LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
LUT School of Energy Systems
Degree Programme in Energy Technology

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THE ROLE OF NUCLEAR AND OTHER CONVENTIONAL POWER PLANTS IN THE FLEXIBLE ENERGY SYSTEM

Examiners: Professor Juhani Hyvärinen
D.Sc. (Tech.) Jukka Lassila

ABSTRACT

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The role of nuclear and other conventional power plants in the flexible energy system

Master's thesis

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103 pages, 25 figures, 4 tables and 1 appendix

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Keywords: nuclear power, conventional power plant, load follow, load duration curve, power system balancing

This thesis reviews the role of nuclear and conventional power plants in the future energy system. The review is done by utilizing freely accesible publications in addition to generating load duration and ramping curves for Nordic energy system. As the aim of the future energy system is to reduce GHG-emissions and avoid further global warming, the need for flexible power generation increases with the increased share of intermittent renewables. The goal of this thesis is to offer extensive understanding of possibilities and restrictions that nuclear power and conventional power plants have regarding flexible and sustainable generation.

As a conclusion, nuclear power is the only technology that is able to provide large scale GHG-free power output variations with good ramping values. Most of the currently operating plants are able to take part in load following as the requirement to do so is already required to be included in the plant design. Load duration and ramping curves produced prove that nuclear power is able to cover most of the annual generation variation and ramping needs in the Nordic energy system.

From the conventional power generation methods, only biomass combustion can be considered GHG-free because biomass is considered carbon neutral. CFB combusted biomass has good load follow capabilities in good ramping and turndown ratios. All the other conventional power generation technologies generate GHG-emissions and therefore the use of these technologies should be reduced.

TIIVISTELMÄ

Lappeenrannan teknillinen yliopisto
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Aleksi Savolainen

Ydinvoiman ja muiden konventionaalisten voimaloiden rooli mukautuvassa energiajärjestelmässä

Diplomityö

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Avainsanat: ydinvoima, konventionaalinen voimala, säätövoima, pysyvyyskäyrä, sähköverkon säätö

Tässä työssä käydään läpi ydinvoiman ja konventionaalisten voimaloiden rooli mukautuvassa energiajärjestelmässä. Työssä hyödynnetään vapaasti käytettäviä julkaisuja ja raportteja, sekä luodaan pysyvyyskäyrät Pohjoismaisen energiajärjestelmän kapasiteetille ja tehonmuutosnopeudelle. Tulevaisuuden energiajärjestelmän tavoite on estää ilmaston lämpeneminen lisäämällä energiajärjestelmään kasvihuonekaasu päästöttömiä uusiutuvia energiantuotantomuotoja, jotka vaativat energiajärjestelmän mukautumista. Työn tavoite on tarjota kattava katsaus ydinvoiman ja konventionaalisten voimaloiden kyvystä tuottaa sähköä mukautuvasti ja kestävästi.

Johtopäätöksenä vain ydinvoima voi tuottaa suuren kokoluokan tehomuutoksia hyvillä muutosnopeuksilla ilman kasvihuonepäästöjä. Suurin osa nykyään toimivista ydinvoimaloista ovat kykeneväisiä toimimaan säätövoimana, koska toimiminen osatehoilla ja nopeat tehon muutosnopeudet on huomioitava laitoksen suunnittelussa. Luodut tehokapasiteetin ja tehonmuutosnopeuden pysyvyyskäyrät vahvistavat ydinvoiman kyvyn vastata pohjoismaisen verkon säätövoimatarpeisiin.

Konventionaalisista energiantuotantomuodoista vain biomassan poltto voidaan laskea kasvihuonekaasu päästöttömäksi energiantuotantomuodoksi. Biomassan poltto CFB-kattilassa sopii hyvin säätövoimaksi, korkean tehonmuutosnopeuden ja pienen minimi tehotason ansiosta. Muiden konventionaalisten energiantuotantomuotojen käyttöä tulisi vähentää niiden tuottamien kasvihuonekaasujen takia.

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Lappeenranta, December 15, 2015

Aleksi Savolainen

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Nomenclature

Roman symbols

C	capacitance	F
G	daily variation in generation	MWh/h
I	moment of inertia	kgm^2
n	generator rotation speed	1/s
P	power	W
p	number of magnetic pole pairs	-
V	voltage	V

Greek symbols

ω	rotating speed	rad/s

Abbreviations

AC	alternating current
AMI	advanced metering infrastructure
AP1000	advanced passive PWR
BFB	bubbling fluidized bed
BWR	boiling water reactor
CAES	compressed air energy storage
CCGT	combined cycle gas turbine
CCS	carbon capture & storage
CFB	circulating fluidized bed
CHP	combined heat and power
CNBS	carbon neutral high bioenergy scenario
CNES	carbon neutral high electricity scenario
CNS	carbon neutral scenario
CO_2	carbon dioxide
CPO	constant pressure operation
DC	direct current
DSM	demand side management
EPR	european pressurized water reactor
FBC	fluidized bed combustion
FES	flywheel energy storage
GHG	greenhouse gas
HRSG	heat recovery steam generator
IEA	international energy agency
LWR	light water reactor
MRFF	model reference feed forward control
MSHIM	mechanical shim
NETP	Nordic energy technology perspectives
NO	nitric oxide
P2G	power to gas
PC	pulverized coal-fired boiler
PHEV	plugin hybrid electric vehicle

PHS	pumped hydro storage
PID	proportional integral and derivative control
PV	photo-voltaic generation
PWR	pressurized water reactor
rpm	revolutions per minute
SAIDI	system average interruption duration index
SMES	super conducting magnetic energy storage system
SO_2	sulfur dioxide
SO_3	sulfur trioxide
VG	variable generation
VPO	variable pressure operation
VVER	water-water energetic reactor

Subscripts

avg	average generation
max	maximum generation
min	minimum generation
r	rated power

1 INTRODUCTION

This master's thesis is part of the FLEX^{e}-project by CLIC Innovation. Project aims to explore the possibilities of the future flexible energy system and to develop Finnish know how and expertizes involving the upgrading of the energy system. This thesis explores the role that conventional power plants will have in the future energy system where the amount of renewables in the energy generation mix is greatly increased. This intermittent renewable energy creates new challenges for power generation which are explored in this thesis. Of the conventional power generating methods the main focus is on nuclear energy since it is the only carbon free method of the conventional plants.

1.1 Background

This thesis is part of FLEX^{e} research program in work package 1 (WP1) task 1.2. WP1 is to assess the value and needs of flexibility options in various systems, including distributed generation in form of customers becoming producers of energy. As the target of this project is to find and create sustainable ways to upgrade the energy system, WP1 is to produce an understanding of sustainability factors on different system designs and business ecosystems, while this thesis provides input for different options regarding sustainable energy system transition.

1.2 Goals and delimitations

Goals of this work are to present the possibilities and restrictions of nuclear power and conventional power plants working as load follow supply as the need for adjustability grows in the future with the increasing amount of renewables that CO_2 free energy system requires. This is done by examining various scientific publications and reports on previous experiences of said actions. In addition to using freely accessible publications, scenarios made for Nordic energy system are used to generate load duration curves to better showcase the need for power adjustment and the possibilities of different technologies to answer that need.

1.3 Structure of the thesis

This thesis is structured in five parts. First, the characteristics of the future flexible energy system are discussed. This section focuses on the function of energy system from the grid point of view, first covering the basics involving the operation of the power system, like maintaining the frequency within the grid and the importance of maintaining supply and demand. Next the most promising technologies to help the future operation of the power system are presented, which include different energy storage methods and the implementation of smart grid.

Second part studies the generation side of the energy system. First the most important parameters for comparing the adjustability of different power generation methods are presented after which a more thorough study is done on the nuclear power and the capabilities it possesses on load following operation. As nuclear power generation is more complex than more conventional power generation methods this section first presents the basics of common reactor types after which the adjusting properties and limitations of nuclear power technology are discussed. Before moving onto more common conventional power generation methods, previous experiences in nuclear power generation adjustment in France and Germany are presented. More common conventional power generation methods in this thesis consist of coal, gas turbines, diesel motors and bioenergy. For every generation technology the most important parameters for power adjustment are presented and compared.

Third section covers the different scenarios for generating load duration and ramping curves. First the scenarios made by IEA for Nordic energy system are presented. The scenarios used in this thesis are based on one of these scenarios and are made by Jarkko Ahokas for his master's thesis on The role of nuclear power in the future energy market (2015). After the scenarios are explained, the curves are created and discussed.

Fourth section covers conclusions and discussion on found results after which the fifth and final part summarizes the topics discussed in the thesis.

2 FUTURE FLEXIBLE ENERGY SYSTEM

According to the FLEX^e-program plan a sustaining and flexible energy system is a combination of centralized and local energy solutions including a greater mix of renewables and energy storages than there are now. Challenges this system faces are the variability and unpredictability of renewable sources, mainly born from wind power generation. In order to increase the usage of these intermittent renewables, the flexibility of the energy system must be improved on all of its levels. What this means is that the future flexible energy system not only needs improved adjustability from the generation side but improved flexibility from the customer side as well. With all this said, the energy system must at the same time be sustainable, cost-efficient and reliable. [1]

2.1 Balancing supply and demand

In order to avoid power outages and interruptions in the distribution of electricity, power system needs to always balance demand and generation. Power system operation therefore involves forecasting of demand for electricity and the operation of appropriate power plants to satisfy the varying demand which is illustrated in Figure 1 for Finland over a time period of year. [2]

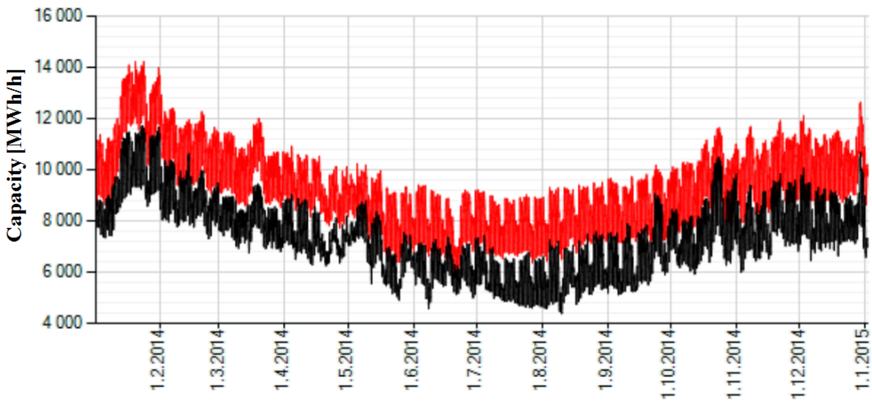

Figure 1: Finnish electricity generation and demand over a time period of year [3].

Red line in the Figure shows the varying electricity demand and black line stands for varying electricity generation. As seen from the Figure electricity generation has to follow the varying demand curve, which includes daily variations as well as seasonal variations. From the Figure it is clear that the highest peak in Finland for electricity demand and generation is during the winter because of cold, while the peak demand was around 14,2 GWh/h and for generation the peak was 11,7 GWh/h. The difference in demand and generation is made up by importing electricity to Finland from the neighboring countries. Seasonal and daily variation patterns are predictable to some degree and operate the same way on annual level with variations in low and high demand peaks occuring mostly due to temperature differences and varying weather conditions between years.

When an unexpected power plant outage or grid malfunction occurs, the electric grid loses the generation of that particular unit/transmission line. As the lost generation must be replaced by other means, the maximum power capacity of single unit to be connected into the grid is capped by the regulator in order to reduce the effect one big power plant has when it loses the connection/generation into the grid [4]. For example 1650 MW is the maximum size for a single power plant to be attached into the Nordic power system. [5]

As shown in Figure 1 the demand for electricity follows a periodic pattern depending for example on the season, time of day, etc. This is due to need for cooling, heating and industrial need for electricity. These needs vary greatly between countries. For example the highest need for electricity in Texas is during summer around mid-day because of the increased need for cooling. In contrast, in Finland peak load occurs during winter due to increased electricity need in heating. [2]

Adjusting the power system to wind power generation is different than adjusting the system with current electricity generation methods. Current adjustment needs are tightly related to changes in demand and disturbances in the power system, while wind power is not affected by demand as it is intermittent by its nature. This means that at times of surplus generation wind power generation must be adjusted by some other means. [6]

In addition to meeting the already mentioned predictable variation in demand, additional reserves must be available to meet unpredictable demand, sudden loss of any generation or importing connection which could affect the operation of power system. These reserves are often referred to as operating reserves which are to take part in frequency regulation, load forecasting errors and bigger contingencies, for example sudden power plant outage. To be able to provide these reserves, plant must be able to rapidly change the power output capacity. [7]

To be able to answer the variable demand properly, a variety of different power plant types is recommended. Different kinds of power plants are separated into three categories depending on their ability to run on part loads and power ramping times. These three are as follows: baseload power plants, cycling plants and peaking plants. Baseload power plants are usually run at full output and with high availability because of their high fixed and low variable costs, for example nuclear and some coal-fired power plants. Variations in demand are usually satisfied with natural gas and some coal plants (cycling plants), which compared to baseload plants possess higher variable costs but lower fixed costs. Peaking plants are low fixed cost, high variable cost plants which are run only couple hundred hours a year during the highest peak load when cycling plants are not enough to answer the peak in electricity demand. [2]

Due to the fact that electricity travels at the speed of light and as of now cannot be stored in large quantities, the electric power in the power system has to be adjusted almost instantly to maintain the balance between generation and demand. This is going to be highlighted in the future as more and more intermittent variables are added into the power system and the generation profile is going to have higher ups and downs. [2]

“Enabling technology” is a term associated with renewables which refers to different ways and technologies to increase the amount of intermittent renewables in the power system. One example for enabling technology is energy storage, which can be used to store the surplus energy produced during, for example, windy times to be distributed to power system during high demand or low generation. The need for these enabling technologies is due to earlier mentioned need to constantly balance the generation and demand of electricity. As far as the generation by renewables goes, they can be considered as demand reduction rather than sources of generation. This helps to picture the need for conventional power generation modes to meet the “residual load” of normal electricity demand minus the reduction in demand (generation) provided by renewable sources. With the increasing amount of renewables this in turn leads to greater need for flexibility in the electrical system with the increased difference between highs and lows of demand on daily scale. For the future this creates a greater need for operating reserves and flexibility as well as greater ramping capabilities to meet the predicted and unpredicted variations in demand. [8]

When eletricity generation is higher than load without energy storage possibilities, additional electricity cannot be added into the power system therefore limiting power output, i.e. power output is curtailed. Denholm [7] presents needed curtailment levels in comparison to wind power penetration with different flexibility levels and levels are shown in Figure 2.

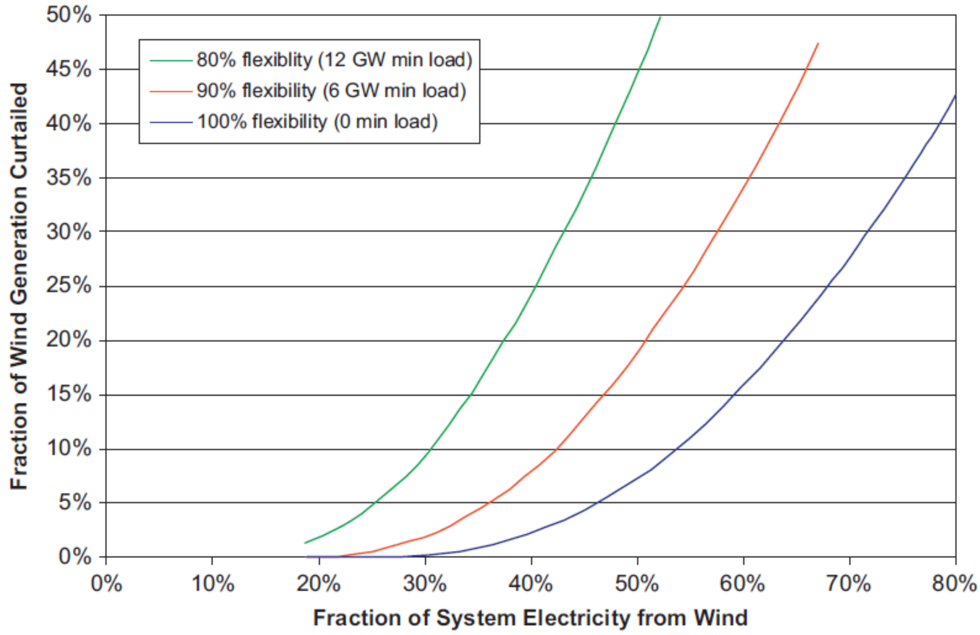

Figure 2: Needed curtailment for different levels of wind power with different flexibility levels [7].

Figure shows how with good flexibility wind power fraction can rise up to 30% and with lesser flexibility options 20% is the point where curtailment might be needed.

2.1.1 Grid frequency

Frequency can be defined as number of cycles in a period of time, usually measured in cycles per second (Hz) [9]. Frequency of the electricity generated into the grid is closely related to the rotation speed of the generator [10]. Equation 1 shows the correlation between frequency and rotation speed of the generator.

$$f = np \tag{1}$$

Where n is the rotation speed of generator and p is the number of magnetic pole pairs in generator. This means that by changing the rotation speed and the amount of magnetic poles in generator one can produce electricity with desired frequency.

Different kinds of power plants require different kinds of solutions in regards to generator design. For example hydro power plants require rotation speeds around 75-500 revolutions/min (rpm), basic steam and gas turbine plants require high rotation speeds from generators (around 3000 rpm) and big nuclear power plants typically use generators with 1500 rpm. [9]

The real power generated by generator is controlled by a turbine or engine depending on the generation method. For steam and hydroturbines, the power generation is regulated by closing and opening of steam/water valves affecting the corresponding flow rate into the turbine and therefore the power output of the turbine. The controlled medium must be monitored closely as the input to generators must constantly match real power demand to maintain desired grid frequency. Failing to do this will lead to further disturbances in the frequency. Therefore in order to achieve satisfactory operation of the power system, frequency in the grid must be kept nearly constant. [10]

Grid frequency, which usually is 50 Hz or 60 Hz depending on the country, must be maintained within a small tolerance of error. If frequency is over the nominal value, production is bigger than demand and if frequency is lower than the nominal value demand is accordingly higher than production. In the Nordic power system the guideline frequency value is 49,9-50,1 Hz. Frequency is allowed to fluctuate between 49,5-50,5 Hz when there is no disturbances and between 47,5-53 Hz in rare anomalies. [4, 6]

Frequency control of the grid is done with primary frequency control and secondary frequency control. Primary frequency control happens in a timescale of couple seconds to tens of seconds and is a dynamic progress, while secondary frequency control is done by regulating the frequency to nominal value after the primary frequency control. Secondary frequency control happens in a timescale of several seconds to minutes. [11, 12]

Balancing frequency and controlling it happens in multiple time-steps with multiple resources as shown in Figure 3. [13]

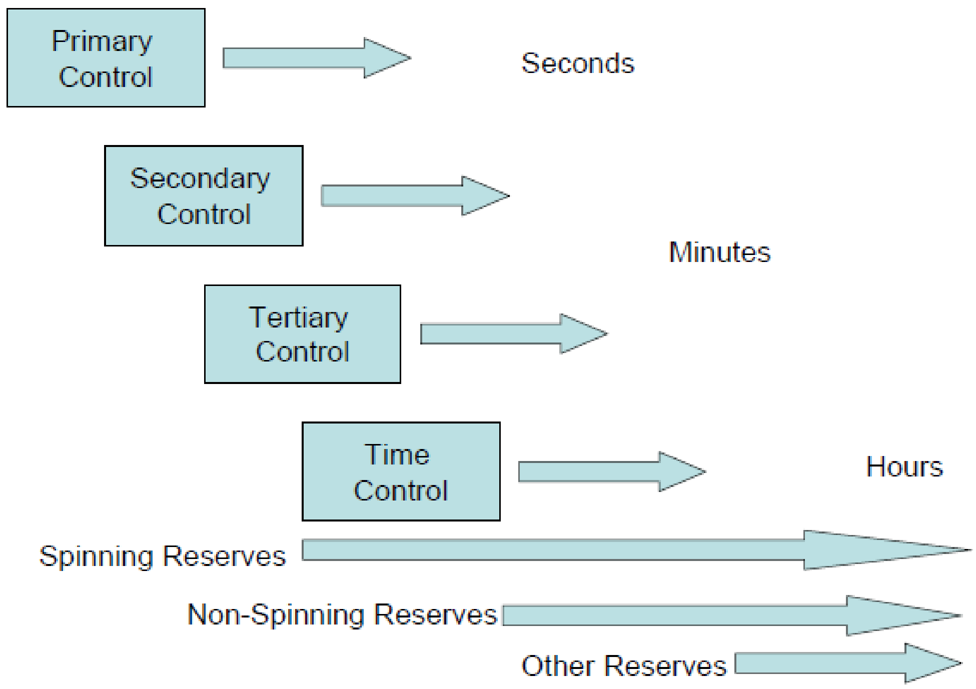

Figure 3: Time-steps for controlling frequency with different methods for it [13].

