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Modelling an Electricity System with Load Following Nuclear Power Plants

Master's Thesis within the Nuclear Engineering programme

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Department of Energy and Environment
Division of Energy Technology
Chalmers University of Technology
Gothenburg, Sweden 2014

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Cover: Picture of two of the pressurized water reactors at Ringhals, Sweden.
Source: http://en.wikipedia.org/wiki/File:Ringhals.JPG acquired 23 may 2014.

Acknowledgments

I would like to thank a bunch of people. First, Joel Goop for all the help and support given during this whole work. This report would be a total mess and the effort needed for the reader to understand it would be tremendous. Thank you Mikael Odenberger for all the help, inspiration and wonderful jokes. Also a big thanks to Lisa Göransson who also helped me with this thesis.

A big thank you, Tyra von Sydow, for all help and support during this work. I hope you understood at least some of my rabbling at last.

I would also like to say a big thank you to all the people at Division of Energy Technology for the welcoming atmosphere and nice coffee.

An extra tanks to you who supported me when doing this thesis. It could be by trying to teach me the math behind linear optimization, sitting together and writing reports or by simply having thoughts on my beautiful and colourful graphs.

Lastly, an enormous thank you to all of you around me during all those years at Chalmers, you are far too many to give each and everyone of you the appreciation you deserve. Thanks for tea, sympathy and sofa.

Göteborg June 2014
Karl Gustavsson

Time is an illusion. Lunchtime doubly so.
Douglas Adams - *The Hitchhiker's Guide to the Galaxy*

Abstract

A significant part of the greenhouse gases emitted today comes from the electricity generation around the world. Since the greenhouse gases contribute to the global warming it is of great interest of how the energy system can be changed to lower these emissions. Another reason for changing the energy system is that the fuels used may become much more expensive, or even become very scarce, when the availability of the fuels decrease. Renewable energy sources have no or low net emissions of greenhouse gases and does not, per definition of being renewable, use any fuel that may become depleted. Some of the renewable sources have variable production, like when the wind is blowing. This has the consequence that the other electricity sources may need to be more flexible to be able to meet the instantaneous electricity demand at each hour, here approximated with a hourly balance between supply and demand.

Since a large part of Sweden's electricity is generated by nuclear power and since nuclear is also a power source with no or very low greenhouse gas emissions, it is of interest what role it takes in an electricity system with large amounts of variable renewable generation. A model that minimizes the total production cost from all power producers of southern Sweden was developed for this purpose. The power limits for load following nuclear power plants (NPPs) were investigated and were thereafter used as input to the model. Acquired data for wind and hydro power were also put into the model to model the electricity system of southern Sweden.

When modelling load following NPPs, the pressurized water reactors (PWRs) could vary between 30 and 100 % of the rated power and the boiling water reactors (BWRs) could vary between 70 and 100 % of the rated power. The results from the simulations shows that the nuclear reactors can be up and running at a higher degree when using load following techniques. When the annual electricity production from wind power stays at 15 TWh or below, it is enough that only the pressurized water reactors use load following techniques to avoid shut down of any reactors when the power from the other sources is high. If the electricity production from wind goes above that, it is necessary to use more reactors as load following reactors if shutdowns of NPPs are to be avoided. At 20 TWh annual electricity from wind power it is necessary that all reactors use load following techniques to avoid shut downs in the model. When comparing the total electricity generated from nuclear at different wind power penetration levels, there is very small differences between when load following is used in the nuclear reactors or not. This is most likely because of the large amount of cheap hydro power in the system and and that export of electricity was forbidden in the model.

Keywords: nuclear power, energy systems modelling

Sammanfattning

En stor del av växtgusgaserna som släpps ut idag kommer från elproduktionen runtom i världen. Eftersom växthusgaserna bidrar till den globala uppvärmningen så är det angeläget att ta reda på hur energisystemet kan ändras så att dessa utläpp kan minskas. En annan anledning till att ändra energisystemet är att bränslena som används kan komma att bli dyrare, eller väldigt sällsynta, när tillgängligheten på bränlsen minskar. Förnybara energikällor har inga eller små nettoutsläpp av växthusgaser och de använder inte bränslen som riskerar att ta slut. Vissa av de förnybara energikällorna är intermittenta, vilket betyder att de produktionen från dem varierar, som när solen skiner eller vinden blåser. Detta har som följd att de andra energislagen kan bli tvungna att bli mer flexibla för att kunna möta elbehovet varje timme.

Efterom en stor andel av sveriges el generas av kärnkraft som har inga eller väldigt låga utsläpp avv växthusgaser, så är det av intresse att veta vad för roll den tar i ett elsystem med stor andel varierande förnybara energikällor. En modell som minimerar den totala produktionskostnaden från alla elproducenter utvecklades av denna anledning. Kärnkraftverkens möjlighet att variera sin effekt undersöktes och användes som indata till modellen. Data för wind och vattenkraft sattes också in i modellen för att modellera södra Sveriges elsystem.

I simuleringarna där reaktorerna kunde variera sin effekt kunde tryckvattenreaktorerna variera sin effekt mellan 30 och 100 % medans kokvattenreaktorerna kunde variera mellan 70 och 100 %. Resultaten visade att reaktorerna kunde vara aktiva till en högre grad när lastföljning användes. När den årliga produktionen från vindkraft var 15 TWh eller mindre var det tillräckligt att endast tryckvattenreaktorerna användes för lastföljning för att undvika att reaktorer stängdes ner. Om vindkraften producerade mer än 15 TWh var det tvunget att använda fler reaktorer för lastföljning för att undvika avstängningar. Vid 20 TWh årlig vindkraft var det tvunget att alla reaktorer använde lastföljning för att undvika nedstängningar. Vid jämförelse av den totala mängden el som producerades från kärnkraft, var det mycket små skillnader mellan fallen med lastföljning och fallen utan lastföljning. Detta beror troligen på att det finns mycket billig vattenkraft i systemet och att ingen export av elektricitet var tillåten i modellen.

Nyckelord: kärnkraft, energisystemmodellering

Contents

1 Introduction

To lower the emissions of greenhouse gases is considered of great importance in many countries around the world. In [1] it is stated that nuclear power may lower the cost for climate change mitigation and the term "nuclear renaissance" is sometimes used as a term for the increased interest of using nuclear power. There are however many technologies, e.g. carbon capture and storage (CCS) and renewable energy sources, that can mitigate the climate change as well.

With the expansion of intermittent energy sources in the Swedish electricity mix, there may be an increasing demand for flexibility among other sources that can generate electricity when output from the variable sources are low. The total solar and wind power installed in Sweden has increased significantly in the last decade and is still on the rise. The solar power is still only a small fraction of the total electricity generated, but the wind power generates several TWh each year in Sweden.

About half of Sweden's electricity comes from hydro power which is a power source that can easily change its electricity production, both in shorter (seconds) and longer (hours) time scales, when needed; this makes hydro power an ideal source to use together with the intermittent sources. Since Sweden has a large share of nuclear power, which is used as base load today, in its electricity mix, it is of interest how the electricity system changes when more intermittent power sources are added to the Swedish system and how the existing nuclear reactors can be used to facilitate integration.

Previous work in the field of modelling electricity systems has involved how e.g. electricity systems react when introducing more wind, see [2, 3], but not much work has been done for nuclear power and its role in an electricity system. Sweden has a quite unique electricity system with high supply from both hydro and nuclear. E.g. Denmark has no nuclear reactors, Norway has mostly hydro power and France where the contribution is large in TWh (similar annual output as in Sweden) yet rather low relative the nuclear power production. How a system with base load reactors combined with variable hydro reacts to a major introduction of intermittent electricity is therefore of interest. It is also of interest of how the system changes if base load reactors are changed into load following reactors.

Recent work on the technical aspect of load following has been made by e.g. [4, 5] while the economical parts are investigated in e.g. [5, 6] but the results from these reports has not been put into a model for the Swedish electricity system. This thesis was therefore born out of the need for integrating the technical aspects of load following nuclear reactors into a model that simulates the Swedish electricity system.

The techniques for using load following in nuclear reactors are investigated in this thesis. Even if it is possible to use the Swedish nuclear power as load following electricity production, it may not be used for other reasons; e.g. it may be cheaper to let the nuclear reactors produce power at their maximum rate and let the hydro power vary its production to compensate wind.

The goals of this master thesis are the following:

- Investigate the technical possibilities and difficulties of varying the power of

NPPs.

- Approximate the economic aspects of using NPPs as load following power plants.
- Develop a model that can investigate the role of nuclear power, both load following and base load reactors, in a future Swedish electricity system.
- Investigate changes in the electricity production in Sweden at different amounts of wind power, both when nuclear reactors use load following and when they are only used for base load.

2 Theory and background

First in this chapter is a description of the the physics in nuclear reactors that is of relevance for the later part where the load following techniques are described. After that follows a description of the economic aspects of using load following techniques in nuclear reactors. Last is a description of modeling of an energy system.

The following concepts will be used in the following chapters:

Primary control is when a power producer can change the electricity generation very fast, within seconds, while **secondary control** is changing the generation at longer time scales (minutes) so the primary reserve can be made available when there is a permanent increase of electricity demand.

