Lappeenranta University of Technology
School of Technology
Energy Technology

Jarkko Ahokas

THE ROLE OF NUCLEAR POWER IN THE FUTURE ENERGY SYSTEM

Examiners: Professor Juhani Hyvärinen
D.Sc. (Tech.) Kristiina Söderholm
Instructors: M.Sc. (Tech.) Ville Lestinen
D.Sc. (Tech.) Kristiina Söderholm

ABSTRACT

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Jarkko Ahokas

The role of nuclear power in the future energy system

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Keywords: nuclear power, energy system model, grid balancing, Nordic energy system, carbon emissions, energy security

Currently widely accepted consensus is that greenhouse gas emissions produced by the mankind have to be reduced in order to avoid further global warming. The European Union has set a variety of CO_2 reduction and renewable generation targets for its member states. The current energy system in the Nordic countries is one of the most carbon free in the world, but the aim is to achieve a fully carbon neutral energy system.

The objective of this thesis is to consider the role of nuclear power in the future energy system. Nuclear power is a low carbon energy technology because it produces virtually no air pollutants during operation. In this respect, nuclear power is suitable for a carbon free energy system. In this master's thesis, the basic characteristics of nuclear power are presented and compared to fossil fuelled and renewable generation. Nordic energy systems and different scenarios in 2050 are modelled. Using models and information about the basic characteristics of nuclear power, an opinion is formed about its role in the future energy system in Nordic countries.

The model shows that it is possible to form a carbon free Nordic energy system. Nordic countries benefit from large hydropower capacity which helps to offset fluctuating nature of wind power. Biomass fuelled generation and nuclear power provide stable and predictable electricity throughout the year. Nuclear power offers better energy security and security of supply than fossil fuelled generation and it is competitive with other low carbon technologies.

TIIVISTELMÄ

Lappeenrannan teknillinen yliopisto
Teknillinen tiedekunta
Energiatekniikan koulutusohjelma

Jarkko Ahokas

Ydinvoiman rooli tulevaisuuden energiajärjestelmässä

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Kirjoitushetkellä yleisesti hyväksytty mielipide on, että ihmiskunnan tuottamia kasvihuonekaasupäästöjä on vähennettävä globaalin ilmaston lämpenemisen hillitsemiseksi. Euroopan Unioni on asettanut jäsenmailleen erilaisia CO_2 päästöjen vähennystavoitteita sekä uusiutuvan energiankäytön tavoitteita. Pohjoismainen energiajärjestelmä on jo yksi maailman hiilivapaimmista, mutta tavoitteena on täysin hiilineutraali energiajärjestelmä.

Tämän diplomityön tavoitteena on pohtia ydinvoiman roolia tulevaisuuden energiajärjestelmässä. Ydinvoima ei tuota juuri ollenkaan ilmasaasteita ja sen elinkaaren hiilipäästöt ovat matalat. Näiltä osin ydinvoima sopii hiilivapaaseen energiajärjestelmään. Tässä diplomityössä esitellään ydinvoiman perusominaisuudet ja verrataan niitä fossiilisiin ja uusiutuviin energiantuotantomuotoihin. Myös Pohjoismainen energiajärjestelmä ja erilaiset skenaariot vuonna 2050 mallinnetaan. Mallin ja ydinvoiman perusominaisuuksien pohjalta muodostetaan näkemys ydinvoiman roolista Pohjoismaisessa energiajärjestelmässä tulevaisuudessa.

Malli osoittaa, että on mahdollista rakentaa hiilivapaa Pohjoismainen energiajärjestelmä. Pohjoismaat voivat käyttää hyväkseen suurta vesivoimakapasiteettia, joka auttaa tasapainottamaan tuulivoiman tuotantovaihtelua. Biomassaan pohjautuva sähköntuotanto sekä ydinvoima tarjoavat vakaata ja ennustettavaa sähköntuotantoa ympäri vuoden. Verrattuna fossiilisiin tuotantomuotoihin, ydinvoima parantaa energiaturvallisuutta sekä polttoaineen toimitusvarmuutta. Ydinvoima on myös kustannuksiltaan kilpailukykyinen verrattuna muihin vähäpäästöisiin teknologioihin.

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The future of energy production and the compositions of energy systems are exceedingly interesting. Nuclear energy has fascinated me from the beginning of my energy technology studies at Lappeenranta University of Technology and I was lucky that Fortum Oyj offered me the opportunity to do my thesis in the field of nuclear energy. Doing this master's thesis with the aforementioned topic has offered me an opportunity to learn greatly from nuclear energy and power professionals.

I want to thank Kristiina Söderholm for giving me the opportunity to work for the summer in 2014 at Fortum and later for enabling me to do my master's thesis. Together with my other instructor Ville Lestinen, they provided a really interesting topic for my master's thesis. Their guidance and experience were invaluable. Input from my instructors and Petra Lundström further helped me to form relevant scenarios for my model. The Nuclear Development Unit offered me good learning experience and interesting discussions. Comments and input from numerous people working at Fortum helped in making this thesis. I want to thank my supervisor, Professor Juhani Hyvärinen, for his guidance and comments on my thesis. Without him, I am sure that my thesis would have even more room for improvement.

Finally I would like to thank my friends and family for their support and encouragement over the years.

Espoo, April 2015

Jarkko Ahokas

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ABBREVIATIONS

All the abbreviations used in this thesis are explained when they first appear. Most important and often used abbreviations are listed here.

CHP: Combined heat and power. Cogeneration of electricity and heat for end users in the same power plant.

CNS: Carbon-Neutral Scenario. Energy scenario found in the NETP. The Base scenario in the thesis is based on this.

IEA: International Energy Agency. An autonomous organisation providing authoritative statistics, analysis and recommendations. It has 29 member countries.

NETP: Nordic Energy Technology Perspectives. A publication by the IEA which provides pathways to a carbon neutral energy future.

PSH: Pumped-storage hydropower. Hydroelectric energy storage which stores energy in the form of gravitational potential energy of water.

1 INTRODUCTION

1.1 Background

The currently, widely accepted consensus is that greenhouse gas emissions produced by mankind have to be reduced in order to avoid further global warming. The energy sector has an important role in reducing these emissions, especially carbon dioxide emissions. Globally, fossil fuels dominate the energy sector and they are likely to do so in the foreseeable future. Emerging economies, such as China and India, are unlikely to abandon fossil fuelled energy generation anytime soon. In more advanced economies, a transition to different low carbon technologies, such as renewables, is being encouraged and even demanded. The European Union has set CO_2 reduction and renewable generation targets for its member states.

The energy system in the Nordic countries as a whole is already one of the most carbon free in the world. Currently the CO_2 emissions produced by Nordic electricity generation are approximately 100 grams of CO_2 per kWh of electricity while the global average is around 550 gCO_2/kWh and the EU average 430 gCO_2/kWh. The majority of the CO_2 emissions in the Nordic power sector come from coal, peat and natural gas power plants in Finland and Denmark. Finland generated around 46 % and Denmark 33% of the 67 million tonnes of CO_2 that the Nordic power sector generated in 2010. Norway, Sweden and Iceland generate less CO_2 emissions as they utilize more renewables and nuclear power (in Sweden). In this thesis, Iceland is omitted from the Nordic energy system as it is isolated from the Nordic power grid. (IEA, 2013)

The overall share of renewables in Nordic power generation was around 60% in 2010 and various IEA scenarios estimate that the share of renewables will increase to 80% by 2050. In this thesis, the Nordic energy sector is assumed to be carbon free by 2050 and this is achieved with using nuclear power together with a large share of renewables. Nordic countries have ambitious targets for decarbonising their energy systems and all the Nordic countries are listed among the top 20 economies in the world. The Nordic region is a valuable and interesting region to study in regards to future, carbon free energy systems in an advanced economy.

Nuclear power is a low carbon technology used globally. Before the accident in Fukushima Daiichi nuclear power plant in 2011, interest in nuclear power was increasing as concerns were displayed over greenhouse gas emissions from the power sector and the security of energy supply. The accident impacted the public acceptance of nuclear power and had an effect on nuclear policies in several countries. The nuclear industry also suffered from the financial and economic crisis of 2008-2009 which reduced the financing capabilities. However, currently the global situation for nuclear energy is improving and the number of constructions commencing are on the rise again. (IEA, 2015)

1.2 Objective of the thesis

The objective of this thesis is to consider the role of nuclear power in the future energy system. In this thesis, the basic characteristics of nuclear power are presented. The role of nuclear power in the future is considered, especially in the Nordic region, and a Nordic, carbon free energy system is modelled with different scenarios. The model and literature is used to determine the power generation mix in the Nordic energy system in 2050.

The model is also used to analyse the roles of different electricity generation sources, including nuclear power, in the future Nordic energy system. Rudimentary emission and cost comparisons between different generation sources are also carried out with the model.

1.3 Scope of the thesis

This thesis presents different characteristics and properties of nuclear power which affect the energy system of a nation or region in regards to energy security, resource supply, emissions and power grid management. Commonly used and most promising future reactor technologies are presented, but technical details are not in the scope of this thesis. A future energy system and its different elements are also presented.

Electricity prices, market mechanisms or detailed production and construction costs of the generation fleet are not considered in the thesis. The energy system in the thesis includes only the power sector. Transport, building and industry sectors are omitted from the thesis and the heat sector is considered to the extent of its electricity generation from combined power and heat. Of course, all these sectors have an impact on the Nordic electricity consumption which is included in the model. The model assumes that Nordic countries have perfect grid connections between them, thus making the Nordic region a solitary entity. Connections to the rest of Europe and Russia are not modelled, but they are assumed to be adequate as the Nordic countries on the whole become net exporters of electricity in the Base scenario of the model.

The different scenarios presented in the thesis are not forecasts, rather they present alternative targets and avenues for a carbon free energy system. Generation mixes used in the thesis are either based on the literature or they are chosen somewhat arbitrarily to construct and study different carbon free energy systems. Future scenarios are set for the year 2050 following the various IEA scenarios and targets found in the Nordic Energy Technology Perspectives 2014. (IEA, 2013)

1.4 Methodology

The future energy system is modelled in different scenarios which are set to happen in 2050. Electricity consumption and generation is modelled over the whole year in one hour increments. The model uses a Nordic load profile from 2013 which is scaled up to correspond to the assumed load in 2050. Different electricity generation sources are added to the model and the model calculates the generation mix and the differences between the consumption and generation of electricity.

Different scenarios have different generation mixes and some of the scenarios even have energy storages. The model results and the roles of the different elements in the model are analysed. Using the information about the basic characteristics of nuclear power and the model, the significance of nuclear power in the future energy system is shown.

2 BASIC CHARACTERISTICS OF NUCLEAR POWER

The compositions of electrical energy systems across the world are different, partly because the availability of assorted fuel and energy sources differ from region to region and partly because some regions are more technologically advanced than others. For example, in Africa there were only 2 operating nuclear reactors at the time of writing this thesis, while in Europe the number of operational reactors was 186 (PRIS, 2015).

Figure 1 shows the world's electricity generation by source for the year 2012. The clear majority of the world's electricity is currently generated by fossil fuels and their share was 68% in 2012. The share of nuclear power in the world's electricity generation was 11% in 2012. The share of nuclear power in electricity production was 26.7% in the EU member states (Eurostat, 2015). At the end of the year 2013, there were a total of 434 commercial nuclear reactors operating and their total capacity reaching 371.1 GWe (IAEA, 2014a).

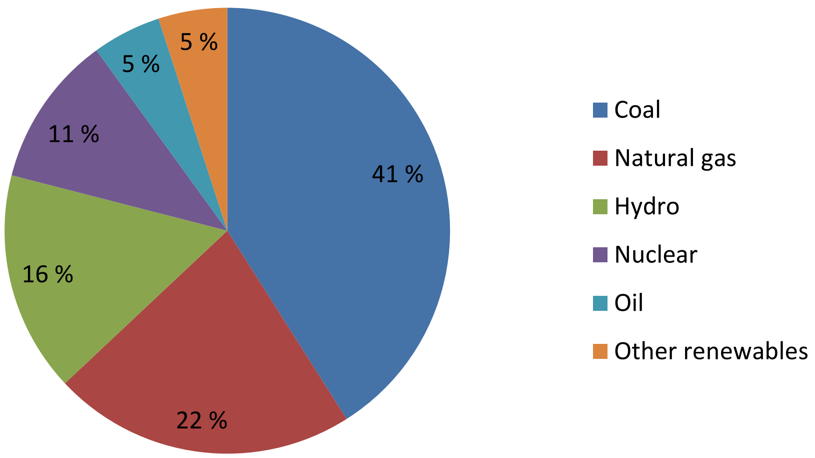

Figure 1. World electricity generation by source in 2012. (chart formed from the data in IEA, 2014e)

About 82% of operating reactors in the 2013 were light water reactors (PWR & BWR), 11% were heavy water reactors (PHWR), 3.4% were light water cooled, graphite moderated reactors (LWGR/RBMK) and 3.4% were gas cooled reactors (GCR/AGR). Two of the operating reactors were liquid metal cooled fast reactors (FR). Light water reactors are clearly the most prevalent and the best known of all the reactor technologies. (IAEA, 2014a)

There were four new connections to national electricity grids in 2013: Hongyanhe 1&2 (1000 MWe) and Yangjiang 1 (1000 MWe) in China and Kudankulam 1 (917 MWe) in India. The construction of ten new reactors started in 2013: four in the United States, three in China and one each in the Republic of Korea, the United Arab Emirates and Belarus. The number of new construction starts dropped from 10 in 2013 to 3 in 2014. 72 reactors were under construction internationally at the beginning of 2014 and at the time of writing this thesis, 65 reactors were under construction. (IAEA, 2014a; PRIS, 2015)

2.1 Technologies

The majority of operating nuclear reactors are Generation II (Gen II) light water reactors, but a transition to Generation III (Gen III) and Generation III+ (Gen III+) reactors is underway. Of the 72 reactors under construction, thirty of them are Gen III reactors. China has announced that as of now it will build only Gen III reactors but of course more advanced future reactor designs are not ruled out. (IEA, 2014a)

Gen II reactors were built from the 1960s to the 1990s. Individual Gen II reactors can greatly differ from each other, even if they nominally represent the same reactor design. Gen III reactors are designed to better withstand severe accidents and external hazards, and they have better performance and longer operating lifetimes. Individual power plants using Gen III reactors of the same design are built to be as similar as possible. This allows for a greater degree of standardisation lowering the construction costs and times of new reactors (Goldberg, S. & Rosner, R., 2011).

Generation IV (Gen IV) reactors are future reactors currently being designed. Some of the Gen IV reactor concepts have been demonstrated in the past. For example, an experimental molten salt reactor was constructed and operated in 1960s and Russia has 80 reactor-years' experience of using lead-cooled fast reactor technology (Rosenthal M.W, 2009; WNA, 2015). Gen IV reactors are supposedly safer, and they utilize nuclear fuel more efficiently, produce less radioactive waste and are commercially profitable. The Generation IV International Forum (GIF) lists six Gen IV reactors in its website that it has chosen to focus its research and development on. These reactors include a Gas cooled Fast Reactor (GFR), Lead cooled Fast Reactor (LFR), Molten Salt Reactor (MSR), Supercritical Water-cooled Reactor (SCWR), Sodium-cooled Fast Reactor (SFR) and Very High Temperature Reactor (VHTR). GIF anticipates that the first commercial Gen IV reactors will be deployed in the 2030s. (GIF, 2015)

2.1.1 Reactor technologies in use

2.1.1.1 Light water reactors

Clear majority of reactors currently operating and under construction are light water reactors (LWR). Light water reactors use light water (i.e. normal water) as both coolant and moderator. These reactors use low enrichment uranium as fuel. Typically the enrichment is 3-5 w% of uranium isotope U-235 and rest of the uranium is isotope U-238. Light water reactors need to be shut down for refuelling. Light water reactors can be divided into two main categories: pressurised water reactors (PWR) and boiling water reactors (BWR).

Pressurised water reactors were originally designed for nuclear submarines and were later commercialized and made into large-sized reactors for electricity generation. The first nuclear-powered submarine was launched in 1955 and the first prototype PWR for electricity generation was made in 1957 in the United States. The first commercial PWR began operation in the United States in 1961. It had a capacity of 185 MWe. (Oka et al., 2014)

Figure 2 presents a typical pressurised water reactor and its water-steam loops. In a PWR, the reactor core heats the water circulating in primary loop. The pressure of the water is so high that it does not boil in the primary loop. Primary loop water flows to a steam generator where it transfers its heat to the water circulating in the secondary loop. This water boils and the resulting steam a rotates turbine and generates electricity. After the turbine, the steam condenses back to water. The tertiary loop transfers the remaining heat to the final heat sink, which may be seawater or a cooling tower.