As seen from the Figure, primary control (usually referred as frequency response) tries to stabilize the anomaly in the system frequency within the first few seconds after the disturbance. Within next minutes secondary control activates, however some methods like hydropower are able to respond faster than that if needed. Secondary control maintains initial reserves for disturbances and is the balancing method to restore frequency to its original value. Frequency restoration like this is provided with both spinning and non-spinning reserves, while rotating inertia generated by steam turbines in big nuclear and coal power plants provide a beneficial dampening effect on frequency fluctuations. Tertiary control includes actions to handle current and possible future uncertainties, for example handling reserves and restoring them after a disturbance. The last control mechanism is time control which is to maintain the average frequency at the designated value on a longer time frame. [13]

2.1.2 Grid stability, flexibility and reliability

Stability of the power system can be described as the ability of certain power system to recover from a disturbance and reach equilibrium state afterwards. This takes both built-in inertia of rotating components in the system and rapidly controllable power supplies. [10]

System flexibility is the responding ability of generator set regarding uncertainties and variabilities in demand. With high amounts of intermittent renewables the system flexibility is strongly connected to the ability of baseload and reserve generators to reliably reduce electricity generation to low levels. Generally power plants that can operate on low power levels, take part in flexible generation and electricity storing, therefore bringing flexibility into the system. [6, 7]

Flexible power system must be able to deal with uncertainties and variabilities in demand and generation with reasonable costs. Power plants capable of load following with good ramp rates, integrated demand side management (smart grid) and connecting power sector with heating all provide flexibility into the power system. Adequate flexibility is important factor when increasing the amount of variable generation (VG) in the power system to be able to reliably provide power. Study by Huber [14] indicates that increasing the penetration of wind and photo-voltaic (PV) generation over 30% of the whole generation mix imposes increasing flexibility requirements. This is especially true with PVs share of over 20% in PV/wind mix which can be considered as a high share on today's standards. Huber's study also pointed out that required ramping rates are reduced with larger power systems, for example required ramping rates would be reduced from 30% of load peak in regional level to 11% with interconnected Europe. In conclusion, required flexibility in the power system is mostly dependent on the size of the power system, the share of renewables and the mix of renewables. [14]

SAIDI, which stands for System Average Interruption Duration Index measures power system reliability and represents average interruption time on low-voltage networks. SAIDI is measured annually in units of time where the consumption of the customer is not weighted in measuring SAIDI. Figure 4 presents SAIDI values for various European countries and for asterisk (*) marked countries a different index is used which gives average interruption time on medium-voltage networks, reasons for why these indexes are used vary between countries. For Finland annual consumption is weighted and for Malta, Norway and Slovenia interruptions coming from low-voltage networks are not considered in the index. [15, 16]

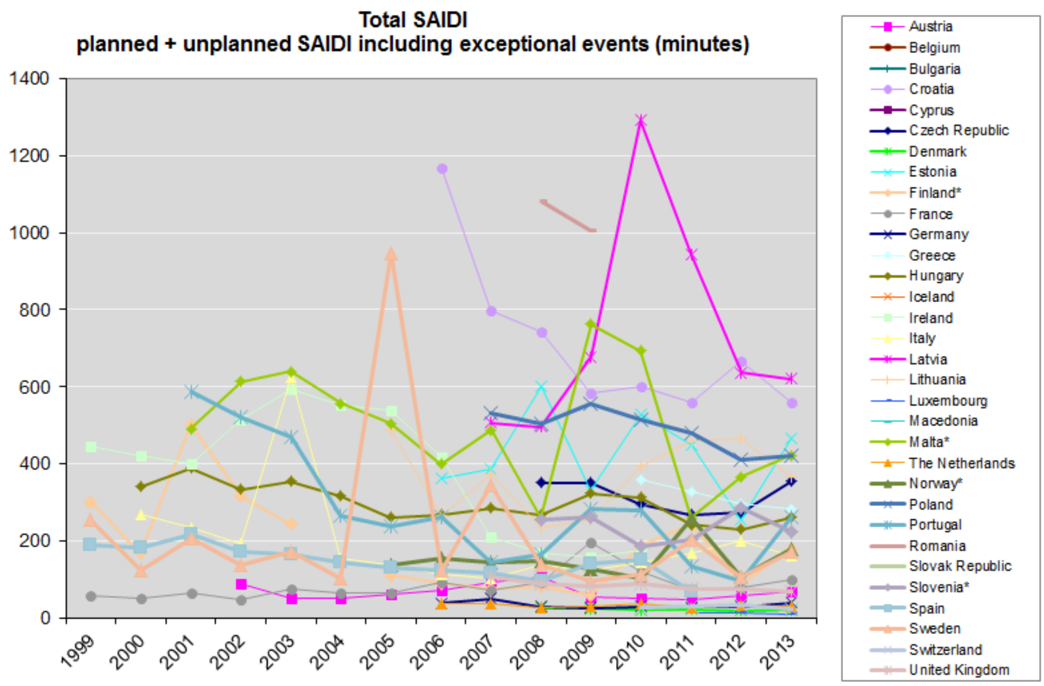

Figure 4: Interruption times between European countries [16].

Figure shows the interruption times between different European countries vary greatly and that there is also noticeable annual variations in some countries. This might be because of unplanned outages or especially rough load patterns for example during a cold winter. The highest peak in years 2010 and 2011 belongs to Latvia and this peak is due to so called exceptional event. Exceptional events when included in measuring SAIDI are events which are not controllable by the system operator.

Events categorized as exceptional events vary between countries. These criterias are presented in the 4th CEER Benchmarking report [17].

2.1.3 Grid inertia

Inertia in the power system is made by the operating generators and depends mainly on inertia of single generators and amount of those generators linked into the system. Generators of the conventional power plants operating in the same frequency generate inertia into the system due to connection between electrical frequency and rotational speed of turbine blades shown already in equation 1. When system frequency deviates from the target value (50 hz or 60 hz) the large and heavy turbine blades and their high amounts of kinetic energy slow down the change in turbine output and therefore prevent possible oscillations of frequency. Thus inertia can also be translated to mean the ability to resist changes in frequency. This means that inertia has a significant role in stabilizing the operation and control of the power system. [18, 19]

Wind and solar power do not generate inertia into the power system because power to the system is supplied through converter, in order to provide AC power at the desired frequency. This is because converter electrically decouples motion of the generator from the frequency of the power system, thus producing no inertia. The effect of renewables on the stability of the power system considering inertia is the most noticeable on low electricity loads as the conventional generators are not in use in favor of renewables and so inertia in the system is at its lowest. This also means that inertialess 100% inverter ran power system is impossible to operate if there is no buffer for sudden frequency changes. However there are operating strategies researched to help alleviate the problems that arise with 100% inertialess system. One of these strategies is so called "virtual inertia" which is based on mimicing power response of classic synchronous generators and producing it. This power response mimicking is based on control system detecting frequency deviation and adjusting power generation into the power system accordingly, so that the turbine producing power acts like it has inertia just like conventional generation units. [18, 19]

2.2 Smart grid

The term smart grid refers to advanced and improved platform for new technologies to provide flexibility and new information for both customers and electricity providers. Technologies that are able to do this include metering, distribution, electricity storage and transmission technologies. All of these combined lead to more efficient usage and distribution of electricity. The defining factor for smart grid is advanced metering infrastructure (AMI) which allows for two-way communication between the electricity provider and the measuring smart meter (customer). This allows the providers to access real-time information on each consumers needs and to offer better services for example dynamic pricing. In dynamic pricing the provider can alter the price of electricity depending on demand and generation, which in turn allows the customers to adjust their electricity usage from peak to off-peak times for cheaper electricity. [20]

A valuable asset smart grid brings to energy system is smart distribution system and its ability to handle more widely spread network of generation, for example household generated wind and solar power or plug-in hybrid electric vehicles (PHEVs) which could sell electricity back to the grid from their batteries if needed. This distributed generation in turn would reduce transmission and distribution losses born from transporting electricity generated in larger centralized power stations to consumers. As renewables in most cases are intermittent, the increase of distributed renewable generation should accompany the increase of electricity storage to "smooth" the peaks in generation which in turn would increase the flexibility of the power system by having electricity reserves during times of low generation or high demand. More flexible power system in turn allows for a far higher deployment of PHEVs, which allows for greater electricity storage possibilities in form of selling electricity from batteries in cars during high demand and charging the batteries during times of cheap electricity (low demand/high generation). While an increase in PHEVs will decrease traffic related CO_2 emissions, it will increase the need for electricity since the vehicles will now rely on electricity instead of gasoline therefore increasing the power sector's CO_2 emissions, unless the electricity is produced by GHG-free large-scale means such as nuclear power. [20]

Study by Brattle Group [21] states that nation wide implementations of AMI, dynamic rates and automating technologies in the USA could lead up to 11,5% reduction in peak demand and shift this demand into time of lower demand. This by itself does not reduce the overall electricity consumed but enables the reduction of running more expensive peaking power plants and reduce the expenses and CO_2 emissions by utilizing the base-load generating power plants more efficiently during off-peak hours. [20]

2.2.1 Demand side management

The principle idea behind demand side management (DSM) is the ability to impact power consumption and thus have some form of control on demand side of the power system. This is based on the consumers ability to decide on their electricity consumption and how these consumption habits might be changed to better suit the needs of the power system. Benefits that can be achieved via DSM are load shifting from high to low demand which allows for more efficient usage of existing and more effective power plants (less need for peaking plants). This also increases system stability as there are less high demand peaks therefore decreasing the chance for blackouts occuring due to reached capacity limit. [22]

DSM can be roughly split into two different control methods, indirect and direct load control.

- Indirect load control allows the consumers to keep full control on their consumption but are given encouragement on shifting their consumption to times which better suit energy system, this usually means the times of low demand. This would most likely be done through affecting the price of electricity to appropriately affect the consumer behaviour. For example when there is surplus generation on intermittent renewables compared to demand, the price of electricity would drop to encourage the use of flexible loads such as charging PHEV. Machinery could be automated to some extent to react to price signals so that when the price of electricity drops to certain level, the machine would turn on and for example do the laundry.
- With direct load control consumer grants the control of some devices to market aggregator so that utilities can more effectively affect the demand. More effective control over demand makes it possible for utilities to offer even cheaper electricity prices or some form of bonuses for the consumer as a compensation for losing the control over these devices.

Limiting the consumers ability to control one's electricity consumption might prove to be problematic in many cases as people might be reluctant to give up their control over heating in winter or ventilation in summer for example. So the applications are limited to some degree in how the direct load control would work. Indirect load control however gives incentive for the consumer to change his consuming habits but is still restricted to some degree. For example Finland's electricity consumption peaks during morning when people wake up and prepare to leave to work. To some degree it might prove to be difficult to affect this demand peak via price signals alone as people still need to make their morning preparations in any case. Nevertheless DSM is able to help in maintaining the increased need in balancing generation and demand and as new technologies and innovations are discovered, DSM might find new opportunities not yet realized.

2.2.2 Supply side

Supply side of the smart grid is operated with the use of a virtual power plant (VPP). VPP consists of many (hundreds to thousands) distributed and renewable power generation stations connected to each other via modern information and communication technologies. The control entity which continuously observes the generation has the power to switch on and off any individual generator as demanded, allowing for scheduled and optimized operation of said plant. The benefit of connecting enough distributed generation is the level of control achievable, which is almost the same as compared to operating conventional power plants. This is possible due to the ability of VPP to offset to a some degree the innate unreliability of intermittent generators with a proper mix of unreliable generators. For example wind and solar power complement each other pretty well as typically good conditions for both generation methods do not occur at the same time therefore offsetting their intermittency to some degree. Intermittency can also be offset by connecting enough generation from different weather conditions through a big VPP to cover large enough geographic area for different weather conditions. [22]

2.3 Energy storage

Energy storages makes it possible to produce energy at one time and then store it for later use. The requirements for using energy storage technologies in different applications vary and there is no single best technology to meet all these different varying requirements. Energy storages are going to have an even greater role in the future energy system as the intermittent renewable energy sources are going to have bigger role and therefore the load-smoothing energy storages provide is going to have greater value. Energy storages as well as conventional power plants are known as dispatchable energy because the power output of those can be adjusted according to the demand. [23]

Applications in power system where energy storage is currently used are as follows: load leveling, operating reserves and end-use applications. Load leveling makes it possible to utilize baseload power plants more effectively and decrease the use of peaking plants by storing the excess electricity during times of high generation and using it during high demand peaks. Operating reserves can be categorized in several different applications but the main focus is to response to variations in generation or load with different applications depending on their response times and to help with black-start after a system-wide failure. End-use applications generally function the same as load-leveling but at the customer side. [8]

In the future energy storage could also provide more power quality and stability control and aid in transmission and distribution of electricity. As distribution systems must always consider the peak demand and be sized appropriately, without energy storage new systems must be installed to meet the growing overall demand and peaks which could only happen once or twice a year for couple of hours. In this scenario energy storage can be utilized by distributing energy storages near load points which can avoid the building of new and expensive distribution lines. High peak demands also have high line-loss rates which can be reduced with the use of energy storage. [8]

Power quality means voltage spikes, momentary outages and the overall quality of the produced power. Energy storage devices can be used to increase/maintain this quality. Customer load sites many times include components that are sensitive to power quality variations and to maintain this quality, storage devices are used as a buffer against power quality variations. Electric power systems can experience frequency oscillations which can limit the utilities' ability to transmit power which in turn affects the whole system's reliability and stability. To help with these disturbances one needs very fast response times (< s) which can be achieved with variety of fast-responding energy storage devices. [8]

Electricity storage technologies can be divided into multiple categories, as there are many different ways to store electricity. Each technology having strengths and weaknesses. Figure 5 presents main electricity storage technologies compared by physical or chemical differences.

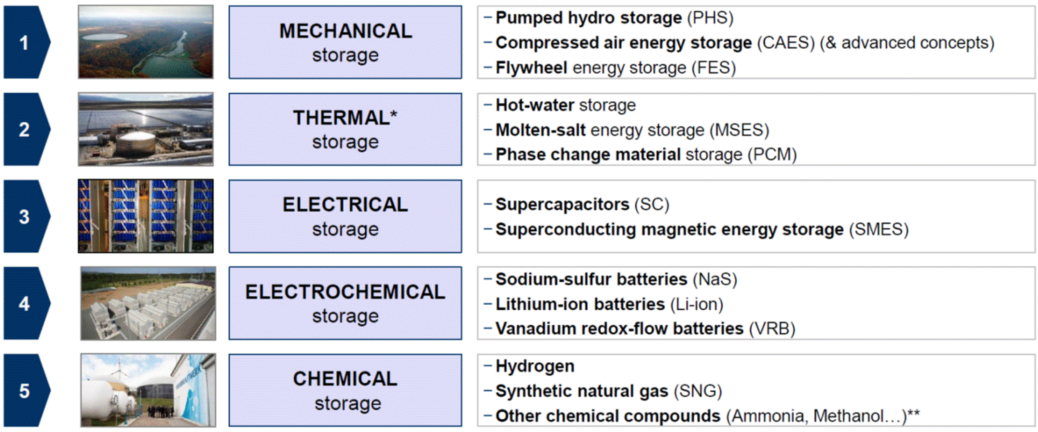

Figure 5: Electricity storage technologies [24].

As seen from Figure 5 storage technologies can be separated into different categories, in this figure depending on the form of energy the electricity is conversed into. Storage categories listed in Figure 5 are discussed in this thesis except for thermal storage as this thesis is focused on balancing electricity demand and generation while conventional thermal storage technologies usually aim to supply heat and cooling.

Storage technologies can also be compared by charge/discarge times, instead of physical or chemical differences as was did in Figure 5. When comparing charge/discharge times there is no clear definition for different categories. A simple way is to divide technologies into power and energy storage applications, where charge times for power storage applications are small and long for energy storage applications. Generally with energy storage short time is in time scale of seconds to minutes and long time is from minutes to hours. [23]

2.3.1 Pumped hydro storage

Of all of the energy storage technologies pumped hydro storage (PHS) is the most widely used at the time of writing this thesis. Figure 6 shows the global grid-connected electricity storage capacity in the year 2014.

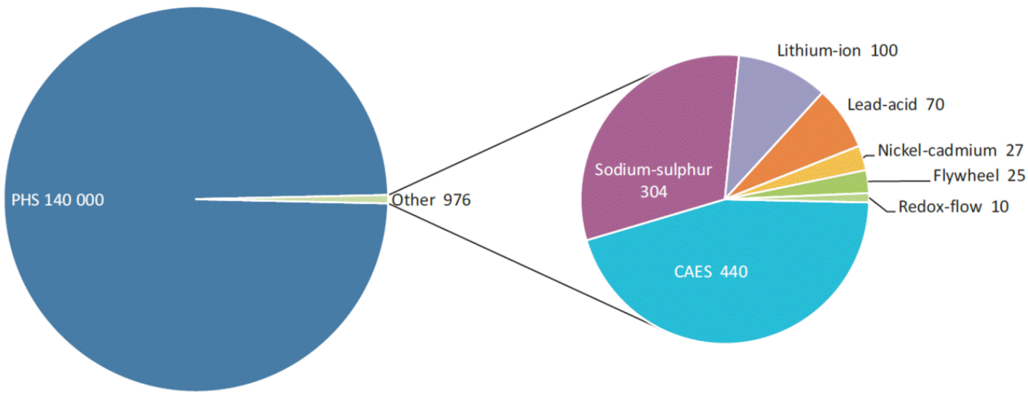

Figure 6: Grid-connected electricity storage capacity in the year 2014 (MW). Modified from [25].