Reactivity (ρ) is a measure of how a reactor changes its power. If $\rho > 0$ the reactor is called supercritical and is increasing its power, when $\rho < 0$ is the reactor subcritical and the power decreases. At $\rho = 0$ the reactor is called critical and produces power at a constant rate.

2.1 Nuclear power basics

Nuclear reactors produce power by fissioning heavy elements into lighter and thereby converting mass into energy. Most reactors use uranium which consists mostly of two isotopes: ^{235}U and ^{238}U. ^{235}U is fissionable but ^{238}U is not. Natural uranium consists of about 0.7% ^{235}U and 99.3% ^{238}U.

Most of the reactors used today requires fuel with a higher ratio than 0.7% ^{235}U and the uranium is therefore enriched to 3-5% ^{235}U before it is inserted into a reactor.

When a ^{235}U is fissioned by a neutron it emits high energy neutrons which can be used to split more uranium atoms and thereby allowing a chain reaction to occur. High energy (fast) neutrons have a much lower probability of splitting ^{235}U-atoms than low energy (thermal) neutrons. A so called moderator is often used in reactors to slow down the fast neutrons. Light water, heavy water and graphite are the most common moderators that have been used in commercial reactors. [7]

The heat produced in the reactor, due to the fission, is used to produce steam that goes through a turbine connected to a generator which thereby produces electricity.

2.2 Different reactor types

A majority of the commercial reactors in the world today are of one of two types: pressurized water reactor (PWR) or boiling water reactor (BWR). Both of these types are so called light water reactors, which means that the moderator and coolant consists of light water. About 60% of the commercial reactors used in the world today are PWRs and about 20% are BWRs [8].

An example of a commercial reactor that uses heavy water as coolant and moderator is the Canadian CANDU-design. Heavy water has a much lower probability of absorbing neutrons compared to light water, which enables the use of natural uranium.

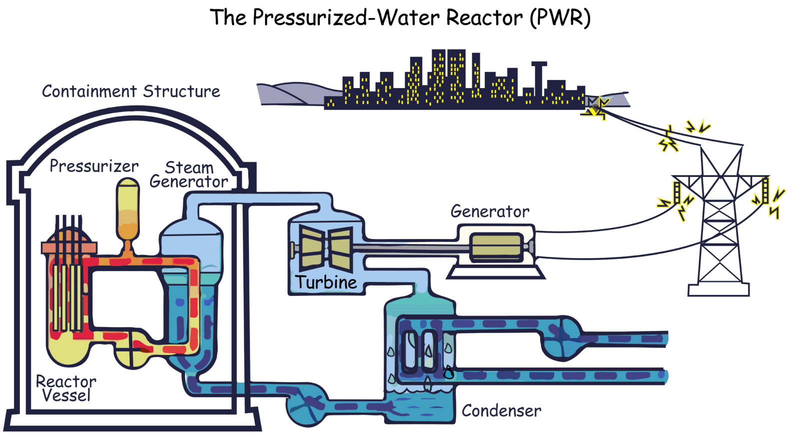


Figure 1: Schematic of a pressurized water reactor showing the two loops used to separate the water in the core from the water in the steam cycle. Source: USNRC [9]

Pressurized Water Reactor - PWR

The water in a PWR is held under a very high pressure, usually about 150 bars, that prevents the water from boiling inside the core. The heated water flows through steam generators that produces steam in another loop (called the secondary loop, blue in Figure 1) which flows through the turbines. The water that flows through the core never leaves this loop (called the primary loop, red in Figure 1), and the produced steam has therefore never been inside the core.[7]

The control rods in a PWR are mostly used during startup, shutdown or to compensate for short term changes. Boric acid is dissolved in the primary system to control the reactor since boron has a large neutron absorption cross section.

Boiling Water Reactor - BWR

The pressure is lower in a BWR compared to a PWR, usually around 70 bars, which allows boiling to occur directly in the reactor core. The produced steam goes through the turbine and therefore a BWR has only one loop, shown in figure 2.

If boiling occurs, the density of the water goes down which leads to worse moderation. This negative feedback is very important for the safety of a BWR; if there is a sudden increase of reactivity in the core the worsened moderation compensates this and the power goes back to a stable level. [7]

Due to that the density of the moderator varies heavily depending on height, the power distribution in the fuel becomes very uneven. To compensate for this, control rods are partly inserted from the bottom of the core to get a more even power distribution.

To increase the flow through the core, circulation pumps are installed in the core to pump the feed water through the core. These pumps are also used to control the power of the core. By increasing the the pump speed the water front gets pushed upward which increases the efficiency of the moderation.

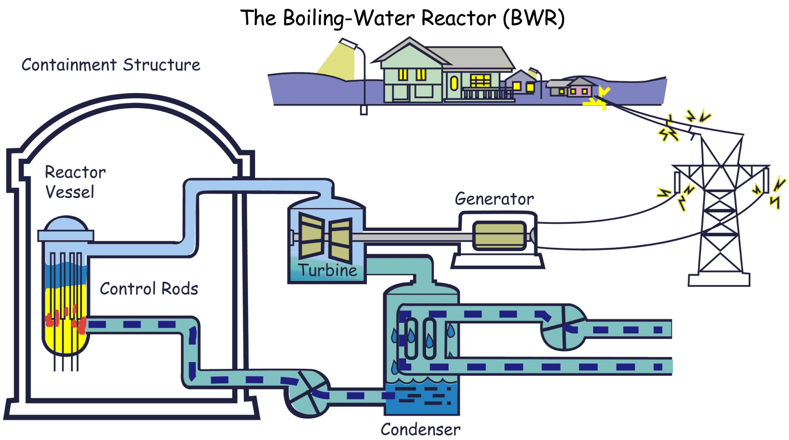


Figure 2: Schematic of a boiling water reactor showing how the water flows throughout the core, turbines and condenser etc. Source: USNRC [10]

2.3 Xenon poisoning

One of the most important difficulties to increase or decrease the produced power is the so called xenon poisoning.

One of the major fission products is the radioactive isotope ^{135}I which has a half life of 6,6 hours. ^{135}I has a low cross section for absorbing neutrons, so the concentration can only be lowered by natural radioactive decay. ^{135}I decays by β^- to ^{135}Xe which itself is only produced in very small amount by fission. ^{135}Xe has a half life of 9,2 hours but it has a huge absorption cross section for thermal neutrons ($\approx 2{,}7 * 10^6$ barn compared to ≈ 500 barn for ^{235}U).

When a reactor has produced power for a while the concentration of ^{135}I and ^{135}Xe comes to an equilibrium and stays there as long as the power remains constant. If the reactor decrease its power, less ^{135}Xe will be consumed through neutron absorption but the production from ^{135}I stays the same. This gives a net increase of ^{135}Xe for a while until the concentration of ^{135}I has decreased to the point where the radioactive decay of ^{135}Xe is larger than the decay of ^{135}I. [11]

Due to the high cross section of ^{135}Xe, even a small concentration can affect the reactivity of the reactor severely. This results in difficulties to increase the power fast after a decrease of power.

Figure 3 shows a curve of how the concentration of ^{135}Xe may vary with time.

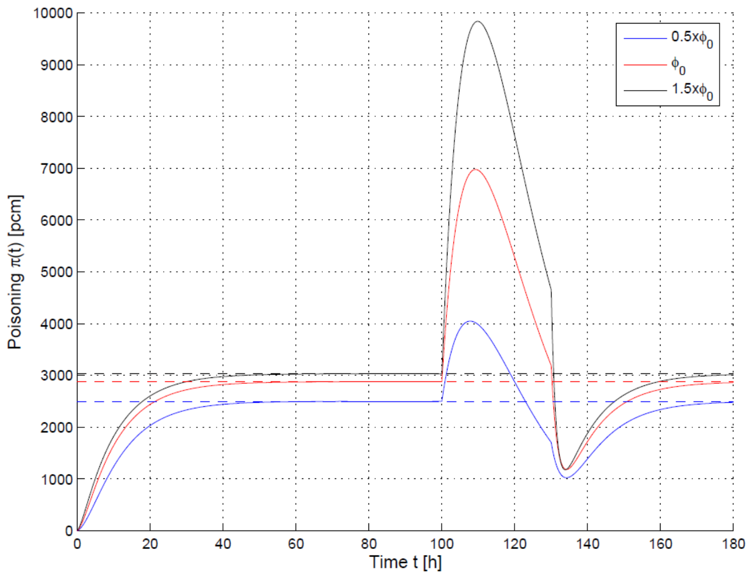


Figure 3: The decrease of xenon poisoning, π, which correlates linearly to the xenon concentration at different neutron fluxes, ϕ_0, which correlates linearly to the power in a reactor. The reactor shuts down at t=100 and is restarted at t=130. The dashed lines are the equilibrium poisonings. Picture from "Physics of Nuclear Reactors" [11].

2.4 Load following techniques

The different load following techniques for the two light water reactors are described in this chapter.

Pressurized Water Reactor

To vary the power in a PWR, three techniques are usually used:

- Grey control rods
- Variation of coolant temperature
- Variation of boron concentration in core

Grey control rods are control rods that has a lower absorption cross section than ordinary control rods. When inserted into the core they do not alter the neutron spectrum as much as the ordinary rods, and are therefore better for fast, much smaller, variations of the power. If grey control are installed, the reactors can be used for primary control. This technique has been used in some reactors in France [4].