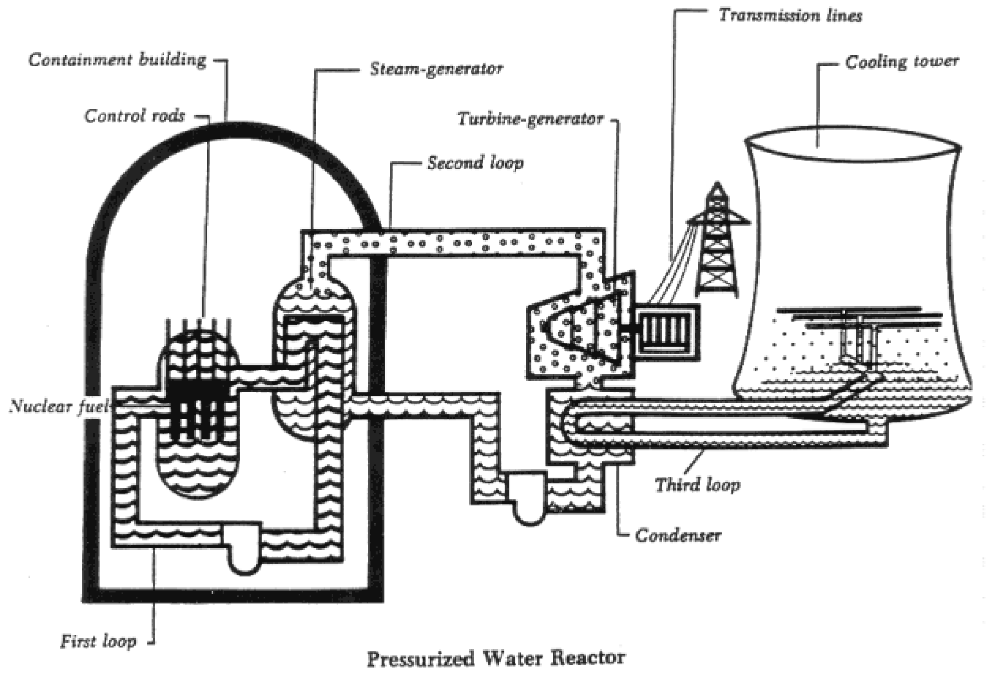

Figure 2. Pressurised water reactor. (NRC, 2012)

In a boiling water reactor, the water in the primary loop is pressurised less than in PWRs. The primary water boils as it traverses through the reactor core. The resulting steam is dried in the upper parts of the pressure vessel and lead to a turbine-generator. After the turbine, the steam is condensed back into water and the remaining heat is transferred to a heat sink located in the secondary loop. In BWRs, the turbine is a part of primary loop and thus also some parts and areas inside the turbine building have to be protected against radiation. Figure 3 presents typical boiling water reactor.

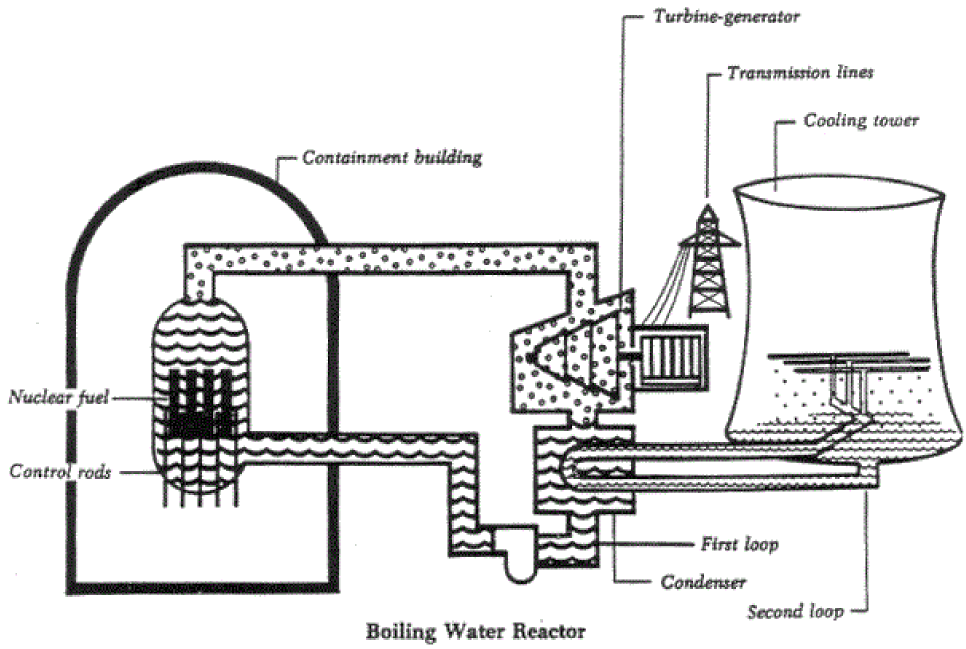

Figure 3. Boiling water reactor. (NRC, 2012)

At the time of writing this thesis, 282 of operating commercial nuclear reactors are pressurised water reactors and 80 are boiling water reactors. The corresponding figures for reactors under construction are 54 and 4. It would also seem that light water reactors will remain the most important and predominant reactor types in the near future. (PRIS, 2015)

2.1.1.2 Other reactor types

There are options other than light water for cooling and moderation, such as using heavy water, gas and graphite. Reactors using these materials as a coolant or moderator are not as popular as reactors using light water.

Heavy water (D_2O) can be used as both coolant and moderator. Deuterium (D_2) has a lower tendency to capture neutrons than hydrogen has, meaning that heavy water absorbs less neutrons than light water. This allows a heavy water reactor to use natural uranium as its fuel because a lower concentration of the fissile uranium isotope is needed in the fuel. Natural uranium contains 0.7% uranium isotope U-235. However, using heavy water as a moderator increases the size of the reactor core when compared to light water reactors because more heavy water is required in order to moderate the neutrons. The fuel of a heavy water reactor is easier and cheaper to fabricate than that of an LWR, but heavy water is considerably more expensive than light water. Heavy water reactors are pressurised water reactors (PHWR) and their development began in the 1950s in Canada. Canadian PHWRs are called CANDUs and nowadays CANDU reactors and their derivatives are operated in Canada, China, India, Argentina, Romania, Pakistan and the Republic of Korea. Generally speaking CANDU reactors operate like pressurised water reactors but CANDU reactors can be refuelled without the need to shut down the reactor. At the time of writing this thesis, there are 49 commercially operating pressurised heavy water reactors and four under construction. (PRIS, 2015; WNA, 2015)

The light water cooled, graphite moderated reactor was designed in the Soviet Union in 1970s. The design of the RBMK (high-power channel reactor) is inherited from a reactor designed principally for plutonium production. Original RBMK design had several shortcomings and it was the design involved in the Chernobyl disaster. The control rod design and the reactor's positive void coefficient negatively affected the reactor safety and were partially responsible for Chernobyl disaster. After the disaster, a number of significant design changes were made to the remaining RBMK reactors. RBMK reactors are a type of boiling water reactors which can be refuelled while the reactor is operating. At the time of writing there are 15 light water cooled, graphite moderated reactors operating and none are being constructed (PRIS, 2015).

The United Kingdom has developed a second generation gas cooled reactor called the AGR (Advanced Gas cooled Reactor). The AGR uses carbon dioxide as a coolant and graphite as a moderator. The AGR was developed from the earlier, gas cooled graphite moderated reactor called Magnox. Gas cooled, graphite moderated reactors are only used in the UK and at the time of writing, there are 14 AGRs and one Magnox reactor operating. There are no AGRs being built at the time of writing and this reactor type is only significant in the UK. (WNA, 2015)

2.1.2 **Future reactor technologies**

2.1.2.1 Water cooled reactors under construction

Most of the reactors under construction are light water reactors and of those, the clear majority are pressurised water reactors (PRIS, 2015). Some of the more modern water cooled reactors under construction are listed here.

In China, there are advanced pressurised water reactors under construction such as AP1000 and EPR designs. China also continues the development of CAP-1400 and CAP-1700 designs. These reactors are large scale versions of the AP1000. Research and development work on a Chinese supercritical water cooled reactor (SCWR) is still ongoing. There are two advanced boiling water reactors (ABWRs) under construction in Japan. Hitachi-GE Nuclear Energy has developed 600 and 900 MWe versions of the ABWR and Toshiba Corporation has modified the ABWR design to satisfy US and EU requirements. (IAEA, 2014a)

At the time of writing, there are four evolutionary 700 MWe PHWRs under construction in India. In addition, India is constructing a prototype of fast breeder reactor (PRIS, 2015).

In the Republic of Korea, an APR-1400 reactor's construction is progressing according to plan. Two APR-1400 reactors are also being constructed in The United Arab Emirates. The design certification process for the APR-1400 is in progress with the NRC, after which the design can be deployed in the US. There are also four AP1000 reactors under construction in the US and the NRC continues reviewing US-APWR reactor design certification. A design certification review of the US EPR reactor has been halted at the request of AREVA. In the Russian Federation, the construction of two VVER-1000 and five VVER-1200 reactors is being continued. In the Russian Federation the construction of a small modular KLT-40S reactor is also progressing. (IAEA, 2014a; WNA, 2015; WNN, 2015)

2.1.2.2 Water cooled reactors at an advanced stage of development

AREVA, a French multinational energy group, continues to market the 1600+ MWe EPR. In addition to its EPR design, AREVA is developing a 1100+ MWe ATMEA1 PWR together with Japanese Mitsubishi Heavy Industries and a 1250+ MWe KERENA BWR with Germany's E.ON. The first ATMEA1 reactor is planned to be deployed in Turkey. (IAEA, 2014a)

In Russia and Japan, research and development of SCWR designs which use supercritical water as a neutron moderator and coolant, is underway. In India, the Bhabha Atomic Research Centre is developing a 300 MWe advanced heavy water reactor which will use LEU (low-enriched uranium) and thorium MOX (mixed oxide) fuel. (IAEA, 2014a)

The Canadian Nuclear Safety Commission (CNSC) completed its third and final pre-licensing review for an Enhanced CANDU 6 (EC6) reactor. The EC6 is a CANDU reactor with a number of safety enhancements in order to meet the latest Canadian and international safety standards. The Canadian energy corporation Candu Energy Inc. has also completed the development of an advanced CANDU reactor called the ACR-1000. This reactor design utilizes very high component standardization and slightly enriched uranium to compensate for the use of light water as the primary coolant opposed to the usage of heavy water. The ACR-1000 has completed two out of three phases of its pre-licensing review. Candu Energy Inc. is also co-operating with international partners to develop variants of the EC6 design in order to utilize advanced fuels such as reprocessed uranium, MOX and thorium fuel. (IAEA, 2014a)

2.1.2.3 Fast reactors

Fast reactors have no need for a moderator as they use fast neutrons to produce nuclear fissions. Fast reactors and their related fuel cycles have an important role for the long term sustainability of nuclear power. Fast reactors can achieve a positive breeding ratio and also re-use the fissile materials obtained from the spent fuel from fast reactors. These factors allow the full utilization of the energy potential of uranium and thorium and thus guaranteeing the adequacy of energy supply for thousands of years. Furthermore fast reactors greatly enhance the sustainability of nuclear power as they reduce high level and long lived radioactive waste. (IAEA, 2014a)

The most mature fast reactor technology is the sodium cooled fast reactor called SFR. This technology has 350 reactor years of experience acquired through different experimental, prototype and demonstration reactors. SFRs have been studied and built in a number of IAEA states, such as China France, Germany, India, Japan, Russia, the United Kingdom and the United States of America. SFR technology has successfully demonstrated that breeding new fuel through the fast reactor fuel cycle is feasible while thermal efficiency reaches 43-45%. Indispensable experience in the decommissioning of several SFRs has also been acquired. (IAEA, 2014a)

At the time of writing there are two SFRs in commercial power operation: BN-600 and BN-800 in the Russian Federation. BN-800 started up in mid-2014 while BN-600 has been supplying electricity to the grid since 1980. Two experimental or test SFRs are operating: the China Experimental Fast Reactor (CEFR) and the Fast Breeder Test Reactor (FBTR) in India. Two fast reactors are also under construction (PRIS, 2014). In the Russian Federation, additional experience has been gathered with fast reactors using heavy liquid metals as a coolant. These were 155 MWth reactors used in seven submarines and used lead-bismuth eutectic as a coolant. At the time of writing, four different types of fast reactors are being developed internationally: a sodium cooled fast reactor, ta lead cooled fast reactor, a gas cooled fast reactor and a molten salt fast reactor[1]. (IAEA, 2014a)

[1] MSFR is being developed by the National Centre for Scientific Research (CNRS, France) and is supported by the Euratom. Euratom is an international organization which develops and distributes nuclear energy to its member states. MSFR is a reactor concept based on the thorium fuel cycle and its liquid fuel is also used as a coolant. (Merle-Lucotte et al., 2013)

2.1.2.4 Gas cooled reactors

The United Kingdom has operated commercial gas cooled reactors for several decades and valuable experience has been acquired in order to develop future high temperature gas cooled reactors (HTGR). In HTGRs, fuel consists of coated particles, the gas outlet temperature is over 750 °C and the coolant is helium instead of CO_2. (IAEA, 2014a)

In China, the construction of an HTR-PM (High Temperature Reactor-Pebble Bed Module) reactor started in December 2012. The HTR-PM power plant has two reactors and the plant is expected to be in operation by the end of 2017. China is also developing fuel manufacturing technology for GCRs and a new fuel fabrication plant began its operation in 2013.

HTGRs are being developed in number of IAEA member states. The development of the Russian-US Gas Turbine-Modular Helium Reactor (GT-MHR) continues. This reactor is designed to dispose of weapons-grade plutonium by using it for electricity production and process heat applications. HTGRs are also being studied in Japan, where a 30 MWth High Temperature Engineering Test Reactor is undergoing regulatory review. The IAEA has two ongoing HTGR research projects and the European Commission is engaged in the Advanced High Temperature Reactors for Cogeneration of Heat and Electricity R&D project, which aims to expand European HTGR technology to support nuclear cogeneration. (IAEA, 2014a)

2.1.2.5 Small modular reactors

Small modular reactors, or SMRs, are reactors with an electric power output of less than 300 MWe and their design is based on modularity. The IAEA classification of the term SMR means both small and medium reactors. The IAEA defines a small reactor as having an electric output of less than 300 MWe and a medium reactor as having an electric output between 300 and 700 MWe (IAEA, 2014b). In this master's thesis, the term SMR refers to small modular reactors with an electric output of less than 300 MWe and thus, excludes medium reactors and small, non-modular reactors.

Modularity means that a single reactor unit can be grouped with other similar modules to form a larger nuclear power plant (Zhitao, L. & Jihong, F., 2013). Standardized reactor units and serial production are essential features of small modular reactors. Ready reactor modules are transported from the factory to plant site for installation. Many SMR designs incorporate integral primary loops, where all the primary components are inside a single pressure vessel. This eliminates large pipe penetrations through the pressure vessel wall and enhances safety as large breaks and loss of coolant accidents are less probable. Small modular reactors are being developed in a number of countries and based on many different reactor technologies. The most advanced and mature SMRs utilize light water technology, but gas and metal cooled SMRs are also under development.

CAREM-25 is a prototype of an integral pressurised SMR with an electric output of 25 MWe. Construction of the CAREM-25 reactor began early in 2014 in Argentina. Once the prototype proves the CAREM design, a larger CAREM reactor (about 100 MWe) will be constructed in Argentina. (WNA, 2015)

The Russian Federation is developing SMRs that are based on the light water reactors used in nuclear ships and submarines. KLT-40 reactors have been used as nuclear propulsion for a few decades in Russian icebreakers. Considerable experience from these reactors has helped in constructing and developing more advanced versions of the reactor. The most mature Russian SMR design is the KLT-40S reactor which is currently being built. The KLT-40S power plant is a floating nuclear power plant with two KLT-40S reactors, which have an electric output 35 MWe each. The KLT-40S reactor is not a truly integral PWR as its steam generators are located outside the pressure vessel. The KLT-40S power plant is meant for the cogeneration of electricity and heat. (ARIS, 2014)

Another fairly mature Russian light water SMR is the ABV reactor, which has many design versions. ABV reactors have lower electric outputs than the KLT-40S, as their electric output is between 4 and 18 MWe. The ABV has an integral primary loop and is designed to be factory produced. The ABV power plant is a floating nuclear power plant and is suitable for cogeneration of heat and electricity. (WNA 2015). The Russian Federation is also developing a small modular fast reactor called the SVBR-100. This reactor uses lead-bismuth (Pb-Bi) eutectic as a coolant and a pilot facility is supposed to be in operation by 2019 (WNA, 2015). The electric output of the SVBR-100 is 100 MWe and it will be factory built. The Russian Federation has some experience with operating prototype Pb-Bi cooled fast reactors which were installed in a few submarines. The SVBR-100 fulfils the GIF's main requirements for a Gen IV reactor system (Zrodnikov et al., 2011).

The most advanced SMR designs in the US are all light water reactors. The NuScale reactor is an integrated PWR with an electric output of 45 MWe. The NuScale power plant consists of a maximum of 12 separate NuScale reactor modules. The modules are factory built and then transported to the plant site. The US Department of Energy has financed the NuScale project. The energy company NuScale Power LLC expects to submit design certification application for the NRC late in 2016 and the first NuScale unit would be under construction in 2020. (WNA, 2015)

Babcock & Wilcox and Bechtel Corporation announced in 2009 that they would develop the mPower reactor, which is an integrated PWR with an electric output of 180 MWe. It would be factory built and originally B&W anticipated that the reactor would be able to obtain its construction permit in 2018 and the first two reactors would be in commercial operation in 2020. However, the development of the mPower reactor has slowed down as B&W announced that it would cut back funding on the project having failed to find customers or investors. (WNA, 2014; WNN, 2014)

The third light water SMR under development in the US is the HI-SMUR reactor, which is being developed by the energy company Holtec International. Holtec especially advertises its 160 MWe version of the HI-SMUR reactor, also known as the SMR-160. The HI-SMUR is not a truly integral PWR because its steam generator and control rod drives are outside the pressure vessel. Holtec expects to submit a design certification application in 2016. Westinghouse Electric Company started its own SMR project in 2012 but has since halted the research and development work as the company assessed that the prospects for multiple deployment of SMRs are inadequate. (WNA 2015).