As seen from the Figure 6 PHS covers the vast majority of all grid-connected electricity storage capacity. PHS is based on pumping water with electricity onto higher ground into a large pool of water and when the electricity need so demands the water can be run down through a turbine producing electricity. Since usually all the prerequisite components to run PHS (dam, reservoir, turbine, generator) exist in hydropower plants already, additional costs involving this energy storage method are minimal. PHS has extra costs when additional pumps or aforementioned prerequisites are needed. The biggest advantage PHS has over other technologies is that PHS can store far greater quantities of energy only limited by the size of water pool. Therefore power output capacity of PHS systems varies greatly between 100-

5000 MW. However PHS has a relatively low energy density (0,5-1,5 Wh/kg) when compared to some other energy storage technologies therefore PHS systems require either large water pools or great height variations to be worthwhile to invest into. Altering between pumping and generating electricity can be done within minutes from once or twice a day to even 40 times a day and a typical expected lifetime of a PHS facility is between 30-60 years with round trip efficiency of 65-85%. As PHS is capable of responding in less than a minute to the changes in load, PHS is great in primary frequency control and providing generation reserves. [23, 26]

2.3.2 Compressed air energy storage

Compressed air energy storage (CAES) is simple as a concept. One can run turbine backwards to compress air when the electricity production is greater than the demand and when the need for electricity so demands the air can be run from the storage through the turbine to meet the demand. Of course the amount of energy that can be stored is dependent on the volume of the storage. Different studies give greatly different values for achievable round trip efficiencies which vary between 40% [27] and 75% [23]. If these highest round trip efficiency values of 75% were achievable they could be compared to values of pumped hydro storage. Achievable ramping rates are up to 20% of load in 30 seconds and depending on paired plant type the storage ramp rates vary between 3-30 minutes for full load ramp. [23, 27]

CAES systems are by design fit to take part in daily load-follow operation. Design approach such as this enables a quick transition from compression to generation mode and vice versa. This means that utility systems with high daily load variations and high variable costs benefit greatly from CAES. Limiting factor with CAES is that it cannot be operated independently and has to be paired up with a gas turbine plant. With the current state of CAES technology it is impossible to pair CAES with other power generation methods. Additional restrictions in CAES siting and compatibility as a storage method come from the need to have a large compact storage area for pressurized air in proximity of the CAES plant. Suitable storage areas include rock mines, salt caverns and depleted gas fields that are compact enough to prevent the high pressurized air from leaking. [28]

Available power output capacity for compressed air energy storage is estimated to be between 15-600 MW. So far, only two CAES plants have been built and operated worldwide with far smaller power output capacities than the estimated maximum of 600 MW. One is located in Germany with electrical capacity of 290 MW and the other in the USA with a capacity of 110 MW. As is the case with PHS the amount of storable energy is dependent on the volume of the storage as the typical energy density of this kind of a system is around 30-60 Wh/kg. CAES system has low self-discharge rates therefore making it well suited for long term storing and is at the time of writing this thesis with PHS the only storage technology capable of large scale power storage. The main benefits for CAES over PHS are in lower capital costs and easier underground storage possibilities. Lifetime of a CAES facility is around 40 years. [26, 27]

2.3.3 Flywheel energy storage

Flywheel energy storage (FES) is based on storing generated energy into rotating flywheels as kinetic energy. When the purpose is to store as much energy as possible a very high rotational speed is required. Modern ultra-high speed wheels, which are made of lighter materials like carbon nanotube fibers, can reach rotational speeds up to 100 000 rpm. The amount of storable energy in a flywheel comes from the equation 2.

$$E = \frac{1}{2}I\omega^2 \tag{2}$$

Where ω is the rotating speed (rad/s) and I is the moment of inertia (kgm^2). High attainable rotating speeds result in high amounts of storaged energy in flywheels, usually around 360/500 kJ/kg or compared to lead-acid batteries three to four times of the energy storaged per kilogram. In addition to strong and light materials extra features are required to achieve even higher speeds and therefore better efficiencies. These features aim on minimising air resistance and friction by enclosing the wheel into a vacuum and having a magnetically levitated suspension which minimises friction losses compared to mechanical suspensions. These features also allow for flywheels to storage energy for significantly longer periods of time and reduce mechanical wear which corresponds to lesser maintenance and greatly increased lifespan, with charge/discharge cycles increasing to 10000 times greater compared to amount of cycles on lead-acid batteries. The high amount of charge/discharge cycles is the major advantage that favors flywheels in applications where frequent cycling is required in addition to high energy recovery efficiensies (around 90-95%) on discharge. This also allows flywheels to have lifetime of around 15 years. [23,26]

Flywheels are great in applications correcting system power interruptions and quality of produced power due to fast discharge times and good efficiencys. Each flywheel is capable of discharging approximately 100 kW in a time-frame of 15-20 seconds which is time required for emergency power sources like diesel generators to start working. This also means that for flywheels to achieve adequate storage levels for correcting system power interruptions a "farm" of flywheels is needed. A farm like this is installed in Stephentown, New York which is capable of storing and delivering 20 MW of electrical power. Disadvantages FES face are relatively low energy densities and large self-discharge rates, closing to 100% if storage period is longer than a day [28]. All in all flywheel energy storage has many applications in storing excess production or power conditioning but should not be used in long-term energy storing but in storage periods of minutes. [23, 26]

2.3.4 Batteries

Batteries can be divided into rechargeable and non-rechargeable batteries with the focus in this thesis on rechargeable batteries since the large-scale energy storage cost effectiveness isn't generally great on non-rechargeable batteries [23]. Generally speaking there are two working methods for rechargeable batteries: method which relies on electrochemical reactions between anode and cathode while charging/discharging and "rocking chair" method in which usually lithium ions travel between anode and cathode materials. [27]

In the "rocking chair" method the state of charge is relative to the concentration of lithium inside the anode and cathode materials. There is an ionconducting liquid and a porous membrane separator filled with organic solvent separating the anode and cathode sides. When battery is being recharged, electrons travel from cathode to anode also making lithium-ions to do the same. This process is reversed when the battery is discharged. [27]

When comparing different batteries from an electrical point of view the lithium-ion batteries are the most efficient due to low internal resistances in each individiual cell. This can lead to roundtrip efficiency of 94% which is greater compared to more commonly in industry used lead-acid batteries, which efficiencies range from 70-90%. Currently biggest power output capacity of lead-acid batteries is around 40 MW with multiple batteries. Lithium-ion batteries have maximum self-discharge rate of 5%/month and can endure 1000-10000 cycles with proper usage, such as not completely discharging the battery. This translates to around 5-15 years of lifetime depending on the usage. Therefore lithium-ion batteries are best suited for power system ancillary services and not large-scale energy storage as opposed to lead-acid batteries which are better suited for larger-scale storing, where the size and robustness of battery is not an issue. [24, 26, 27]

Lithium-ion batteries have usually been more expensive compared to lead-acid batteries as the cost to store electricity into lithium-ion batteries is according to some studies over 600 $/kWh as compared to cost of lead-acid batteries (300-600 $/kWh). This is the main reason for lithium-ion batteries to be more commonly used in small scale applications, like cell phones or in electric vehicles. However the cost for electric vehicle lithium-ion batteries is rapidly decreasing as the technology is developed as is shown in Figure 7. [24, 27]

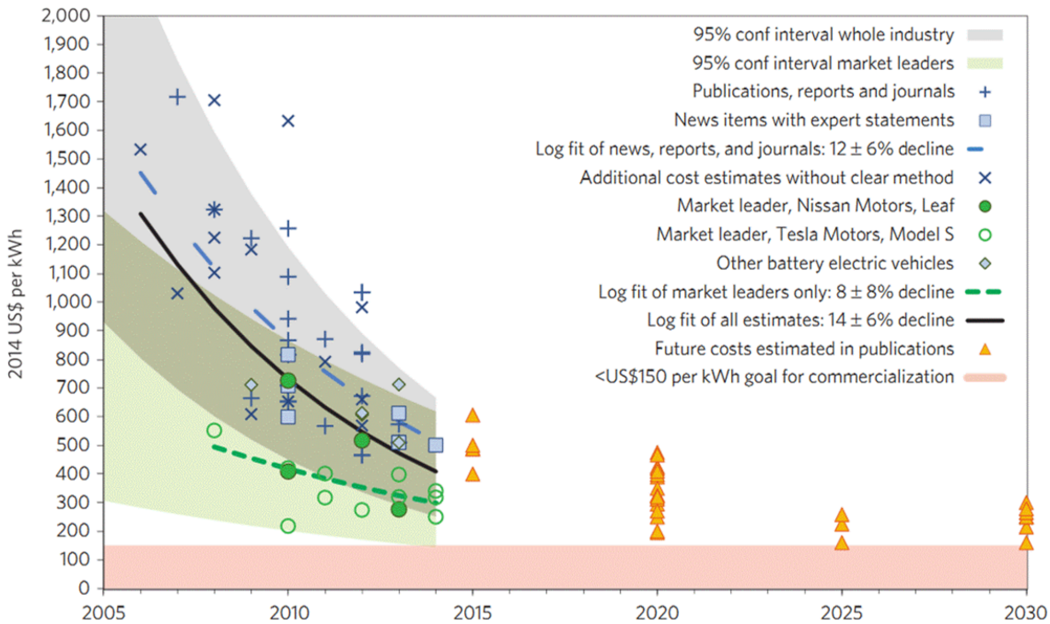

Figure 7: Development in lithium-ion battery prices. Modified from [29].

As seen in the figure the electricity prices between different publications can vary quite drastically but the trend in cost reduction is clear. This means that if the cost of lithium-ion batteries continues to decrease and/or the usage of electrical vehicles increases, the electricity storage in lithium-ion batteries will play bigger role between different battery technologies.

Nuclear energy storage happens in the form of batteries where the electricity is generated from the radioactive decay heat. Currently nuclear batteries are used in applications where high energy densities and very long lifetimes are required for example in space ships and remote locations like some lighthouses. Currently nuclear batteries are quite expensive and robust but research is being done to improve them. As opposed to chemical batteries presented earlier, nuclear batteries cannot be recharged because they simply convert radition energy from nuclear decay processes to electricity. [23]

2.3.5 Capacitors

Energy storing with capacitors bases on separating positive and negative charges on a pair of plates separated by an insulating material. This means that when one side is charged with direct current electricity the other side induces a charge of the opposite sign. Difference with capacitors compared to batteries is that there is no chemical reactions and no conversion from chemical energy to electricity. Energy storage capacity in a capacitor can be solved from equation 3. [23, 26]

$$E = \frac{1}{2}CV^2 \tag{3}$$

C is the capacitance of the capacitor and V is the voltage, where capacitance is positive or negative maximum charge in each plate divided by the voltage across them. Equation 3 shows how the storaged energy can be increased either by increasing voltage or capacitance. However there are certain limitations considering the maximum voltage that can be sustained between capacitor plates even with great insulation and with plates separated by a given distance. For example air will break down when voltage exceeds 3 MV per meter of separation. Capacitance value can be affected by modifying the size of plates, the distance of plates or by changing the insulating material. Advantages that capacitors have are long cycle lifes and the ability to perform immeadiate recharging. Main problem for capacitors is low energy density which makes large-scale energy storing uneconomic. [23, 26]

The supercapacitors can attain far greater capacitance values compared to ordinary capacitors. Supercapacitors operate the same as normal capacitors but insulating material is replaced with porous spongy conducting material thus granting greater effective surface area and greater energy density compared to normal capacitors. This leads to hundreds of times better capacitance and energy stored compared to conventional capacitors. Still supercapacitors are not able to achieve the same level of energy density batteries are. However supercapacitors have a far greater power density than batteries which translates into far greater ramping rates. Single supercapacitor can store a few Wh and connected supercapacitor modules can store up to 1 kWh of energy with larger energy storing still possible with further connections. At the time of writing this thesis some trial systems reach power output of 50-100 kW and the expected life-time for supercapacitors is the same as it is for large conventional capacitors, around 10 years. The roundtrip efficiency for supercapacitors is very good (> 90%) but the self-discharge rate is also very high when compared to batteries, measuring around 20-40% of storaged capacity per day [28]. As capacitors have very fast response times but small capacities they are used in power failures as short-term bridging power. Currently the restricting parameter for the usage of supercapacitors is the high cost of the technology, around 5 times to cost of lead-acid battery, for example. [23, 26]

2.3.6 Fuel cells

Fuel cells are comparable to batteries. They have the same basic elements in cathode, anode and electrolyte generating electricity from chemical reactions and convert chemical energy into electricity. The difference in batteries and fuel cells is that the fuel cells require fuel flow through the cell to generate electricity, usually hydrogen gas. This means that the cell itself doesn't store energy and the terms charge/discharge are not used and the cell generates electricity only as long as there is fuel entering into the cell. [23]

Advantages fuel cells posses against more common power generation methods are:

- Low sulphur and nitrogen oxide emissions.
- Few moving parts leading to less noise and vibration.
- No need for recharge as long as fuel is provided.
- Possibility for long storing thanks to very low self-discharge ratios (∼0).

Factors limiting the commercial use of fuel cells, which require future research are:

- Currently high costs compared to technologies already in use.
- Relatively unproven status as a commercial power generation method.
- Figuring out the best way to produce hydrogen.

High costs of fuell cells can be reduced to certain degree with mass manufacturing and further research. In principle, fuel cells offer a way to produce CO_2 free electricity from hydrogen with only emitting water. However the problem currently lies in the hydrogen manufacturing process. Two most realistic ways to manufacture hydrogen are to produce it from fossil fuels or via electrolysis of water. Of these two only the method utilizing water electrolysis can be considered as CO_2 free generation as long as the electricity used in this process is from carbon free source such as wind or nuclear power. [30]

Power to gas (P2G) technology enables the transformation of electricity into hydrogen or methane which can be classified as a renewable source. These gases can then be storaged into underground storage reservoir, gas grid or alternatively sold directly in the markets. The conversion rates for hydrogen and methane respectively are 75-80% and 60-65% as producing methane needs further conversion compared to hydrogen. When the storaged gas is converted back to electricity in fuel cell the total conversion efficiency ends up around 36%. The estimated power capacity of fuell cells varies greatly between 0-50 MW and the life cycle of hydrogen fuel cell is around 15 years with charge/discharge cycles totalling around 20000. [26, 31]

2.3.7 Magnetic storage

Closest comparison to magnetic storages is the energy storing in electric fields in a capacitor. The magnetic field is created by current in a coil of wire where the magnitude of the magnetic field is proportional to the size of the current. Usually large amounts of current requires continuous input of power because of resistance losses, but this can be negated with superconducting wires which are necessary for the magnetic energy storage to work. Superconductivity enables the creation of large magnetic fields which can be stored indefinately because of the coil having zero resistance. Superconductivity, to be achieved, usually requires very low temperatures depending on the material. A super conducting magnetic energy storage system (SMES) consist of the coil of superconducting wire, a refrigeration unit and a power conditioning system which is to create magnetic field by converting the outside source AC into DC. Since there is no losses in the magnetic field due to superconductivity the only losses in the charge/discharge cycle are involved with the power conditioning unit leading to overall efficiency per cycle to be around 95%. [23]

Energy content in currently operating SMES is around 1 kWh but the power output cap is in the MW range, only restricted by power electronics. SMES is not ideal for low power outputs as the refrigerating system is complex and expensive therefore making low power output systems not cost-efficient. Advantages SMES has over other storage technologies include high efficiency, very short time delays in charging/discharging, great reliability, number of charge/discharge cycles and long lifetimes which most likely exceed those of competing technologies (over 20 years) [26]. Self-discharge rate of SMES is around 10-15% of stored capacity per day [28]. These properties suit the best for power quality control as it requires fast response times. Reasons why SMES isn't widely used at the time of writing this thesis lie mostly in the expensiveness of making superconductive wire and refrigeration units and their power providing costs. [23]

2.3.8 Conclusion and comparison between storage technologies

Next the most important parameters of storage technologies are compiled into Table 1 and discussed.

Table 1: Storage capabilities for energy storage technologies [26, 28].

	Power output capacity [MW]	Energy density [Wh/kg]	Self-discharge rate [%/day]	Response time[1]	Conversion rate [%]
PHS	100-5000	0,5-1,5	Very small	Fast	65-85
CAES	15-600	30-60	Small	Fast	40-75
Flywheel	0,1	10-30	100	Very fast	90-95
Batteries	0-40	30-200	0,1-0,3	Fast	70-94
Supercap.	0,3	2,5-15	20-40	Very fast	>90
Fuel cells	0-50	800-10000	~0	Good	36
SMES	0,1-10	0,5-5	10-15	Very fast	95

As pointed out earlier PHS and CAES are currently the only technologies applied in large-scale energy storing thanks to good conversion rates, low self-discharge rates and maturity of the technology. However energy densities of both of these technologies are relatively low, which translates to larger storage volumes. Even though PHS has the lowest energy density of all of the technologies presented it is the preferred storage technology in large-scale storage as it is relatively easy and cheap to store large amounts of water.

[1] Response time is divided into three categories: Very fast (< ms), fast (ms) and good (< s).

SMES technology provides excellent response times, conversion rates and good lifetime expectancies which benefit power quality control applications the most. As SMES is currently very expensive due to superconductive wire and refrigeration units, more research and development is required for making SMES cheaper in order for the technology to be more widely adopted in power quality applications. Flywheel energy storage is another technology fit for power quality applications as seen from similar values compared to SMES in table 1. However flywheels have far greater self-discharge rates compared to SMES and therefore are only suitable for energy storing in time-scale of minutes. Also for flywheels to reach the same power output capacity as SMES, a "farm" of flywheels is required. Supercapacitors have similar capabilities compared to SMES and flywheels and is currently used as short-term bridging power in power failures. Each of these technologies have relatively poor energy densities which is acceptable in power quality applications where large storages are not required. Even though each of these technologies have great parameters for power conditioning, the reason these technologies are not yet widely adopted is the expensiveness of each technology.

Batteries and fuell cells are comparable technologies as both of these technologies have similar capacities and have far greater energy densities compared to technologies used in power quality applications. Depending on battery technology, batteries are able to partake in either power system ancillary services or help in load-follow operation as the response times needed are not as strict as in power quality control applications and the amount of energy stored is sufficient. A more in-depth comparison between different battery technologies is presented in Appendix I. Fuel cells are also able to take part in load following thanks to their high power output capacities and energy densities. However, additional research is needed in more efficient hydrogen and methane production for making fuel cells more competitive.

3 ROLE OF CONVENTIONAL POWER PLANTS IN THE FUTURE ENERGY SYSTEM

In the future energy system the role of variable renewables is greatly enhanced due to international agreements to reduce carbon dioxide emissions. These renewables are intermittent by their nature (like wind, solar, etc.) and due to that nature they create limitations and needs for the power system to adapt to. This is due to fact that power system needs to always balance the generation and demand to maintain safe and continuous transmission of power.

This section is structured into eight parts. First GHG emissions of various power production technologies are briefly inspected and compared. Second part presents important properties required for adjusting electricity production. Next basic and adjusting properties of nuclear power are researched with previous load-follow operation experiences from France and Germany. Last subsections are divided between other conventional power generation methods and their ability to operate on part loads with the last subsection compiling and comparing the different power generation technologies.

3.1 GHG emissions of power production technologies

As mentioned the aim of the future energy system is to greatly reduce greenhouse gas (GHG) emissions especially carbon dioxide from the current levels. GHG emissions of different electricity generation technologies can be measured and compared by calculating their life cycle GHG emissions as shown in Figure 8 for renewable and nuclear sources. [32]

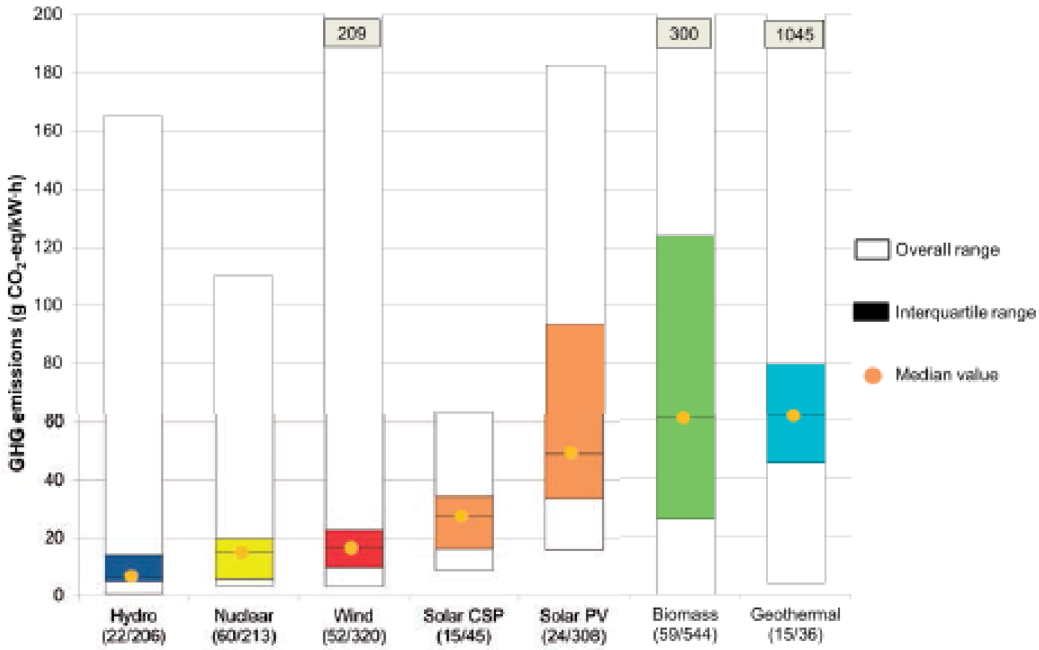

Figure 8: GHG emissions for different renewable and nuclear technologies over their life cycle [32].