Variation of the coolant temperature can be used for load following since colder water improves the moderation since cold water has higher density than warm water.

Boron is a strong neutron absorber which can be dissolved as boric acid in the water in the primary loop. By dissolving more boron in the water the power level can be decreased. To lower the amount of boron, water can be extracted from the core where it can be treated in different ways to get rid of the boron. This kind of system is not fast enough to be used for primary control.

PWRs has been used e.g. in France, both for primary and secondary control, but to use primary control, it is needed to have grey control rods installed to avoid large transients.

The power change in a PWR is often between 1-3 % of the rated power per minute, but can be as high as 10 % per minute. The power in a PWR can go down to 15 - 30% of the rated power when using load following techniques. [4].

Boiling Water Reactor

In BWRs, two techniques are mainly used:

- Circulation pumps
- Control rods

The circulation pumps in a BWR can be used to vary the power produced in the core very rapidly. If the pump speed is increased, the liquid coolant gets pushed upwards in the core which improves the moderation of neutrons and thereby increasing the reactivity. This in turn increases the power and therefore increases the amount of steam in the core. Since steam is less dense than liquid water the reactivity goes back to zero and the power stabilizes at a new, higher, level.

The control rods in a BWR are often of two types; one type that are only used for shutdowns while the other type can be used to vary the power or increase the reactivity to compensate for burnt up fuel.

No examples of where BWRs are being used for primary control has been found, but it has been used as secondary control in several places, e.g. Sweden in the past. It was tested to use BWRs in Sweden for primary control, but it was abandoned due to uncontrollable power variations [4].

The power change rate in the range between 70 and 100 % of the rated power can be as high as 1 % of the rated power per second in a BWR. It is possible for BWRs to go down to around 30 % of the rated power with the use of both control rods and the pumps, and about 60 % when only using the pumps, but the power is often at the higher power ranges when using load following.[4]

2.5 Economic aspects due to load following

The reactors in Sweden have already used, and are designed to be able to use, load following. There are therefore no major investment costs if it is desirable to use load following again. But if grey control rods are to be installed in the PWRs the investment cost can be very high and the reactor has to be shut down entirely for several years during the reconstruction [4].

If the load following is planned long beforehand, the fuel cost per MWh is not increased. Otherwise, in worst case scenarios, it may increase up to about 25% [6].

If the power variation is not too fast and the power stays within a range of $\approx 60-100\%$ in BWRs, there is no large increased maintenance costs. For PWRs it may go down to $\approx 20\%$ of its max power without any major increase in maintenance cost.

The additional cost comes from the increased inspection and wear of components. [5, 6]

For PWRs the maintenance cost may increase if it is used for primary control. This is because the grey control rods are used to a high degree and the pressurizer need more inspection and maintenance due to the temperature variations. [6]

2.6 Energy system modelling

Energy system modelling is a very broad term and can treat a vast amount of different aspects. An electricity system, the vehicles in a country or heating of a city can be examples of energy systems which can be modelled. Energy system models are often divided into simulating models, commonly used for predictive purposes, and optimizing models, commonly used for normative purposes.

Simulating models try to simulate the dynamics of some kind of system, often to predict some future state of the system based on information regarding current and previous states. An example is chemical processes where there can be lots of inputs, such as temperature, pressure and density and the output can be for example how long it takes for the system to reach an equilibrium.

Optimizing models instead tries to optimize a system of some kind. It can e.g. be to minimize the total cost for a system or see how to get the highest return per invested unit of money in a business. An optimizing model is often a perfect foresight model which can mean for example that it knows the input for all technologies at all times. This is not realistic and it is therefore of great importance to have this in mind when interpreting the results. [12] It is also possible to use so called limited foresight which restricts the information available in the optimization.

A cost dispatch model, which is used in this thesis, tries to minimize the production costs for a system while satisfying the demand and under an additional set of constrains, such as maximum power output from producers or maximum annual power. The different costs, like production costs and costs for starting up a power plants are used as a basis for optimization in such a model. [13]

The development of an electricity system over time can also be modelled. There may be power production units that are decommissioned and new ones may be built. This kind of development is not treated in this thesis.

3 Method

This chapter provides a description of the modelling methodology as well as model inputs. Special emphasis is put on the description of NPPs in the model including setting up boundaries and limitations including economic and physical. Finally, a description of measurements and indicators applied in the result is given.

3.1 Overview of the model

The model that is developed and used describes the electricity system of southern Sweden and do not take what happens in the neighboring regions into account. The exception to this is that the hydro power is seen as in import from the north of Sweden and is therefore limited by the capacity of the transmission lines between the regions. The model has time steps of 1 hour and it can therefore not simulate what happens within those hours.

The model is an economic dispatch model that tries to minimize the total cost of the electricity generation for a full year. The model is written in GAMS[1] which is designed for linear, nonlinear and mixed integer optimization problems. Models written in GAMS can then be solved by several third party solvers. The solver used for this thesis is CPLEX.

3.2 Power producers

All electricity in this model comes from four different sources: wind, hydro, nuclear and backup. The backup power is here modelled as aggregated gas plants.

The wind data comes from results from a model that uses wind speed data from ECMWF[2] and then uses the investment model ELIN that determines where it is desirable to build wind power [14]. This is then used to get the data used in this model. This wind power acquired correspond to about 10 TWh. For the simulations where more wind power is used, the acquired data from 10 TWh is scaled linearly.

All hydro power are aggregated into one hydro power provider. The hydro power has both a maximum power output, but also a maximum annual energy production. Since most of the hydro power is located in the northern parts of Sweden the maximum power is determined of how much can be transmitted through the power lines between electricity regions SE3 and SE2. Nuclear power is not aggregated, each reactor has its own characteristics.

3.3 Nuclear specifics

The nuclear reactors have some specific characteristics which are implemented in the model.

[1] General Algebraic Modeling System
[2] European Centre for Medium-Range Weather Forecasts

- Every reactor involved in the model has to be shut down once a year for refuelling and cannot produce power during that time.
- A reactor takes some time to start and does not do it for free. To model this a start up-cost is used.
- Both reactor types can be used as secondary reserve.
- Xenon poisoning is modelled so that the power rise and decrease of the reactors can increase at a maximum rate each hour.

3.4 Implementation

The model tries to minimize the total cost of electricity production over a year. The production has to be the same as the demand at all times; export, import or storage is not allowed but curtailment of wind is allowed.

The cost does not come only from the production itself, some plants can have a startup cost that has to be added to the total cost. The startup cost is approximated as running the plant at its minimum power during the whole startup. The cost, *startmax*, of starting up a plant is therefore:

$$startmax(i,t) = starttime(i) * power_{min}(i,t) * z_{production}(i,t) \quad (1)$$

where $power_{min}(i,t)$ is the minimum power output of unit i at time t, $starttime(i)$ is the start time for unit i and $z_{production}(i,t)$ the production cost of unit i at time t which is the sum of the fuel cost plus the maintenance cost which can be written as:

$$z_{production}(i,t) = z_{maintenance}(i,t) + z_{fuel}(i,t) \quad (2)$$

The total cost of electricity production during a time period becomes equation (3).

$$z_{tot} = \sum_{i} \sum_{t=1}^{t_{max}} z_{production}(i,t) * g(i,t) + startmax(i,t) * on(i,t) \quad (3)$$

Where $g(i,t)$ is the electricity production from unit i at time t and $on(i,t)$ is a binary variable that is 1 the hour when a unit is turned on and zero otherwise.

A primary and secondary reserve has to be available at all times and the different electricity producers have different characteristics in that aspect. The primary reserve $reserve_{prim}$ at time t is computed as:

$$reserve_{prim}(t) = \sum_{i_{prim}} spin(i_{prim},t) * (z_{max}(i_{prim},t) - g(i_{prim},t)) \quad (4)$$

Where i_{prim} are all the units that can be used as primary reserve, $spin(i_{prim},t)$ is a binary variable indicating if unit i_{prim} is up and running or not. A *spin* of 1 means up and running while a 0 means that the plant is shut down. $z_{max}(i_{prim},t)$ is the maximum power output of unit i_{prim} at time t and $g(i_{prim},t)$ is the actual output of unit i_{prim} at time t. The equation for secondary reserve is the same except that every unit that has no start time can be used.

A maximum power increase and decrease per hour for nuclear is also implemented, to somewhat simulate xenon poisoning and to avoid too large power variability since that may increase the maintenance costs. The whole difference between maximum power and the actual power each hour can still be used as reserve even though the ramp rate seems to hinder that. This is allowed since is it possible to increase the power in the reactors very fast if needed.

3.5 Limitations

- The model is a perfect foresight-model. Since the model knows when the wind power can produce power, is always knows the optimal time to use hydro power and when to shut down the reactors due to high wind in the future.
- The description of xenon poisoning in the model is heavily simplified since the xenon concentration is heavily dependent on the reactor power history.
- The coast down-effect is not treated in the model. This means that the maximum output of the reactors does not decrease and the possibility of using the reactors as secondary reserve is not affected at the end of the fuel cycle.
- The efficiency of all power providers are the same for all power ranges. This may not be the case.