2.2 Energy security and security of supply

Security of energy supply and the continuous availability of energy at an affordable price is invaluable for society. Security of the electricity supply is indispensable as electricity is used all around us. It not only provides essential services for production, communication and trade but is also invaluable in maintaining basic human needs such as heating, ventilation and food and water supply. Electric motors and pumps are used everywhere. Activities such as food production, transportation, storage and distribution on the present scale would be nigh impossible without electricity.

The International Energy Agency defines energy security as "the uninterrupted availability of energy sources at an affordable price" (IEA, 2014c). Energy security and the security of the energy supply is the energy system's ability to withstand unique and unforeseeable events that threaten the physical integrity of energy flows and the functioning of the energy system. These events may lead to brownouts or blackouts, which in turn have a serious disruptive effect on society as electricity is used to supply basic human needs. These events may also lead to discontinuous energy price rises which are independent of economic fundamentals.

Security of supply is especially important in the power sector. Electric storage technologies have their own challenges and these storages are yet to be widely utilized with the exception being pumped-storage hydropower. Of course, pumped-storage hydropower can only be utilized near large bodies of water. According to the IEA, there is 140 GW of large scale electricity storage capacity installed and connected to the electricity grids worldwide and around 99% of this is pumped-storage hydropower. Generally speaking, electricity is still deemed as non-storable on an industrial scale, but this may change in the future to some extent. Research and development of large scale[2] energy storage is underway with some already in the demonstration and deployment phase. More about energy storages can be found in chapter 3.3. The need to balance supply and demand in power markets and inelastic nature of demand for electricity require close coordination between suppliers and the operators of electricity transmission grids. (NEA, 2010; IEA, 2014b)

The energy security of a nation can be assessed through external and internal factors. External factors include geopolitics, access to primary fuels, safety and adequacy of international infrastructures, international climate policy and unanticipated resource exhaustion. Internal factors include national energy infrastructures (e.g. grid, transportation), operational reliability, adequacy of market design as well as the regulation and adequacy of generation capacity. Nuclear power has, in particular regarding external factors, clear advantages for enhancing energy security compared to other non-renewable sources of energy. Renewables have good energy security ratings in respect of fuel supply because wind, solar and hydropower do not use fuel in traditional sense. As such, their electricity output is not in any way dependent on imported fuels or neighbouring countries. Of course, production from these sources is dependent on weather conditions and the production and consumption of electricity might not match. There really is no electricity generation from solar or wind power on a calm winter night and thermal power plants, hydropower or energy storage are needed. (NEA, 2010)

The generalized Simplified Supply and Demand Index (SSDI) is an indicator of the security of supply for a defined region. The SSDI includes major underlying supply-side and demand-side factors. This indicator incorporates following aspects of the security of supply:

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[2] Different flow battery technologies up to 10 MW capacity. Pumped hydropower and CAES storage can have capacities ranging from 100 MW to 1 GW and these technologies are already mature. (Sandia, 2013; IEA, 2014b)

- import dependency and diversification of fuel and energy supply,
- resource and carbon intensity, measuring the efficiency of resource use and
- system adequacy, "technical capability of energy system to maintain adequate supply and transport under a wide range of operational conditions" (NEA, 2010).

The SSDI is normalised to range from 0 to 100, where 0 indicates and extremely low security of supply and 100 an extremely high level of security. Here it is based on the generalized SSDI but adapted to work with only the IEA Energy Statistics. The basic structure and principles of the SSDI are presented in Appendix 1. Figure 4 shows the evolution of the SSDI for selected OECD countries. (NEA, 2010)

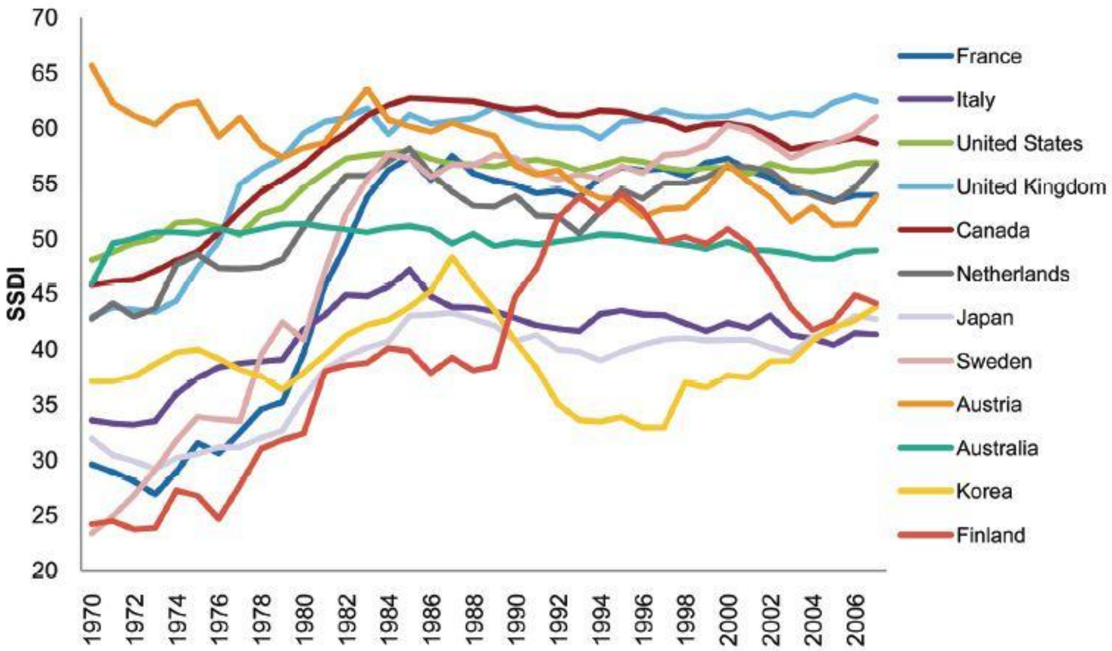

Figure 4. The evolution of the SSDI in selected OECD countries from 1970 to 2006. (NEA, 2010)

From the Figure 4, one can see changes in the trend when important policy changes have been implemented. For example, the United Kingdom's switch from coal to gas and the introduction of nuclear programmes in Finland, France, and the United States improve the value of the SSDI. Generally, the improvement in the SSDI coincides with the introduction of nuclear power and decreases often relate to increases in imports.

Figure 5 presents only the contribution of nuclear power to the SSDI and clearly shows its great effect on enhancing the SSDI scores. Contrary to fossil fuel technologies, nuclear energy has low sensitivity to the variations in the price of its fuel i.e. uranium. Nuclear energy is a competitive power generation source with a high energetic density. More reasons why nuclear energy improves energy security and thus also contributes to better SSDI scores are presented in the following chapter. (NEA, 2010)

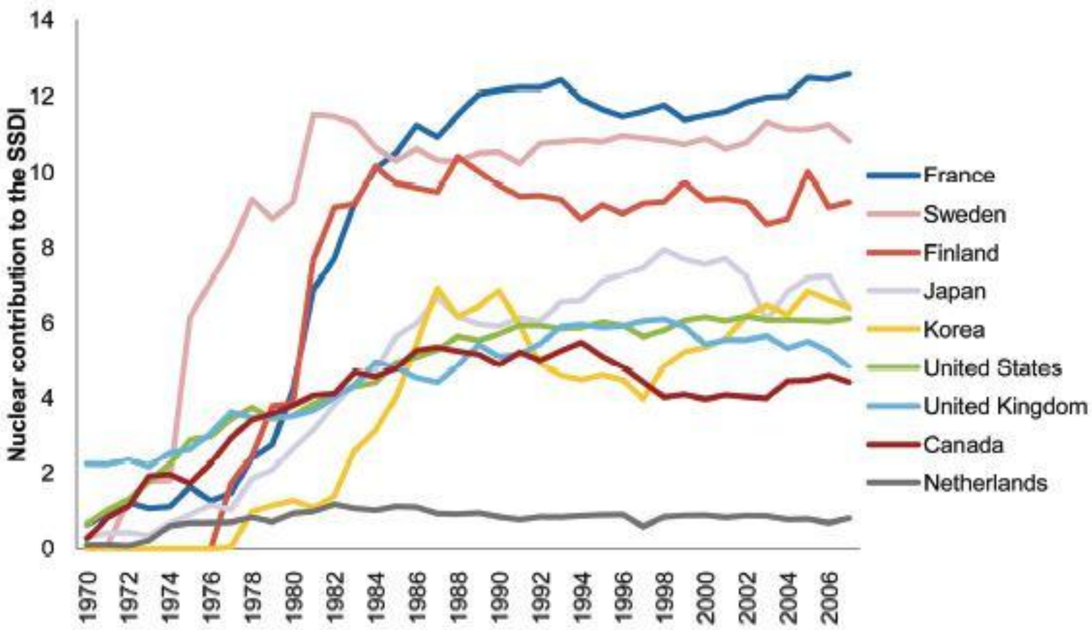

Figure 5. The contribution of the nuclear power to the SSDI. (NEA, 2010)

In 2007, the contribution of nuclear power to the SSDI was more than 12 points (about 30% of the overall SSDI score) in France, 11 (21 %) points in Sweden, 9 points (26%) in Finland, and 6 points (17%) in Japan and Korea. Nuclear power significantly enhances a nation's security of energy supply. (NEA, 2010)

2.2.1 The role of nuclear energy in improving energy security

The security of the energy supply can be divided into external and internal dimensions, seen in Figure 6. Nuclear power improves both of these dimensions.

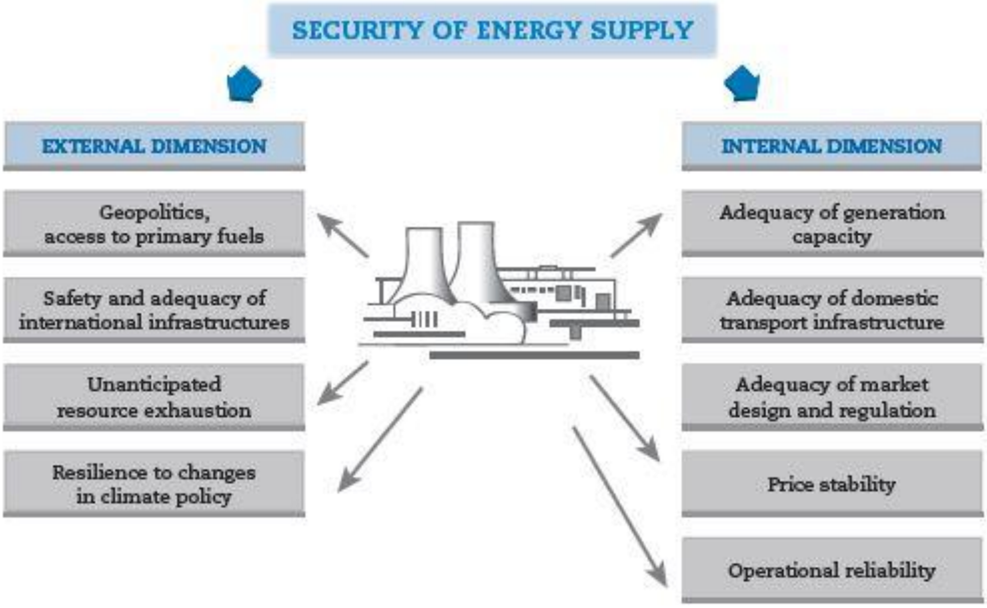

Figure 6. Dimensions of energy supply security. (NEA, 2010)

The external dimension refers to the aspects of security of energy supply, which are not under the direct control of the country in question. Geopolitical risk refers to the geographical location of the primary fuel sources. Different primary fuels have different levels of geopolitical risk due to the distribution of fuel sources or deposits. Production of the fuels and their consumption are often physically far apart and take place in countries and regions with different political situations, cultures, histories and values (NEA, 2010). Geopolitical risks depend on relations between producer and consumer countries. All imported fuels are exposed to geopolitical disturbances in the countries which produce these fuels and the risks of disturbances occurring are naturally lower if the particular primary fuel sources are present in a number of countries. The safety and adequacy of international infrastructures have a somewhat similar effect on the security of energy supply and the risks linked to international infrastructures can be alleviated the same way: by having a number of fuel producing countries. If, for example, the safety of the infrastructure between producer and consumer countries is compromised, another producer country can circumvent this problem by providing an alternative fuel source. Moreover, the global nuclear fuel supply chain has yet to experience a serious disruption and nuclear power involves long lead times allowing the nuclear industry to have ample time to anticipate and respond to changes in uranium demand. (IEA, 2014e)

Internationally traded oil and gas have a relatively few sources and countries of origin. Political instability there, or in the countries through which the fuel is transported, is a constant risk to energy security and thus, also a major economic vulnerability (WNA, 2015). Fossil fuels are also subject to regional price disparities and volatility (IAEA, 2014a). Coal supplies are geographically more diverse than oil and gas supplies and hence less uncertain to acquire. Raw uranium supply and uranium fuel processing and manufacturing services are multiply redundant. Uranium resources are available from more diverse sources than fossil fuels, both geographically and politically. This lessens the political risk of acquiring uranium and gives it a very high rating in respect to energy security. There are also numerous nuclear fuel fabricators and thus, nuclear power plant operators are not restricted to acquire the fuel just from the original plant suppliers. Nuclear energy also benefits from the very high energy density of uranium fuel. Uranium, oil and coal fuelled power plants in regard to their fuel consumption are compared in Table 1.

Table 1. How much of a specific fuel a 1000 MWe power plant requires annually. (EURELECTRIC, 2003)

Fuel	Amount [t]
Lignite	7 600 000
Hard coal	2 000 000
Oil	1 290 000
Gas (combined cycle)	920 000
Nuclear	20

Table 1 shows how much fuel a power plant with electrical capacity of 1000 MWe requires annually. The amounts presented are estimates and depend, for example, on quality of fuels. Table 1, however, gives an idea of just how much more coal, lignite, oil, and gas are required when compared to uranium and supports the idea that uranium is more affordable fuel to stockpile. In the table, the fuel consumption in a power plant with a generation capacity of 1000 MWe and 6600 full load hours per annum is compared. A nuclear power plant with a generation capacity of 1000 MW uses 20 tonnes of fabricated uranium fuel, while a coal power plant with the same generation capacity uses 100 000 times more coal. (EURELECTRIC, 2003)

The relatively small volume of nuclear fuel required to run a reactor makes it easier to establish strategic inventories, even if the overall trend in recent years has been towards supply security based on diverse and reliable markets for uranium and fuel supply services. Still, nuclear fuel and uranium offer the option of keeping relatively low cost strategic inventories for countries and utilities that consider these important (IAEA, 2012).

The cost of uranium is a small fraction of the total cost of nuclear power generation and so it is a more affordable fuel to stockpile than fossil fuels or coal. Also fuel price spikes have a much less severe economic impact for nuclear generation than fossil generation. As generating costs for nuclear are less sensitive to changes in fuel costs, nuclear generation provides stability in wholesale electricity costs. According to the IEA (2014e), a 50% increase in nuclear fuel costs will only increase the levelized cost of electricity[3] by 5%. Equivalent rises in gas prices push up the generating cost of a combined-cycle gas turbine by around one-third.

The oil crises of the early 1970s showed that electricity generation's dependency on imported fuels is a real problem. For example, France increased its nuclear generating

[3] The levelized cost of electricity (LCOE) represents the per-kilowatthour cost (in real currency) of building and operating a generating plant over an assumed life and duty cycle. (EIA, 2014)

capacity significantly since the late 1970s and nowadays over 75% of France's electricity generation is based on nuclear power. This enhances energy security and security of supply and can also be seen in the Figure 4. (WNA, 2015)

The internal dimension of the security of energy supply is affected greatly by a country's government, policies and legislation. Governments can influence the adequacy of generation capacity by providing incentives for the private sector to install facilities domestically for the production, transport, conversion and consumption of energy. Important elements to the enhance internal dimension of energy security include regulatory stability, market organisation, governmental and policy support for low carbon energy sources, such as nuclear, and fiscal coherence (NEA, 2010). These elements affect all sources of electricity generation but especially nuclear energy, which generally has to have political support for construction. Operational reliability naturally affects energy security as utilities and consumers expect that power plants produce their promised capacity. Nuclear power, especially in Finland, has been reliable in this regard. Nuclear power plants are not subject to unreliable weather or climate conditions, unlike renewable generation. The operational reliability of nuclear energy is discussed in chapter 2.4.