Figure shows how different renewable electricity generation methods and nuclear energy rank up with each other. The problem with comparisons like these is that the life cycle GHG emission calculations are never exact since there are approximations and differences in opinions on what should be included in the calculations. These variations are visible in the huge differences between overall range and median values. Nevertheless Figure 8 gives a good picture of how renewable and nuclear technologies rank up when comparing the median values of GHG emissions. Figure shows how small GHG emissions nuclear power has even when compared to most renewables and since running a nuclear power plant doesn't generate GHG emissions, listed GHG emissions for nuclear power come from fuel manufacturing and construction & decommissioning of the plant. With all this said these values are far smaller when compared to fossil fuels as shown in Figure 9, which presents GHG emissions for fossil fuels with and without carbon capture & storage.

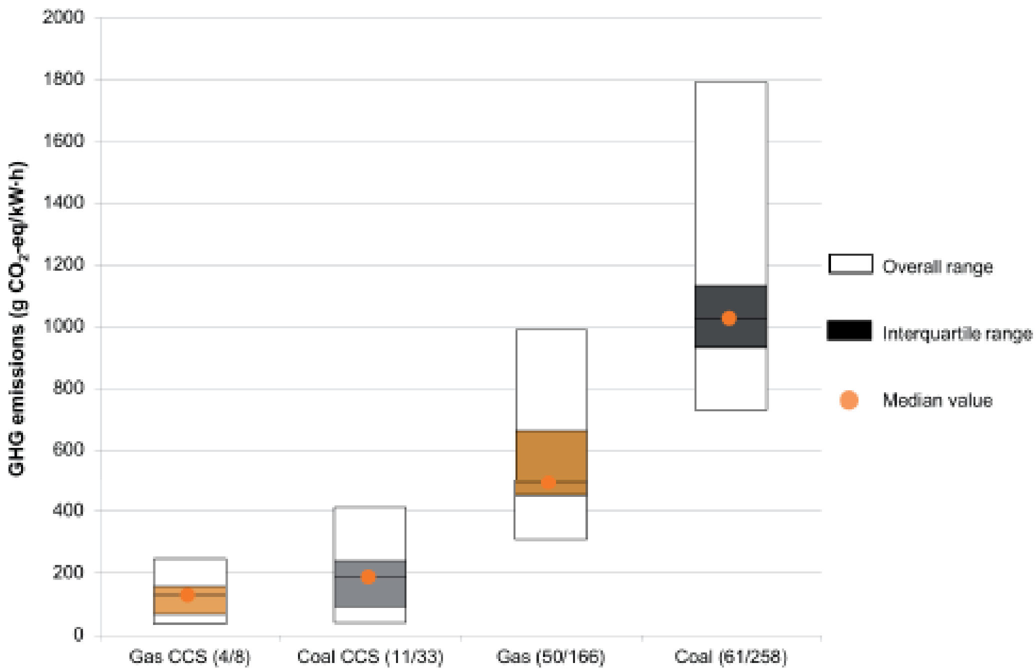

Figure 9: GHG emissions in electricity generation for different fossil fuels and carbon capture & storage over their life cycle [32].

As Figures 8 and 9 are compared the difference in magnitude between the two needs to be noted. As expected it is clear that the fossil fuels generate far greater amounts of GHG emissions when compared to renewables and generation with carbon capture & storage systems.

3.2 Adjustability in electricity production

Minimum power output, start-up and ramping speed all affect the adjusting properties of power plants. Table 2 presents adjusting properties for different power plant types. [6]

Table 2: The adjusting properties for different plant types [2, 6].

	Unit size [MW]	Start-up time [h]		Ramping speed		Min. power output [MW]
		Cold	Hot	[%/min]	[MW/min][2]	
Gas turbine	10-300	0,16	0,16	5-10	15-30	5-150 [50%]
Diesel motor	1-20	0,25	0,08	25	5	0,3-6 [30%]
Nuclear	1000-1600	48	2-4	5	80	500-800 [50%]

Table 2 presents gas turbines and diesel motors which are usually used as peaking plants and nuclear power which is used as base load power generation. First two are used as peaking plants due to their fast start up times. Diesel motor plants also have the biggest ramping speeds and the lowest minimum power outputs. But with modern nuclear plants ramping speed is also considerable as the power levels are much higher compared to other technologies on the list. This table also proves that nuclear plants are able to participate in pre planned load following with good response times starting from couple of hours from a hot shut-down.

3.3 Nuclear power

Nuclear power production is based on transfering released heat from the fuel into the turbine via coolant just like in any other conventional power plant, only real exception between the technologies is that the heat energy is released from the fuel through nuclear reactions instead of fuel combustion. Fuel consists of fissile[3] nuclides and usually of fertile[4] materials. Place where fuel is located and heat from the fuel is released is called the reactor core. Core is located inside a pressure vessel which is required because of high pressure levels needed to achieve good power conversion efficiencys in turbine. This is due to the connection between tempera-

[2]Percentage taken from the biggest unit size.

[3]Fissile material is material that is capable of continuing fission chain reaction.

[4]Fertile material cannot continue fission chain reaction but can convert into fissile material via neutron absorptions.

ture and pressure of the heated medium as the power conversion efficiency is highly dependent on the temperature of the medium entering the turbine. [33]

There are many different kinds of reactor types but the most common reactor types are so called thermal reactors where fast neutrons are "slowed" to lower energy levels by the moderator medium in the core. Neutrons in the lower power levels (slow neutrons) are more likely to produce new fissions compared to fast neutrons, therefore slowing the fast neutrons into slow neutrons improves the fission efficiency and makes it easier to maintain a safe chain reaction of fissions. Moderator in most commercially used reactors is normal water, which also is the most common coolant type. Other used coolants are liquid sodium, some liquid organic compounds, carbon dioxide and helium. To be able to convert the heat released from the fuel into electricity, the heat must usually be transferred from the coolant into a working fluid via heat exchangers to produce vapor or hot gas. After the heat is transferred into the working medium through heat exhchangers a turbine-generator system converts the heat stored into electricity. Some reactor types boil the water into vapor straight in the reactor core therefore solutions like these don't need heat exhangers as the produced vapor can be utilized straight in the turbine. [33]

As explained earlier reactor types can be classified by the speed of the neutrons (kinetic energy). Nearly all neutrons born in a fission are fast neutrons and if neutrons are slowed to a lower power level with moderator the reactor is called a thermal reactor. If there's nothing to slow the neutrons and the majority of the fissions happen through fast neutrons the reactor is called a fast reactor. The fuel used in fast reactors contains significatly bigger proportion of fissile nuclides than in thermal reactors. For fast reactors the fraction of fissile nuclides has to be at least 15% in the fuel material and for thermal reactors the corresponding number is somewhere between 2-4% depending on the type of moderator due to more efficient usage of fissile nuclides in fissions. [33]

At the time of writing this thesis basically all commercial reactors producing power are based to utilize the heat from fissions to boil water and the most common types of reactors worldwide are pressurized-water reactors (PWR) and boiling-water reactors (BWR). PWRs generated 68% and BWRs 20% of the total electricity produced by nuclear power plants worldwide in the year 2014 [34]. Therefore the focus in this thesis is on PWR and BWR reactor types.

3.3.1 Pressurized-water reactors

The reactor core of a PWR contains usually approximately 40000 cylindrical fuel rods which are placed in fuel assemblies with one assembly usually containing close to 200 rods. The fuel used in PWR is uranium dioxide (UO_2) which is slightly enriched in the fissile uranium-235. Uranium dioxide powder is sintred and compressed into small cylindrical pellets which are then stacked into a tube of zirconium alloy [33]. This zirconium alloy tube is called fuel rod cladding and is show in Figure 10 with other internal components of a PWR.

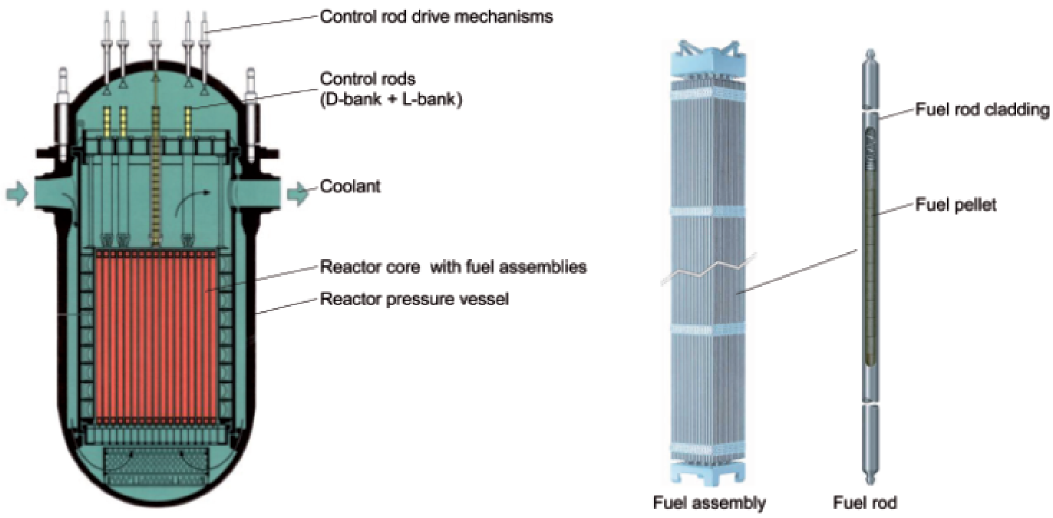

Figure 10: Internal components of a PWR [35].

Figure shows the route coolant is forced to take in the vessel as it is pumped into the reactor vessel and then lead to the lower part of the vessel through the downcomer. From there the coolant is lead into the fuel assemblies and after the assemblies the heated coolant leaves the pressure vessel at the same height it entered. The multiple loops from where the coolant enters and leaves the vessel are at the same height and are called "hot leg" (outlet) and "cold leg" (inlet) in reference to the temperature of the water.

The pressure in the core is maintained under a pressure of 15,5 MPa to reach high temperature levels of coolant at the same time preventing the boiling in the core. Pressure is maintained by using a component called pressurizer which is located in one of the primary coolant loops. In modern PWRs there are several primary coolant loops whose job is to remove the fission heat from the reactor core and transfer it to the heat exchangers from where the heat energy is transferred into the secondary loop. Secondary loop then transfers the newly formed steam from the heat exchangers into the turbine-generator system to be transformed into electrical energy. [33]

3.3.2 Boiling-water reactors

As with PWR the BWR contains 40000 fuel rods with similarly enriched uranium dioxide in zirconium alloy claddings. The difference between the two is the gap between the fuel rods in BWRs which is significantly larger. This leads to less fuel rods in one assembly and a wider but at the same time shorter core compared to PWRs. The pressure maintained in BWR (around 7,24 MPa) does not need to be as high as in PWR since the water boils in the reactor core and therefore BWRs does not require as thick of pressure vessel walls as PWRs do. The steam produced in both reactor types is however approximately equal in pressure and temperature levels. Instead of primary and secondary loops, BWR only needs a single circulating loop as the steam required to run the turbine is generated directly in the core.

Internal components of a BWR are shown in Figure 11. [33]

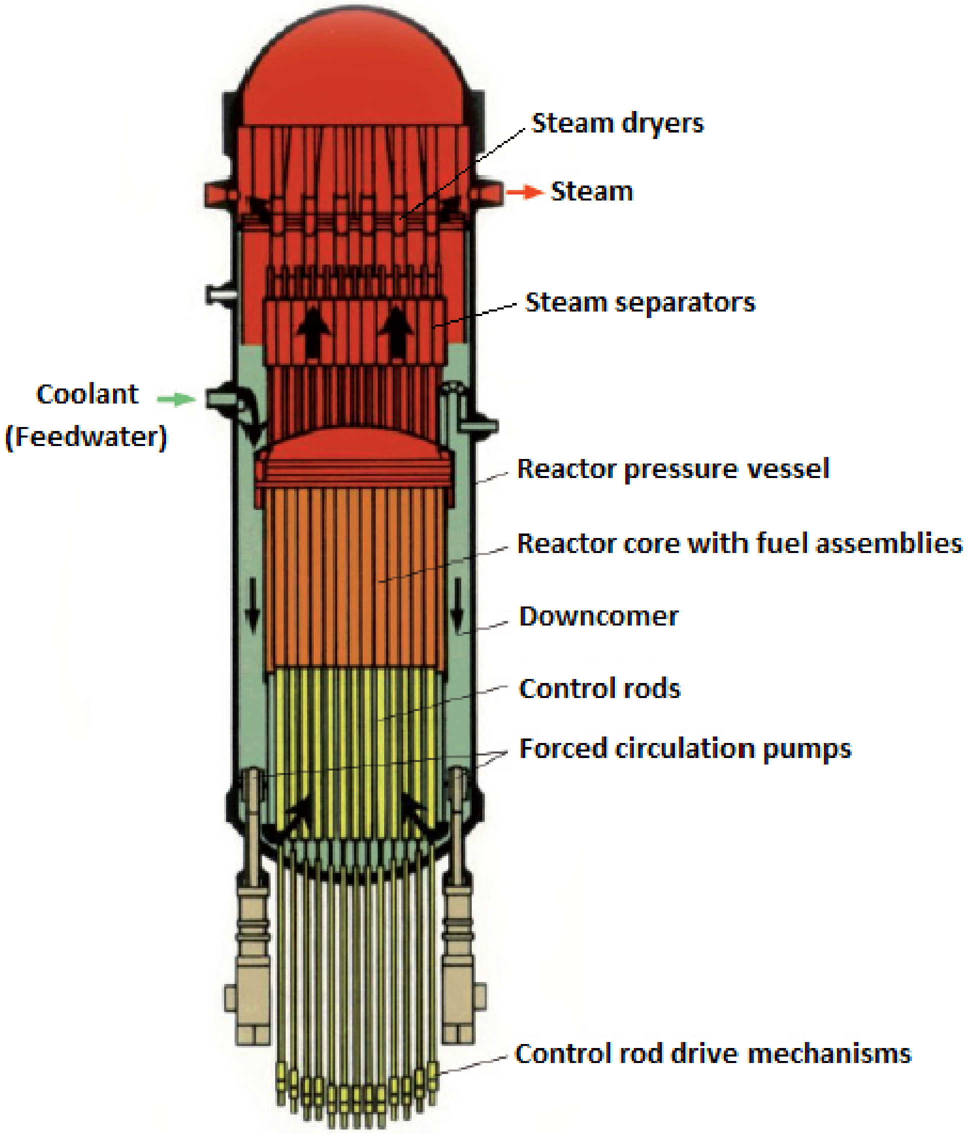

Figure 11: Internal components of a BWR. Modified from [35].

As shown in Figure 11 structure of BWRs differs greatly to that of PWRs. Coolant is channeled into the vessel from mostly the same place but the first major difference between the two types is that the coolant is pumped into the fuel assemblies with circulation pumps which are located inside the pressure vessel. Second bigger difference is the location of control rods which are located at the bottom of the pressure vessel unlike in PWR where the rods enter the vessel from the top. Third major difference between the two is steam dryers and separators which are the reason why control rods are injected from the bottom in BWRs. Reason for the steam dryers and separators in BWR is the boiling of water in the reactor and the fact that the steam is directed straight into the turbine without heat exhangers hence the need to separate water droplets from the steam and dry it.

When altering the power levels of reactor the plant operator must take into account so called fission-product poisoning. Fission-product poisoning means neutron absorptions into non-fissile materials affecting the reactivity[5] and thus power level of the reactor. Most notable of these materials are xenon-135 and samarium-149. Concentration of fission-product poisons is tied to power level in the reactor and changes in power level will affect the concentration of fission-product poisons and therefore change the reactivity and power levels again. Of the mentioned two fission-product poisons xenon-135 is of greater importance due to its large capture cross section which affects the ability of xenon to capture neutrons born from fissions. A small portion of xenon-135 in the reactor is born directly from fissions but the way most xenon-135 originates is through radioactive decay. Xenon-135 originates from iodine-135 and tellerium-135, where half-life[6] of xenon is 9,2 hours, iodine's 6,7 hours and tellerium's is under 1 minute. Half-lifes with iodine and xenon affect the behavior of power curve when there is a change in power levels until a new equilibrium in their concentration is found. As power level in reactor is decreased xenon still originates from iodine through radioactive decay but absorbs less neutrons due to lowered power level thus leading to increased concentration of xenon. This in turn leads to greater neutron absorption and even greater reduction in power level. This reaction must be accounted for by the plant operator and compensated by the use of control rods to keep the wanted power level until a new equilibrium in xenon concentration is found through the amount of absorptions and delay in radioactive

[5]Reactivity indicates the change in reactor state from the critical state (state where one fission averagely causes one more fission).

[6]Half-life is the time required for amount of something to reduce to half of its original amount.

decays. This makes it a prerequisite for a power plant operator to know the power history of the reactor before reducing/increasing power output since xenon equilibrium is dependent on the power step and the amount of fission products already in the reactor. Fission-product poisoning complicates the alteration of nuclear reactor power level in rapid succession. [33, 36]

What makes these fission-product poisons so potent at capturing neutrons is their significant absorption cross section. Term cross section means the probability of neutron-nucleus interaction of a certain nucleus and is dependent of the nucleus and energy of the neutron which is responsible for the interaction. This means that because fission-product poisons have high absorption cross section values it is very likely that neutrons born from fissions get absorbed into xenon instead of fuel therefore increasing the needed amount of neutrons to maintain a chain reaction of fissions. [33]

Moderator in usual thermal reactors is liquid water. When the temperature of the liquid grows the liquid also expands significantly leading to decreased density. Decrease in density leads to lesser neutron moderation which leads to decrease in the reactivity of the reactor. This helps to control the reactor and stabilises the system. On the other hand, increase in the moderator temperature has a destabilising effect on the reactor due to decreased amount of parasitic absorptions and concentration of boric acid. These reactivity increasing effects are however minor in contrast to the stabilising effect of the density decrease, therefore the overall reactivity in the reactor tries to decrease when the temperature of the moderator rises. [36]

Increasing the power output of the reactor leads to increased temperature in the fuel which in turn leads to wider but more shallow absorption cross section. This is referred to as Doppler effect or Doppler broadening and is shown in Figure 12. [33]

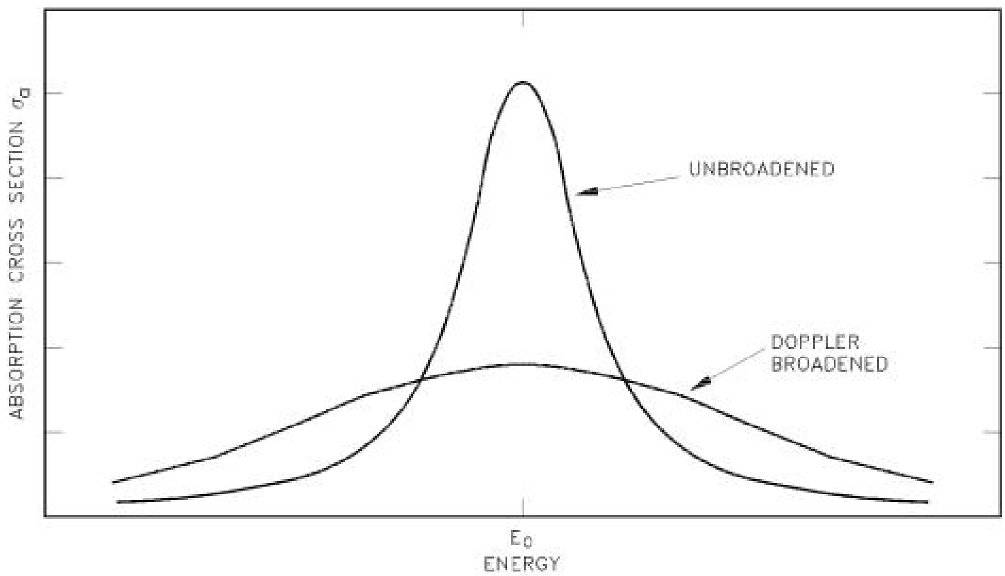

Figure 12: Doppler effect on absorption cross section [37].

This phenomenon is very important feature when designing and considering safety aspects of nuclear power plant fuel and safety features. This phenomenon leads to increased amount of absorptions with increase in temperature therefore leading to less neutrons available to produce fissions. This means that when the power level of the reactor rises the temperature of the fuel also rises and due to Doppler effect the temperature rise tries to prevent the rise in power level. This is referred to as negative temperature coefficient. Negative temperature coefficient is beneficial for the safety of the reactor since this makes the power variations in the reactor slower and prevents the power level from rapidly rising as would be the case with positive temperature coefficient. Temperature coefficient depends on the type of fuel, temperature and moderator, thus all of these should be taken into consideration when considering safety aspects and load following possibilities. All thermal reactors have a large negative fuel temperature coefficient value thanks to using natural uranium or moderately enriched uranium due to uranium-238 possessing several high and narrow absorption cross section peaks. [33]

Manoeuvrability of the reactor greatly diminishes as the fuel cycle nears its end.