One flaw is the time scale used in the model. The time steps are one hour, so the model cannot determine what happens within those hours.

3.6 Assumptions and input data

The input into the model is presented in Table 1. Prices for hydro and wind are set very low, but not zero, since the variable costs for these are very small compared to the other techniques. The nuclear and gas prices are taken from the model provided in [15].

The demand curve comes from simulations from the EPOD-model [14] in the year 2020, but the demand is first scaled down by a fixed amount for all hours and then multiplied by a constant to get a curve that corresponds better to what the nuclear and hydro can produce together; the peak power is mostly used when there are production problems from nuclear or exceptionally high demand, not for regular use. This manipulation of the demand curve is also needed since combined heat and power is not treated at all in this thesis to avoid having to include district heating system in the model. In total the demand is about 102 TWh per year.
Apart from these assumptions the following limits are also used in the model:

- Each reactor has to be shut down for 45 days for refueling. During this time the reactor cannot produce any power.
- No export or import from other regions except for the hydro power which is seen as an import from the northern parts of Sweden.

Table 1: Input data describing the different characteristics of the different power sources

Plant Type	FC [1]	MC [2]	VL [3]	Sec res [4]	Prim res [5]
PWR	4.5	11.5	30–100	Yes	No [6]
BWR	4.5	11.5	70–100	Yes	No
Wind	0	1	0–100	No	No
Hydro	0	1	0–100	Yes	Yes
Peak (Gas)	28.4	2.2	0–100	Yes	No

[1] Fuel cost (Euro/MWh)
[2] Maintenance cost (Euro/MWh)
[3] VL: Variation limits (%)
[4] can be used as secondary reserve
[5] can be used as primary reserve
[6] The Swedish PWRs cannot be used for continuous primary control today and the investment cost to enable it is very high [4]

- No storage of electricity.
- A primary and secondary reserve has to be available at all times. The primary is set to 230 MW and the secondary to 1500 MW. The number for the primary reserve was found in [16] while the exact number used for the secondary reserve could not be found. It is stated in [17] that the secondary reserve has to be equal to the power of the largest generating unit plus a part that compensates for unexpected fluctuations. A secondary reserve of 1500 MW was therefore used.
- Nuclear can be used as reserve except when they are shut down. Hydro and peak can be used as reserve at all times.
- Only hydro can be used as primary reserve at all times. The PWRs can be modified to allow continuous primary control, but the Swedish reactors cannot do so today and the investment cost to enable it is high [4]; there are therefore no simulations where PWRs can be used as primary reserve.
- The nuclear reactors can increase or decrease its power by 10 % of their rated power per hour. This is to simulate xenon poisoning and to avoid increases in maintenance costs. The power change rate is set much more conservative than found in [4] where it is shown that some German reactors can change their power power from 50 % to 100 % within 15 minutes, but when planned load following is used it is usually much slower than the maximum power change rate. In [6] it is stated that the main load following model in France is "12-3-6-3" which means 12 hours of full power, 3 hours of power decrease, 6 hours at lower power and lastly 3 hours of power increase. Ringhals 4 was designed for being able to use this load following model as well [4]. The power change rate is still set a bit more conservative than that.
- The variation limit for the PWRs is set as the higher value (30 % of max power) stated in chapter 2.5. The limit for BWRs is almost the same as for

the BWR KKP1 in Germany found in [6], but a little higher than stated in chapter 2.5.

3.7 Relevant measures

The capacity factor, cf, is computed for each reactor to see which of them produces the most power. The capacity factor can vary between 0 and 1, where 1 means that a reactor produces electricity at full power during the whole year. Since every reactor has to be shut down for refueling for 45 days, the maximum cf each reactor can achieve is 0.876. The total capacity factor, which measures all nuclear reactors together, takes the rated power into account and is calculated as

$$cf_{total} = \frac{\sum_i cf_i * max_i}{\sum_i max_i} \tag{5}$$

where max_i is the maximum power of unit i.

The spin factor, sf, only measures if the reactor is running or not, regardless how much much power it produces. A spin factor of 1 means that the reactor is running during the whole year, regardless of the power produced at each hour, and a 0 means that the reactor is never running. Since each reactor has to refuel for 45 days each year, the maximum spin factor a reactor can achieve is 0.876. The total spin factor does not take the rated power into account and is therefore calculated by the following equation:

$$sf_{total} = \frac{\sum_i sf_i}{\sum_i 1} \tag{6}$$

where sf_i is the spin factor of each unit i.

4 Results

The results from the simulations are presented in this chapter. First are the results from when only the PWRs can use load following, then comes the results when all reactors can use load following and after that comes the results when the reactors do not use load following at all. Following these results are some interesting notes from the simulations. The wind curtailment, the production from peak power and the number of restarts of the nuclear reactors presented are presented last in this chapter.

More detailed results are given in the appendices. Figures for each simulation for a full year are presented in the appendix in Chapter C while the results for each individual reactor is presented in the appendix in Chapter B.

4.1 Variable PWR

All reactors can be up and running at all times, except for refueling, when the PWRs use load following and the total electricity from wind does not exceed 15 TWh. When the wind power exceeds 15 TWh the PWRs' capacity factor and spin factor (explained in chapter 3.7), cf and sf increases compared to the BWRs.

The graphs in Figure 4 are the results between the beginning of March and the beginning of May. At a first look it seems that the load following capabilities of the PWRs are not used when going above 15 TWh wind since the production from all the nuclear reactors is quite stable, but this is since the PWRs are able to lower their production so much that they avoid shut downs of the reactors but the system can use almost all the wind power available. At hour 2880 there is a small decrease in nuclear power since Ringhals 2 is shut down for refueling. The small decrease is since the reactor, which is a PWR, is already running at low power. At 10 TWh wind power the PWRs increase their power when it is needed and thereby use their load following capabilities.

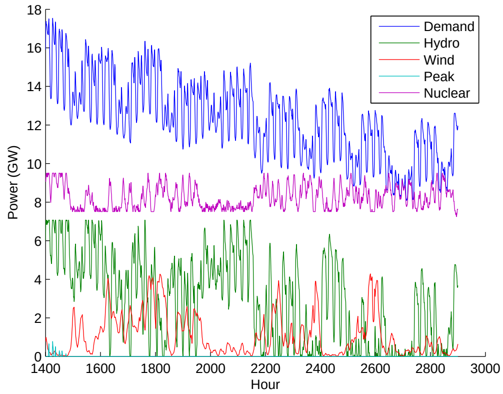
The results for the individual reactors can be be found in Appendix B while figures for the whole year can be found in Appendix C.

Table 2: Capacity factor for the nuclear reactors when using load following PWRs at different amounts of annual wind power.

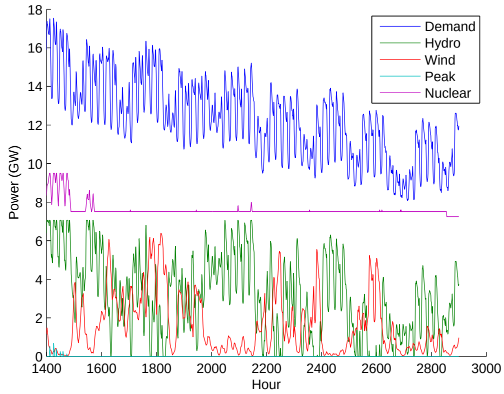
Reactor type	10 TWh	15 TWh	20 TWh	25 TWh	30 TWh
BWR	0.876	0.876	0.608	0.503	0.430
PWR	0.486	0.311	0.719	0.771	0.754
Total	0.759	0.706	0.641	0.584	0.528

Table 3: Spin factor for the nuclear reactors when using load following PWRs at different amounts of annual wind power.

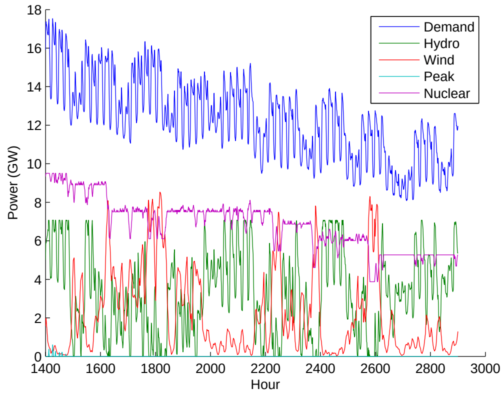
Reactor type	10 TWh	15 TWh	20 TWh	25 TWh	30 TWh
BWR	0.876	0.876	0.626	0.528	0.472
PWR	0.876	0.876	0.851	0.847	0.847
Total	0.876	0.876	0.693	0.624	0.584



(a) 10 TWh wind



(b) 15 TWh Wind



(c) 20 TWh wind

Figure 4: Demand and production from all the power producers in the model between the beginning of March to the beginning of May when the PWRs use load following. Note that the production in (b) seems smoother than (a). This is since the PWRs goes down to minimum production but no shutdowns are needed. Shutdowns are however necessary in (c).

Table 4: Capacity factor for the nuclear reactors when all reactors uses load following at different amounts of annual wind power.

