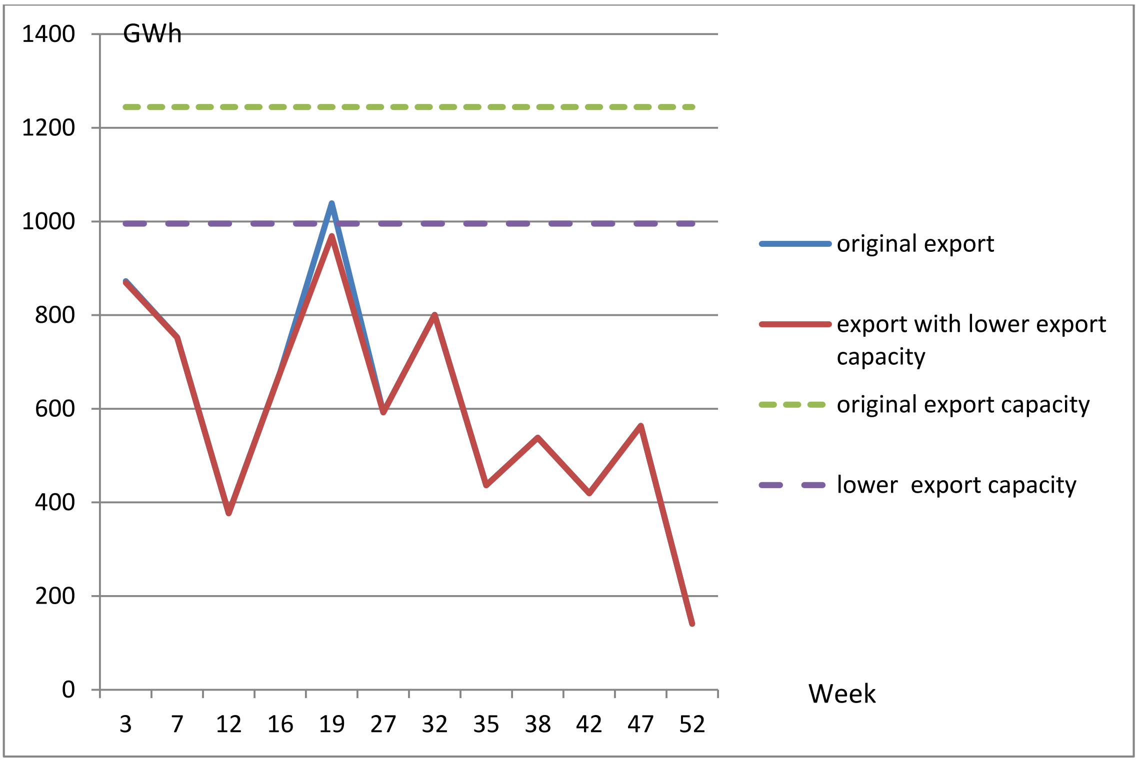

Figure 5.10 Comparison of export in different weeks, original model

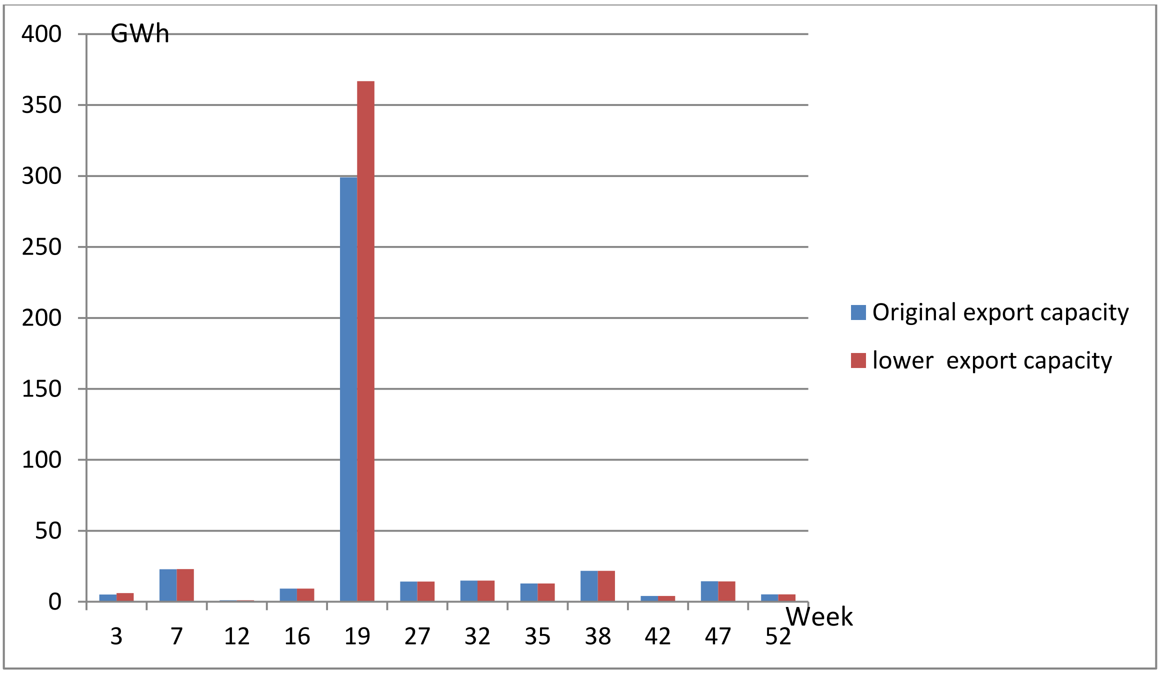

Figure 5.11 Comparison of spillage in different weeks, original model

Figure 5.10 and figure 5.11 show that when the export capacity is scaled down, in week 3 and week 19, the spillage will increase since there isn't sufficient export capacity and the surplus power cannot be exported to other countries. Besides, it is not possible to store more water.