This is because boron[7] concentration is at its lowest and the control rods are withdrawn to the uppermost position due to decreased reactivity of the fuel. This leads to restrictions in load following with nuclear power plants when the fuel cycle is nearing its end. [36]

Burnup of fuel indicates the lifetime of fuel in the reactor and is measured as thermal energy generated per quantity of certain material in the core. For example with common light water reactors (LWR) the fresh fuel used is plutonium free uranium and therefore the burnup is measured in thermal energy produced per kilogram of uranium in the reactor[8]. The desire to increase fuel burnup stems from increased profitability of generating energy from the fuel as well as possible. However this puts more stress on the fuel structure and cladding, therefore reaching higher fuel burnups increases costs in fuel manufacturing. Fuel burnup can be increased by increasing enrichment levels in the fuel, this however further increases the costs in fuel manufacturing. There is usually a maximum burnup value for fuels which is not to be exceeded. These values are made up by regulators to enforce the safe usage of nuclear fuel. As the fuel is approaching the end of the fuel cycle and the burnup is approaching it's maximum value, the fuel is producing less thermal energy into the core as there are less fissile materials in the fuel thus leading to lesser reactivity, this means that the reactor cannot be operated as it normally would be and operation mode called stretching is used. In BWRs streething is achieved via reducing feedwater temperature. This keeps the thermal power output of the reactor the same while increasing the reactivity in the reactor to keep the fission chain reaction going. This enables the fuel cycle extension with the cost of electric power generation as the decrease in feedwater temperature also affects the produced steam flow. Extension to fuel cycle might be needed in situations where fuel burn up is nearing its limits but the scheduled fuel outage is still couple weeks away. [33]

[7] Boron is used in PWR as reactivity compensation medium to absorb surplus neutrons

[8] Burnup can be expressed as mentioned in text (J/kg U) or in thermal megawatt-days per ton of said material in the reactor (MWd/t).

The amount of generated electricity in nuclear power plant as well as in any conventional power plant depends on the pressure and temperature of the steam lead into the turbine. In PWRs the steam is generated in steam generators in the secondary circuit as shown in Figure 13.

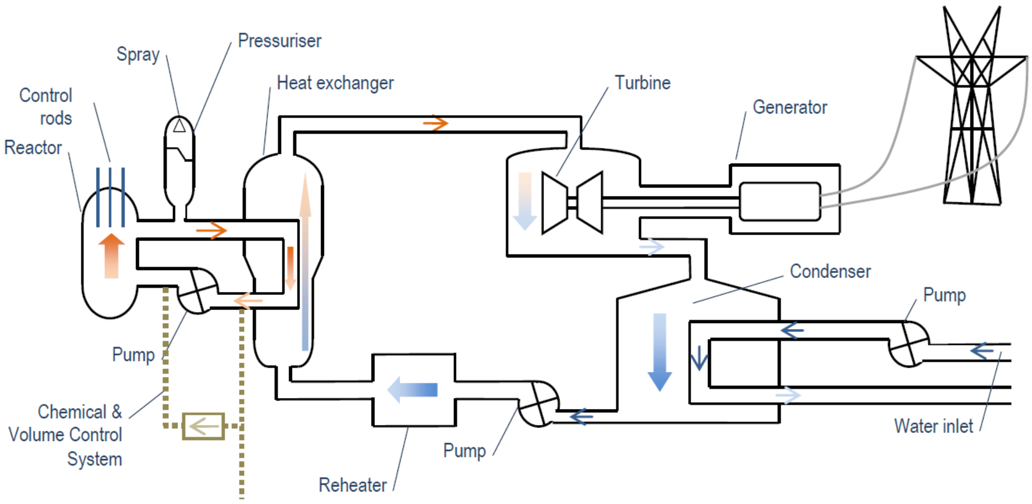

Figure 13: General scheme of a PWR [36].

The energy conversion efficiency depends on the saturation temperature of the steam in the secondary circuit while the temperature and the pressure of said coolant depends on the thermal power transferred throught the heat exchangers from the primary circuit and the amount of power consumed by the turbo generator. This means that the power output of nuclear power plant can be varied either by varying the thermal output of the reactor or by adjusting the power consumption of the turbo generator. Figure 14 presents how turbo generator can be regulated depending on power system needs. Affecting power output of nuclear power plant this way affects the temperature and pressure of coolant in the secondary circuit. [36]

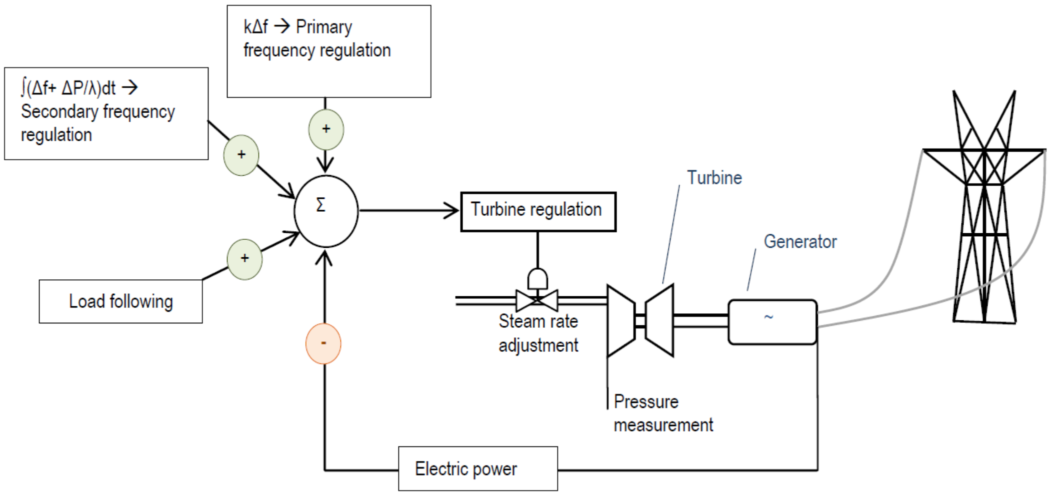

Figure 14: Use of turbine control when regulating a PWR [36].

Because of primary and secondary circuits' thermal powers are at equilibrium, there exists two ways to adjust thermal power levels of the two circuits. The possibilities are to keep either constant average temperature of the fluid in the primary circuit or constant pressure in the secondary loop. Both methods have their advantages and disadvantages. For primary circuit control the main benefit is the primary coolant volume remaining constant with power. This control method requires a compact pressurizer for adjusting pressure/temperature of the loop. This method however, leads to greater requirements in steam generator design as the saturation temperature in the secondary loop increases with decreasing power levels. In case of secondary circuit control the main advantage is the high energy conversion efficiency but as the volume of the coolant in the primary circuit is free to expand thanks to variations in the temperature, a larger pressurizer is needed to accommodate changes in the coolant volume than is needed in the primary circuit control method. In addition, additional control rods are required in the core to control the variating temperature and thermal power output of the core. [36]

Usually a combination of primary and secondary circuit control is used. There are various different combinations leading to almost equal thermodynamic efficiencys. For example in a French PWR with electric power output of 1300 MW, when the power grows so does the average temperature of the coolant in the primary circuit in addition to pressure decreasing in the secondary circuit. For the more modern EPRs and with some German PWRs a different combination is used where the adjustment method changes after the power level reaches 60% of the P_r. At power levels of 0-60% the temperature of primary coolant rises while the secondary circuits pressure slowly decreases. After reaching the power level of 60% P_r, the adjustment is only done via primary circuit control as the average temperature of the primary coolant is kept constant and the pressure decrease in the secondary circuit grows more rapidly. [36]

The difference in adjusting power levels between PWRs and BWRs stems from the BWRs lack of secondary circuit, steam generators and pressurizer as the water boils directly in the core unlike in PWRs. Scheme of a basic conventional BWR power plant is given in Figure 15.

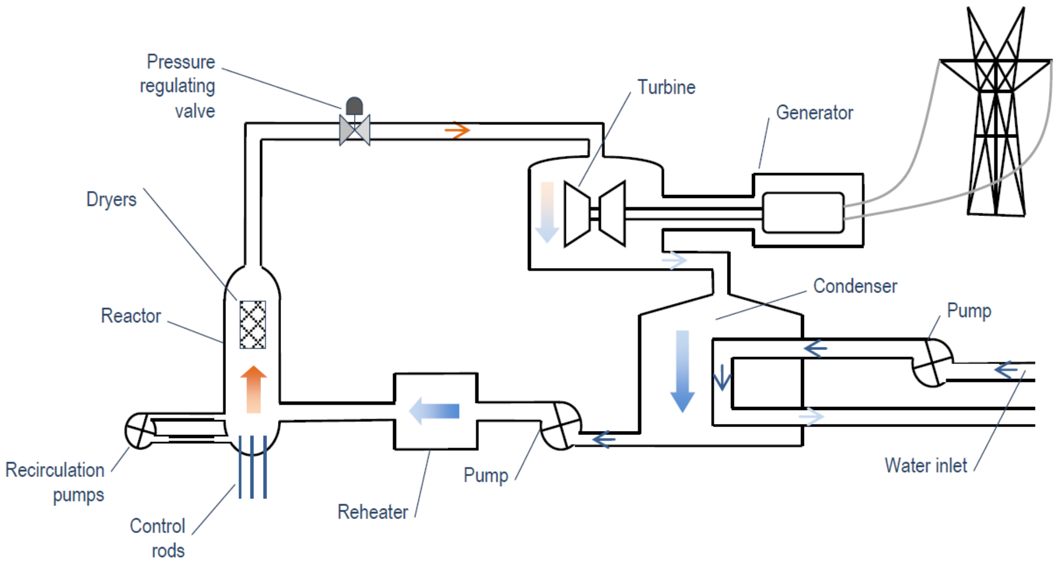

Figure 15: Basic scheme of a BWR plant [35].

The regulation in BWRs can be managed with either adjusting the position of control rods or by changing the flow speed of coolant via recirculation pumps. Maneuvering between power levels of 60% to 100% of P_r is done with recirculation pumps as altering the coolant flow does not significantly affect core power distribution and therefore puts lesser stress on fuel rods and core components. Maximum achievable ramping rates with only using recirculation control are around 10% of P_r/min. Going under 60% of P_r is feasible with the deployment of control rods and power levels between 20% and 100% of P_r with good power gradients (ramping rates) are achievable with optimized use of control rods [35]. Altering the coolant flow rate in power level adjustement is based on the negative temperature coefficient of coolant. This means that when the coolant flow rate is increased the temperature of the coolant decreases therefore reducing the amount of boiling happening in the reactor. This in turn means increased density in the coolant which increases the neutron moderation leading to increased overall reactivity in the reactor. Figure 16 presents the reactor power level as a function of coolant mass flow with recirculation control and constant control rod position. [36]

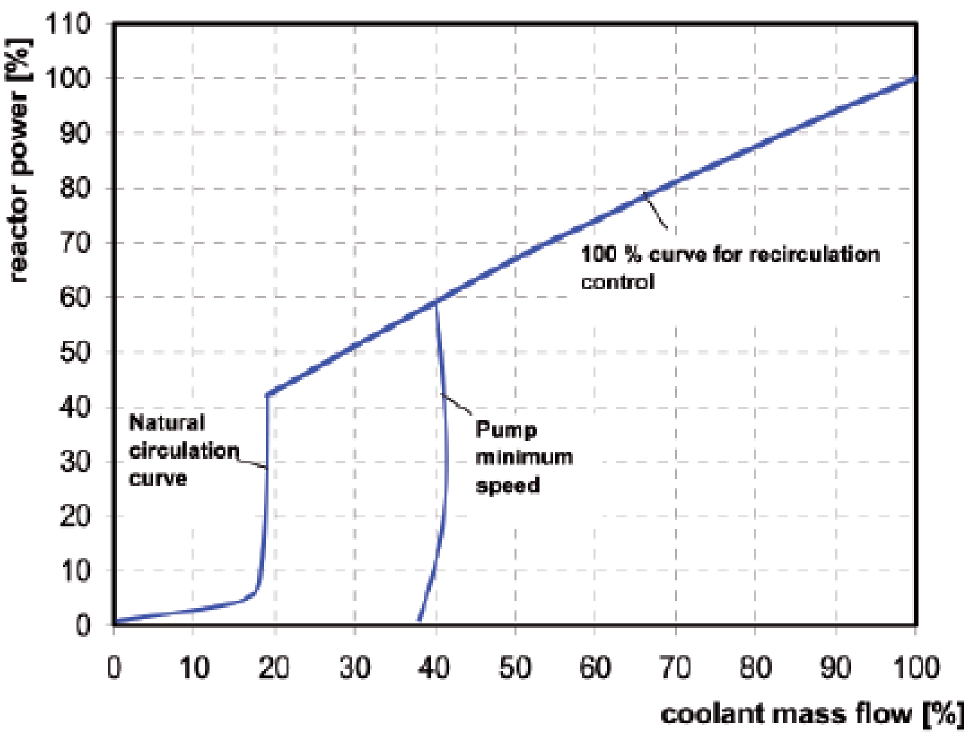

Figure 16: Correlation between reactor power level and coolant mass flow in BWR [35].

Figure 16 shows how recirculation control decreases the power level equally to coolant flow rate until there's a sudden reduction in power level approximately at 43% of P_r after which cooling is done via natural circulation.

Ramping rates of 10% P_r are feasible for both plant types but as the recirculation control in BWRs does not change the power distribution like control rod maneuvering does in PWRs, larger ramping rates of up to 100 MW/min in the range of 60-100 P_r are more easy to achieve in BWRs without breaking the design limits [35]. Some designs, mainly early BWR and some ESBWR models use only natural circulation in the pressure vessel, meaning that there are no recirculation pumps in these designs. [36]

3.3.3 Adjustment of nuclear power

Nuclear power is mainly used as a base load since it is more cost efficient and easier to operate as such. There are exceptions to this like France and Germany, who run some of their nuclear plants as load following plants. This is not as cost efficient as running nuclear power plant as base load because of the high fixed costs and low variable costs of nuclear power generation.

The reasons vary between the two countries as to why they run nuclear power plants as load following plants. For Germany it is the high penetration of variable energy and for France it is the high portion of nuclear energy in the energy generation mix of France. An example of daily variation in German nuclear power generation is given in Figure 17. [12]

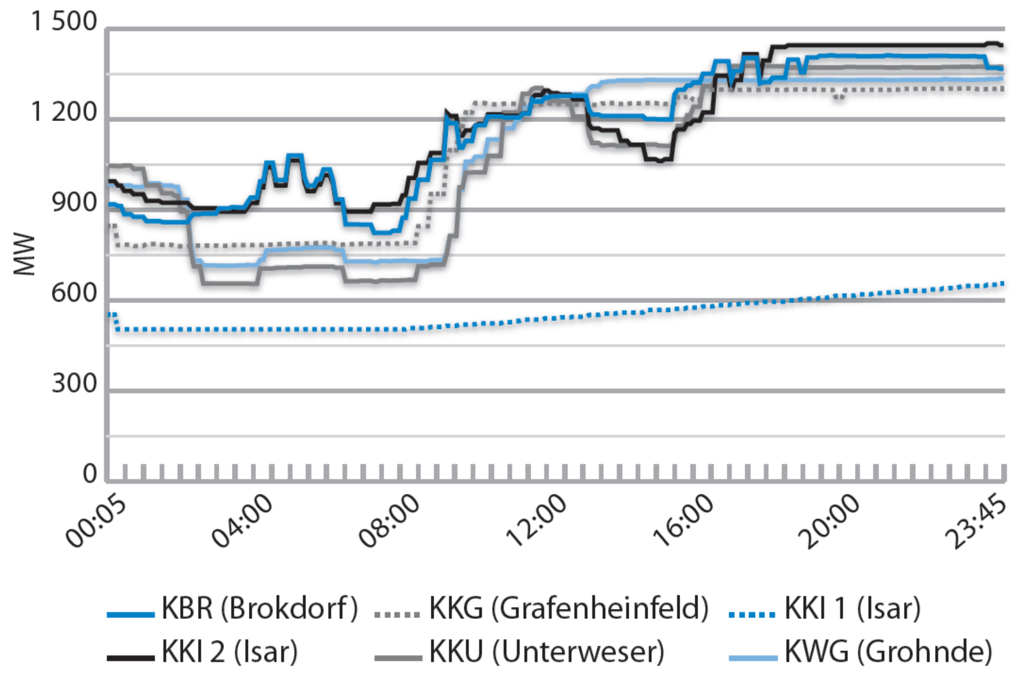

Figure 17: Example on daily variation in German nuclear power production [36].

While the Figure only presents a portion of German nuclear power plants, it shows the maneuvering capabilities of nuclear power plants and how the plants are operated in Germany due to high renewable generation. Because of the agreements made by nations to reduce carbon dioxide emissions by 80% till 2050 the amount of intermittent renewables in the countries energy portfolios is going to increase by a considerable amount, leading to similar problems Germany has already faced.

3.3.4 Adjustability in PWRs and BWRs

As stated earlier nuclear power plants are capable of producing quite big power changes in quite a short time, but there are certain limitations and many considerations to be made by the plant operator, when changing the power output. To illustrate the adjustability capabilities of nuclear power plants, Figures 18 and 19 show the annual and daily variations of a certain French nuclear power plant as a percentage of rated power.

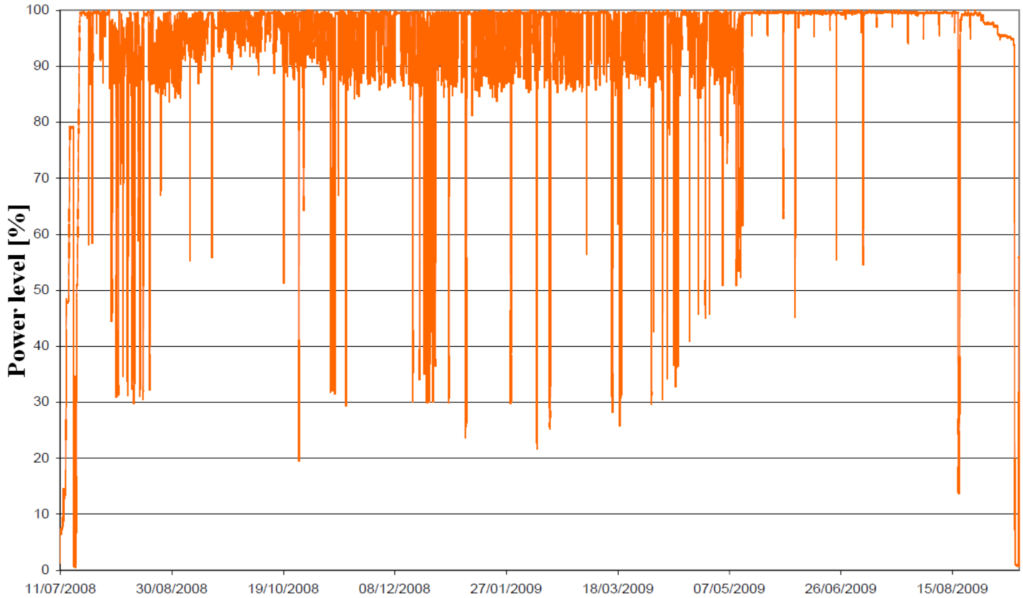

Figure 18: Annual variations in power levels in a French nuclear power plant as a percentage of rated power [36].