Reactor type	10 TWh	15 TWh	20 TWh	25 TWh	30 TWh
BWR	0.787	0.751	0.719	0.511	0.455
PWR	0.688	0.578	0.472	0.748	0.700
Total	0.757	0.699	0.645	0.583	0.529

Table 5: Spin factor for the nuclear reactors when all reactors uses load following at different amounts of annual wind power.

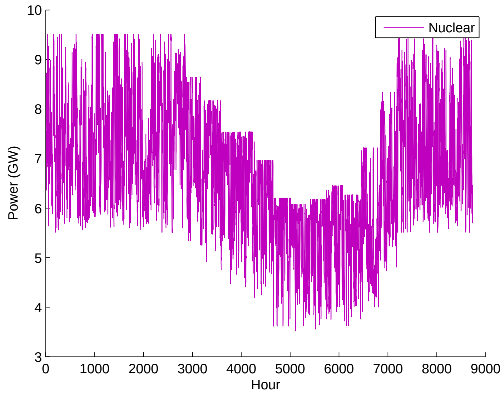
Reactor type	10 TWh	15 TWh	20 TWh	25 TWh	30 TWh
BWR	0.876	0.876	0.876	0.542	0.502
PWR	0.876	0.876	0.876	0.861	0.826
Total	0.876	0.876	0.876	0.638	0.599

4.2 All reactors use load following

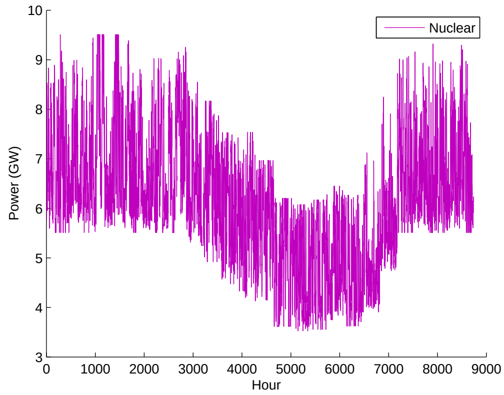
When all reactors are using load following there is no need to shut down reactors when the annual wind power stays at 20 TWh or below. The capacity factor is a bit larger for BWRs when no shutdowns are needed, but the PWRs have higher capacity factor and spin factor when reactors need to be shut down.

In Figure 5 is the combined power of the nuclear reactors plotted. The output at 15 and 20 TWh are similar but are very different from the 25 and 30 TWh simulations. When looking at the spin factor for 15 and 20 TWh wind, it can be seen that all reactors are up and running at all times, except for refueling, but this is not the case for the highest wind production. This means that the combined output of wind, hydro and nuclear power at high annual wind power has a too large excess of power that cannot be stored by hydro for use at other hours the year. The result is that the pattern for the whole electricity system changes significantly when a certain amount wind is used and the reactors cannot vary their power to compensate for this, Several reactors are shut down for most of the year and there is even a small time frame at about hour 6200 (middle of September) where all reactors are taken down when the annual wind power is 30 TWh.

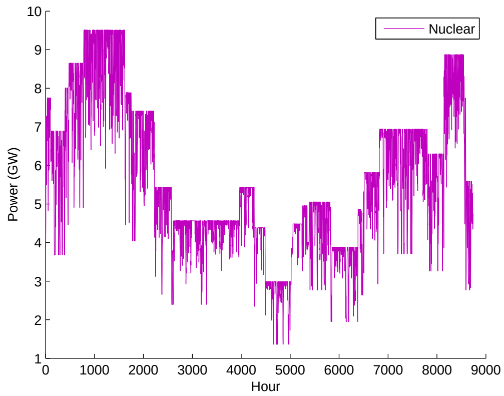
The results for the individual reactors can be be found in Appendix B while figures for the whole year can be found in Appendix C.



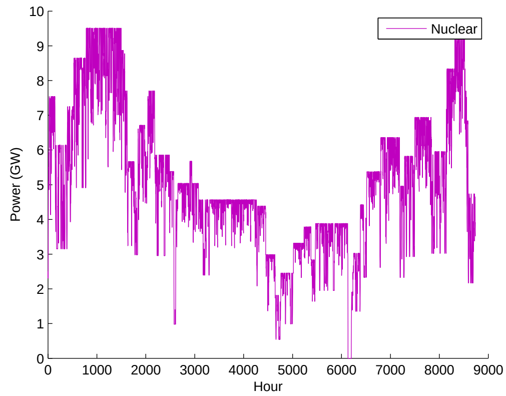
(a) 15 TWh wind



(b) 20 TWh Wind



(c) 25 TWh wind



(d) 30 TWh wind

Figure 5: Production curves for the nuclear reactors in the model when all reactors use load following. Note the significant difference between (b), where no shutdowns are needed, and (c) where shutdowns are necessary.

Table 6: Capacity factor for the nuclear reactors when no reactors use load following at different amounts of annual wind power.

Reactor type	10 TWh	15 TWh	20 TWh	25 TWh	30 TWh
BWR	0.757	0.739	0.653	0.569	0.500
PWR	0.759	0.606	0.622	0.626	0.596
Total	0.758	0.699	0.643	0.586	0.529

Table 7: Spin factor for the nuclear reactors when no reactors use load following at different amounts of annual wind power.

Reactor type	10 TWh	15 TWh	20 TWh	25 TWh	30 TWh
BWR	0.729	0.717	0.626	0.547	0.442
PWR	0.758	0.601	0.622	0.620	0.594
Total	0.738	0.682	0.625	0.569	0.442

4.3 No load following reactors

Even when no reactors use load following the nuclear power varies heavily with time. There are many start ups and shut downs to balance the electricity system at all times. Some reactors are shut down at different times even in the lowest annual wind case and the total nuclear power used decreases with increase in wind.

The results for the middle of January is plotted in Figure 6. There are clearly some peaks when the wind power decreases rapidly from a high level and the hydro power cannot compensate for this fully even when going to maximum power. There are also clearly reactors that aren't started up during those peaks. An important note is that the peak power production occurs even when using load following. The gas power peaks are about the same size when the PWRs use load following but smaller when all reactors use load following, but this does not necessary mean that the annual peak power production is higher. The amount of hydro used during these hours is also decreased with increasing amount of load following reactors.

The results for the individual reactors can be be found in Appendix B while figures for the whole year can be found in Appendix C.

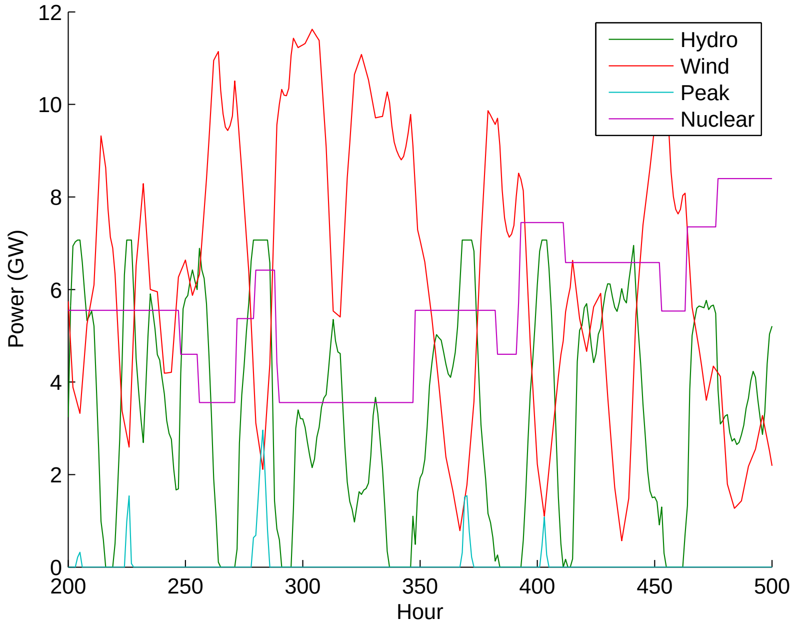
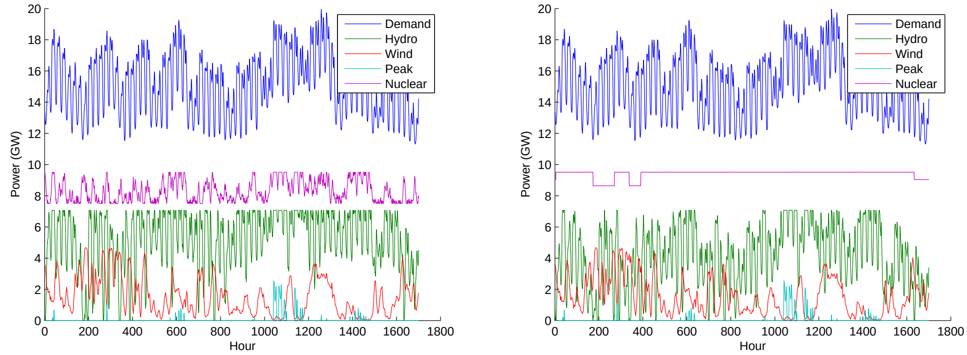


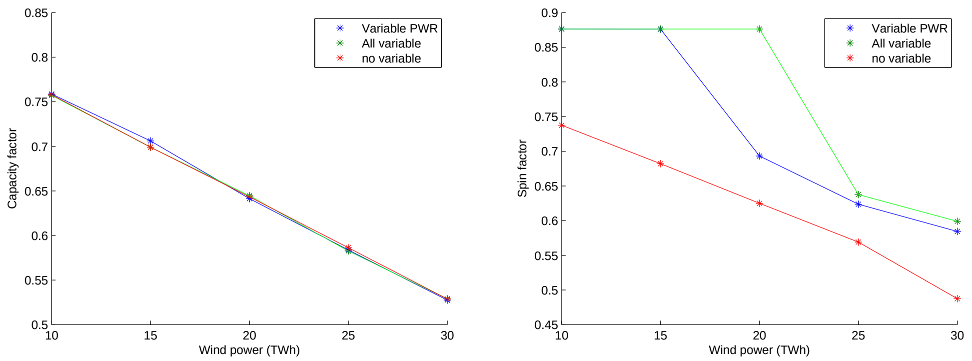
Figure 6: The middle of January with 25 TWh wind and no load following. There is some gas peak production when some reactors are shut down due to the high wind power.