2.2.2 **Resources**

Renewables and nuclear energy have one significant common feature: when using nuclear and renewable energy, mankind is not depleting resources useful for other purposes. These sources of electricity generation give access to virtually limitless resources of energy with negligible opportunity cost. Other fuels used for energy production, such as oil, wood or coal, also have other uses. There are visions of a time when fossil carbon-based fuels will be too valuable to burn on the present scale, not to mention the desire to move to a CO_2-free from of energy production in order to mitigate climate change. (WNA, 2015)

In total, there were about 5.9 million tonnes of known recoverable uranium resources worldwide in 2013. Reasonably assured resources plus inferred resources of uranium come to total of 7.635 million tonnes. Current uranium usage is about 66 000 tU/yr, meaning that the world's present measured uranium resources (5.9 Mt) in the cost category around 1.5 times of present spot prices are enough to last for about 90 years when used in conventional reactors. Higher uranium prices and further exploration will yield further resources as present ones are used up. The amount of known resources which are economically extractable is directly proportional to the price of mineral commodity. Based on the analogies with other metal minerals, when a price of the metal mineral doubles from present levels, about a tenfold increase in measured economic resources could be expected. This is due to increased exploration and the reclassification of resources regarding what is economically extractable. Figure 7 presents how recoverable uranium resources are distributed in the world. (WNA, 2015)

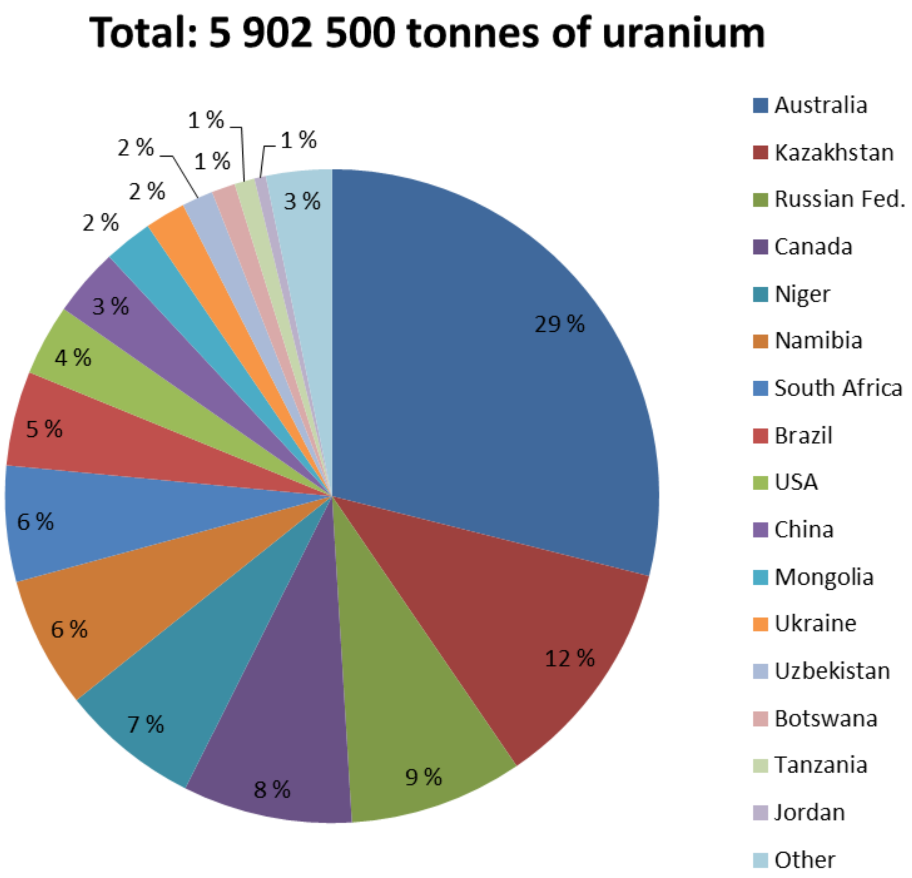

Figure 7. Known recoverable uranium resources in 2013. (data from WNA, 2015)

Current estimates that cover all conventional resources (uranium as the main product or a major by-product), including those not yet economic or properly quantified, consider that there is 200 years' supply of uranium at today's consumption rate. These reserves are estimated without considering the technological factor. Widespread use of the fast breeder reactors could increase uranium utilization 50-fold or more. Also non-conventional uranium resources, such as phosphate/phosphorite deposits (up to 22 Mt of uranium), black shales (5.2 Mt U) and seawater (up to 4 000 Mt U), are omitted from previous estimates. Most non-conventional resources are uneconomic to extract in the foreseeable future but research into extracting these resources is ongoing. (WNA, 2015)

The aforementioned uranium supplies and their consumption rates are estimated for present nuclear reactors and their fuel cycles. With fast reactors and advanced fuel cycles that recycle nuclear fuel, known conventional resources are estimated to be able to last over 3 000 years and with non-conventional resources over 21 000 years. Advanced fuel cycles have also the benefit of reducing the volumes of high-level radioactive waste. Advanced cycles have the ability to consume, or burn, the heavy long-lived isotopes (minor actinides or transuranics) formed in nuclear fuel during irradiation in the reactor. Minor actinides and a few long-lived fission products dominate the activity present in the spent fuel in the longer timescales. Thus, burning these minor actinides and long-lived fission products can significantly reduce the long-lived component of high-level waste. (IEA, 2010a)

2.2.3 Resource efficiency and energy density

Resource efficiency means maximizing the use of resource and in this case, nuclear fuel i.e. uranium. Measuring different aspects of resource use, such as the carbon or land footprint, is a key tool of defining resource efficiency. Nuclear energy's carbon emissions are discussed further in the chapter 2.3.

One way to compare resource efficiency for different electricity generation technologies is to compare the energy densities of the fuels used. The energy density is the quantity of fuel used to produce a given amount of energy. The energy density influences the fuel extraction activities, transport requirements and quantities of environmental releases and waste, thus determining to a large measure the magnitude of environmental impacts. Table 2 presents how much heat energy one kilogram of a specific fuel can generate. Uranium fuel used in LWRs has a 3 to 5 % concentration of uranium-235. In the Table 2, 1kg of pure uranium-235 is compared to coal and mineral oil. One kilogram of natural uranium with a concentration of uranium-235 of about 0.7 % enables the generation of 45 000 kWh of electricity, a much higher amount than coal or oil enables. (ENS, 2015)

Table 2. How much heat is generated by one kilogram of fuel. (ENS, 2015)

Fuel [1 kg]	Heat generated [kWh]
coal	8
mineral oil	12
uranium-235	24 000 000

Table 2 shows the extraordinarily high energy density of uranium-235 relative to fossil fuels and as shown previously in Table 1, this directly affects how much fuel a power plant requires annually.

2.3 Emissions

Greenhouse gases emitted by a nuclear energy system are not limited only to carbon dioxide, but also other greenhouse gases. However, there is lack of data available on the other greenhouse gases, so here the analysis is limited to the emission of CO_2 (Storm van Leeuwen, 2012). Nuclear power generation does not directly emit greenhouse gas emissions or other air pollutants during operation and generally produces very low emissions over its full life cycle. Assessing the greenhouse gas emissions of nuclear power includes the whole nuclear process chain: mining the uranium, milling it, the treatment and enrichment of the uranium, fuel fabrication, construction of the nuclear power station and finally dismantling and disposal operations (Princiotta et al., 2011).

According to the IEA's World Energy Outlook 2014, the greenhouse-gas emissions intensity[4] is currently about 15 grams of CO_2-eq per kilowatt-hour for nuclear energy. This figure is comparable to that of wind, solar and hydropower. Sovacool (2008) screens 103 lifecycle studies of greenhouse gas-equivalent emissions for nuclear power plants. He omits studies done before 1998, studies not available in the public domain or not published in English, studies relying on unpublished data and studies utilizing secondary sources. This leaves 19 lifecycle studies and according to these, the range of emissions for nuclear energy over the lifetime of a plant is from 1,4g of carbon dioxide equivalent per kWh to 288g CO_2-eq/kWh. The mean value in the Sovacool study was 66g CO_2-eq/kWh for nuclear energy. The wide disparity comes from the different scopes and assumptions these 19 studies used. Some studies included just one or two parts of the nuclear fuel cycle and others provided explicit details even for subcomponents of the fuel cycle. The highest lifetime greenhouse gas emission estimates for nuclear fuel cycle are not universally accepted. In his article, Sovacool mentions another study consisting of numerous lifecycle studies and in this study the range of 2-77g CO_2-eq/kWh was most common. Estimates above 40g CO_2-eq/kWh were in the minority. Overall, there is no universally accepted value for greenhouse gas emissions associated with the nuclear lifecycle. Nuclear energy raises a lot of opinions especially regarding to its eco-friendliness. Both sides of the nuclear debate attempt to make nuclear energy look cleaner or dirtier than it really is. (IEA, 2014e; Sovacool, B., 2008)

In this thesis, the lifecycle carbon emission estimate for nuclear energy is 15g CO_2-eq/kWh (IEA, 2014e). The IEA's value puts nuclear energy carbon emissions on the same level as the emissions from renewables. It is important to remember that nuclear

[4] The amount of CO_2-equivalent (CO_2-eq) emissions per kilowatt-hour. (IEA, 2014e)

energy's emissions during operation are virtually non-existent and the high value of 66g CO_2-eq/kWh comes from different technologies and work phases associated with the nuclear process chain, mainly isotope enrichment during fuel manufacturing. These technologies and work phases and their carbon emissions are evaluated differently in different studies. It is likely that the technologies involved in the nuclear energy lifecycle will further develop and their carbon and energy intensities and use of electricity will decrease. This in turn will lower the lifecycle carbon emission estimate for nuclear energy. In Table 3 lifecycle carbon emissions for different technologies are presented. Table 3's contents are modified from the original source by combining different configurations and biomass fuels. These values are later used in the model to compare emissions in different scenarios and with two different values for nuclear energy lifetime emissions.

Table 3. Lifecycle carbon emission estimates for different electricity generation technologies. (modified from Sovacool, B., 2008; IEA, 2014e)

Technology	Capacity/configuration/fuel	Estimated carbon dioxide emissions [gCO2-eq/kWh]
Coal	Various generator types with/without scrubbing	960-1 050
Heavy oil	Various generator and turbine types	778
Fuel cell	Hydrogen from gas reforming	664
Natural gas	Various combined cycle turbines	443
Biomass	Various fuels and configurations	14-41
Geothermal	80 MW, hot dry rock	38
Solar photovoltaic	Polycrystalline silicone	32
Nuclear (IEA value)	Various reactor types	15
Solar thermal	80 MW, parabolic trough	13
Hydroelectric	300 kW run-of-river/hydroelectric 3.1 MW reservoir	13/10
Biogas	Anaerobic digestion	11
Wind	1.5 MW onshore/2.5 MW offshore	11/9

Studies show different values for each generation technology, but the common trend is that nuclear power has significantly lower CO_2 emissions than fossil fuels. At the time of writing, nuclear power is the world's second-largest source of low carbon electricity after hydropower and in OECD countries it is the largest source of low carbon electricity (IEA, 2014e). It should be noted that as nuclear power does not directly emit greenhouse gases, it has the potential to have even lower CO_2 emissions in the future when technologies involved in the lifecycle emissions improve. A shift from an electricity intensive gaseous diffusion uranium enrichment process to a centrifuge enrichment process has lowered the electricity requirements in uranium enrichment considerably. Laser enrichment technologies will also lower the electricity requirements of uranium enrichment, and together with the increased share of electricity that is based on low or non-carbon fuels, reduces emissions of nuclear life cycle. (IAEA, 2012)

Extended lifetimes for nuclear power plants further reduce the emissions per kilowatt-hour associated with construction and the future's increased fuel burnups mean reduced emissions per kilowatt-hour associated with uranium mining and fuel manufacturing. Improvements in nuclear fuels and reactors allow better utilization and unit capability factors. Future energy production will be more efficient and together with extended lifetimes for nuclear power plants will reduce the need to build new facilities. (IAEA, 2012; IAEA, 2014a)

Germany offers a fine example how an aggressive energy policy aimed at reducing CO_2 emissions and the phasing out of nuclear energy really impacts the CO_2 emission levels in the power sector. Germany adopted an energy policy called Energiewende in 2010-2011 and the aim of the policy is to fully decarbonise the power sector by 2050 while also phasing out nuclear power by 2022. One goal is to achieve a 55 % reduction in greenhouse gas emissions by 2030 compared to 1990 levels. Nuclear energy's share in the power generation mix has decreased from 29.5 % in 2000 to 15.4 % in 2013. The share of renewables has increased from 6.6 to 23.9 % over the same period. The decline of nuclear generation is offset by the increase in renewable generation. (Agora, 2014)

Even though Germany has increased the share of renewables in its power generation mix, the CO_2 emissions from the German power generation sector have been on the rise since 2009. The market conditions in Germany have resulted in coal-fired power plants pushing gas plants out of the market thus increasing CO_2 emissions from the power sector. Coal and CO_2 emission prices have decreased while simultaneously gas prices have increased. In 2013, lignite fired generation reached its highest level since 1990. Nuclear phase-out does not itself entail an increase in CO_2 emissions as long as the nuclear generation is replaced with renewables. The simultaneous increase in fossil fuelled generation has increased the overall CO_2 emissions from the German power sector. As it stands, renewables alone cannot produce all the electricity that the German market requires. Operating nuclear power plants produces virtually no CO_2 emissions and the nuclear generation would help the German power sector to achieve the desired reductions in CO_2 emission levels. However, the German energy policy, Energiewende, aims to phase out nuclear power and thus some other measures are needed in order to meet the government's climate targets. (Agora, 2014)

According to the publication by Agora Energiewende (2014), from 2013 to 2030 lignite generation will need to drop by 62% and coal fired generation by 80%. This would result a generation mix of 55% renewables, 22% gas and 19% coal (lignite and hard coal) in 2030. Consumption of natural gas in the power sector would increase from the 2013 levels but this increase will be offset by the decreased use of gas in the end-use sector which uses more gas than the power sector. The Agora publication did not consider the balance between consumption and production, which is one of the main reasons why fossil fuels are still used in Germany. Renewable generation cannot guarantee its production and timing of production; high demand for electricity may very well take place when there is no wind and the weather is cloudy. Whether the aforementioned shares of gas and coal can satisfy the electricity demand at all times is uncertain. Increasing the share of renewable generation may very well require building more fossil fuelled backup or peak power plants as nuclear power is phased out. This in turn is not in line with the aspirations and targets to reduce the carbon emissions from the power sector.

2.4 Predictability and stability of nuclear generation

Nuclear power plants have traditionally been reliable sources of electricity generation. This reliability can be measured and compared with other generation sources by using the capacity factor. The capacity factor for a power plant describes the ratio of actual power generated to its maximum potential generation. The U.S Energy Information Administration (EIA, 2014) has published tables of monthly capacity factors for different fossil and non-fossil fuel and technology combinations in the United States. These factors are presented in Figure 8.

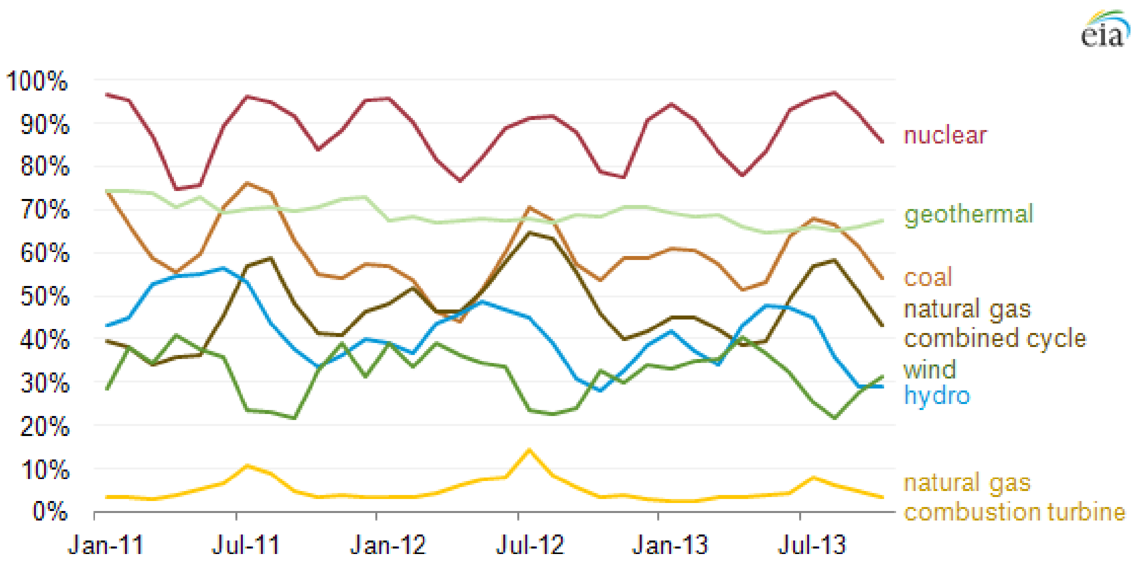

Figure 8. Monthly capacity factors for select fuels and technologies in the United States. (EIA, 2014)

According to the EIA data and Figure 8, nuclear power has the highest average capacity factor, meaning that the US nuclear fleet offers reliable energy to the national grid. Utilities and consumers generally, and not just in the US, can trust that nuclear power plants produce the promised capacity of electricity.