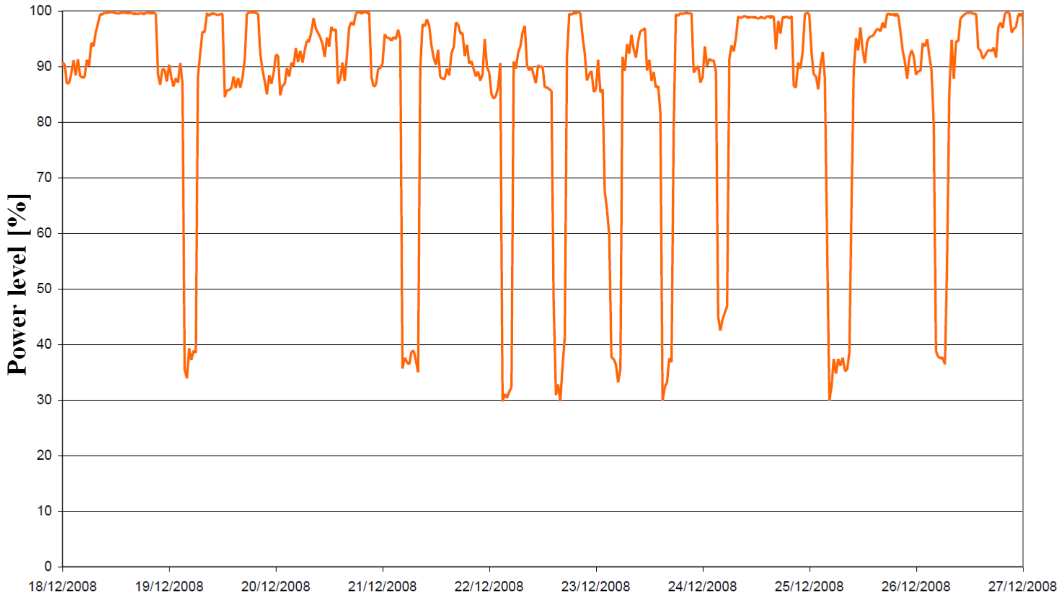

Figure 19: Daily variations in power levels in a French nuclear power plant given as percentage of rated power [36].

Figures 18 and 19 show the major variation in power output this particular French nuclear power plant has on annual and even on daily scale. Power reductions to 30% of P_r are quite common and even reductions to $\sim$20% are possible.

3.3.5 EUR requirements

European Utilities Requirements (EUR) requires from modern nuclear reactors the ability to operate in load following operation and to have significant maneuverability capabilities. According to requirements made in 2001, EUR requires units to be capable of taking part in load following with 50% to 100% of the rated power (P_r) with ramping speed 3% of P_r /min. However it is possible to operate the plant on lower power levels if plant designer provides necessary standard design. During low demand from power system, system operator may require lower minimum load from the power plant which allows the plant to be operated without shutting down and therefore saving time in returning back to the original power levels if needed. [12]

These requirements also include the plant to be able to participate in scheduled and unscheduled load following for 90% of the complete fuel cycle. Restrictions apply during the end of the fuel cycle due to increased burn-up of the fuel and at the start of the cycle because of the rising power levels (fission product poisons accumulate with delay). The load following should be doable 2/day, 5/week and 200/year with one transition covering a reduction in power to minimum power level and then returning to full power. [12]

Load following varies with different reactor types. With PWR the load follow should be achieved without changing the concentration of boron, which means that the adjustment of power should happen only with control rods. In the case of BWRs the load following should be achieved with the use of recirculation pumps and with a minimal movement of control rods. If there is no recirculation pumps which is the case with designs utilizing solely natural circulation, the adjustment requirements and criteria are different. [12]

In most countries the prerequisite for connecting into the grid is that the plant must be capable of participating in the primary frequency control of the power system. The control range in the primary frequency control is +-2% of P_r, but if needed wider range up to 5% of P_r can be negotiated with grid and plant operators. Primary frequency control is automated as the balancing of load and demand must be adjusted in the timescale of few seconds to stabilize the frequency. [12]

The plant standard design should allow for the secondary frequency control, but the participation is decided between the company producing the electricity and the grid owner. The minimum control range for this control method is +-10% of P_r over the minimum power output level while considering the control range with ramping rate of 1% of P_r /min. If needed, plant and system operator can agree to use higher ramping values of 5% P_r /min. [12]

Depending on the agreement between the power system and plant operator, the plant can take part in power system restoration, nevertheless the plant must be able to participate in the system restoration process. In this process the unit should be able to withstand sudden changes in load up to 10% of P_r . [12]

3.3.6 EPR

Maneuvering capabilities of EPRs include all before mentioned requirements made by EUR. In addition EPR units are designed to take part in daily load follow operation between 25% and 100% of P_r with two different load follow profiles, “light” and “deep” load follow. “Light” load follow profile is defined to operate between 60-100% of P_r with a maximum ramp of 5% of P_r /min, while “deep” load follow is designed to operate between 25-60% with a max ramping of 2,5% of P_r /min. Both load follow profiles are able to be used during 80% of the whole fuel cycle and there’s no constraints for the duration of operating at part-load. [38, 39]

3.3.7 VVER-1200

AES-2006 (VVER-1200) is the reactor type planned to be built by Fennovoima and Rosatom into Pyhäjoki. The reactor type is designed to take part in frequency control and to able to load follow daily between 50-100% with power drops of 20% P_r /min or with fast ramps up to 5% of P_r/s (with max ramp of +-10% of P_r). Such fast variations in power are limited due to stress to equipment and fuel, and are reserved mainly for emergency situations. [12]

3.3.8 AP1000

Advanced Passive PWR (AP1000) is a GenIII+ reactor type designed by Westinghouse which focuses on improving nuclear plant's safety aspects via passive safety systems which utilize natural driving forces such as naturalized circulation flow and gravity flow. AP1000 is by design capable to operate in load following for up to 90% of the fuel cycle by operating in so called mechanical shim (MSHIM) operation mode which is developed by Westinghouse. According to Westinghouse main benefits in MSHIM operating strategy are:

- Can respond quickly to changes in electrical load due to power adjustment happening through control rod positioning instead of boron concentration alteration.
- Simplifies operator actions involving soluble boron where the frequency of changes in boron concentration is reduced during base-load operation and the amount of boron concentration changes is reduced during load following.
- Automated control rod movements for temperature and power distribution control reduce the needed operator involment thus reducing the chance for human error.

Additional benefits include reduced waste water generation, maintainable axial power shape and reduced radial power distributions as the critical boron concentration remains constant during the load-follow operation.

AP1000 is designed to be able to alter the power levels between 15-100% with ramping speeds of 5% of P_r/min with restriction in power step equaling 20% of P_r to take around 10 minutes. AP1000 is capable of cycling power levels between 100-50-100% daily during 90% of the fuel cycle and is able to participate in power system frequency control with rate of 2% of P_r/min. [40, 41]

3.3.9 Experiences in France and Germany

German's and France's nuclear fleet has been used in load following mode for multiple decades [35]. The reason to use nuclear power in load following mode varies between these two but in France the need to respond to daily variations stems from the high percentage of nuclear power production in the nation's total production capacity, which was over 76% of the total electricity produced in 2014 [42] and in Germany the reason for the use of load following nuclear power is the nation's high share of intermittent electricity generation sources in the national mix [36]. Power plants in France take part in four different types of operating modes: base-load generation, load following operation and primary & secondary frequency control. Major share of the plants are operated in base-load mode, while some hydro and nuclear plants are operated in load follow mode. [36].

Daily variation in generation (G) is the difference between the daily maximum and minimum generation divided by daily average generation as shown in equation 4.

$$G = \frac{G_{\text{max}} - G_{\text{min}}}{G_{\text{avg}}} \tag{4}$$

In year 2010 the average daily variation of nuclear power production was about 6,7% while the typical daily variation is lesser than 5-10% of the whole production in the French nuclear fleet. Daily variation can get as high as 20% or higher during warm periods when the nuclear power production is lower due to to increased temperature of cooling water and therefore increasing the daily variation [12]. Figure 20 presents the daily averages for nuclear generation and variations in generation in France for year 2010.

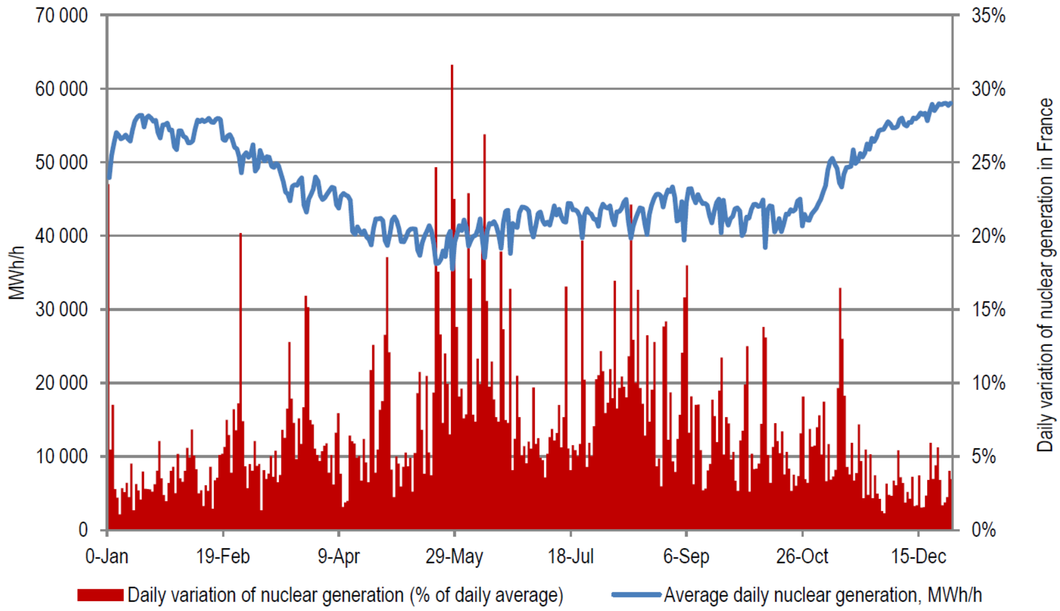

Figure 20: Daily average on France nuclear power production and variation in year 2010 [12].

From the Figure it is visible that the biggest variations occur during summer when the generation is at its lowest, especially during the generation drop spikes. This is most likely due to increased temperature in the coolant water and the increased overall need for electricity due to air-conditioning and cooling which must be mostly met with nuclear generation.

French nuclear power plants taking part in load following operation are able to adjust their load once or twice in 24 hours per instructions by the power system operator and the utilities. Several ramps of 1-5% of P_r/min are allowed depending on load pattern which depends on power demand and maneuvering capabilities of corresponding power plant. In addition there is a special operating mode where plants can be operated 18 hours at maximum power after which the plant can be operated for 6 hours at low power levels with ramping values around 2-5% P_r/min. While operating in this operation mode the reactor is capable of returning from low power levels to full power in very minimal time. [12]

In Germany nuclear power plants take part in primary frequency control where reactor's power control is linked straight into the frequency of the power system without the intervention of the operator. In this control mode the maximum power ramps are limited at 5% of P_r which are approximately 65 MW for a unit. In addition primary control mode requires quick ramping speed. Larger power ramps are handled manually by the plant operator. Also preparations for the usage of automated secondary frequency control, where the power output is controlled via an outside signal, are already finished or being made for multiple plants in Germany. All plants in Germany have run with part-load during their operation and some plants have run almost their entire operating time in the load-follow mode. Ramping rates in Germany are up to 2% of P_r/min running in the optimal range of primary circuit control in PWRs and recirculation control in BWRs. This ramping rate practically covers the flexibility need for wind power fluctuations in Germany as the 2% of P_r/min equals to roughly 400 MW in 15 minutes for the bigger nuclear plants in Germany. [35]

In German extensive operational experiences with ramping rates of up to 2%/min and operating in power levels between 50-100% of P_r exist. These load patterns would total with the current nuclear power plants up to 10000 MW. Even larger ramping rates and power ramps can be achieved in the future with the optimization of fuel management, control rod maneuvering and forecasting of operating strategies. Load following is not affecting the safe operation of the nuclear power plant as long as reliable limitation systems are available, all relevant plant states are considered in proper safety cases, continuos monitoring of fatigue on exposed parts is made and periodic inspections on critical safety-related components are done properly. These all criterias are already applicable in German nuclear power plants and as such these nuclear power plants are suitable option for their large and rapid power ramps to support the expansion of intermittent renewable sources. [35]

3.4 Coal

Coal plants currently are used as base-load power plants and are typically quite big in generation and can have as big a generation as 1650 MW, but are usually around 300-1300 MW range [43]. As the need for flexible generation increases and coal plant is planned to be used in load-follow operation, additional requirements in boiler design must be considered. These considerations relate to rapid increase/decrease of load and increase in number of shutdown/start-up cycles. This makes it important to make a conservative estimation on the total amount of operating cycles during the lifetime of the plant so that the component integrity can be maintained during all types of loads. Main focus points to take in consideration in these estimations are the total number of cycles, operating temperature, heating and cooling rates and component parameters (thickness, diameter and material). [44]

Minimum load available for coal plant depends on the type of boiler the plant is running. Coal combustion usually happens with pulverized coal-fired boilers (PC), where coal is first grinded into very fine dust in pulverizers and then combusted in the furnace with the use of burners. Coal can also be burned in circulating fluidized bed (CFB) boilers, which is not as usual as combustion in PC boilers but allows for wider range of fuel quality to be used [45]. CFB boilers will be explained in more detail in section 3.6.1. Boilers can be once-through boilers where water passes through the boiler once during a cycle or drum boilers where water passes through boiler multiple times during one cycle. For boiler which holds spiral waterwalls the minimum load typically is around 40% of P_r. However boilers with vertical waterwalls are able to reach as low rates of power as 10% by utilizing auxiliary firing system in combustion but more regular levels of minimum load using this boiler type are around 20-25% of P_r when only using primary fuel. However on very low loads problems such as acid dew point corrosion must be accounted for. Acid dew point is mainly determined by the SO_3 concentration in the flue gas, which is highly connected to sulphur content of the combusted fuel. This problem occurs when the temperatures in flue gases are allowed to drop to low levels and metal temperatures especially in the airheaters and precipitators fall below acid dew point temperature and start forming corrosion. In these cases some form of heating procedure is needed to ensure the temperatures in these metal parts can not drop below acid dew point. [44]

Limiting factor for boiler start-up and loading ramps is in thermal stresses caused by temperature differences, control system and the operator staff capability. Ways to improve ramping rates include advances in programmable control systems, stress monitoring in critical components and keeping the boiler warm during shut-downs with warm water or steam from auxiliary system to reduce stress in boiler components during start-up and heating. High ramping rates during start-ups might increase the need for treated water to such levels which are not providable by the pre-treatment facilities. This might lead to increased corrosion rates in boiler components as there might be oxygen contamination or other corrosion increasing substances due to lack of pre-treated water. High ramping rates during load raising process can lead to problems with component integrity in the steam circuits and in the turbine as dissolved solids such as silica and phosphate might carry over and damage the turbine blades for example. As more volatile chemicals are used in water treatment with once-through boilers as well as these plants having more extensive pre-treatment facilities, once-through boiler plants are less vulnerable to water quality issues. [44]

As mentioned earlier plants designed to operate on base-load generation require additional modifications to run in non-baseload operation. These modifications include changes in every part of the plant. Generally these modifications aim to:

- Reduce thermal stress in components by reducing temperature differences in/between components.
- Improve monitoring in temperature, component wear and quality of water.
- Improve the quality of water in the process cycle.

Changing the power output of the plant can be done with adjusting the pressure of the boiler or by keeping it constant. Variable pressure operation (VPO) reduces thermal stresses in the turbine as the load is reduced by dropping the pressure thus leading to decrease in steam flow which in turn leads to constant temperature in the steam. In constant pressure operation (CPO) the adjustment of load happens through the operation of control valves by reducing/increasing the steam flow. When the steam flow is reduced like this the temperature also decreases in the turbine and depending on how low the temperature is allowed to drop, restrictions in ramping rate might be needed in regards to thermal stresses. [44]

3.4.1 Control Systems

During non-baseload generation, control systems play major role in plant operation, especially if the plant is not originally designed to be used in this kind of generation mode. When running on extremely low loads the room for error is very small and requires well tuned control system and capable staff to operate it. This requires the plant components (feed pumps, pulverisers, etc.) to be run at the lowest possible speed in addition to utilizing low- and high pressure turbine bypasses to divert extra boiler steam flow. These conditions impose problems in their usage and are problematic for traditional control systems and field instrumentation to monitor. [44]

Most control systems are based on proportional integral and derivative (PID) control which is not designed to work at power levels away from full load as these controllers cannot be tuned for multiple different operating conditions without causing oscillation. This is due to natural system time delay between the temperature and temperature's adjusting methods such as increased firing in boiler. When increasing electrical load through increased boiler firing for load following operation, this time delay makes the temperature controller over correct these variations in temperature leading to oscillation in spray-water. In thick components the thermal stresses these oscillations can produce can be significant. Small changes in load and firing can be managed with PID controllers but in case of larger load variations a smooth transition to wanted power level is increasingly difficult with said controllers. This can be a limiting factor in unit's ramping rates. [44]

Oscillations can be reduced and prepared for by implementing smart algorithms into the control system which can foresee the instability and react accordingly. This is referred to as Model reference feed forward control (MRFF). Introducing MRFF into existing systems has in some cases improved the parameters enough to keep them under required limits. In addition to introducing new improved algorithms into the control system, existing control system should be kept as updated and well-tuned as possible as the plant ages and therefore the physical condition of the plant changes too. These updates include calibration of field instruments and validation of control parameters reflecting the aging of plant. [44]

In addition to load following operation there is an operation method called two-shift operation. In two-shift operation boiler and turbine unit is shut down restarted every day in the week and then again during weekend. Thermal stresses and ability of control system to maintain stable operations during run-up determine the time it takes the boiler to reach full load from shutdown status. As the plant is operated out of design conditions the role of fully integrated operation system and adequate instrumentation is highlighted as the ramping rate is reduced if the control system is not able to maintain stability during load variations which leads to increased start-up times. Traditional PID controls without MRFF have had problems in handling increased ramping rates. This operation mode also increases the work-load of operating staff and can therefore lead to increase in start-up times in addition to increased chance for operator error. This can be however eased by the introduction of automated sequences in control system. These sequences consist of sequential steps with checkpoints between them to make sure each sequence is a valid action with the possibility of being completely automatic or to have "hold" points for the operator to take action. When used with drum boilers VPO usually has slower response times compared to CPO. This usually leads with drum boilers to operation mode where load following is done via CPO and during shut-downs two-shift mode is used with sliding temperature and pressure to cool off the turbine. [44]

3.4.2 Combustion and fuels

During load reductions combustion plays important role due to lesser fuel-air mixing and decreasing temperatures which leads to uneven temperature distribution in the furnace. Uneven temperature distribution and lower furnace temperatures can be because of less active burners working due to lesser need of fuel and air during reduced load. This also negatively affects the combustion aerodynamics between primary and secondary combustion nozzles. These issues combined lead to decreased stability values. These issues can be however alleviated with the use of auxiliary firing and special burners and fuels. For moister fuels the issue with operating on lower loads is that moist fuels need adequate drying before combustion which is more problematic due to lower temperatures. High moisture fuels such as brown coal can impose limitations on low-load operations due to these combustion stability issues. [44]

There are positive effects on furnace and superheater that load cycling and running on low-loads create. These effects are involved with ash slagging and fouling which cause problems commonly on high-load coal combustion operation. During combustion the ash contained in coal is released into furnace as solid particles or in vapor-phase. This ash can then attach into colder heat transfer surfaces like in furnace (slagging) or superheater/heater (fouling) regions. The rate of slagging is reduced partly due to lesser fuel feed into the system but mainly due to thermal effects. This is due to ash particles being less sticky, because of lower temperature flame, to attach into colder heat transfer surfaces. There might however be in certain circumstances increased slagging and fouling at low-loads. Usually this is because of combustion problems which can be results from insufficient boiler heat, excess moisture in the fuel, poor combustion air mixing or poor pulverizer performance. Another effect on ash slagging and fouling is ash shedding in which thermal shocks born from temperature variations break already accumulated ash deposits. Ash shedding can therefore have effect on heat transfer distribution by opening up more heat transfer area in the furnace and superheaters but at the same time falling ash deposits might damage the furnace inner components. In conclusion ash slagging and fouling should decrease in load cycling due to lesser ash deposition rates and ash shedding. [44]

In conclusion once through boilers are limited to minimum load of 40% P_r and therefore forced to operate on two shift operation more often than drum boilers. Once through boilers also have higher construction costs due to complex design in spiral waterwall. Drum-type boilers burning black coal usually have minimum loads around 25% of P_r but with systems specifically designed for very low loads and/or with auxiliary fuel firing even lower loads are achievable. Problems with load following usually occur with plants that are designed to operate as base load power plants and less with plants that are expected in design to operate at part loads. Many of these problems have been solved and especially with older plant models proper modifications must be implemented before operating the plant in load follow operation. [44]

Adjustability of new coal plants is under a constant research work. Main research point is on improving the minimum power output by improving coal grinding system and developing more fuel flexible burners. Aim is to go as low as 20% of P_r. Different kinds of techniques are also under development to allow greater temperature rise speed and solutions which allow to keep main components' temperature at higher levels during shutdowns. [6]

3.5 Gas turbines

Burning methane produces less carbon emissions compared to other fossil fuel sources due to methane's chemical structure. Inerts are nonhydrobarbon particles in natural gases that do not burn. When comparing different natural gases, inert impurities makes the gas less valuable and for example methane averages 12% nonhydrocarbon impurities and is therefore a good natural gas to burn. [43]

A typical combined cycle gas turbine (CCGT) station contains two gas turbines and one steam turbine while running the generated exhaust gases through a heat recovery steam generator (HRSG) which produces superheated steam for the steam turbine for additional power [46]. With natural gas this leads to thermal efficiencies of 60% and possibly 70% in the future with the use of liquefied natural gas (LNG) [47]. Thermal efficiencies for comparable coal fired plants are between 30-36% while emitting vastly greater GHG emissions [48].