Improved model

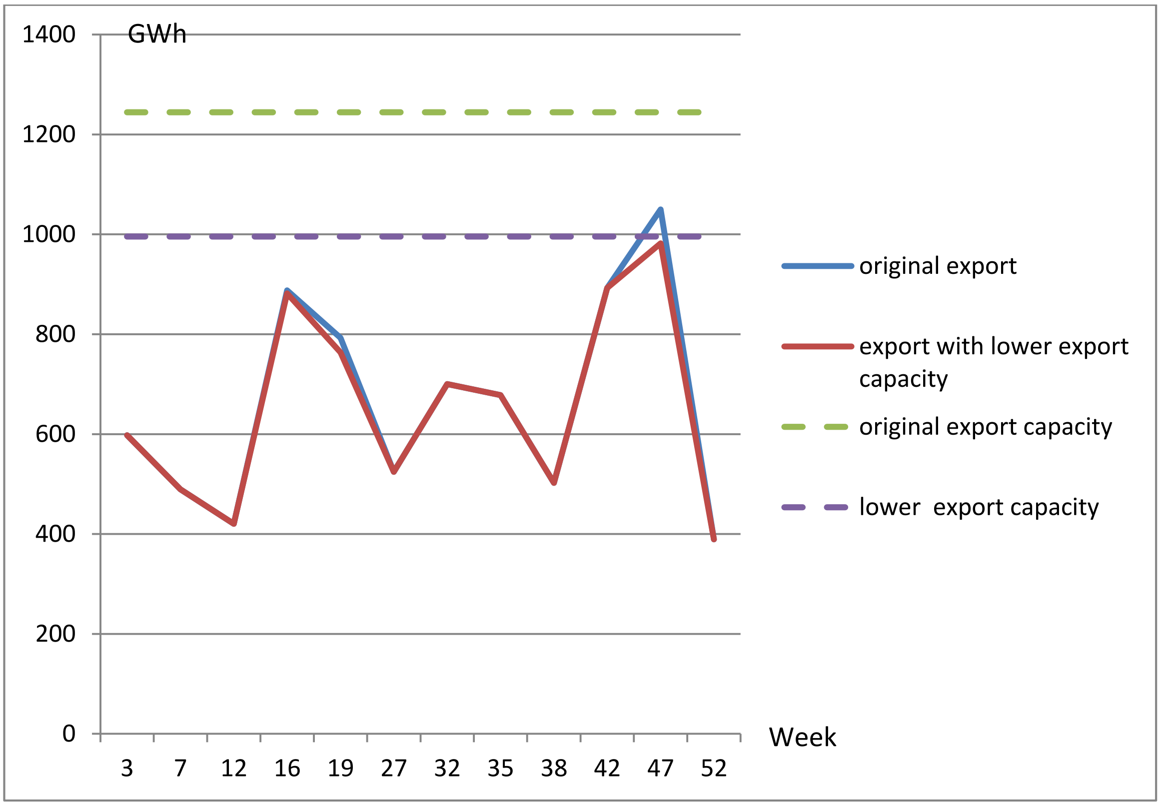

Figure 5.12 Comparison of export in different weeks, improved model

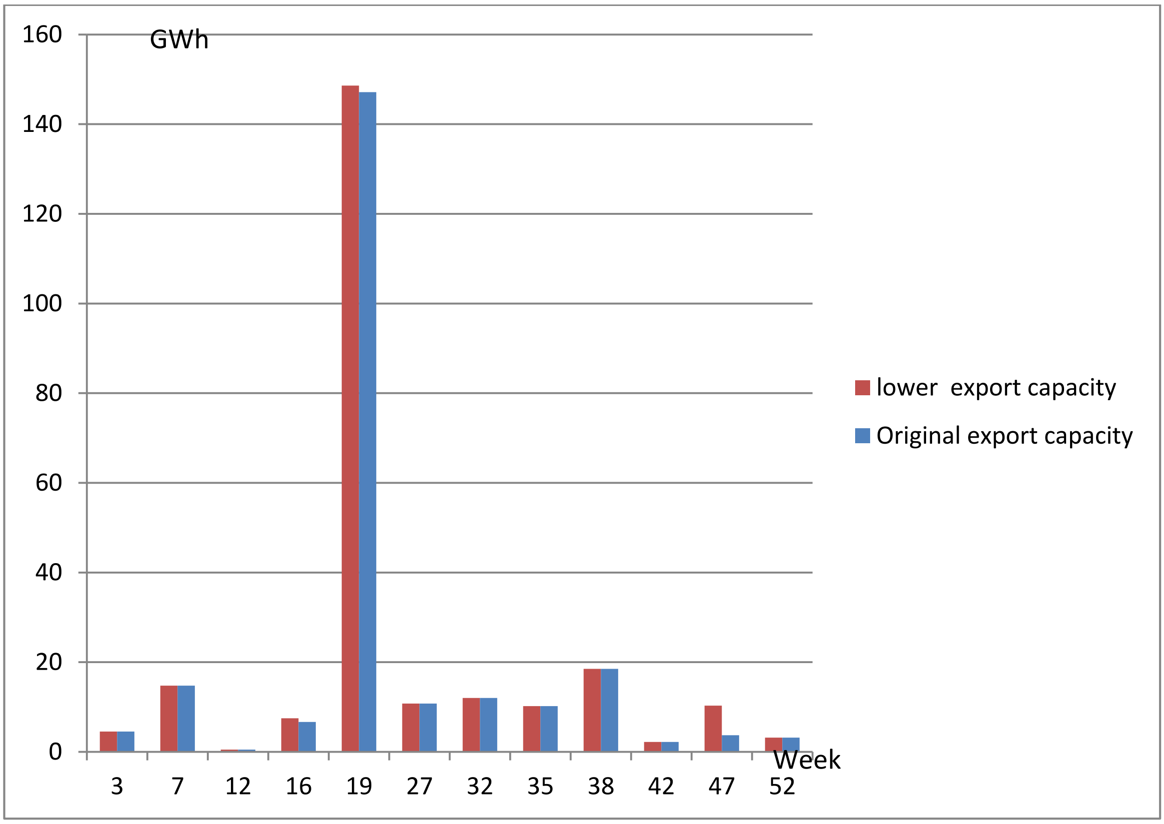

Figure 5.13 Comparison of spillage in different weeks, improved model

As shown in figure 5.11 and 5.12, when the export capacity is scaled down, spillage in week 16, 19 and 47 is increased since the available export capacity is reduced. Since the surplus energy cannot be consumed by exporting to neighboring countries during some hours, spillage increases in order to meet load balance.

5.6 Test on the selection of import cost

From figure 5.5, import occurs in week 3, 7 and 52, which means the load balance needs to be achieved by importing energy from other countries. As discussed in chapter 4, when $\lambda_{im} \geq \lambda_f$, it is more profitable to use hydropower as balancing power. As a result, the import will be limited and the requirement on the regulation capacity of power system is increased. When $\lambda_{im}<\lambda_f$, it is more profitable to import energy to balance wind power rather than regulate hydropower. So it is interesting to study whether different selection of import cost will have a significant impact on the regulation capacity of the power system. In the previous cases, the cost of import energy is selected as $\lambda_{im} = 100$. In this section, the situation of normal years with 4000 MW installed capacity of wind power is studied. week 3, 7, 27 and 52 are mainly studied in this case. The cost of import energy will be $\lambda_{im} = 90$.