The IAEA Power Reactor Information System (PRIS, 2014) reports a global average unit capability factor of 76.3% over the period of 2011to 2013. This factor includes all reactors that were in commercial operation during this period. In Finland this factor was 93.4% over the same period. The unit capability factor is the ratio of the available energy generation over a specified time period to the uninterrupted production at full power over the same period. The available energy generation is the energy that could have been produced considering only limitations within the control of plant management. Uninterrupted energy generation is the energy that could be produced if a particular unit were operated continuously at full power. The unit capability factor reflects the effectiveness of plant programs and practises and more or less describes the same thing as the capacity factor mentioned previously. Simply put, Finland's nuclear power plants in 2011 to 2013 produced 93.4% of their theoretical maximum energy. In Finland, the majority of nuclear power plants' downtimes are due to planned annual maintenance and refuelling periods. Refuelling and maintenance are scheduled in the early and late summer because the demand for energy in Finland is generally lower during the summer. Generally most shutdowns are planned and as they can be foreseen, shutdowns are scheduled to take place when demand is expected to be lower than normal. Unplanned shutdowns are a minority of all the shutdowns and shutdowns which do occur, mainly for refuelling work, are relatively short. Nuclear power plants generate electricity in a predictable manner at stable prices and their availability is known in advance. (PRIS, 2015)

Nuclear power plants have long operating lifetimes, typically 40-60 years. They can generate electricity continuously for extended periods before going offline for refuelling and maintenance. Nuclear power plants help maintain grid frequency as their generating capacity is available, adjustable and predictable for the majority of the time.

Some of the grid management services that the nuclear power offers to the power grid include:

- primary and secondary frequency control,
- predictable and controllable availability and
- rotating inertia.

Primary frequency control means that the power plants monitor the frequency on the grid and immediately adapt their level of generation if the frequency alters from the defined value. The purpose of primary frequency control is to keep the frequency stable at the desired value. Some deviation remains after primary frequency control and this deviation can be corrected with secondary frequency control. Secondary frequency control calculates the average frequency deviation over a period of time. For example, the grid operator can send a digital signal to the power plant to modify its power level in order to take into account the balance of electricity exchanges with other grids. Frequency control and the flexibility of nuclear power plants is discussed later in chapter 2.5. (NEA, 2011)

2.4.1 Grid inertia

Power grid frequency measures the balance between consumption and generation. For example, in the Nordic countries the frequency of the power grid is 50 Hz and if the frequency drops below this value, the overall electricity consumption is greater than generation. Power grid inertia is one parameter the synchronized operation of the grid is based on and it determines the immediate frequency response. This inertia is introduced to the power grid by the rotating masses of synchronous generators and turbines which are connected to the grid. These components will inject or absorb kinetic energy into or from the grid to counteract the frequency deviation from the predetermined frequency value. If the overall inertia in the power grid is low, the grid frequency reacts nervously to sudden changes in generation and load patterns. To put it simply, inertia is the grid's resistance to change. (Tielens, P. & Van Hertem, D., 2012)

Basically all thermal power plants, whether they are fossil, nuclear or biomass fuelled, introduce rotating inertia to the power grid as their synchronous machines, generators and turbines, are connected to the grid directly. However, wind turbines and solar panels have practically no inertia. Even though wind turbines have kinetic energy stored in the blades and the generator, they are generally equipped with doubly fed induction generators or full converter synchronous generators and these electrically decouple the generator from the grid. Thus wind and solar power do not produce any inertia for the power grid. (Tielens, P. & Van Hertem, D., 2012)

Nuclear power plants are generally large units with large generators and turbines and thus they introduce large rotating masses to the power grid. This increases the overall kinetic energy and inertia in the power grid and in turn the grid's resilience to abrupt changes in generation and load patterns, stabilising the grid. (Päivinen, 2012)

The large unit sizes of nuclear power plants also have a downside in regards to grid management. If a large generator would unexpectedly drop from the grid, the frequency of the grid would also suddenly and temporarily drop. The frequency of the grid has set limits in regards to minimum and maximum frequency values and these values together with the total amount of connected synchronous rotating mass (i.e. turbines and generators) limit the maximum unit size of the power plants. (Päivinen, 2012)

Overall nuclear power plants offer large amounts of inertia and kinetic energy to the power grid which in turn improves system's fault tolerance in regards to other thermal power plants and their possible failures. However, if a nuclear power plant experiences a fault which drops the unit from the power grid, the grid loses a substantial amount of kinetic energy and inertia. As a result, the frequency of the grid drops more than if a smaller sized unit would drop from the power grid.

Fingrid Oyj, the enterprise responsible for managing the Finland's nationwide high-voltage grid, is prepared for the grid connection of the Olkiluoto 3 nuclear power plant. Olkiluoto 3 is a nuclear power plant under construction with a net electrical capacity ca. 1 600 MW and once it is finished, it's generator will be the largest in the Nordic energy system. A large unit like this will increase the inertia in the power grid and if the unit works as intended, the overall fault tolerance of the power grid will increase. At the time of writing, the Nordic energy system can accept a unit with a capacity of 1 650 MW at most. (Haarla, 2013)

2.5 Flexibility of nuclear power plants

Traditionally nuclear power plants have been considered as base-load sources of electricity. This is due to nuclear power being a technology with high fixed costs and low variable costs, so the most profitable way to run a nuclear power plant is with close to full capacity as long as prices are stable. Response to variations in electricity demand is traditionally left to power plants with low fixed cost and high variable costs, such as gas plants or fossil fuel plants. Still, nuclear power plants offer valuable grid management services and they can also operate in load following mode.

In some countries, such as France, the share of nuclear power in the national electricity generation mix has become so large that utilities have to be able to operate some nuclear reactors in a load following mode. A nation's electricity demand changes daily and seasonally and electricity generation has to be able to follow these changes. In France, more than 75% of the nation's electricity is generated by nuclear power plants and remaining 25% is generated by various sources, not all of which can be operated in a load-following mode. Furthermore, nuclear capacity in France exceeds the base-load needs during certain periods during which it is necessary to reduce the overall nuclear load. (Lokhov, A., 2011)

Another reason for a load following operation mode with nuclear power plants is due to the large scale deployment of intermittent electricity sources like wind or photovoltaic power. Several OECD countries have a growing share of renewable electricity sources which has introduced significant and irregular variation in the available power supply. This has made balancing the national electricity supply and demand more difficult.

As the share of renewables increases and the share of fossil fuelled generation decreases in the future energy system, the need for manoeuvrable and load following nuclear power plants increases. In Germany, the deployment of large amounts of variable renewable generation with heavy government induced subsidies has repeatedly led to prices below the marginal cost of nuclear power, including several instances of negative prices and prices that were lower than the variable costs of nuclear power plants. Nuclear power plants have the lowest variable costs among the large scale established power sources and German utilities have started operating their nuclear power plants in load following mode. The French and the German experiences have shown that nuclear power has the technical capability to engage in load following modes of operation. Table 4 presents the load following ability of four different power plant technologies. Maximum ramp rates in MW per minute are calculated from the ramp rate in percentages per minute by using capacities in parentheses. The capacities chosen are quite typical values for these generation technologies. (Lokhov, A., 2011; NEA, 2011)

Table 4. The load following ability of different power plants in comparison. (NEA, 2012)

Technology	Start-up time	Maximal change in 30 sec	Maximum ramp rate [%/min]	Maximum ramp rate [MW/min]
Open cycle gas turbine (200 MW)	10-20 min	20-30 %	20	40
Combined cycle gas turbine (580 MW)	30-60 min	10-20 %	5-10	29-58
Coal plant (600 MW)	1-10 hours	5-10 %	1-5	6-30
Nuclear power plant (1 200 MW)	2 hours - 2 days	up to 5 %	1-5	12-60

When comparing just the ramp rates, nuclear power's short-term load following capabilities are comparable to those of coal-fired power plants but somewhat below combined cycle gas turbine plants. Open cycle gas turbines clearly have the best load following capabilities in regards to start-up time, maximal change in 30 seconds and the relative maximum ramp rate, but they have very high variable costs limiting their use to cover the most extreme demand peaks. Furthermore, as can be seen from the absolute maximum ramp rate [MW/min], nuclear power plants can offer the same amount of adjustable capacity. The start-up time is a non-issue when the nuclear power plant is already running. Nuclear power has the longest start-up time, but when the respective generating capacities are taken into account, nuclear power can offer as much or more adjustable capacity than gas turbines but with a much lower relative change in power level. One percent of rated power in a nuclear power plant is much more than one percent in a gas turbine. (NEA, 2012)

According to the NEA (2011), most of the currently operating nuclear power plants were designed to have strong manoeuvring capabilities. One of the key features for the load following capabilities of the plant is the existence of an accurate core monitoring system. It is important to accurately evaluate the difference between the maximal local power density in the core and its safety limit. Rapid and precise power distribution measurements provide significant margin for manoeuvring. (Lokhov, A., 2011)

Generally speaking, four types of nuclear power plant manoeuvring or operating modes are used:

- base-load generation mode;
- primary and the secondary frequency control and
- load following mode.

In the base-load generation mode, a power plant generates electricity at constant power, usually at the maximum rated power, during almost the whole cycle. Primary and secondary frequency control depends on the current grid demand; the power demand can never be exactly estimated in advance and thus power plants have to monitor the frequency of the grid and adapt their level of generation to maintain the desired value. Primary frequency control is for short term adjustment of electricity production (a time frame of about 2 to 30 seconds) and secondary frequency control is for longer timeframes (from several seconds to several minutes). Finally, nuclear power plants operating in a load following mode follow a variable load program which has one or two power changes per period of 24 hours. (NEA, 2011)

The European Utilities' Requirements (EUR) was founded in 1991 by five European utilities and it covers a broad range of conditions for a nuclear power plant to operate efficiently and safely. The EUR has explicit requirements for modern reactors concerning their manoeuvrability capabilities and in particular the EUR requires that modern plants are able to operate in load following modes. According to the EUR requirements, a nuclear power plant must be capable of a minimum daily load cycling between 50% and 100% of its rated power P_r, with a rate of change of electric output of 3-5% P_r/min (Lokhov, A., 2011; NEA, 2011)

According to the final report made by technical consulting company ÅF Consult (2012), EPR reactors have the following manoeuvrability features:

- power decreasing rates of 5% per minute in the power range of 100% → 60% and back to 100% rated power, in daily use
- changing power levels from 100% to 25% at a rate of 5%/minute and from 25% to 60% at a rate of 2.5%/minute.

It is reported that the reactors designed by Mitsubishi, Toshiba and GE-Hitachi have similar capabilities. Nuclear power plants usually generate power at their rated power level, so possible grid balancing with nuclear power would first consist of decreasing the power levels when there is an oversupply of energy. Of course, after the initial power level decreases the nuclear power plant can be readjusted to its previous power levels if needed. (ÅF, 2012)

Economically, using nuclear power for base-load generation is the most profitable operation mode, but the demand for electricity fluctuates throughout the day and there has to be some way to answer this demand. In the future energy system, nuclear power might be needed to stabilise the grid. Modern and future nuclear power plants have the manoeuvring capabilities to do so.

3 FUTURE ENERGY SYSTEM

According to the current, generally accepted view, one of the biggest challenges for the energy sector is climate change mitigation. Thenergy sector's solutions for mitigating climate change include the efficient use and production of energy from CO_2-free sources of electricity generation and carbon capture and storage (CCS). As was shown in Table 3, nuclear power and renewables have the lowest CO_2 emission per kWh of energy and thus a transition to an energy system consisting mainly of these generation sources is essential in order to mitigate climate change.

Current trends are unsustainable in relation to the environment, energy security and economic development. Continuing dependence on fossil fuels drives up both CO_2 emissions and the price of fossil fuels. Using a combination of existing and new technologies, it is possible to halve global energy-related CO_2 emissions by 2050. According to the International Energy Agency (2010), the greatest potential for reducing CO_2 emissions over the period to 2050 comes from increasing energy efficiency. The second-largest source for emissions reductions is decarbonising the power sector, and thus the transition to an energy system dominated by renewable generation, together with nuclear power, will be essential. Currently, OECD countries strive to reduce their greenhouse gas emissions. Electricity sectors generally have limited exposure to international competition and together with their stationary nature, they are frequently called upon to generate a major share of these emission reductions (NEA, 2012; IEA, 2010)

Globally, the current energy system is based on large, centralised generation using mainly fossil fuels. The future low carbon energy system will have greater diversity of technologies and fuels, and more renewables especially will be used (IEA, 2012a). In addition to renewables, nuclear power will be a major contributor to the decarbonisation of the electricity supply (IEA, 2010). This, however, presents new challenges. For example, renewable energy output has a tendency to fluctuate depending on the weather. Today's energy system uses mainly hydropower and fossil fuelled power plants as regulating power to stabilise the power grid and to meet the supply and demand challenges. In this master's thesis, a future energy system is envisaged to be carbon free and thus, the share of fossil fuel dependent energy generation is significantly lower, or zero, in the future energy system. Decarbonising the energy system requires alternative grid stabilising methods and technologies. Increased volumes of variable and intermittent production from wind and solar will highlight issues related to regulating power. In Nordic countries, the large share of hydropower will help the transition and will become increasingly valuable in regulating electricity systems in these countries and Northern Europe in general (IEA, 2013).

The level of nuclear growth envisaged will not require major technological breakthroughs. The possible obstacles for rapid, short to medium term, nuclear growth are primarily policy-related, industrial and financial. If nuclear capacity is to grow in the 2020s and beyond, the global industrial capacity to construct nuclear power plants will need to double by 2020. This requires significant investments over the next few years and the prerequisite for these investments is a clear indication that sufficient orders are on the horizon. Nuclear growth also requires increased human resources. Utilities, regulators, governments and other stakeholders will need more nuclear specialists, highly qualified scientists, engineers and skilled crafts-people. In addition to industry recruitment and training programs, universities and governments also have a vital role to play in the development of available human resources. (IEA, 2010)

The Nordic countries have set their ambitions and energy targets on a Carbon-Neutral Scenario (CNS), in which CO_2 emissions in the region are reduced by 85% by 2050 compared to emission levels in 1990. Within this strategy, some Nordic countries would achieve a carbon-neutral energy system by 2050 (IEA, 2013). In this master's thesis, the energy system covers electricity and combined power and heat generation. The Nordic energy system in the thesis consists of Denmark, Finland, Norway and Sweden and is considered to be carbon free by 2050. The energy system in this scenario consists of renewable energy generation and nuclear power. Nordic electricity generation is currently dominated by traditional renewables i.e. hydropower, especially in Norway, Sweden and Iceland. Denmark and Finland still rely quite heavily on fossil fuels and in order to achieve a carbon free energy system, these countries need to replace fossil fuelled power generation with alternative generation methods, namely by increasing the share of new renewables and nuclear power. The potential for new hydropower in Finland and Denmark is low and the increase in renewables will need to come from other sources like wind, solar and biomass. Figure 9 presents Nordic electricity generation capacity by source in 2010.

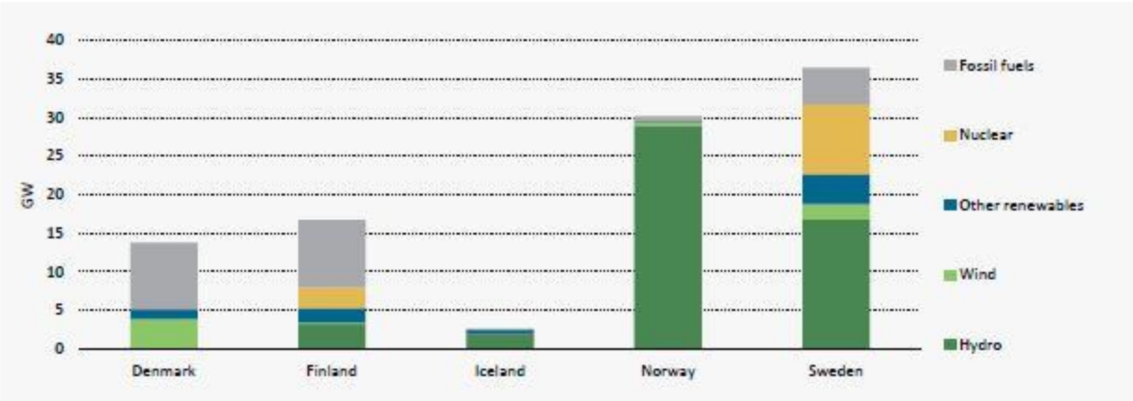

Figure 9. Nordic electricity generation, 2010. (IEA, 2013)

The IEA presents pathways to a carbon neutral energy future in the Nordic countries in its publication Nordic Energy Technology Perspectives, NETP. In this publication, the IEA presents different scenarios and compositions of the Nordic energy system in 2050:

- The 2010 bar graph presents what the electricity mix was in 2010.
- 4DS is a scenario where global temperature increase by 2050 is capped to 4°C. This requires significant changes on a global scale in current policies and technologies. In the Nordic countries, the total primary energy supply increases by less than 5% compared to 2010 and energy-related CO_2 emissions decrease by 29% compared to 1990 levels. Dependence on fossil fuels in the transport sector falls significantly. 4DS the least ambitious NETP scenario.
- 2DS is a scenario describing an energy system that would give an 80% chance of limiting average global temperature increases by 2050 to 2°C. The Nordic

2DS scenario not only transforms the energy sector but also the greenhouse gas emissions in non-energy sectors are reduced.