Analysis made by Bass [48] on impact of variable demand to modern CCGT plants shows significant issues considering the effects of load following and departure from optimal performance range. These issues include: extra fuel usage and higher CO_2 emissions for every MWh exported, for every shutdown and restart NO_x emissions increase and due to all this operation, maintenance and capital costs grow higher for every generated unit of power. As mentioned earlier CCGT plants are great at rapid changes in power levels but the results of the analysis present that in start-up periods, step changes and in modulation periods of operations more CO_2 emissions are emitted when compared to operating in optimum performance range. Energy storage devices in conjunction with gas turbines could help to reduce CO_2 emissions which stem from balancing the load as more and more intermittent renewables are generated into the power system. [48]

CCGT plants that own electrical power output of over 300 MW typically have ramp-up rates of 3-5% of P_r/min and smaller simple cycle gas engines with electrical output in the range of 10s of MW have ramp-up rates around 20% of P_r/min. [49]

Smaller (around 1-25 MW) gas turbines can be used in distributed power generation. The aim of distributed generation is minimizing the need for peaking plants in the transmission grid and to generate base load power when it is financially beneficial. Therefore benefits that distributed generation provides include peak load reduction in areas of high-load growth, reduction in transmission electrical losses and decrease in costs regarding transmission lines. [43]

In order to reach higher efficiencies than 60% more research and development is required especially in designing cooling systems, developing and improving materials and improving thermal barrier coatings. Improvements have been made in gas-path cooling system which allows for higher firing temperature (allowing higher thermal efficiency) while having no impact on combustion temperature (therefore does not affect NO_x generation). Advances have also been made in improving turbine materials, for example adding ceramics in turbine blades allowing for higher inlet temperatures and thus higher fuel efficiencies and power upgrades. [43]

3.6 Bioenergy

Biomass is plant or animal matter, whether it is living or dead or wastes from said organisms. The chemical energy biomass contains originates from the sun's solar radiation and is commonly referred as bioenergy. Recently created biomass sources are in many cases considered as renewables and for this reason fossil fuels are not generally considered as bioenergy even though fossil fuels contain bioenergy from ancient plants. Of all of the fuels made from biomass (biofuels) 63% fall under the heading of renewable energy sources. Biofuels can be solids, liquids and gases. [23]

When comparing biofuels with fossil fuels the biggest factor separating the two is that unlike fossil fuels biofuels can be in many cases considered as carbon-neutral or even carbon-negative sources of fuel. To be carbon-negative, the fuel needs to bind more CO_2 from the atmosphere during the growth of the biomass than it releases during the consumption and production of the fuel. [23]

However if only certain types of biofuels are used excessively and the reproduction of the said fuel is not taken care of, for example wood, the consequences to the local environment can be severe and the biofuel cannot be considered renewable energy anymore. [23]

3.6.1 Combustion with CFB

CFB is a form of Fluidized Bed Combustion (FBC) together with Bubbling Fluidized Bed (BFB). BFB boilers operate by mixing the fuel mix into a solid particle bed which allows for a more complete fuel combustion and less emissions emitted in the process. CFB boilers operate on same principle as BFB boilers where fuel is mixed into solid particle bed, however in CFB technology the gas velocity in the boiler is high enough to transport the mix of solid particles and fuel from furnace to solids separator and from there the separated solid particles are returned to the base of furnace. CFB provides great gas-solid and solid-solid mixing and so fuel particles lead to furnace are quickly mixed into large solid bed. This in turn allows for fuel particles to quickly heat over the the ignition temperature without having a real impact on the temperature of the solid bed. Solid particle and fuel mixing of this kind enables a more uniform temperature distribution in the furnace which in turn leads to more complete fuel combustion and less emissions emitted than with BFB boilers. [50]

Biggest advantage CFB boilers have over other boiler types in regards to biomass combustion is the fuel flexibility offered by uniform temperature distribution and fuel/solid particle mixing. For other boiler technologies the varying moisture content of biomass is quite troublesome but for CFB boilers this is not a problem due to fuel/solid bed mixing and long combustion zone. [50]

In regards to future flexibility needs born from increased renewable generation sources, CFB boilers can quickly respond to varying loads. Ramping capability of CFB boiler is around 4-6% of P_r/min with the possibility to operate on power levels between 25-100 of P_r. This means that plants utilizing CFB boilers are capable of operating as base-load, load following or peak-load power plants. Cold start-up of CFB boiler is possible in 6 hours and warm start-up in 2 hours after a shut down of 12 hours. Overall plant efficiency can be further increased by Combined Heat and Power production (CHP) which is a common practice in countries that have need for heating, like in Finland. [51]

Load control in CFB plant happens through controlling the amount and properties of produced steam. CFB plant has two basic options for controlling the generated steam: furnace- and external heat absorption control. Furnace heat absorption control happens through controlling the amount of primary air entering the furnace. This affects the bed density which in turn affects heat transfer from the fuel-particle bed mixture and also the amount of steam produced. External heat absorption control happens through controlling heat transfer of circulating solids outside of furnace and in external heat transfers. This is done by controlling the temperature of the bed by adjusting the solid flow through bed with the use of valves. [51]

Co-fired biofuel CFB plants can reach electic outputs of 250+ MW in addition to reducing CO_2, NO_x and SO_2 emissions. Co-firing also has beneficial effects on the boiler as the chance for temperature corrosion and bed agglomeration is diminished in biomass co-firing operation. [52]

3.7 Diesel motors

Diesel motors' ability to adjust power output are superior compared to other conventional options except simple cycle gas turbines which have pretty similar properties to diesel motors. Load following also allows the possibility to reduce maintenance costs of motor plant by reducing the total run time of the motor to under 50 000 hours when the most expensive maintenance phase begins. Maintenance costs make up for the major part of total costs of the plant, so skipping this maintenance phase greatly diminishes the total cost of the plant. [6]

The main problem with diesel motors as with other fossil fueled generation technologies is the amount of GHG-emissions they generate. Also a major factor is that these fuel types are not renewable and will eventually run out. Way to reduce GHG-emissions in diesel power generation is to mix ethanol into diesel oil. Ethanol is able to reduce GHG-emissions of diesel power generation because it has high latent vaporization heat and is produced from renewable sources. One major limitation associated with diesel-ethanol blends is the problems in mixing of ethanol into diesel causing phase separation because of chemical structure differences. Separation of ethanol from diesel begins to occur when water is introduced into the mix or when the temperature falls under 10 °C. The concentration of ethanol has also impact on the mixing ability of liquid combination. Study by Lapuerta et al. [53] concludes that mixing of ethanol-diesel blend can be eased with increased temperature and with the addition of additives. [54]

Diesel motor run power units typically run on power range 3-23 MW with plant sizes usually ranging between 3-100 MW. Ramping speeds for diesel run plants are around 25% of P_r/min with start up times around 15 and 5 minutes for cold and hot start-up respectively. Minimum power output of diesel motor is around 30% of P_r but with multiple units in single plant the change in demand is usually satisfied by operating diesel motors in on/off operation thanks to good ramping and start-up times. [6, 55]

3.8 Comparison between power generation technologies

The most important load follow properties of different power generating technologies are compiled into Table 3.

Table 3: Important properties for power generation technologies.

	Unit size [MW]	Start-up time [h]		Ramping speed		Min. power output [MW]
		Cold	Hot	[%/min]	[MW/min]	
Nuclear	1000-1600	48	2-4	5	50-80	500-800 [50%]
Coal	300-1300	6	2	6	18-78	412,5 [25%]
Biomass	250	6	2	6	15	62,5 [25%]
Gas turbines	10[9]/300[10]	0,16	0,16	20[9]/5[10]	2[9]/15[10]	3[9]/90[10] [30%]
Diesel motors	3-23	0,25	0,08	25	5,75	0,9-6,9 [30%]

Start-up times and ramp rates for coal and biomass are treated the same in table 3 for both technologies because if coal combustion is to be used in load following op-

[9] Simple cycle
[10] Combined cycle

eration CFB combustion is preferred over PC-fired combustion as CFB has superior capabilities for operating at part loads and is able to operate on wider variety of fuel quality. These values for coal are to give guideline on the possibilities coal has to offer and can vary between plants.

From the table only big scale power generation technologies able to provide good ramping rates are nuclear and coal. Start-up times for nuclear power are poor compared to other power generation technologies presented, however if nuclear power is to be operated in load following mode it should not be run into shut-down state therefore long start-up times are not an issue. Biomass can output decent ramping rates depending on the size of the plant and whether plant uses co-firing or not and is therefore good option for operating in load following. Combined cycle gas turbines are also able to take part in load follow operation as the unit sizes are bigger compared to simple cycle gas turbines which are more suitable to operate as peaking plants. Both gas turbine technologies have very good start-up times thus allowing them to operate as peaking power plants. Diesel motors have similar properties to those of simple cycle gas turbines and are usually used as peaking plants. Out of these technologies only nuclear and biomass (depending on the fuel used) can be considered as GHG-free generation technologies and should be favored over the other listed technologies if the GHG-emissions are to be reduced in the future. If coal or gas are to be used in the future, CCS technologies should be implemented to reduce the GHG emissions as much as possible.

For diesel motors to reach the same adjustability compared to a single nuclear reactor, approximately 16 diesel motors with single unit having capacity of 23 MW would be required to reach the ramping ability of Olkiluoto 3 plant which has the capacity of 1600 MW. If unit size of motor is closer to 1 MW approximately 320 of these diesel motors would be required to reach the same ramping capability as Olkiluoto 3. For diesel motors to reach the same load follow capacity as Olkiluoto 3 plant, approximately 50 diesel motor (23 MW) are required.

Comparing the ability of Olkiluoto 3 power plant to partake in load following to that of biomass combustion in CFB, approximately 5 biomass combustion power plants of 250 MW would be needed to reach the same level of ramping ability and approximately 4 plants to reach the same load follow capacity.

Comparing gas turbines to Olkiluoto 3 plant show the following results:

- 40 simple cycle gas turbines are required to match the ramping ability.
- 114 simple cycle gas turbines are needed to reach the same load follow capacity.
- $\sim$5 large CCGT are required to reach the same ramping ability.
- $\sim$4 large CCGT are needed to reach the load follow capacity of Olkiluoto 3.

As simple cycle gas turbines have such low unit sizes they should only be used as peak plants whereas CCGT plants can be utilized in both peaking and load follow operations.

4 SCENARIO ANALYSES ON LOAD FOLLOWING REQUIREMENTS

In this section the requirements that increased amount of renewable generation impose to power system are researched with the help of different scenarios. This is done by producing load duration curves and ramping curves from the produced data. Scenarios used in this thesis are based on International Energy Agency's (IEA) publication Nordic Energy Technology Perspectives (2013) NETP and made by Jarkko Ahokas for his master's thesis (2015) [56]. Model Ahokas used is based on Olli Paukkeri's (2013) model which studied German energy system with different shares of renewables. Since Nordic and German energy system vary quite a lot, the model was modified by Ahokas. Model generates load and generation values for included generation methods for every hour of the year using real data for Nordic load in 2013 obtained from Nord Pool Spot.

4.1 Different scenarios

This subsection presents different scenarios to be used in defining load duration and ramping curves later on. There are five different scenarios presented by International Energy Agency (IEA) in its publication Nordic Energy Technology Perspectives (NETP) which are 2DS, 4DS, Nordic carbon neutral scenario (CNS) and its variants carbon neutral high bioenergy scenario (CNBS) and carbon neutral high electricity (CNES) scenario, while scenarios used in this thesis are based on CNS scenario. [57]

- 4DS aims for long-term temperature rise of 4 °C by limiting emissions and by improving energy efficiencies. To accomplish 4DS scenario countries would need significant changes in policies and technologies.

- Goal of 2DS is to reduce energy related CO_2 emissions by over 50% in 2050 from the values of 2009 and to limit the average global temperature increase to 2 °C. This is achieved not only improving the energy sector but with also reducing GHG and CO_2 emissions in non-energy sectors.

- CNS aims to reduce Nordic CO_2 emissions by 85% by the year 2050 when comparing to emissions emitted in 1990. The remaining 15% are compensated via international carbon credits.

- CNBS expects lower biofuel import prices when compared to other scenarios used here and this brings up the possibility to use some of domestic biomass for electricity and heating. CNBS also phases out the oil usage from the transport sector completely by 2050.

- CNES relaxes the constraints and trading between the Nordic countries and Europe and assumes new ways to expand transmission capacity both in the Nordic region and the neighbouring countries. CNES also assumes net electricity generation to increase by 45% when compared to levels of 2010.

During the next four decades the 4DS predicts the demand for electricity to rise by over 20% of what it was in 2013. This is mainly due to needs in industry which translates to approximately half of the growth in demand for electricity. Wind power production is forecasted to increase the most rapidly with it consisting 20% of the total production mix in the year 2050. Figure 21 presents the net electricity generations by scenario.

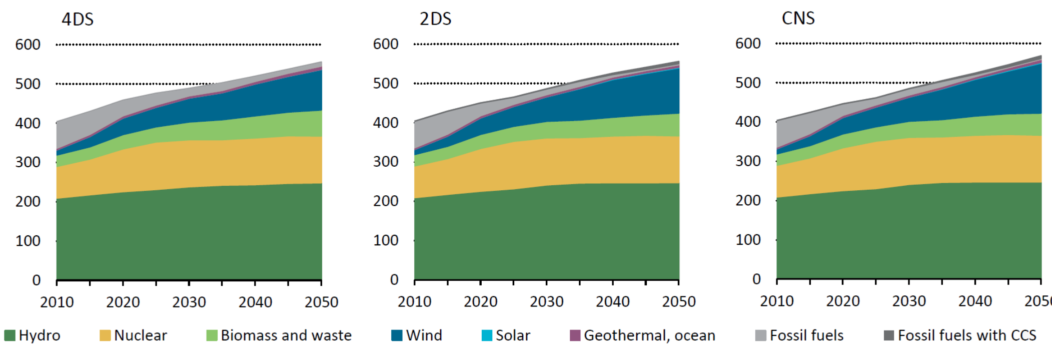

Figure 21: Net electricity generation with 4DS, 2DS and CNS [57].

Figure shows how in all scenarios nuclear production increases by over 40% during the projected timeline. This growth is based on Finland's current plan to operate new nuclear power plants increasing the generation capacity from 2,7 GW to 6,4 GW by the year 2050 in addition to Sweden having the same capacity as in the year 2010. The growth in Figure 21 can be partially explained by Sweden's nuclear power plants low availability in the year 2010. In all senarios the share of fossil based conventional power plants decrease significantly with 2DS having coal combustion power production reduced by 85% and gas fired production cut by over 90%. These scenarios also include the implementation of carbon capture & storage (CCS) in the remaining coal based generation.

Scenarios by NETP expect nuclear power generation to expand in the Nordic region. The increase in generation equals to roughly 40 TWh in 2050, while the generation at the time of writing this thesis is around 80 TWh. But since electricity generation is expected to rise in other aspects aswell, the nuclear power share in the Nordic electricity generation mix remains at approximately 20% which equals to that of now. NETP study concludes on nuclear power generation that it is going to play significant role on the entire electricity market in the year 2050, whether it is electricity generation, demand and prices or electricity trade between borders.

In case of nuclear power generation the total cost of electricity production consists of four categories: construction, operation & maintenance, waste disposal and decommisioning. Operation and maintenance category includes fuel costs, which in case of nuclear generation are minimal when compared to total costs as is also the case with decommision and waste disposal costs. Main costs in electricity produced by nuclear power are the fixed costs which come from the construction phase, typically ranging between 70-80% of the total costs. This is due to many reasons which include more strict safety requirements and more complex plants compared to more common conventional power plants. But the main reasons are attached to long construction times and the discount or interest rate paid for the construction of the plant. As the main blunt of costs is associated with fixed costs nuclear power plants are usually operated as base-load power plants. However with SMR plants this might change as the relative fixed costs are to be lower as the main benefit of SMR plants is that they can be mass manufactured and therefore decrease the relative building costs. Load following with SMR technology might be economically more feasible compared to current nuclear plant types as the number of operating reactors is greater due to decreased unit sizes and required load following could be provided by turning appropriate amount of reactors on/off. [23]

With wind energy capacity increasing to almost 40 GW by 2050, the whole electricity generation capacity in the Nordic energy system increases from 100 GW to 140 GW. As variable energy sources are forecasted to consist one-third of the whole generation mix in 2050, this once again highlights the need to consider the energy system flexibility options and resources. Flexibility options considered in these scenarios are:

- 35 GW of hydropower from the total capacity of 60 GW.
- 8 GW of gas fired generation to be used during low generation and high demand.
- Growing electricity trade between the Continental Europe as well as within Nordic region itself, to ease the balancing of intermittent wind generation.

Flexibility options not considered in these scenarios but might be possible in the future are as follows:

- Load following with nuclear power. Nuclear power plants have great ramping rates and ranges due to high generation capacities of plants, however load following operation with nuclear power plants decrease the efficiency of the plant and therefore profitability if the value of flexibility is not considered in the calculations.
- Demand-side management which is highly attached to smart grid technology. This would bring further flexibility options as it makes it possible to balance the generation/demand equilibrium not only from the generation side but also from the demand side.

The target for Nordic countries in CNS scenario is to achieve 85% reduction in CO_2 emissions when compared to levels in 1990, while the remaining 15% is compensated with carbon credits. Scenarios made by Ahokas are carbon free by 2050 and the energy system used in these scenarios consists of Finland, Norway, Sweden and Denmark. Ahokas used five different scenarios in his thesis to produce different future views and to validate his model. In this thesis only two scenarios (base and storage) are used since these scenarios are the most probable to come true by 2050.

Table 4 presents the generation mix of different energy generation methods in base and storage scenarios used in this thesis.

Table 4: Production mixes by scenario [56].

	Base		Storage	
	Net electricity generation [TWh]	Capacity [GW]	Net electricity generation [TWh]	Capacity [GW]
Nuclear	122,43	15,9	93,94	12,2
Wind	130,6	40	65,3	20
Biomass	60	12	50	10
Hydropower	192,65	65	226,12	55
Total	505,68	132,9	435,36	97,2

As seen from the table, the capacity and net electricity generation is lower in Storage scenario as the storages can maintain the balance between generation and load during load peaks with lower capacity compared to Base scenario where there is no storage capability. In both scenarios half of the capacity of hydropower is considered dispatchable.

4.2 Load duration curves

Load duration curves display load levels on hourly level for the duration of whole year. As the model for every scenario is based on real load data, where input parameters are values for generation mix, the load duration curves for different scenarios are identical in shape but vary in maximum/minimum load levels. Load duration curve produced by base scenario is presented in Figure 22.