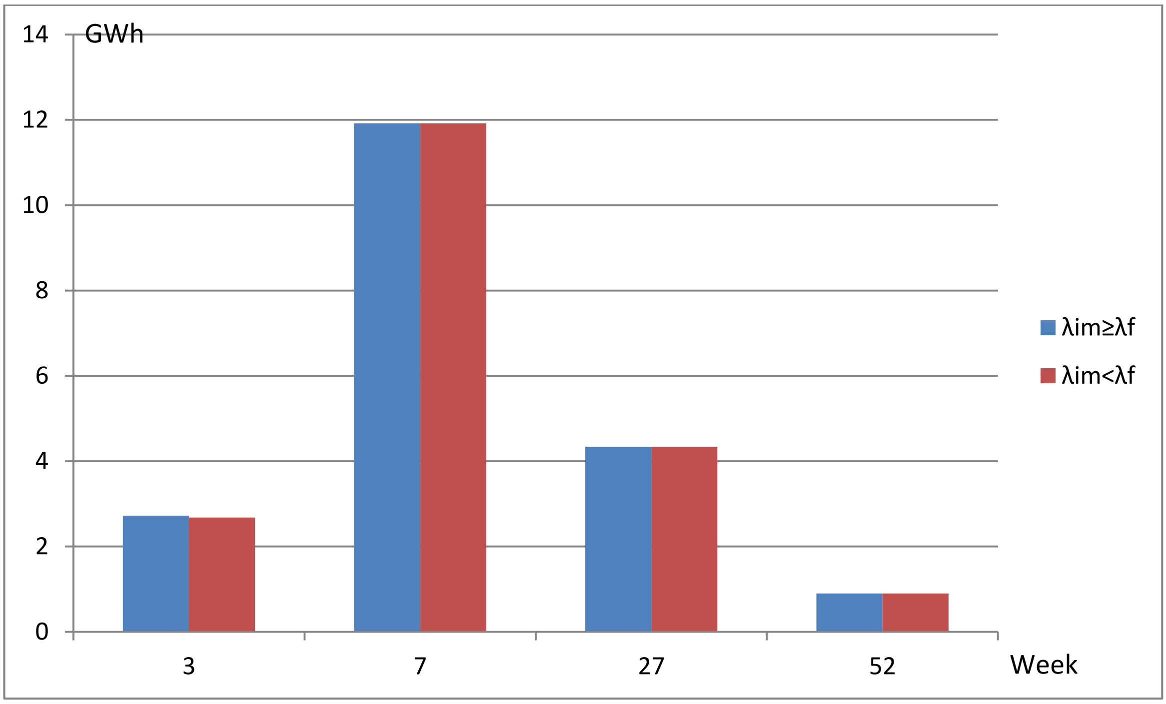

Figure 5.14 Results of spillage

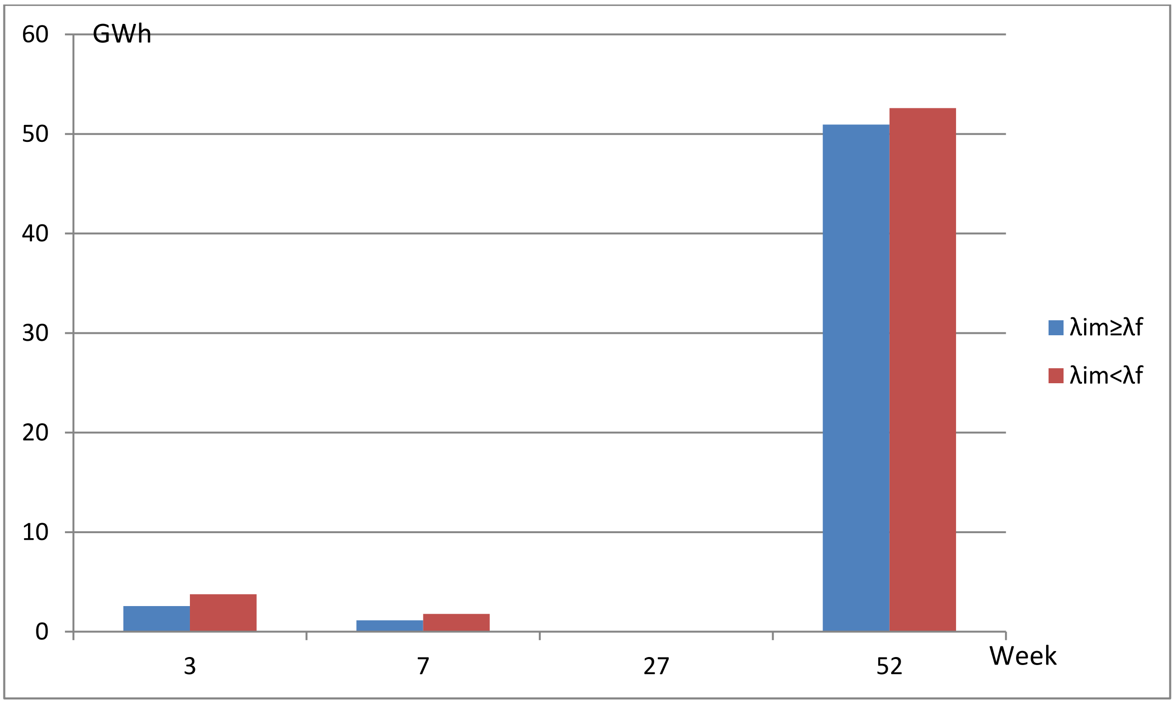

Figure 5.15 Results of import

Figure 5.14 shows the comparison of spillage in each tested week when the cost of import energy is decreased. Figure 5.15 shows the comparison of import energy in each week when the import cost is decreased. From these two figures, it can be noticed that when the cost of import energy is lower than future price, import energy is higher since it is more profitable to balance wind power by importing energy than by regulating hydropower. However, the spillage in these four weeks is almost unchanged.

Chapter 6

Conclusions

In this chapter, the summary of the whole thesis, main conclusion and possible future study will be presented. First of all, the background and main tasks of this project will be summarized. Then the major conclusion obtained from case studies in the previous chapter will be given. Finally, some discussion and possible future study will be suggested.

6.1 Summary

Large amount of wind power are planned to be introduced in Swedish power system in the following years. Due to the variation and unpredictability of wind power, the flexibility of Swedish power system needs to be studied. In Sweden, half of the electrical power is produced by hydropower plants. Thanks to the possibility of storing water and the characteristics of hydropower generation that it can be quickly changed, hydropower can be used as a balancing power. Besides hydropower, thermal power is also possible to contribute to balancing the difference between production and consumption in the system.

In earlier studies, an original model has already been built in GAMS. This model includes 256 hydropower plants whose production covers 96.5% of all installed hydropower in Sweden and mainly studies the flexibility of hydropower in Swedish power system. However, the original model doesn't consider the future value of stored water and the flexibility of thermal power, therefore, it will underestimate the regulation capacity of Swedish power system. To study the flexibility of Swedish power, an improved model is presented. This new model is built as a mixed-integer linear optimization problem in GAMS. The model covers the Swedish hydropower and thermal power generation. The distribution of hydropower plants is the same as the original model. Since it is difficult to obtain the actual data and constraints for the real thermal power plants, the thermal power are modeled based on hourly generation of thermal power per area in years from 2008 to 2012. In each bidding area, the thermal power is considered as three units, namely gas turbine, nuclear power plant and other thermal power plant.