- CNS means a Carbon-Neutral Scenario. In this vision Nordic CO_2 emissions are reduced 85% by 2050 compared to 1990 levels and international carbon credits are used to offset the remaining 15%. The total primary energy supply decreases by 15% compared to 2010. In addition to transforming the energy system also the non-energy sectors, such as transportation, need to invest in low carbon technologies. These other sectors are not considered in this thesis. In the CNS the Nordic energy system would achieve carbon neutrality by 2050.
- CNBS means a Carbon-Neutral high Bioenergy Scenario. As the name suggests, in this scenario the use of biomass is higher than in other scenarios. The CNBS makes optimistic assumptions about the availability and import costs of biofuels. The transport sector does not use oil in 2050 and the use of biomass and waste in the buildings and construction sectors is higher than in the CNS.
- CNES means Carbon-Neutral high Electricity Scenario. In this scenario, increased electrification and grid integration throughout the Nordic region and between the Nordic and Central European grids are assumed. Net electricity generation is assumed to be 45% higher than in 2010 and electricity generation capacity 50% higher than in 2010. Grid interconnections with Central Europe, Russia and the Nordic countries are facilitated by assuming an additional 11 transmission projects to be built. This would double the number of transmission lines currently available.

Figure 10 presents the Nordic electricity generation mix in 2050 in different IEA scenarios. The Base scenario and composition of the energy system in this thesis is based on the IEA's Carbon-Neutral Scenario, CNS.

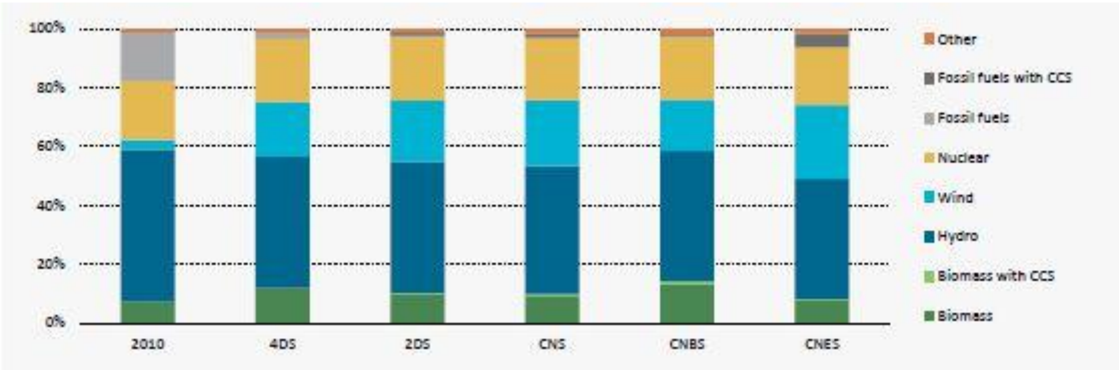

Figure 10. The Nordic electricity generation mix in 2050. (IEA, 2013)

As can be seen from Figure 10, almost 80% of the electricity is generated with renewables and about 20% with nuclear. These shares are indicative and different scenarios and their electricity generation mixes are explained and analysed in chapters 5 and 6.

3.1 Balancing and stabilising the energy grid

The demand for electricity fluctuates throughout the day, week, and season and the demand cannot be evaluated accurately in advance. Fluctuation stems from the natural rhythm of the day; during typical office hours the electricity demand in households is lower than in the evenings and vice versa in the workplace. Generally the electricity demand is lowest during the night. Electricity demand is also greatly dependant on outside weather because heating demand is naturally higher during cold periods and respectively cooling demand is higher during warmer periods. Still, electricity demand is unique from day to day and hard to estimate accurately.

Electricity generators need to react to these load changes. Traditionally, this is achieved with load following plants and peaking power plants, which include hydroelectric, gas turbine or steam turbine power plants. Load following power plants operate at higher output levels during the day and evening when the electricity demand is greatest and they curtail their output during the night. Peaking power plants operate during the times of peak demand. These plants have fast start-up times and their duration of operation varies greatly throughout the year.

In the future energy system, most of the electricity is generated with CO_2-free sources of generation i.e. with intermittent renewable electricity generation and nuclear energy. The possibility to use natural gas, coal or fossil fuelled power plants to balance the power grid is diminished. As an alternative to these, the future energy system uses renewable generation suitable for regulating power (hydro), smart grids, load following nuclear power plants and energy storages to balance the power grid and to meet the challenges of constantly fluctuating electricity demand.

Economically it would be wisest to use hydropower plants as load following or peaking power plants. Hydropower is an excellent source of electricity for balancing the electrical grid as its start-up time is only a few minutes (ÅF Consult, 2012). In some countries, however, there is no hydropower available and other renewable generation sources are not suitable for load following as their power output fluctuates depending on the current weather. Moreover, even hydropower is not immune to weather changes. Norway, Denmark, Sweden, Finland, Estonia, Latvia and Lithuania form a common NordPool Spot electric market. History has shown that in dry years the Nordic countries have become more dependent on thermal and imported power even though Norway has large hydropower reservoirs. These reservoirs are lower or depleted during dry periods and electricity producers have to use more expensive sources of electricity.

In the case of Finland, most of its hydropower plants are run-of-river power plants. These power plants have limited water basins and thus their manoeuvring and adjusting capabilities are limited. The run-of-river plants are capable of high power grid control only for a few hours at time. After long nonstop power adjusting these hydropower plants need to wait for their water basins to fill up. With appropriate flow rates and adequate production need forecasts, the run-of-river hydropower plants are capable of continuous adjustment corresponding to the demand. In Finland, balancing of the electricity grid is mainly done with hydropower, but there problems due to periods of abundant and very small flows in the rivers due to the small size of the water basins. In Finland, water right permits determine the minimum and maximum water levels permitted in the hydropower plant's basin. Hydropower utilities voluntarily restrict the variations in the water levels more strictly than the regulatory limits require, especially in the summer holiday season. This limits the available hydropower available for grid balancing. According to the IEA's Nordic Energy Technology Perspectives (2013), around 60% of the Nordic hydropower capacity in 2050 can be considered dispatchable. Nuclear power and energy storages at least offer alternative grid balancing methods. (ÅF Consult, 2012)

3.2 Smart grid

According to the European Technology Platform's (ETP) SmartGrids document (2010) a smart grid is an electricity network that intelligently integrates the actions of all users connected to it, including generators and consumers, in order to efficiently deliver sustainable, economic and secure electricity supplies. With the introduction of modern information and communication technologies into the power system, the whole power system becomes intelligent and this so-called smart grid would be able to manage supply and demand efficiently (Knab et al., 2009). With smart grids, the flow of electricity from utilities to consumers becomes a two-way conversation as opposed to the one-way conversation that is in use today. A smart grid would incorporate intelligent monitoring, control, communication and self-healing technologies. According to the ETP (2010), the purpose of the smart grid is to:

- better facilitate the connection and operation of generators of all sizes and technologies,
- allow consumers to play a part in optimizing the operation of the system,
- provide consumers with greater information and choice of supply,
- significantly reduce the environmental impact of the whole electricity supply system
- deliver enhanced levels of reliability and security of supply.

Smart grids support greater deployment of variable generation and transmission technologies by providing operators and utilities with real-time system information. This enables them to manage generation, demand and quality of power, which in turn, increases the system's flexibility and helps maintain stability and balance (IEA, 2011). According Knab et al. (2009), the smart grid can be divided to four elements: supply side, demand side, electricity network and energy storage.

3.2.1 Supply side

Future smart grids could have virtual power plants which enhance controllability through diversification. The idea of a virtual power plant is to connect several hundred or thousand distributed and renewable power generating facilities by modern information and communication technology. This virtual power plant has a central control entity that monitors the generation data and is able to connect individual generators in and out of the system at any time. This enables a central control to schedule and optimize the operation of the connected facilities. The object of the virtual power plant is to reach approximately the same controllability and manoeuvrability as with the conventional gas or fossil fuelled power plants, only with carbon free generation sources. There are two elements in virtual power plants that contribute to the achievement of this objective; a well-chosen mix of intermittent generators and the inclusion of selected controllable generators. Of course, these controllable generators will also need to be carbon free in the future energy system in order to comply with greenhouse gas reduction targets. (Knab et al., 2009)

A mix of different types of intermittent generators can offset their inherent unreliability to some extent. The connection of different intermittent systems with different fluctuation patterns can level out the fluctuations in the electricity generation and lead to decreased overall volatility. This logic is applicable to renewable electricity generation. For example, in many regions strong winds and bright sunshine do not typically appear simultaneously and thus, a solar power plant and wind farm complement one another well. Additionally, a virtual power plant may include electricity generators from different regions with different weather conditions to help offset volatility. However, there has to be some generation that can be fully controllable and flexible in case weather conditions simply do not support electricity generation from solar or wind power. (Knab et al., 2009)

The inclusion of selected controllable generators in the virtual power plant can compensate the remaining unreliability. These fully controllable renewable power plants could, for example, be pumped hydro facilities or biogas plants. Nuclear power plants can also offer controllability and grid stabilising services while being a CO_2 free electricity source. The introduction of distributed CHP facilities may challenge the grid operator. Most distributed CHP facilities in Central Europe are run in heat-led operation mode meaning that the operator's need for heat defines the power output. Distributed generation is operated to the benefit of its owner and this often disregards overall system efficiency and reliability. All in all, changes in the distributed CHP plants' operating mode may occur irregularly and spontaneously from the overall system's point of view. When several distributed CHP facilities are integrated into one system, the virtual power plant, the control entity of the system is able and legitimated to shut down certain facilities in case of oversupply. In addition to distributed CHPs in the virtual power plant, the integration of fully controllable renewable sources and manoeuvrable nuclear power plants may compensate the remaining unreliability in the system. (Knab et al., 2009)

In Finland, and the other Nordic countries, CHP plants do not bring same challenges to the grid operators as described above. Finland has one of the world's most efficient and extensive CHP industries and district heating networks. Extraction and condensing CHP plants can be very flexible with their production of electricity and heat, especially when coupled with heat storages (EURELECTRIC, 2014a). The demand for heat and electricity generally go hand in hand in Finland. Many CHP plants in Finland provide heat and electricity directly for industry, particularly for the forest industry, and their fuel inputs (often forestry by-product) and energy demand are strongly correlated with the economic situation. In 2011, the share of CHP in the industry total heat production was 2011 and 75% of district heat produced was cogenerated. Overall, CHP production in Finland has proven to work well. (CODE2, 2014)

Controllability has substantial value in the power market. The power facility can contribute more to the system's stability the more controllable it is and provide regulating energy source. (Knab et al., 2009)

3.2.2 Demand side

The idea behind demand side management (DSM) is to actively influence power consumption and reach a certain degree of controllability on the demand side of the energy system. DSM is based on the underlying assumption that consumers in principle have some flexibility in how and when they use electricity. The consumer may be willing to change his habits when given both incentives and the ability to manage power consumption. The main objectives of the DSM are:

- reduction of demand peaks when power consumption comes close to its limits of availability,
- load shifting from times of high consumption to times of low consumption and
- load shifting from periods of low generation to periods of high generation from volatile sources like wind and solar power. (IEA, 2008; Knab et al., 2009)

Demand Side Management can be differentiated into indirect and direct load control, both of which help to achieve the main objectives listed above.

Indirect load control has incentives that are given to consumers in order to shift their electricity demand according to the energy system's requirements. Consumers still keep full control over their individual efficiency patterns. Consumers' behaviour can be influenced the most efficiently by using price signals. This allows balancing supply and demand with economic market forces. When there is oversupply in the system, consumer prices would drop and thus giving the incentive to shift flexible loads. Oversupply could be the result of heavy winds or bright sun shine increasing the electricity production from renewable generation sources. Respectively, when electricity is in great demand, consumer prices would be increased and consumers would shift their flexible loads to periods of lower electricity prices. (Knab et al., 2009)

Load shifting, or indirect load control, using price signals could be automated to a certain extent. Some devices could process price signals automatically and react to them according to the owner's preferences. For example, a washing machine could be preloaded and programmed to receive and process price signals and it would autonomously decide when to start the wash cycle. Of course the wash cycle could not be postponed indefinitely and some kind of deadline would have to be programmed, but load shifting offers some leeway in regards to costs. Load shifting is already used for example for controlling water storage heaters. In some countries night tariff electricity is cheaper than during the day and water is heated during the night. There are future visions where domestic appliances and home electronics could be capable of communicating with each other, or even in the whole neighbourhood, and coordinate consumption. There are of course some inflexible electrical loads such as general heating for a household. During cold periods there really is no load shifting potential in households using electricity for their heating. Living comfort would decrease considerably if the heating, lighting or cooling need would be determined solely on price of electricity. (Knab et al., 2009)

In direct control, the consumer transfers control over some devices to his utility or grid operator. The consumer would sign up for a demand side management program to allow the utility to switch off or limit power consumption for some devices like pool pumps, water heaters or air conditioning. Direct load control is a more effective way for utilities to influence demand and consumers might be willing to accept a loss of control over some devices for compensation such as cheaper prices or bonuses. According to Knab et al. (2009), industrial refrigerated warehouses could be a strong candidate for direct load control. These warehouses have several well-suited characteristics: they are energy-intensive facilities, the number of processes performed in these facilities is limited and well understood and most refrigerated warehouses are not sensitive to short-term (2 to 4 hours) decreases in power and thus direct control management would not be disruptive to facility operations. Refrigerated warehouses could have a load reduction potential of up to 30% by introducing direct control management, meaning that the warehouses could be allowed to warm up when electricity is expensive and when the electricity price is cheaper they are cooled again. (IEA, 2008; Knab et al., 2009)

3.2.3 Electricity network

Controlling the power flow and linking supply and demand effectively are key factors in the smart grid. In the alternating current (AC) grid, the power flows along the transmission lines from generation surplus areas to load surplus areas. There are generally multiple paths between areas, especially in meshed grids. Electricity usually flows through the lines which have the least reactance to resist the flow. Reactance is a function of the length of a line and thus reactance values typically differ for different lines. The way electricity power is distributed over the network depends on the pattern of generation and load, and the reactance values on the paths between these. For example, power flowing from off-shore wind farms in the northern Germany to load excess areas in the south may not take a direct path, but in part could also flow to the west and east and through neighbouring countries before arriving in the south. This kind of parallel flow is undesirable as the electricity traverses over the country's borders and this may introduce unnecessary political or infrastructural risk to energy security. Parallel flow can be reduced by operating network control devices, such as phase-shifting transformers and flexible AC transmission system devices. Some of these devices modify the composite reactance of a path and since the reactance of the path can be changed, it is possible to change the power flow patterns. Linking geographically separated supply and demand effectively is essential in future smart grids and network control devices can become important elements of the smart grid. (Knab et al., 2009)

3.3 Energy storages

Energy storage is capable of absorbing energy and storing it for a period of time before releasing it to supply energy or power services. Energy storage technologies can bridge temporal gaps between energy supply and demand. Energy storage can be implemented on large and small scales in distributed or centralised manners. Energy storage can store electricity or thermal energy and serve as generator or consumer of energy.

Energy storage technologies include a large set of centralised and distributed designs and energy storage is a technology that can support the decarbonisation of the energy system (IEA, 2014b). Large-scale energy storage is generally regarded as an option for providing additional flexibility for balancing the power grid and for facilitating the integration of intermittent renewables. As stated before, the supply and demand in the power supply needs to match at every given moment. Energy storage eases this constraint. In periods of oversupply, storage devices artificially create additional demand and during periods of high demand, they act as energy suppliers. However, the cost of energy storage should be included in the intermittent generation cost estimates, especially if the energy system does not have any other elements to offset the fluctuating nature of wind or solar power and energy storage is required in order for the system to work. According to F. & M. Genoese (2013), the role of energy storage in the future energy system is debated as the economic viability of large-scale energy storage technologies is uncertain due to their high capital cost and decreasing price spread between peak and off-peak hours in recent years. However, the situation could be reversed in the future when more intermittent renewables enter into the system.

According to the International Energy Agency (2014b), large-scale thermal storage technologies are competitive for answering heating and cooling demand in many regions. The IEA deems also some smaller-scale electric battery systems as cost competitive or nearly competitive in remote communities and off-grid applications. Table 5 presents the conversion efficiencies of some different types of energy storage which vary depending on source. The storage technologies in Table 5 have different uses in regards to their discharge times (Figure 11) and they are at different stages of development and deployment (Figure 12). (IEA, 2014b)

Table 5. Conversion efficiencies of some forms of energy storages. (Ibrahim et al., 2007; IEA, 2014b)

Technology	Conversion efficiency (Ibrahim et al., 2007)	Conversion efficiency (IEA, 2014b)
Pumped-Storage Hydropower (PSH)	65-80 %	50-85 %
Compressed Air Energy Storage, underground (CAES)	70 %	27-70 %
Small-Scale Compressed Air Energy Storage (SSCAES)[5]	50 %	-
Flow Battery Energy Storage (FBES)	75 %	-
Flywheel Energy Storage (FES)	85% instantaneously 78% after 5h 45% after 24h (friction losses)	90-95 %
Superconducting Magnetic Energy Storage (SMES)	95% instantaneous efficiency	90-95 %
Supercapacitors	95%	90-95 %
Electrochemical batteries (Li-Ion, NaS, lead-acid)	-	75-95%

[5] SSCAES conversion efficiency when the system uses an electric compressor which can be turned into a generator during retrieval. The SSCAES system here has pressure of up to 300 bars compared to CAES which has a pressure of up to 100 bars. (Ibrahim et al., 2007)

Energy storage can be differentiated on the basis of storing and discharging times and the capacity of the storage. Figure 11 presents the discharge time at rated power for different forms of storage. Also the storage applications are shown.