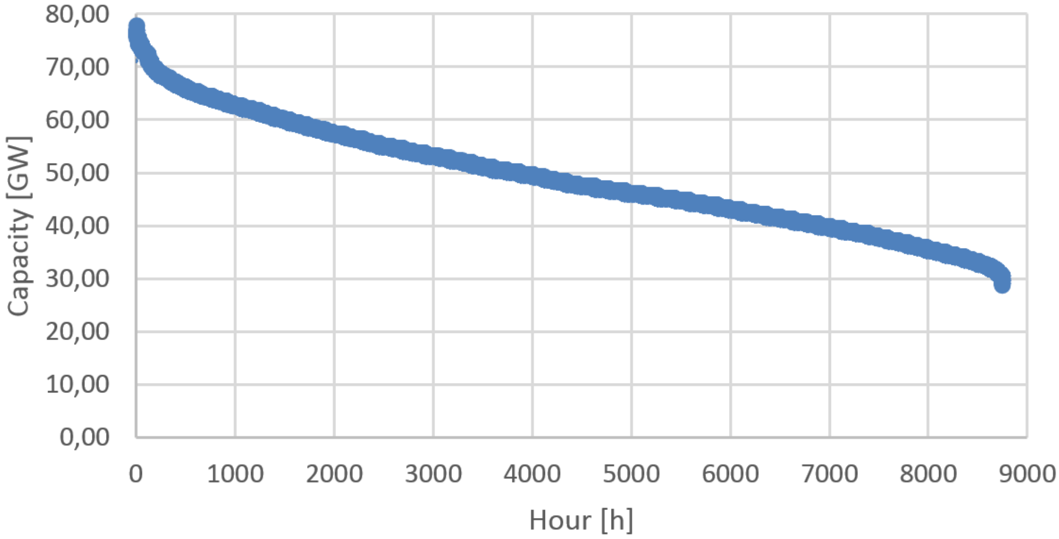

Figure 22: Load duration curve for Nordic energy system in base scenario.

Load duration curve for base scenario shows how the maximum load is around 80 GW (77,68 GW) and minimum load around 30 GW (28,56 GW) and that the distribution between loads is pretty evenly distributed using this model which is based on real data. This means that the variation in needed capacity according to this model is 49,12 GW during the modelled year.

Derivation of the load data using limit definiton method gives the load duration curve for ramping speed on hourly scale. This curve like the load duration curve earlier is identical in shape between different scenarios with different maximum/minimum values. As the base scenario has higher installed capacities it is now inspected as it has bigger needs for flexibility and ramps. Figure 23 presents load duration curve for ramping speed.

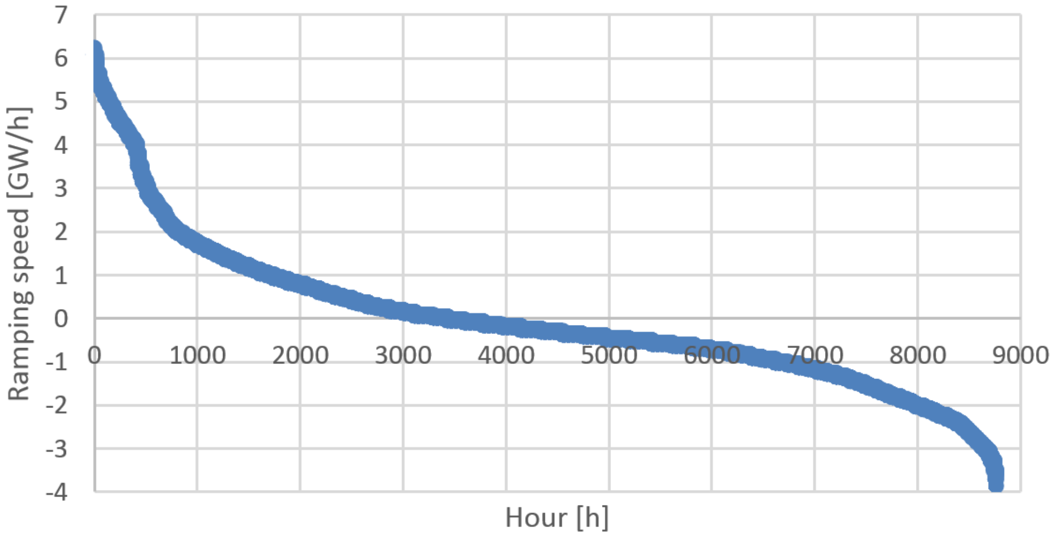

Figure 23: Ramping curve for base scenario.

This Figure shows how the curve is not as evenly distributed as it is with load duration curve and that the maximum ramp is higher when increasing the power (6,29 GW) than it is when reducing the power (3,82 GW). However majority of the needed power ramping is on negative side (after hour 3512). Figure 24 presents the same ramping speed curve with combined adjusting properties of Forsmark and Olkiluoto nuclear power plants and with separate units Olkiluoto 3 and proposed Hanhikivi 1 to show their ability to take part in load following operation.

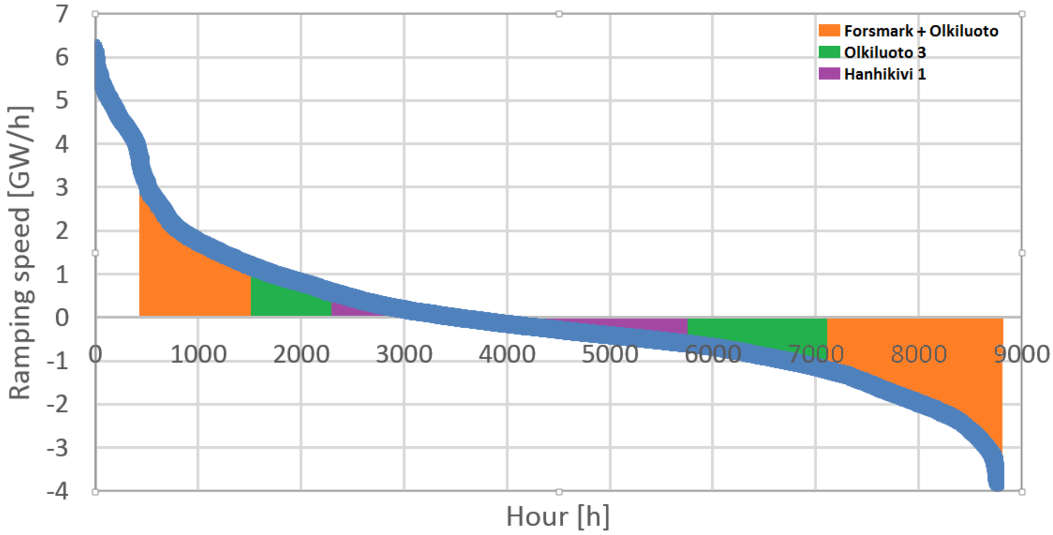

Figure 24: Ramping curve for base scenario with units combined from Forsmark and Olkiluoto and with single units Olkiluoto 3 and Hanhikivi 1 [GW/h].

As stated earlier EPR plants are able to participate in load follow operation in the power range of 25-100% and VVER-1000 type reactors in the range 50-100%. All three of Forsmark's reactors are BWR as are Olkiluoto 1 and 2. For Olkiluoto 3 this means the ability to adjust the electrical output from 1600 MW to 400 MW and for Hanhikivi 1 VVER-1000 plant this means the ability to adjust the power level from 1200 MW to 600 MW. The combined load follow ability of Forsmark and Olkiluoto plants with six reactors is to change the power output by 3685 MW. In the Figure 24 the orange area shows combined ability of Forsmark and Olkiluoto (3685 MW) to handle needed ramps, the green area represents Olkiluoto 3 (1200 MW) and the purple area represents Hanhikivi 1 plant (600 MW). This means that Olkiluoto 3 plant is able to answer to the power ramping need of whole Nordic energy system during 5577 hours of the year alone and Hanhikivi 1 for 2967 hours of the year if these particular plants are used as flexibility resources and the needed load changes can be anticipated. The combined ability of Forsmark and Olkiluoto covers the ramping need of Nordic energy system for 8327 hours of the year and is able to meet the demand in power reduction for 5209 hours out of 5211 hours where power reduction is needed. As nuclear power is usually ran at full capacity due to low variable costs the power output reduction is more feasible option in regards to flexibility brought by nuclear power. This highlights the importance of load forecasting as the power ramping of nuclear power can be utilized after a power reduction or after an annual outage. Nevertheless even if a single nuclear power unit is used in load following operation and only the power reduction ramping is taken into account, power reduction capacity of Olkiluoto 3 unit alone could match the need in load reduction for 2273 hours of the year. This also means that multiple large nuclear reactors could perform the service over a larger fraction of time and/or with better geographical coverage providing less need for transmission. In base scenario the capacity of nuclear power is estimated to be 15,9 GW which means that if those nuclear plants are capable of load following between power levels of 50-100% as is the case with most nuclear power plants, this means that the resulting 7,95 GW is more than enough to handle the biggest of ramping speeds alone (6,3 GW) in the whole Nordic energy system. This would of course demand the needed power plants to be at 50% of rated power when the maximum power ramp is needed to meet the 6,3 GW change in power capacity and the plants to not be at the end of the fuel cycle[9] where the power level of the plant can not be adjusted. Even in the storage scenario where the nuclear capacity is estimated at 12,2 GW, the resulting 6,1 GW is almost enough to answer the ramping need for every hour of the year without considering the beneficial effects of storage technologies included in the scenario, where only the biggest ramps would need additional flexible generation like hydropower.

As nuclear power is most profitable to run at rated power the possibility to ramp up power is only an option after first operating at a lower power level. This means that load following with nuclear power, is the most suitable to be used as pre-planned load following power as is done in France because the power level changes can be planned accordingly beforehand. Alternatively, ramping capability could be valued to provide revenue for also the load follow (adjustment) capability.

[9]The last 10-20% of the fuel cycle depending on the type of the plant.

4.3 Other conventional power plants

Load duration curves produced in this work present the changes in load and ramping speed in hourly level, therefore plants that are able to produce balancing power with little to no delay and with quick ramping speeds are not properly presented. This includes simple cycle gas turbine plants which at the time of writing this thesis run crucial role as peaking power plants to balance the highest of demand peaks. The implementation of different storage technologies should smooth the highest load demand peaks and therefore reduce the need for high variable cost peak load plants with high GHG-emissions. According to the model, one biomass combustion plant of 250 MW could cover the needed ramping capacity for 1134 hours of the year if used only as a load following plant which equals roughly to 13% of the year.

4.4 Conclusion

Nuclear energy as a technology is a feasible option to use in load following operation as most of the current nuclear power plants are designed to be able to operate at part loads for extended durations and are able to adjust the power output at relatively rapid rates. Whether such mode of operation is economically reasonable depends on how governments decide to value the flexibility available in nuclear plants. As the share of intermittent renewables in the generation mix is to increase in the future, the need for flexibility and reliability in the power system will increase.

Needed variation in capacity over the duration of one year is as high as 49,12 GW between the highest and lowest load level for Nordic energy system in base scenario and the highest ramp rates are 6,3 GW in the same scenario. According to the scenarios analyzed, just one large reactor would be capable of providing the ramping needed to stabilise the Nordic energy system for 64% of the year as opposed to 13% of large biomass plant. Multiple large nuclear reactors could perform the service over a larger fraction of time and/or with better geographical coverage (less need for transmission). Combined load follow ability of Forsmark and Olkiluoto nuclear power plants covers 95% of needed annual ramping in Nordic energy system and 99% of needed power reduction ramps in base scenario.

5 DISCUSSION AND CONCLUSIONS

5.1 Balancing load and demand

As more and more intermittent renewable energy generation methdos are pushed into the power system the balancing of demand and production becomes increasingly more difficult and important. Energy storages might bring ease to this in the future as technologies mature and more research is done to improve efficiencys and costs of the technologies. Most promising large-scale energy storage technologies currently are PHS and CAES technologies which are able to store quite large amounts of energy and able to respond to changes in load fast enough for most load variations (in a time scale of ms). However different energy storage technologies have different strengths which might be valued more in the future energy system. Usually the biggest barrier blocking the use of said technology is the cost of the technology which can in many cases be reduced with further research.

5.2 Power generation methods

Nuclear power is adjustable to quite a high degree, contrary to common belief. The reason that nuclear power is run as a base-load generation lies in the high fixed base costs and low variable costs which make it more efficient to operate the plant constantly at rated power instead of operating the plant on part loads. However most of the plants already working and plants to be built are capable of altering the load-level with high ramping rates and with big load-steps. The disadvantages of load following with nuclear power lie in already mentioned low variable costs making the load following operation less cost-efficient and in quite long start-up times in both cold- and hot start-up. The cost effectiveness of load following with nuclear power is subject to change (in the form of load follow capability providing revenue) as the flexibility of current and future technologies is in the future highlighted and more valued as the share of renewables is sure to increase. Long start-up times can be alleviated with proper planning and forecasting so that at time of low demand (and/or high intermittent renewable generation) the plant can operate at minimum power output without the need for shutdown. Properly executed load following operation of nuclear power should not affect the lifetime or safety of the plant.

Coal as a power generation method is highly adjustable if the plant is planned to do so by design. However if plant is by design planned to operate as base load generation then necessary modifications and adjustments must be done to the plant before switching to load follow operation. Coal plants are usually ran at unit sizes of 300-1300 MW and can therefore produce quite big power ramps if needed and are therefore comparable to nuclear power in the size of produced power ramps. However as the reduction of CO_2 emissions is of a big concern the usage of coal as energy generation method is to be reduced to as low levels as possible and with remaining plants the usage of CCS is highly recommended to reduce the generated CO_2 emissions as much as possible.

Bioenergy in the form of biomass combustion or biofuel usage in diesel motors are GHG-free power generation methods depending on the used fuel or fuelmix. Biomass combustion in CFB boilers can participate in load following operation with good ramps and can operate on wide part-load range (25-100% P_r). Both cold and hot start-up times of CFB boilers are short enough for these plants to operate in load following. Major advantage CFB boilers have considering biomass combustion is the ability of the boiler to combust various different fuels with varying levels of moisture as biomass fuels usually have high levels of moisture. Also co-firing of biomass with other fuels like coal is possible with CFB. Co-firing like this brings not only reduced GHG-emissions but only brings beneficial effects on the durability of the boiler.

Gas turbines depending on the type of technology used are fit for operating as load follow or peaking power plant. CCGT plants have higher capacities of the two but lower procentual ramping rates. These properties are comparable to those of bioenergy and are more compatible to load follow operation. Smaller simple cycle gas turbines in the range of tens of MW have much higher relative ramp rates and are more suitable to operate as peaking plants thanks to lower power output capacities and fast start-up times. Electricity generation with gas turbines is not GHG-free and the usage of such technologies should be reduced to prevent further global warming.

Power level adjustment capability of diesel motor is comparable to that of simple cycle gas turbine and is superior to other technologies. As diesel motors designed for power generation are quite small in capacity (3-23 MW) and have great start-up times and ramping speeds they are mostly used as peaking plants. Main problem with diesel motor power generation is the amount of GHG-emissions emitted. GHG-emissions created can be reduced with adding ethanol into the diesel, however there are problems regarding the miscibility of ethanol into diesel which can be eased with increasing the temperature of the mix or/and adding additives.

5.3 Scenario analysis

Scenarios in this thesis were used to produce load duration and ramping curves to project the capacity differences and needed ramp-up rates on hourly level. These curves showed that the variance in demand and generation could be adjusted in hourly scale with only nuclear power if plants are used primarily as load follow plants. However as the balance in demand and generation must be constantly balanced without energy storages, a time-scale in hours is not enough to properly present the adjustability needs of a energy system and the need for quickly responsive power generation methods. However, these curves prove that pre-planned load following with nuclear power is a possibility in the future as the needed response times in these situations are more lenient and hourly time-scale is enough to demonstrate this.

5.4 Future research

The need for peak power plants is not properly accounted for when the model is run at hourly scale therefore if the need for peaking plants is to be properly accounted for a time scale of minutes or even seconds should be used in modelling the system.

This thesis only takes into account the technical possibilities and restrictions of different technologies and does not delve into cost or profitability calculations. Many publications have been made regarding profitability of different techonologies in different scenarios. However as flexibility is hard to measure in these calculations it usually is left unmeasured. Future research could therefore be done on measuring comparative flexibility value of different technologies including nuclear power on part-loads.

As this is a review for FLEX^e-project on possibilities of different technologies for the future energy system this work provides input for tasks 1.3 (System wide value of flexibility resources), 4.1 (Boundaries of combustion-based generation for flexibility) and for WP3 (Flexibility management of distributed resources). Task 1.3 analyses the flexibility needs as the share of wind and solar power increases in the energy markets which was addressed earlier in this thesis. Task 4.1 is to delve deeper into specifics of combustion-based power plant usage in rapid load follow-up and part-load operation which was tackled in this thesis for coal and biomass combustion. WP3 researches the distributed resource management and flexibility it brings and requires, which was touched in sections including smart grid technology and AP1000 reactor type which provide input and hopefully new points of view.

6 SUMMARY

With the increasing amount of intermittent renewables added into the generation mix the need for balancing power in the future energy system is highlighted currently operated and future power plants must be able to adapt to this properly. Power plants currently operating as base load generation may need to change into load follow operation and implement necessary modifications to be able to do so. Most currently operating nuclear power plants can be operated in load following operation as the requirements to do so are already required in the plant designs. Of the currently known power generation technologies, only nuclear power is able to provide large-scale GHG-free load-follow generation. Other conventional power plants presented in this thesis which are able to operate on load follow operation either produce GHG-emissions (coal, CCGT) or operate on much lower power generation capacities (biomass combustion).

Energy storage and smart grid technologis are to ease the balancing of generation and demand. This could happen in the form of load shifting provided by smart grid technology in which the demand of electricity is shifted from peak times to off-peak times with demand-side management. This reduces the need for expensive to operate peaking plants (diesel, simple cycle gas turbine) which also produce high GHG-emissions. Generation and demand balancing that energy storage provides enables higher penetration of intermittent renewables in the energy system as the surplus electricity produced during high generation can be stored and used later when demand surpasses generation. Different storage technologies have different strengths and different applications, however most of these technologies require further research and improvement to be worthwhile to invest into. Of the currently existing storage technologies PHS and CAES are the most promising technologies in large scale energy storing, while supercapacitors, SMES and flywheels might prove to be viable options in the future in power conditioning applications.

Scenarios used in this thesis prove that using nuclear power in load following power operation as a part of 100% carbon free Nordic energy system is a viable option. Load and ramping curves produced from these scenarios for Nordic energy system show how even a single nuclear reactor in load follow operation can provide needed power ramps for majority of the year and multiple large reactors could provide the needed ramping for even larger fraction of time with possibly covering larger geographic area, thus leading to lesser transmission losses. The most effective way to use nuclear power as load follow plant is to forecast the changes in demand and pre-plan the operation of the plant properly which allows for the most profitable use of the plant.

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Appendix I

COMPARING TECHNICAL PERFORMANCE OF BATTERIES

	Sodium-sulfur (NaS)	Lithium-ion (Li-ion)	Nickel-cadmium (NiCd)	Lead-acid (LA)
Efficiency *%*	70 - 90	85 - 98	60 - 80	70 - 90
Self-discharge *% energy / day*	0.05 - 20	0.1 - 0.3	0.067 - 0.6	0.033 - 0.3
Cycle lifetime *cycles*	2,500 - 4,500	1,000 - 10,000	800 - 3,500	100 - 2,000
Expected lifetime *years*	5 - 15	5 - 15	5 - 20	3 - 20
Specific energy *Wh / kg*	150 - 240	75 - 200	50 - 75	30 - 50
Specific power *W / kg*	150 - 230	150 - 315	150 - 300	75 - 300
Energy density *Wh / Liter*	150 - 300	200 - 400	60 - 150	30 - 80
Other consideration *(environment & safety)*	Need to be maintained at temperatures of 300°C to 350°C, entailing safety issues and preventing suitability to small-scale applications	Lithium is highly reactive and flammable, and therefore requires recycling programs and safety measures	Cadmium is a toxic metal that needs to be recycled. NiCd also requires ventilation & air conditioning to maintain the temperature	Lead is toxic and sulfuric acid is highly corrosive, requiring recycling and neutralization. Air conditioning required to maintain stable temperature

Figure 25: Technical performances of different battery technologies [24].