In order to estimate the regulation capacity of Swedish power system, the improved model has been used to study how much the spillage will occur at different expansion levels of wind power. Different case studies are conducted and relevant results are obtained in chapter 5. The aim of this thesis is to study the possibility of Swedish power system to balance large amount of wind power. The studied results are used to analysis the operation of Swedish power when wind power is introduced to the system. However, the actual planning schedule of each power plants in the system cannot be provided by simulated results. Since the simulation is performed based on assumptions of perfect information and some other conditions. However, in a real short-term planning problem, some conditions cannot be exactly achieved and some information cannot be accurately forecasted.

6.2 Results and conclusions

Hydropower production obtained from both the original model and the improved model follows the actual production in Swedish power system. In week 19 the hydropower production peaks since it is one of the spring flood weeks. For both models, the deviation between the simulated result and the actual production data is expected since both models are built based on certain simplifications and assumptions.

In normal years, it can be noticed that in different weeks, the spillage is different. For most of the weeks, the spillage will stay constant when different installed capacity of wind power is introduced. In week 19, the spillage is much higher than other weeks because of the spring flood inflow. Comparing the two models, generally speaking, the spillage of the improved model is much lower than the spillage of the original model. The reasons for this difference can be summarized as 1) the improved model considers the future value of stored water and the flexibility of thermal power. More water can be stored in the reservoir means that less water will be spilled; 2) the model also consider the running water which is released from the upstream power plant and will arrive beyond the planning period. Since the water has higher value when it is saved in the upstream reservoir than released to the downstream reservoir, the running water at the end of the week will be limited in order to maximize the profit.