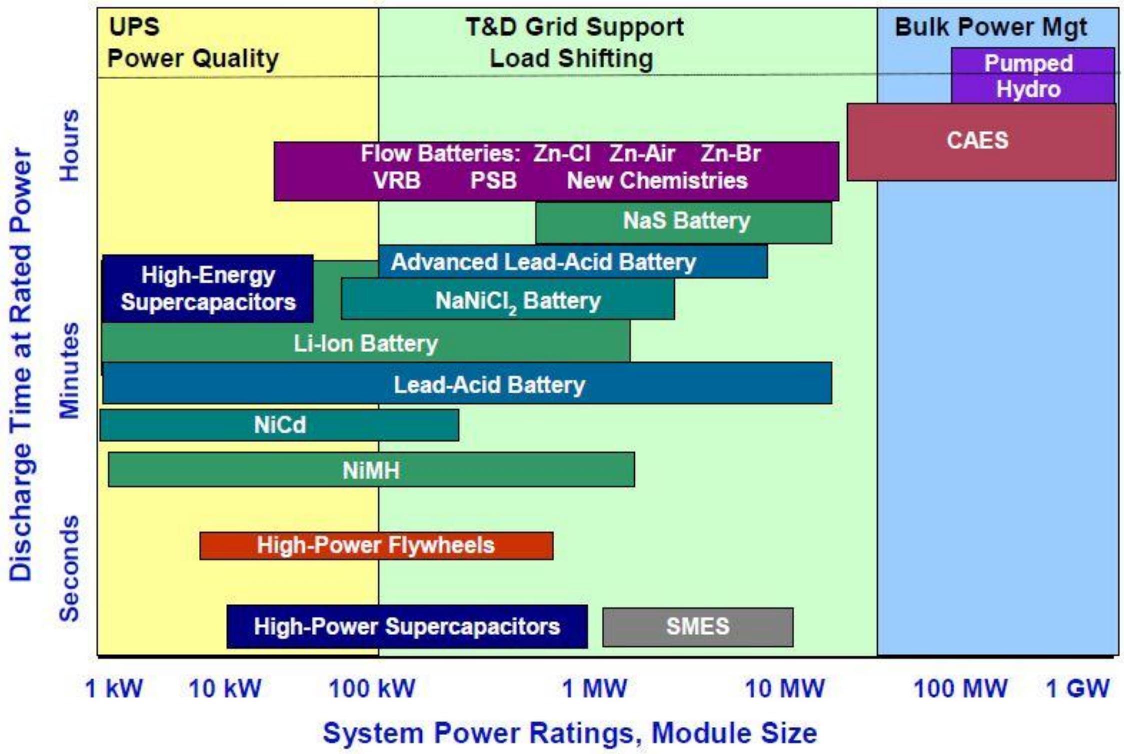

Figure 11. Discharge times of different forms of storage. (Sandia, 2013)

Electricity and thermal storage exists at many levels of development; from the early R&D stages to mature, deployed technologies. Figure 12 visualises this in respect to their associated initial capital investment requirements and technology risk versus their current phase of development (IEA, 2014b).

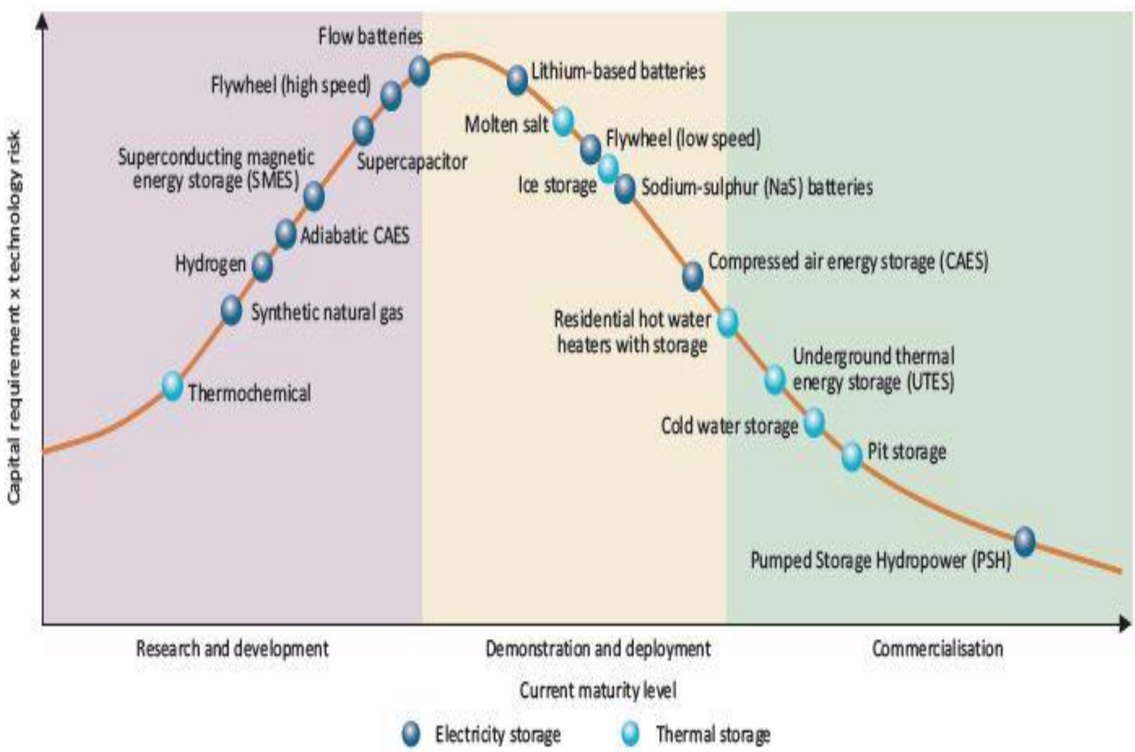

Figure 12. Maturity of energy storage technologies and their related capital requirements and technology risks. (IEA, 2014b)

IEA (2014b) estimates that 310 GW of additional grid-connected electric storage capacity would be needed in the United States, Europe, China and India, in order to support the electricity sector's decarbonisation. In addition to grid-connected electric storage, thermal and off-grid electric storage offers significant potential.

Energy storage in general helps to facilitate the effective utilization of intermittent renewable energy sources, and can enhance grid reliability, increase end-use sector electrification (e.g. transport sector) and reduce the need for increased peak generation capacity. However, storages require additional infrastructure and space, some of the energy is lost in round trip inefficiencies and some energy storage technologies are still cost prohibitive, such as thermochemical energy storage and electrochemical capacitors. The United States Department of Energy has identified four key barriers that should be explored to promote the widespread deployment of energy storage:

- Cost competitive energy storage systems. The total cost of storage systems (all the subsystem components, installation, etc.) need to be cost competitive with other options available to utilities.
- Validated performance and safety. For example, significant uncertainties exist over the usable life of batteries and the length of time that a form of storage can generate revenue.
- Equitable regulatory environment. Consistent pricing or market plan for grid storage does not exist.
- Industry acceptance. System operators have limited experience in using storage resources. (DOE, 2013)

3.3.1 Electricity storages

High-power electric storage technologies, such as electrochemical batteries, capacitors, flywheels, superconducting magnetic energy storages (SMES) etc., aim at supplying the electricity system with large amounts of power on short notice. These forms of storage are applicable for fast-response voltage and power quality management, but only for a short time, up to a few seconds or minutes. Fast response times make these types of electric storage ideal for regulating network stability i.e. load levelling and for this purpose their short uptime is not a problem. Electric storage is suitable for intra-hour regulating of the electric network and can be used to introduce more load or energy to the network. In some cases these types of electric storage can respond more quickly or cheaply to the changes in network power balance than more traditional regulating power plants, for example when gas or steam turbines are shutdown and they need to be cold started. Moreover, larger storage projects with these technologies are under consideration. SMES with a capacity of 5 000 to 10 000 MWh would require very large coils, several 100 meters in diameter, in order to generate the required electromagnetic forces. This would of course mean that they would have to be installed underground to limit infrastructure costs.

High-power storage devices are used to react to abrupt demand peaks or power drops to ensure the stability of the grid and uninterrupted power supply. High-power storage can be used to maintain the voltage level during the start of the emergency generators (bridging power). For example, the start-up time of an open cycle gas turbine is between 10 to 20 minutes meaning that CAES or pumped-storage hydropower could be used during this time as these both have long enough discharge times (up to some hours) and power ratings (100 MWe to 1 GWe). (IEA, 2008; Ibrahim et al., 2007)

Electric storage technologies can be divided roughly into two size categories. Pumped-storage hydropower (PSH) and CAES can have sizes over 100 MWe, while fuel cells, electrochemical batteries and flow batteries are in the range of few kW to 10 MW. Discharge rates of PSH, CAES and flow batteries are measured in hours while other forms of electric storage have significantly shorter discharge rates at their rated power. Generally, storing and discharging electricity over longer time periods sacrifices efficiency and response times. High-energy storage is used in daily cycles for economic gain and it shifts some electricity production. PSH plants can also be used for short term storage and balancing if the rated power is large enough in relation to the energy storage capacity. (IEA, 2008; Gimeno-Gutiérrez & Lacal-Arántegui, 2013)

Li-Ion batteries are perharps the most interesting electrochemical battery technology as it has higher energy density than many other electrochemical batteries, short response times in the order of 20 milliseconds and their round trip efficiency is high (85-95%). Li-Ion batteries have become a popular choice for electric vehicle and aerospace applications and interest in demonstrating the battery's potential to perform utility functions has increased. Li-Ion batteries can provide, for example, peak shaving, photovoltaic smoothing and time shifting services for the grid in respect to renewables. Li-Ion batteries have disadvantages as well. The expected lifetime of a battery is related to the cycling depth of discharge, meaning that Li-Ion batteries should not be used in applications if full discharge is required. Over discharging or overcharging can result in thermally unstable metal oxide electrodes and the battery is subject to thermal runaway if left unchecked. Li-Ion batteries have high production costs and they are sensitive to over temperature, overcharging and internal pressure build-up. (DOE, 2013; Carnegie et al., 2013)

When the capital costs of the energy storages is taken into account, pumped hydropower and compressed air energy storage are the cheapest methods per charge/discharge cycle. The problem for these storage technologies is that they need to be installed at specific sites. The biggest storage batteries are built from the best-known technologies, i.e. Li-Ion, lead-acid and Ni-Cd. However, batteries generally have limited depth of discharge. Flywheels are deemed to be suitable for power quality systems or for short maintenance of power because they have limited energy storage time due to their high frictional losses. Flow battery is a rechargeable electrochemical battery which has two chemical components dissolved in liquids. Liquids are stored in tanks and these tanks are separated from one another by a membrane. Flow batteries have a slow discharge rate, can be used in energy management and have lower replacement costs, since only the tanks have to be refilled. Other batteries need to have the whole system replaced. Flow batteries have lower energy density than electrochemical batteries and their design is complicated and not mature for commercial scale development. (DOE, 2013; IEA, 2008)

3.3.2 Thermal energy storages

Thermal energy storage uses stored energy for heating or cooling purposes. These forms of thermal storage can be grouped by storage temperature: low, medium and high. Thermal storage technologies are suited for both the supply and demand side portion of the energy system. According to the International Energy Agency (2014b), heating and cooling requirements represent 45% of the total energy use in buildings and demand side energy storage can represent significant value to the energy system. Some thermal energy storage technologies have already been deployed to a significant extent in electricity and heat networks, such as in UTES systems (Underground Thermal Energy Storage) and ice storage systems for residential cooling. Research and development of thermal energy storage is primarily focused on cost efficiency for high-density storage, including thermochemical processes and phase-change material development. Thermal storage facilities reduce the operation of peak load boilers and help to avoid costly restarting processes. (IEA, 2014b)

In Finland, there are a number of short-term thermal storage solutions in use and their energy efficiency in short-term operation is over 90%. For example, in Oulu there is a rock cave, which has been modified for thermal energy storage for the district heating system. Previously this cave was a stockpile for liquid fuel. Thermal energy storage is especially relevant in the case of Combined Heat and Power (CHP). Many of these CHP plants prioritise heat demand in their production and the production of electricity depends on the production of heat. Heat storage brings flexibility to the CHP systems. (ÅF, 2012)

3.4 Combined Heat and Power as part of the energy system

Combined Heat and Power (CHP) or cogeneration, is an energy generation process that transforms primary energy into both thermal and electrical energy. Thermal energy is used in heat applications such as district heating or as process heat for industry and the generated electricity is used locally or fed into the grid. District heating systems commonly distribute heat as pressurised water while the industrial process heat is usually distributed and used as low-pressure steam. Figure 13 presents a traditional condensing power plant and a condensing power plant with two different CHP technologies: back pressure and extraction. (EURELECTRIC, 2014a)

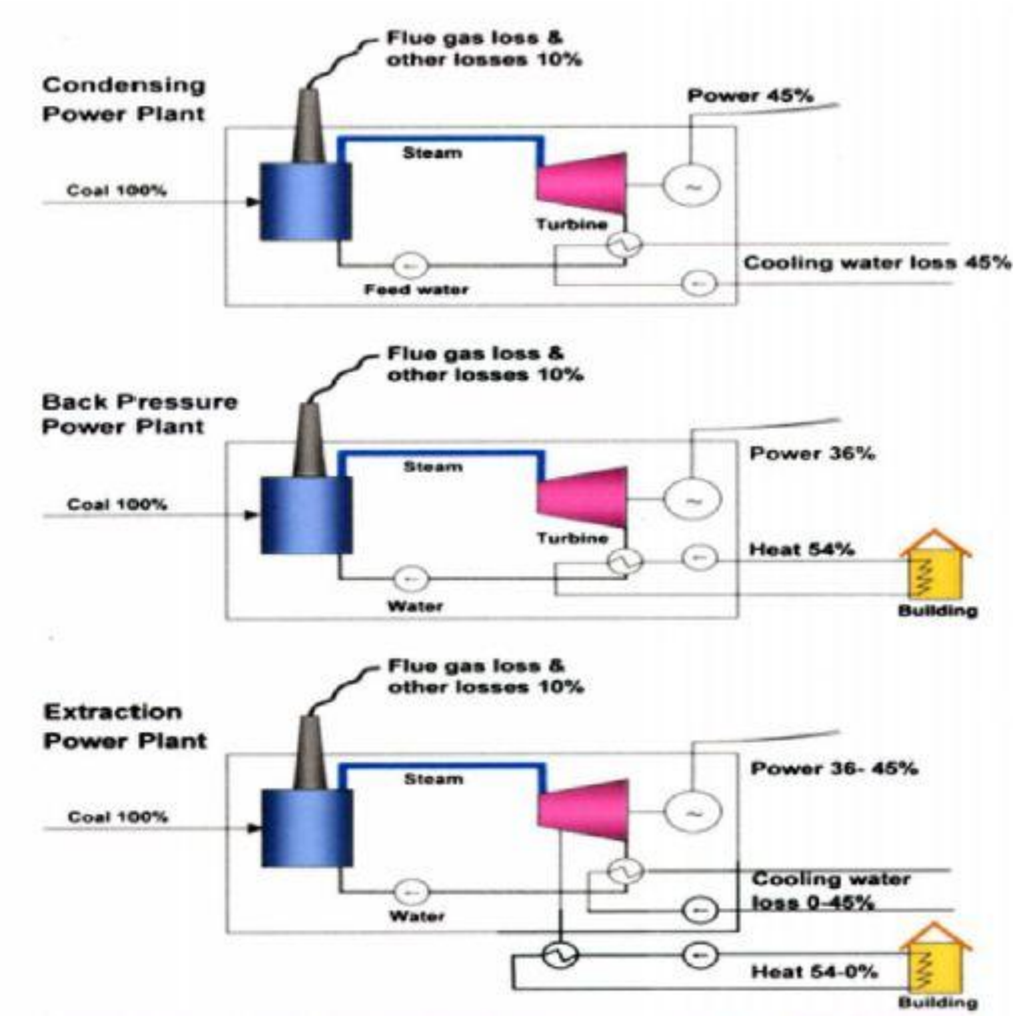

Figure 13. Condensing power plant with and without CHP technologies. (EURELECTRIC, 2014a)

The Union of the Electricity Industry, EURELECTRIC, sees Combined Heat and Power as an important element of Europe's transition to a more diverse and low carbon energy mix. EURELECTRIC has committed to make Europe's electricity cleaner and they envisage carbon-neutral electricity in Europe by 2050. One way to achieve this, in addition to renewables and nuclear power, is the improvement in energy efficiency. A condensing plant without CHP technology loses the residual heat released while producing electricity. A CHP plant utilizes this heat and thus increases overall plant efficiency. This effect is illustrated in Figure 13. According to EURELECTRIC, a well-designed CHP plant can achieve up to 90% efficiency in suitable applications, which is a major improvement in efficiency when compared to the separate production of electricity and heat. High efficiency saves primary energy and contributes to low carbon dioxide emissions. (EURELECTRIC, 2014a)

CHP plants usually operate as base-load plants and electrical power generation depends largely on the demand for heat or steam. Back pressure CHP plants have a fixed ratio between heat and electricity production, meaning that if the heat or electricity output has to be adjusted, the other's production is also changed. An extraction CHP plant is more flexible as the ratio between heat and electricity can vary significantly. Many CHP plants are able to generate electricity regardless of heat demand by using additional cooling. The largest district heating systems have amounts of large water storage which act as heat storage or batteries. When combined with thermal energy storage, CHP provides flexibility to the power system. (ÅF, 2012; EURELECTRIC, 2014a)

Thermal energy storage can increase the operational flexibility of CHP plants by enabling the decoupling of the heat demand and the requirements of the electricity. Together with electric storage in CHP facilities, thermal storage could enable higher levels of participation in balancing power markets. In the context of district heating, the thermal storage stores heat in the form of hot water in tanks. These tanks are either atmospheric storage systems or pressurised systems and they have heat storage capacities of 10 MWh up to 2 GWh per load cycle. Atmospheric storage facilities have comparatively lower investment costs than pressurised ones, but pressurised storage technologies show a 30% to 40% higher specific storage capacity per volume, meaning that they store more heat in the same volume than atmospheric systems. (IEA, 2014b)

In Finland, CHP district heating contributed 21% of electricity generation in 2011 and about half of the heat required in housing for the entire country. CHP in industry contributed 15% of Finland's electricity generation in 2011. With CHP generation, it is possible to use variety of fuels. The main fuels used in CHP generation in Finland are coal, peat and gas. In the future CO_2-free energy system, CHP will use renewable energy sources or possibly nuclear cogeneration. Biomass CHP for district heating is an excellent option for increasing the share of renewable heating in cities. (ÅF, 2012; EURELECTRIC, 2014a)

3.4.1 **Nuclear cogeneration**

Carlsson et al. (2011) evaluate the economic viability of small nuclear reactors in future European cogeneration markets. CHP reactors can support the European Union's low carbon society goals. The European heat market is very large and so is the potential for nuclear cogeneration. In 2010, approximately 30% of the heat demand for industrial applications was provided by cogeneration and the remainder by boilers and burners. Small nuclear reactors supporting cogeneration may be suited to support existing process heat markets as the smaller sizes of the reactors align well with the capacity requirements of process industries.