(a) Variable PWR.

(b) No load following.

Figure 7: These figures shows the electricity system from the beginning of January to the middle of March. When load following is allowed for the PWRs, the power production becomes more variable. The figures for the whole year can be found in the appendix Figure C.1a and Figure C.3a respectively.



(a) Total capacity factor

(b) Total spin factor

Figure 8: Capacity and spin factors at all different scenarios

4.4 Some interesting notes

Figure 7a and 7b show the electricity system between the beginning of the year and to the middle of March. Here it can be seen that the use of peak power occurs when the wind is low and both the nuclear and the hydro are at their maximum output. It can also be noted that less hydro power is used in this time period when the nuclear does not use load following, it is instead used at other times during the year.

The graphs in Figure 8 show rough plots of the total capacity factor and spin factor at different amounts of annual wind power production. Here it can be seen that the total capacity factor does not change much between when no load following is used, if load following is allowed for the PWRs or if all reactors use load following. The spin factor is however very dependent on how many of the reactors can use load following.

Table 8: Curtailment of wind, in TWh, at different amounts of annual wind power. The * denotes simulations where reactor shutdowns are needed.

Load following reactors	10 TWh	15 TWh	20 TWh	25 TWh	30 TWh
PWRs	0.22	0.80	0.40*	0.64*	1.00*
All	0.09	0.21	0.64	0.54*	1.03*
None	0.16*	0.32*	0.54*	0.84*	1.10*

Table 9: Total peak power production, in TWh, at different amounts of annual wind power. The * denotes simulations where reactor shutdowns are needed.

Load following reactors	10 TWh	15 TWh	20 TWh	25 TWh	30 TWh
PWRs	0.10	0.08	0.10*	0.14*	0.20*
All	0.10	0.08	0.07	0.15*	0.12*
None	0.11*	0.19*	0.10*	0.14*	0.21*

4.5 Wind curtailment

The amount of curtailed wind power is presented in Table 8. The total amount of curtailed wind goes up when the annual wind power is increased but most of the wind power available is used in all simulations. The curtailment is about a few percent for each simulation, with a maximum for 15 TWh annual wind power with load following PWRs where the curtailment is slightly above 5 %.

An interesting note is that the curtailment can be higher when more load following reactors are used, see for example the 20 TWh case. This may be due to the different production pattern of nuclear. It may be more economical to curtail some wind instead of shutting down reactors, but if shut downs are necessary anyway, more wind may be used.

4.6 Peak power production

The annual peak power production for each wind case is presented in Table 9. The amount of needed peak power is higher for the simulations where reactor shutdowns are needed compared to those where with no shutdowns.

4.7 Reactor restarts

The total amount of restart, including restarts from refueling, for all reactors are presented in Table 10. It can clearly be seen that there are many more restarts when no load following is used but it is the lowest when all reactors use load following.

Table 10: The total amount of restarts, including restarts after refueling, for all the reactors at different amounts of annual wind power.

Load following reactors	10 TWh	15 TWh	20 TWh	25 TWh	30 TWh
PWRs	10	10	13	21	37
All	10	10	10	12	26
None	15	28	51	81	117

5 Discussion

In this chapter there is some discussion about the model, the input data and the results.

5.1 The model

The model tries to minimize the total production cost, which means that there may not be a unique optimal solution; there may be different power production solutions that have the same, or very similar, costs.

The perfect foresight takes away the uncertainty about the wind since it is known beforehand when the wind power can provide electricity to the system. The model can therefore determine the best times to use hydro power and when to shut down the reactors. The impact of the uncertainty may not be that great however; it is known that wind power production will vary but there are other sources in the system that can vary to compensate for this. The impact will therefore depend on how flexible the other sources are. It is also hard to make wind predictions, but if the uncertainty between the prediction and actual wind is known, the impact can be approximated.

An important aspect that the model does not try to simulate is the combined heat and power plants. This source is not negligible in the Swedish electricity system and could be of great importance for further development of the model. District heating is of great importance during the winter months and the inclusion of this power source may take away the peak power needs found in the results since the Swedish system uses next to no gas power at all. Also, district heating is mostly used to satisfy the demand for heat and is therefore not as flexible as the peak used in the model.

5.2 Input data

The wind power curve is scaled linearly from the 10 TWh wind-curve for higher wind power. If more wind power is installed it is possible that the curve becomes smoother than the curves used in the simulations and may affect the results for the simulations with high, and very high, wind power. How much the curve will be smoothed is hard to say, the placement of more wind tubines and the correlation of wind speeds at different sites will affect the smoothing.

How fast the reactors can vary their power is set conservative and it is possible the reactors may vary the power faster than put into the model. The model never uses any peak power during up ramps for the reactors and limiting the power increase to 10 % per hour in nuclear reactors has minor or no effect on the total spin factor.

5.3 Results

The total electricity generated from nuclear does not seem to change depending on whether the reactors can use load following or not, but the number of hours when the reactors can be up and running changes to varying degree.

Since the reactors can change their power when using load following, the amount of shutdowns are decreased but the total power production from nuclear power stays constant. When the intermittent energy comes up to a very high amount, around 20 TWh (approximately 20 % of the demand in the region), in this model, it is necessary that all reactors uses load following if the reactors are to avoid shutdowns, except from refueling. The results show that the production from peak power is increased when there are shutdowns of nuclear reactors. It is important to note that the model does not take export into account which may change the role of nuclear somewhat. The export of excess electricity may prevent extra shutdowns but no definitive conclusions in that matter can be made only from this model.

It is very important to note that the wind data is very spiky and it is possible that the wind power curve becomes a bit smoother when the amount of installed wind power increases. The smoothening effect when installing more wind power plant may therefore not be that great. If the wind power curve becomes smoother it may however result in that the reactors are not shut down that much since most of the shutdown occurs at very high wind power hours.

The fact that the total capacity factor remains constant regardless of load following can be caused by several factors. Most likely is that the large amount of hydro power can compensate the wind power changes enough. The load following capabilities are therefore used to avoid shutdowns which decreases the total system cost since extra startups can be avoided.

6 Conclusions

The reactors operating today can vary their power to some extent; in general they cannot vary their power at the speed needed for continuous primary control, but secondary control is possible. A literature study revealed that primary control is possible in PWRs if grey control rods are installed, but no examples of continuous primary control with BWRs could be found.

If the load following is planned beforehand and the variation is not too fast, the cost per MWh produced is not affected. The main reason for not load following is that nuclear power plants have large investment cost, but relatively low production costs. Due to this the investors want to utilize the reactors as much as possible, but in [4] it is stated that it may be interesting for load following nuclear power plants to bid on the secondary reserve market.

If the variation of power is high it is believed that the maintenance cost may rise due to increased stress on components. The fuel utilization does not worsen from using load following if the fuel is prepared beforehand, but unprepared variations can worsen it somewhat. If grey control rods are used in PWRs for primary control the maintenance cost may be increased due to increased inspection and wear on the pressurizer and on the mechanism controlling the rods.

The results from the simulation shows that the total spin factor changes significantly depending on whether load following is used or not, but the total capacity factor is very similar between the simulations when the annual wind power production stays the same. This means that the total amount of electricity from nuclear stays almost the same regardless if load following is used, but the possibility to increase power rapidly is increased when using load following since the reactors can be up and running during more hours. The total capacity factor does not change that much since hydro power can vary its production very rapidly, has no start up times and is cheap. It is therefore desirable to use as much hydro as possible, but the wind is still used to a large degree since the hydro can easily compensate for the high or low wind power during different hours.

The amount of startups is heavily dependent on the load following capabilities of the reactors. At the highest annual wind there was more than 4 times as many reactor start ups when no load following was used compared to when all reactors could use load following.

The curtailment of wind was around a few percent for all simulations but one of the simulations had a wind curtailment slightly above 5%.

Is seems that load following reactors have a larger spin factor than base load reactors at low wind power, but both the spin factor and the capacity factor increases for the load following reactors when there is need for reactor shut downs.

The production from gas power increases when reactor shutdowns are needed but decreases somewhat with increasing annual wind when no reactor shutdowns occurs.

When no load following is used at all, the larger reactors seems so have a larger spin and capacity factor.