During all the simulated weeks, the spillage in wet year is much higher than the spillage in normal years. Similar to normal years, the spillage obtained by the improved model is lower than original model. Moreover, the export capacity is also sufficient in wet years. To further study the impact of the export capacity limitation, the export capacity is scaled down (20%). The result shows that spillage will increase during the weeks in which the export capacity is insufficient.

Finally, the impact of selection for import cost is tested. The results show that the selection of import cost doesn’t has significant impact on the spillage.

Based on all the simulated weeks, it can be concluded that the Swedish power system has good regulation capacity. The system can balance the variation of the wind power production. However, in the cases when export capacity is not sufficient, spillage will increase.

6.3 Future studies

The model in this thesis can be used to study the operation of the system and estimate the flexibility of Swedish power system. However, some simplifications and assumptions are made which result in inaccuracy in the estimation. Therefore, further improvement and development can be implemented to this model to get more realistic results.

- Thermal power

As described in chapter 4, the operational cost for the thermal power plants is regarded as merit orders and keeps constant regardless the generation level. Consequently, for most of the simulated weeks, the thermal power generation is constant regardless the power generation. However, in reality, the operational cost is a complex non-linear function of the generation. When the power output is different, the operational cost changes. To model the variation of operational cost with the power output, the operational cost can be regarded as a stair function or a piecewise function of power output. Furthermore, the model in this thesis doesn't consider the start-up cost. For real thermal power plant, start-up cost depends on the technology used and the temperature of the boiler.

- Export and import

In this model, the value of the export energy and the cost of the import energy are the same at different hours and for different countries. Only the transmission capacity is included as a constraint. In fact, the trading prices are different for different countries and the transmission is depending on the prices. One step further, the trading price should also depend on the amount of trading energy. Therefore, in future studies, the price can also be modeled as a stair function of trading energy.

- Hydropower

Although the model in this thesis further includes the value of stored water, some more development can be also suggested. As mentioned before, the efficiency of a hydropower plant is a non-linear function of the head height and the discharge. But in this model, the efficiency is approximated as a two-segment piecewise linear function of discharge and the influence of head height is neglected. Moreover, in reality, the efficiency at low discharge is actually very low, but in the model, it is considered that the power will be generated at the maximum efficiency when discharge is lower than the 75% maximum discharge, which will give rise to overestimation. Therefore, more segments of the piecewise linear model should be introduced in order to model the variation of efficiency with discharge better. It is also possible to use forbidden discharge to avoid the overestimation at lower discharge. Additionally, the power production is also dependent on the natural inflow and the water released from the upstream power plants. In this model, the local inflow is simplified by scaling yearly average water flow in Sweden and the water released from the upstream power is considered constant within one hour. To get more accurate result, better inflow data should be collected and more realistic expression of the discharged/spilled water should be come up with.

As mentioned before, the usage of the same percentage of the target level for all reservoirs will introduce underestimation of regulation capacity. In the future study, instead of applying target level for each individual reservoir, minimum target reservoir level can be used for the sum of the reservoir content in each bidding area.

- Seasonal planning

In reality, it is preferable that the hydropower plants should generate less electricity in the windy week and save the water for the weeks with less wind. The time span of the simulation is one week. As a result, it is impossible to move the water from the week with lower electricity price to the week with the higher electricity price. For future study, the short-term planning should be combined with long-term planning so that the water will not be forced to spill in windy weeks.

- Wind power generation

In this model, the wind power is given by a time series which is known and deterministic at the beginning of the planning week. In reality, it is difficult to forecast the wind power generation within one week. The regulation rules regarding wind power will also have impact on the wind power generation. To improve the model, a better stochastic model for wind power generation and the limitations of share of wind power generation should be considered.

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Appendix

Appendix 1 Results of Case study-Normal year

Spillage:

Introduction: Summary of the spillage, including three different wind level. Normal year												
Original model:												
Week	3	7	12	16	19	27	32	35	38	42	47	52
Without wind (GWh)	2,8578	17,4524	0,2640	1,8880	110,1345	6,1012	5,9890	5,2053	8,0566	0,8307	2,0399	0,9002
With 4000 wind(GWh)	2,8107	17,2759	0,2640	1,8212	110,2278	6,0862	5,8296	5,2053	8,0692	0,8307	3,0673	0,9002
With 8000 wind(GWh)	2,7946	17,1487	0,2629	1,8753	110,2400	6,0962	5,9576	5,1900	8,0518	2,2209	3,0673	0,9002
With 12000 wind(GWh)	2,8277	17,4527	0,2642	1,8818	110,2328	5,9892	5,9766	5,1909	8,0433	1,5679	2,9169	2,8267
Improved model												
Week	3	7	12	16	19	27	32	35	38	42	47	52
Without wind (GWh)	2,6169	13,3227	0,2001	1,7830	56,0035	4,3893	4,2060	3,6172	5,6468	0,8532	1,1151	0,9002
With 4000 wind(GWh)	2,7197	11,9173	0,2273	1,7830	55,9808	4,3371	4,2059	3,6176	5,5962	0,8532	1,1151	0,9001
With 8000 wind(GWh)	2,6688	11,9296	0,2314	1,7830	55,9808	4,3632	4,2056	3,6160	5,6028	0,8532	1,1151	1,4392
With 12000 wind(GWh)	2,6633	11,9111	0,2312	1,7830	55,9808	4,3632	4,2059	3,6160	5,6061	0,8532	1,1151	1,3600

Export:

Introduction: Summary of the export, including three different wind level. Normal year												
Original model:												
Week	3	7	12	16	19	27	32	35	38	42	47	52
max export (GWh)	1244,46	1244,46	1244,46	1244,46	1244,46	1244,46	1244,46	1244,46	1244,46	1244,46	1244,46	1244,46
With 4000 wind (GWh)	221,16	192,46	-19,60	140,30	319,10	36,28	289,52	-70,73	35,36	-173,19	-176,12	-379,96
With 8000 wind (GWh)	489,56	442,68	141,71	274,12	434,54	164,42	407,27	49,90	146,86	24,52	73,38	-180,43
With 12000 wind (GWh)	757,79	692,60	304,14	407,92	550,00	292,55	525,01	171,74	258,188	228,62	324,86	15,76
Improved model												
Week	3	7	12	16	19	27	32	35	38	42	47	52
max export (GWh)	1244,46	1244,46	1244,46	1244,46	1244,46	1244,46	1244,46	1244,46	1244,46	1244,46	1244,46	1244,46
With 4000 wind (GWh)	-2,57	-1,14	29,64	370,07	100,33	0	205,99	186,61	13,73	304,25	322,38	-50,94
With 8000 wind (GWh)	224,08	185,61	191,58	503,73	215,79	124,05	323,72	308,17	124,62	506,89	573,65	76,05
With 12000 wind (GWh)	492,35	434,98	353,78	637,39	331,25	252,04	441,45	429,63	235,45	709,53	825,09	274,19

Appendix 2 Results of Case study-Wet year

Spillage:

Introduction: Summary of the spillage, including three different wind level.wet year

Original model:

Week	3	7	12	16	19	27	32	35	38	42	47	52
Without wind (GWh)	5,6771	22,5144	1,0127	9,2783	298,4201	14,1454	14,9011	13,0853	22,1612	3,5239	13,0965	3,0394
With 4000 wind(GWh)	5,1181	22,9407	0,8256	9,2540	299,1906	14,1698	14,9015	12,8672	21,6934	4,4828	14,2326	3,0394
With 8000 wind(GWh)	5,1408	22,8548	1,0129	9,3013	298,4853	14,2074	14,8975	12,6760	21,7564	4,0492	14,6590	5,3462
With 12000 wind(GWh)	5,1530	22,9652	1,0129	9,3016	299,0996	14,2534	14,8978	12,9080	21,8145	4,1212	14,4141	5,2073

Improved model

Week	3	7	12	16	19	27	32	35	38	42	47	52
Without wind (GWh)	4,7758	16,4861	0,4036	6,5545	146,0482	10,7459	12,0329	10,0855	18,3141	2,1926	3,7091	2,8018
With 4000 wind(GWh)	4,6209	14,6299	0,4775	6,5545	146,0794	10,7592	12,0329	10,1817	18,3492	2,1955	3,6926	3,3829
With 8000 wind(GWh)	4,5382	14,7675	0,4775	6,5545	146,0793	10,7662	12,0329	10,1817	18,5242	2,1955	3,6926	3,3569
With 12000 wind(GWh)	4,5326	14,7683	0,4787	6,6542	147,1579	10,7663	12,0329	10,1817	18,5262	2,1955	3,7124	3,1742

Export:

Introduction: Summary of the export, including three different wind level. Wet year												
Original model:												
Week	3	7	12	16	19	27	32	35	38	42	47	52
max export (GWh)	1244,46	1244,46	1244,46	1244,46	1244,46	1244,46	1244,46	1244,46	1244,46	1244,46	1244,46	1244,46
With 4000 wind (GWh)	336,38	252,62	51,90	410,94	810,27	335,96	565,19	192,59	315,83	10,74	60,51	-254,83
With 8000 wind (GWh)	604,76	502,84	214,41	544,74	925,68	464,08	682,94	314,55	427,11	215,63	312,08	-59,90
With 12000 wind (GWh)	872,57	752,75	376,84	678,49	1039,03	592,17	800,69	436,35	538,26	419,35	563,68	140,71
Improved model												
Week	3	7	12	16	19	27	32	35	38	42	47	52
max export (GWh)	1244,46	1244,46	1244,46	1244,46	1244,46	1244,46	1244,46	1244,46	1244,46	1244,46	1244,46	1244,46
With 4000 wind (GWh)	65,32	-0,33	96,25	621,40	571,94	268,11	464,77	435,16	280,38	487,41	546,59	-6,54
With 8000 wind (GWh)	329,56	240,15	258,13	755,06	687,39	396,30	582,52	556,76	391,36	690,05	797,86	191,39
With 12000 wind (GWh)	597,80	489,59	420,35	887,75	792,61	524,34	700,26	678,23	502,49	892,69	1050,01	389,45

Appendix 3 Result of the case study-Reducing export capacity

Introduction: Comparison between export capacity and 80% export capacity, original model												
Spillage												
Week	3	7	12	16	19	27	32	35	38	42	47	52
Original export Capacity (GWh)	5,1530	22,965	1,0129	9,3016	299,09	14,253	14,898	12,908	21,815	4,1212	14,414	5,2073
lower export capacity(GWh)	6,1494	23,081	1,0129	9,2552	366,82	14,253	14,898	12,912	21,819	4,1203	14,413	5,2073
Export												
Week	3	7	12	16	19	27	32	35	38	42	47	52
Original export capacity (GWh)	872,57	752,75	376,84	678,49	1039,0	592,17	800,69	436,35	538,26	419,35	563,68	140,71
lower export capacity (GWh)	869,16	752,20	376,84	678,12	968,93	592,17	800,69	436,35	538,26	419,35	563,68	140,71
max export (GWh)	1244,4	1244,4	1244,4	1244,4	1244,4	1244,4	1244,4	1244,4	1244,4	1244,4	1244,4	1244,4
lower export capacity (GWh)	995,57	995,57	995,57	995,57	995,57	995,57	995,57	995,57	995,57	995,57	995,57	995,57

Introduction: Comparison between export capacity and 80% export capacity, improved model												
Spillage												
Week	3	7	12	16	19	27	32	35	38	42	47	52
Original export capacity(GWh)	4,5326	14,7683	0,4787	6,6542	147,1580	10,7664	12,0329	10,1818	18,5262	2,19551	3,7124	3,1742
lower export capacity(GWh)	4,5326	14,7683	0,4787	7,4697	148,6095	10,7664	12,0329	10,1818	18,5262	2,19551	10,2989	3,1742
Export												
Week	3	7	12	16	19	27	32	35	38	42	47	52
Original export capacity(GWh)	597,80	489,59	420,35	887,75	792,62	524,34	700,27	678,23	502,49	892,69	1050,01	389,45
lower export capacity(GWh)	597,74	489,59	420,36	881,90	763,48	524,34	700,26	678,23	502,49	892,69	982,04	389,45
max export(GWh)	1244,46	1244,46	1244,46	1244,46	1244,46	1244,46	1244,46	1244,46	1244,46	1244,46	1244,46	1244,46
lower export capacity(GWh)	995,57	995,57	995,57	995,57	995,57	995,57	995,57	995,57	995,57	995,57	995,57	995,57

Appendix 4 Result of the case study-Test on the selection of import cost

The comparison of spillage between different selection of import cost

Week	3	7	27	52
λim=100 (GWh)	2,7197	11,9173	4,3371	0,9001
λim=90 (GWh)	2,6784	11,9178	4,3371	0,9001

The comparison of import energy between different selection of import cost

Week	3	7	27	52
λim=100 (GWh)	2,5730	1,1431	0	50,9432
λim=90 (GWh)	3,7573	1,7871	0	52,6033

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