When all reactors can use load following, the PWRs have larger spin factor and capacity factor for the years when there is need for reactor shutdowns, but they have smaller capacity factors when no shutdowns are needed. This is since the PWRs was able to vary their power between 30 and 100 % compared to the 70-100 % for the BWRs in the simulations.

The results show that it is enough if the PWRs use load following to avoid reactor shutdowns at up to 15 TWh wind power but at 20 TWh wind it is necessary that all reactors use load following techniques to avoid shutdowns. At 25 TWh and above there are shutdown regardless if load following is used or not.

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Appendix

A Nuclear reactors in the model

Table A: The nuclear reactors used in the model

Reactor	Maxpower (MW)	Type	Starting year
Forsmark 1	1015	BWR	1980
Forsmark 2	990	BWR	1981
Forsmark 3	1170	BWR	1985
Oskarshamn 1	494	BWR	1972
Oskarshamn 2	664	BWR	1975
Oskarshamn 3	1450	BWR	1985
Ringhals 1	855	BWR	1976
Ringhals 2	866	PWR	1975
Ringhals 3	1051	PWR	1981
Ringhals 4	935	PWR	1983

B Results for each individual reactor

B.1 Load following PWRs

Table B: Capacity factor for the nuclear reactors when using load following PWRs at different amounts of annual wind power

Reactor	10 TWh	15 TWh	20 TWh	25 TWh	30 TWh
F1 (BWR)	0.876	0.876	0.797	0.420	0.637
F2 (BWR)	0.876	0.876	0.649	0.175	0.129
F3 (BWR)	0.876	0.876	0.677	0.482	0.274
O1 (BWR)	0.876	0.876	0.725	0.630	0.649
O2 (BWR)	0.876	0.876	0.577	0.700	0.627
O3 (BWR)	0.876	0.876	0.375	0.587	0.389
R1 (BWR)	0.876	0.876	0.582	0.704	0.600
R2 (PWR)	0.485	0.295	0.557	0.723	0.706
R3 (PWR)	0.462	0.298	0.774	0.783	0.767
R4 (PWR)	0.511	0.338	0.805	0.802	0.783
BWR	0.876	0.876	0.608	0.503	0.430
PWR	0.486	0.311	0.719	0.771	0.754
Total	0.759	0.706	0.641	0.584	0.528

Table C: Spin factor for the nuclear reactors when using load following PWRs at different amounts of annual wind power

Reactor	10 TWh	15 TWh	20 TWh	25 TWh	30 TWh
F1 (BWR)	0.876	0.876	0.797	0.420	0.637
F2 (BWR)	0.876	0.876	0.649	0.175	0.129
F3 (BWR)	0.876	0.876	0.677	0.482	0.274
O1 (BWR)	0.876	0.876	0.725	0.630	0.649
O2 (BWR)	0.876	0.876	0.577	0.700	0.627
O3 (BWR)	0.876	0.876	0.375	0.587	0.389
R1 (BWR)	0.876	0.876	0.582	0.704	0.600
R2 (PWR)	0.876	0.876	0.805	0.805	0.805
R3 (PWR)	0.876	0.876	0.874	0.864	0.863
R4 (PWR)	0.876	0.876	0.873	0.870	0.873
BWR	0.876	0.876	0.626	0.528	0.472
PWR	0.876	0.876	0.851	0.847	0.847
Total	0.876	0.876	0.693	0.624	0.584

B.2 All reactors uses load following

Table D: Capacity factor when all reactors uses load following at different amounts of annual wind power

Reactor	10 TWh	15 TWh	20 TWh	25 TWh	30 TWh
F1 (BWR)	0.784	0.751	0.717	0.402	0.340
F2 (BWR)	0.786	0.748	0.716	0.378	0.381
F3 (BWR)	0.787	0.750	0.717	0.672	0.403
O1 (BWR)	0.832	0.792	0.754	0.571	0.647
O2 (BWR)	0.780	0.748	0.715	0.417	0.511
O3 (BWR)	0.782	0.749	0.716	0.554	0.583
R1 (BWR)	0.781	0.745	0.713	0.560	0.401
R2 (PWR)	0.695	0.588	0.480	0.729	0.661
R3 (PWR)	0.680	0.570	0.463	0.753	0.699
R4 (PWR)	0.689	0.578	0.476	0.760	0.736
BWR	0.787	0.751	0.719	0.511	0.455
PWR	0.688	0.578	0.472	0.748	0.700
Total	0.757	0.699	0.645	0.583	0.529

Table E: Spin factor when all reactors uses load following at different amounts of annual wind power

Reactor	10 TWh	15 TWh	20 TWh	25 TWh	30 TWh
F1 (BWR)	0.876	0.876	0.876	0.437	0.373
F2 (BWR)	0.876	0.876	0.876	0.409	0.419
F3 (BWR)	0.876	0.876	0.876	0.719	0.431
O1 (BWR)	0.876	0.876	0.876	0.594	0.675
O2 (BWR)	0.876	0.876	0.876	0.448	0.552
O3 (BWR)	0.876	0.876	0.876	0.582	0.623
R1 (BWR)	0.876	0.876	0.876	0.604	0.435
R2 (PWR)	0.876	0.876	0.876	0.841	0.788
R3 (PWR)	0.876	0.876	0.876	0.873	0.825
R4 (PWR)	0.876	0.876	0.876	0.869	0.865
BWR	0.876	0.876	0.876	0.542	0.502
PWR	0.876	0.876	0.876	0.861	0.826
Total	0.876	0.876	0.876	0.638	0.599

B.3 No load following reactors

Table F: Capacity factor when the reactors does not use load following at different amounts of annual wind power

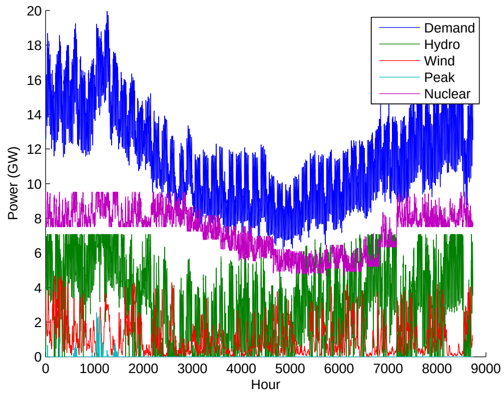
Reactor	10 TWh	15 TWh	20 TWh	25 TWh	30 TWh
F1 (BWR)	0.797	0.735	0.338	0.447	0.407
F2 (BWR)	0.778	0.703	0.821	0.560	0.520
F3 (BWR)	0.851	0.809	0.716	0.717	0.543
O1 (BWR)	0.593	0.593	0.646	0.440	0.168
O2 (BWR)	0.604	0.655	0.539	0.489	0.272
O3 (BWR)	0.820	0.828	0.855	0.635	0.804
R1 (BWR)	0.661	0.693	0.468	0.542	0.381
R2 (PWR)	0.687	0.481	0.593	0.490	0.501
R3 (PWR)	0.744	0.622	0.574	0.688	0.593
R4 (PWR)	0.842	0.701	0.700	0.683	0.648
BWR	0.757	0.739	0.653	0.569	0.500
PWR	0.759	0.606	0.622	0.626	0.596
Total	0.758	0.699	0.643	0.586	0.529

Table G: Spin factor when the reactors does not use load following at different amounts of annual wind power

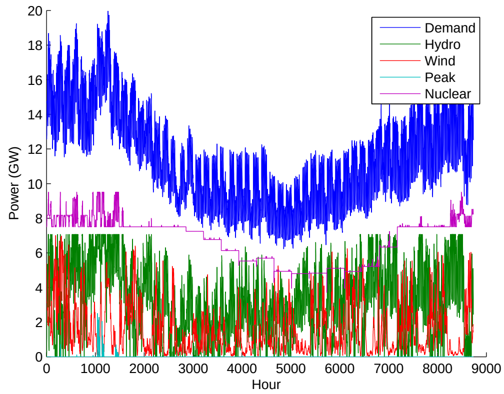
Reactor	10 TWh	15 TWh	20 TWh	25 TWh	30 TWh
F1 (BWR)	0.797	0.735	0.338	0.447	0.407
F2 (BWR)	0.778	0.703	0.821	0.560	0.520
F3 (BWR)	0.851	0.809	0.716	0.717	0.543
O1 (BWR)	0.593	0.593	0.646	0.440	0.168
O2 (BWR)	0.604	0.655	0.539	0.489	0.272
O3 (BWR)	0.820	0.828	0.855	0.635	0.804
R1 (BWR)	0.661	0.693	0.468	0.542	0.381
R2 (PWR)	0.687	0.481	0.593	0.490	0.501
R3 (PWR)	0.744	0.622	0.574	0.688	0.593
R4 (PWR)	0.842	0.701	0.700	0.683	0.648
BWR	0.729	0.717	0.626	0.547	0.442
PWR	0.758	0.601	0.622	0.620	0.594
Total	0.738	0.682	0.625	0.569	0.488

C Graphs for the simulation results

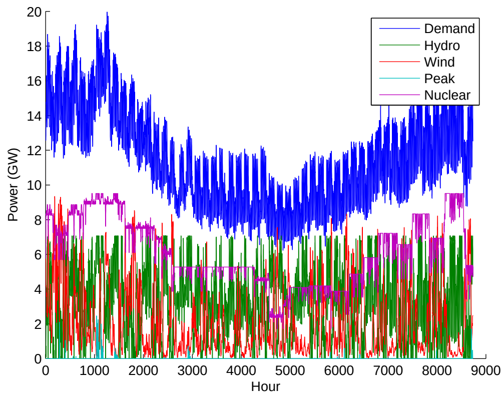
C.1 Load following PWRs



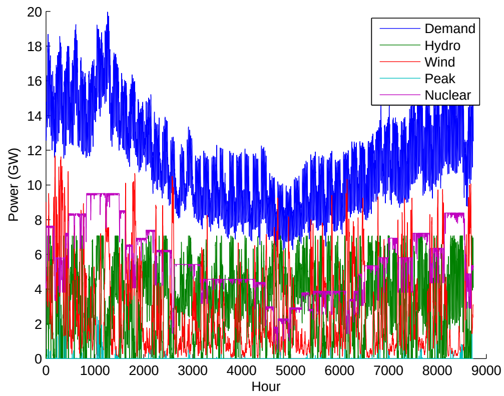
(a) 10 TWh wind



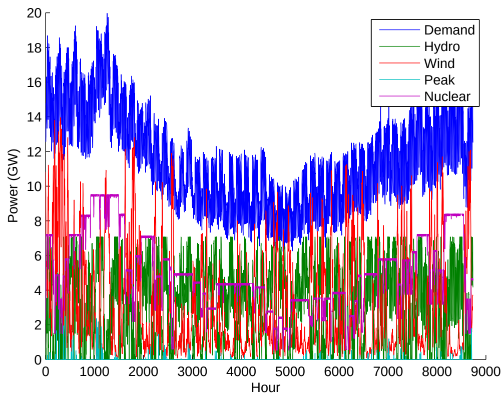
(b) 15 TWh Wind



(c) 20 TWh wind



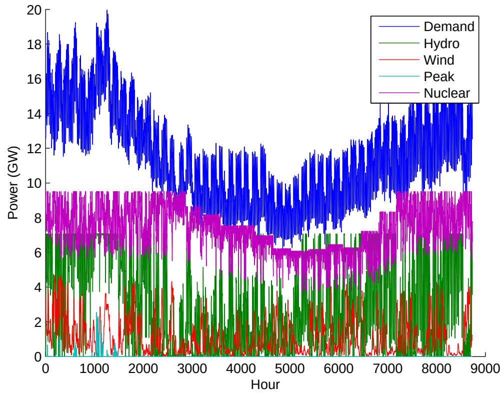
(d) 25 TWh wind



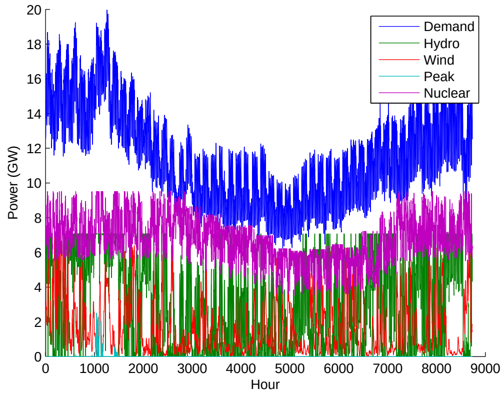
(e) 30 TWh wind

Figure C.1: Results from the model when the PWRs use load following.

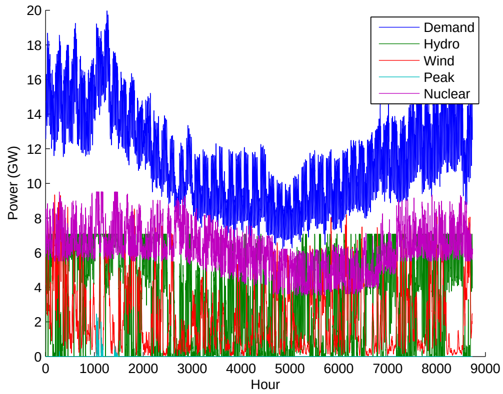
C.2 All reactors use load following



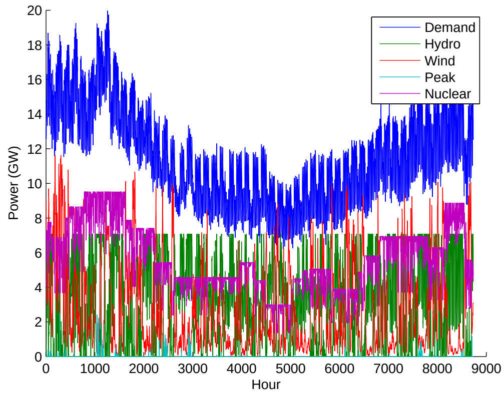
(a) 10 TWh wind



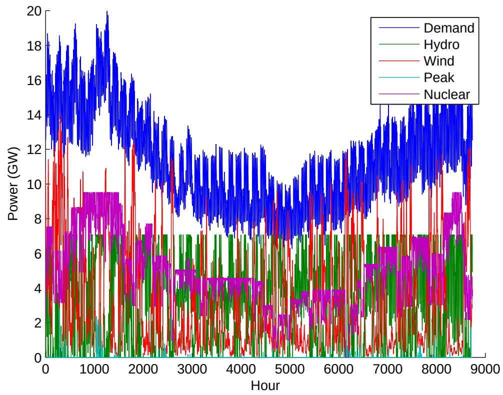
(b) 15 TWh Wind



(c) 20 TWh wind



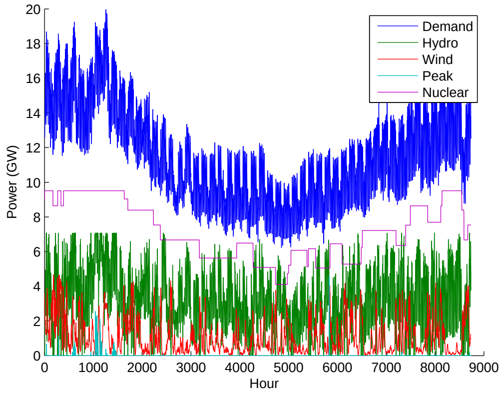
(d) 25 TWh wind



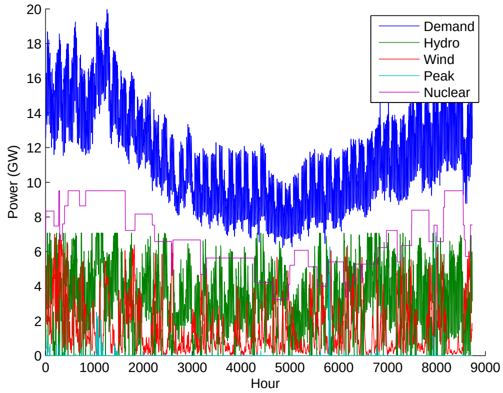
(e) 30 TWh wind

Figure C.2: Results from the model when all reactors use load following

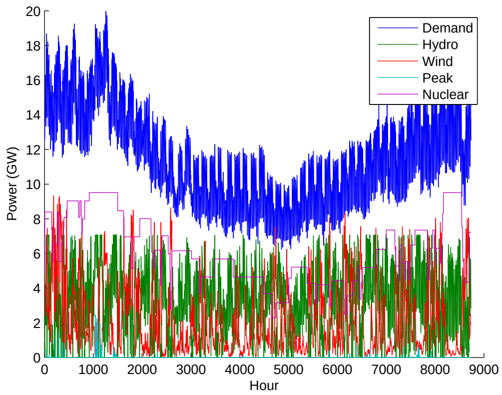
C.3 No reactors use load following



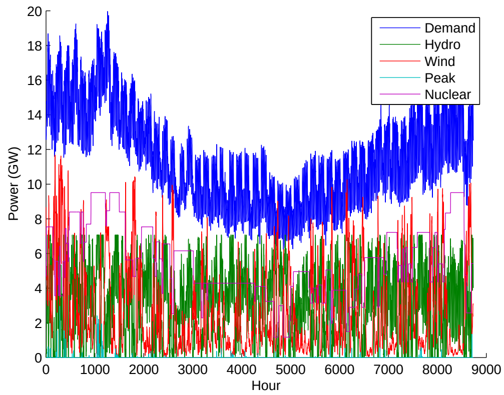
(a) 10 TWh wind



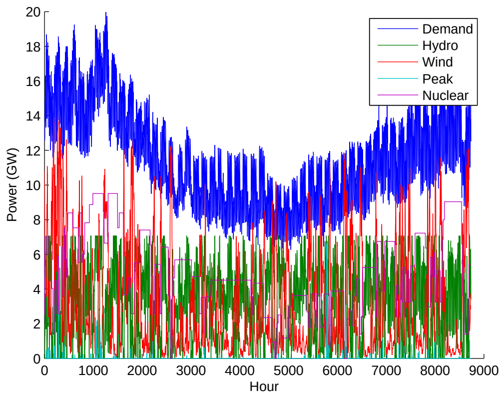
(b) 15 TWh Wind



(c) 20 TWh wind



(d) 25 TWh wind



(e) 30 TWh wind

Figure C.3: Results from the model when the reactors does not use load following