There has been interest in small and medium sized reactors as these reactors have simpler designs and more affordable economics. In the future energy system with more small scale and intermittent renewable generation, small and medium reactors have the potential to become important aspects of the energy system. These reactors may be better suited for flexible generation or even cogeneration needed to balance renewable power generation. The market potential for small and medium sized reactors is promising but varies between EU member states. (Carlsson et al., 2011)

Industrial applications require a wide range of thermal energy; from low (<100 °C) and moderate temperatures (100-400 °C) to very high temperatures (>1000 °C). Relatively small sized reactors (<300 MWth) have the capability of supporting processes in 200-550 °C temperature range. Some examples of applicable industrial processes or industries suitable for nuclear cogeneration are:

- The chemical industry produces a wide array of end products and thus, requires a wide range of temperatures. Chemical companies in big clusters typically use fossil fuelled CHP for part of their heat supply. For example, ethylene production is a very energy intensive process that appears suitable for nuclear cogeneration.

- Refineries are a major consumer of heat and steam. Most of the processes require process heat with temperatures below 550 °C (hydrogen production by steam methane reforming excluded). At the time of writing, refineries primarily use oil and gas for heat and electricity production. Heat not provided through recycling comes from fossil cogeneration plants, but carbon-free nuclear cogeneration is a feasible alternative.
- Biomass drying and torrefaction[6] uses process heat in the temperature range of 200-300 °C. Processed biomass can either be used as fuel (co-fired with coal) or to produce synthetic transportation fuel. The temperature range is well suited for nuclear cogeneration. (Carlsson et al., 2011)

Nuclear cogeneration, similar to traditional nuclear generation, requires large upfront capital investment. This makes it suitable for industries and processes with continuous and high (in volume) heat demand. In addition to the processes listed above, district heating with nuclear cogeneration could be attractive in the future. Nowadays, the majority of nuclear power plants focus on generating electricity in base-load operating mode and the residual heat is wasted. According to Carlsson et al. (2011), cogenerating nuclear reactors may be competitive against coal- and gas-fuelled CHP plants, particularly if carbon constraints and fuel uncertainties continue driving up costs in these markets in the future. Small reactors have no carbon emissions from operations and fuel cost increases have low impact. Carlsson et al. omitted CHP plants using renewables (e.g. biomass) from their study and compared nuclear cogeneration only against fossil-fuelled CHP plants. (Carlsson et al., 2011)

[6] Torrefaction is a thermal process used to produce high-grade solid biofuels. Solid biomass is heated to a temperature of approx. 250-350 °C. Heating is done in the absence of oxygen (or drastically lower levels of oxygen) and the torrefaction process leads to a loss of moisture and partial loss of the volatile matter in the biomass. The biomass material becomes brittle and easy to grind. (IEA, 2012b)

There is some experience of operating nuclear district heating and extracting process steam. In Switzerland, residential buildings and industries near nuclear power plants of Mühleberg, Beznau 1 & 2, Leibstadt and Gösgen utilise the heat produced in these plants (Schmidiger, 2013). The Beznau power plant makes 80 MW of heat available to industries and homes with over a 130 km long network serving 11 towns. The potential energy reaches up to 2.5 PJ/yr. In Russia, several reactors supply district heating (a total of over 11 PJ/yr). Commercial nuclear reactors in the Leningrad II site will provide 9.17 PJ/yr. of district heating once their operation begins (due in 2018). (WNA, 2015)

Studies and previous experiences show that nuclear cogeneration is a feasible option for district heating and generating process heat for industries. Utilization of nuclear cogeneration depends on whether other cogenerating plants using fossil fuel are abandoned. Industries and households will need heat in the future also. Nuclear and renewable CHP generation could replace fossil fuelled CHP.

4 ENERGY SYSTEM MODEL

4.1 Model overview

The future energy system in the Nordic countries in 2050 is studied and analysed by constructing a basic model representing the energy system in the Nordic countries. The model is based on Olli Paukkeri's model which studied the German energy system in the future with 50%, 80% and 100% shares of renewables and the role of energy storage in each case (Paukkeri, 2013). The energy system in this thesis is different and also contains nuclear power so some modifications had to be made.

The model uses real 2013 Nordic load data from Nord Pool Spot. Every hour of the year has a load value, i.e. how much electricity was consumed in any given hour in the Nordic countries in 2013 and the model has 8 760 rows, one for every hour of the year. According to the data from Nord Pool Spot, the load in Nordic countries in 2013 was about 380 TWh while the IEA estimates that the Nordic countries will have a combined load of between 430 and 450 TWh in 2050, depending on scenario (Nord Pool Spot, 2013; IEA, 2013). The 2013 load data is scaled up by a factor of 1.13 to achieve the anticipated load in 2050 presented in NETP. The load demand is then satisfied with different types of electricity generation in a particular order. This order depends on short-run marginal costs for different types of generation in today's market but it also depends on the adjustability of the electricity generation sources. The scenarios analysed with the model and different types of generation used are explained in the following chapters. The model logic is illustrated in Figure 14.

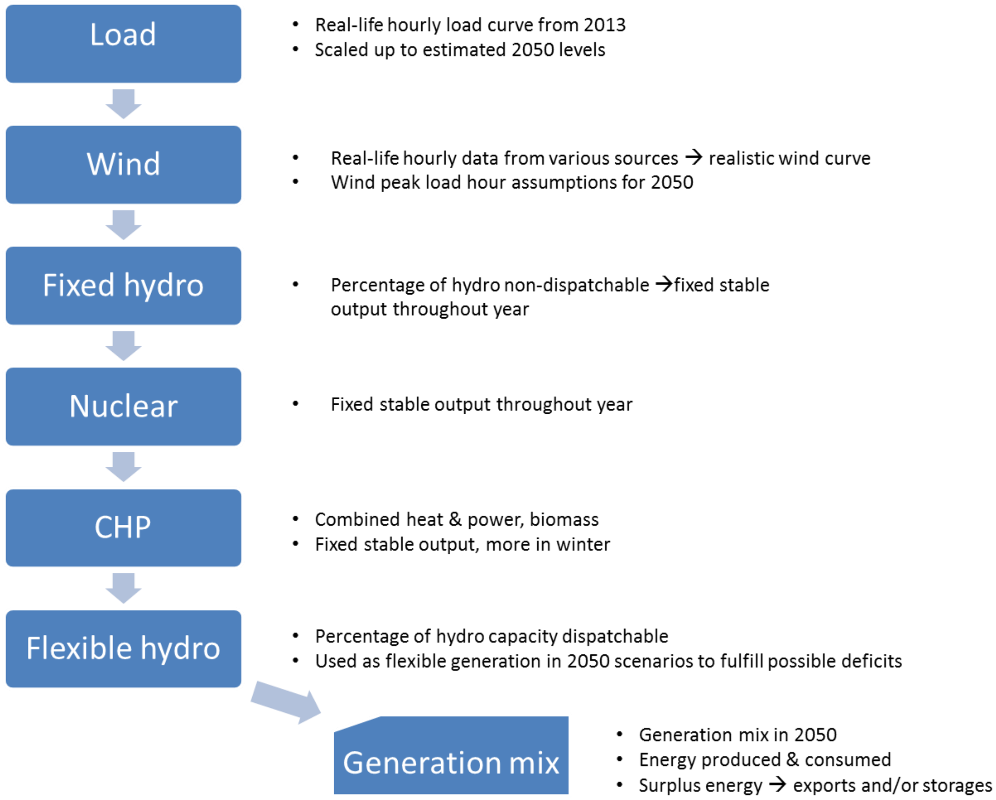

Figure 14. Illustration of model logic.

The Nordic grid connections between Denmark, Finland, Norway and Sweden are considered to be more than adequate in 2050, meaning that Nordic countries and their electricity grid is considered as a single unit. International grid connections, possible heat storage and the geographic distribution of wind generation are not directly analysed in the model. In all future scenarios, both the IEA's and the ones analysed in the model, growth in electricity generation outpaces electricity demand in the Nordic countries, implying a rise in the net exports from the Nordic region.

4.2 Generation mix in the future energy system

The generation mix used in the model is based on the IEA's scenarios found in their publication Nordic Energy Technology Perspectives, NETP. Figure 10 shows different IEA scenarios found in this publication and the Base scenario in the model is based on the CNS scenario. As mentioned before, the future energy system in this thesis contains only renewable and nuclear generation; wind, hydro, biomass and nuclear. The estimated net electricity generation in 2050 by scenario is presented in Figure 15.

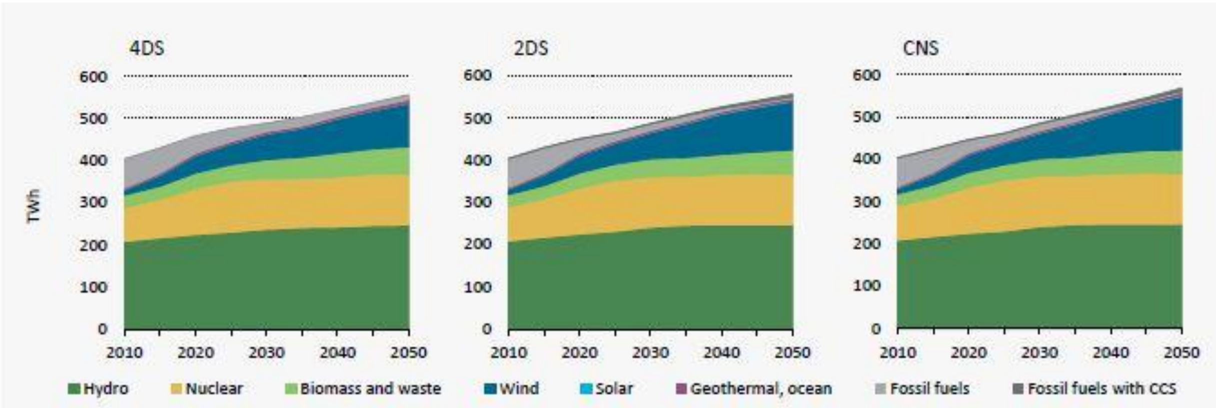

Figure 15. Nordic net electricity generation in 2050. (IEA, 2013)

The total energies presented in this figure are not accurate but offer a good basis to construct the generation mix for the model together with Figure 10 and the NETP document. The CNS scenario still has some fossil fuelled generation, opposed to none in the model, and about 2 GW of solar capacity. Solar generation is also neglected in the model as its capacity in 2050 is estimated to be only 1.4% of the total capacity and there was not such extensive solar data available as there was for wind data in the Nordic countries. The lack of data meant that it was not possible to construct a similar hourly production curve for solar as was done with wind generation. This production curve is essential in order to gain realistic wind or solar power curves because their outputs fluctuate throughout the year depending on weather conditions. Table 6 presents the amount of energies produced and capacities for different sources of electricity found in the Nordic Energy Technology Perspectives and the ones used in the Base scenario in the model. The majority of the NETP values are estimated from different figures.

Table 6. Capacities and corresponding energies and shares for different electricity generation sources. (IEA, 2013)

	Base scenario in the model			**Nordic Energy Technology Perspectives**		
Electricity source	Share of total energy	Net electricity generation [TWh]	Capacity [GW]	Share of total energy	Net electricity generation [TWh]	Capacity [GW]
Wind	26 %	131	40	23 %	130	40
Hydro	38 %	193	65	41 %	230	60
Nuclear	24 %	122	16	23 %	120	16
Biomass	12 %	60	12	11 %	50	12
Other	0 %	0	0	2 %	20	14
Total	100 %	506	133	100 %	550	142

The base model was constructed by choosing capacities and peak load hours for different electricity generation sources. Net electricity generation is the product of peak load hour and capacity. Capacities are based on the Nordic Energy Technology Perspectives and the peak load hours are either estimated or based on the literature. Details of the each generation source are explained later in the thesis. The goal was to obtain shares of different electricity generation sources close to those presented in the NETP. The shares and electricity generation estimates are not exactly similar to those of the NETP due to real-life limitations such as including realistic values for peak load hours and the estimated share of dispatchable hydropower generation. As mentioned before, the NETP also still has some fossil generation present in its scenarios and no fossil fuelled generation is present in the 2050 scenarios in the model. Overall, the generation mix in the Base scenario is fairly close to the generation mix presented in the NETP even though overall electricity generation is lower.

4.3 Wind power

Hourly output data in 2013 for the Nordic wind power was extracted from various sources. Danish wind production data was obtained from the website of the state owned public enterprise Energinet.dk (Energinet, 2014). Installed wind power capacities at the beginning and the end of 2013 were obtained from Danish Energy Agency (DEA, 2014). Swedish hourly wind data was obtained from the Svenska Kraftnät's website. Svenska Kraftnät is a state-owned public utility and one of its main tasks is managing the national grid of Sweden (Svenska, 2014). Installed wind power capacities in Sweden were obtained from the website of Swedish Wind Energy, which is a trade association for companies working with wind power (SWE, 2014). Norwegian hourly wind data was obtained from the website of Norwegian Water Resources and Energy Directorate (NVE, 2014). Installed wind power capacities were obtained from the IEA Wind website (IEA Wind, 2014). No hourly data for wind power production in Finland was found. The Finnish wind power profile for the year 2013 was constructed by downloading monthly production data from the ENTSO-E website and dividing the monthly production by number of hours in the given month (ENTSO-E, 2014). This method gives a rough wind production profile for Finland over the year 2013 as the profile is unrealistic and linear between the months. However, Finland's share of the total Nordic wind production in 2013 was only about 3%, so the method described does not produce too much error in the overall Nordic wind profile. Installed capacities were obtained from the VTT Technical Research Centre of Finland wind energy statistics website (VTT, 2014).

Installed capacities at the beginning and end of 2013 were linearly interpolated in order to calculate the installed capacity for every hour of the year. Peak load hours were calculated by dividing the hourly generation by the hourly installed capacity. The peak load hours for Sweden, Denmark and Norway were close to each other as their values were between 2 446 and 2 472 hours. Finnish wind power had 2 160 peak load hours in 2013. The Nordic wind profile in 2013 was finally obtained by summing the hourly installed capacities and hourly production data of all the Nordic countries over the year

2013. The Nordic wind profile had 2 448 peak load hours and a nominal capacity of 10.45 GW.

These values are for 2013 and the peak load hours need to be modified for the year 2050 in order to take into account better windmills and turbines, larger wind farms and the possibly larger share of offshore wind power. The combined Nordic wind profile has 2 448 peak load hours but this profile also contains the data from older wind farms. In this thesis, it is assumed that in 2050, all the onshore wind power in the Nordic countries will have been refurbished or newly built and they will have 2 600 peak load hours. This estimation is supported by analysing the Swedish wind data, which shows that the newer wind farms with capacities over 2 MW had an average of 2 614 peak load hours in 2012 (Vindstat, 2014). The source did not have data for the full year for 2013.[7] The European wind resources map shows that all the Nordic countries have sites with good onshore wind conditions (AWS Truepower, 2012).

Offshore wind power usually has much better peak load hours than onshore wind power. Offshore wind conditions are fairly similar in Nordic countries. Each country has access to potential offshore wind farm sites with similar wind speed conditions as can be seen from the European wind resources map (AWS Truepower, 2012). According to Danish Energy Agency (2014), good wind conditions at the chosen sites allow offshore wind farms to produce for around 4 000 full-load hours a year. Germany also has similar offshore wind conditions as the Nordic countries have. Alpha Ventus, a German offshore wind farm with a 60 MW capacity, had 4 450 peak load hours in its first full year of operation in 2011 (Alpha Ventus, 2012). In this thesis, it is estimated that Nordic offshore wind farms will have 4 500 peak load hours in 2050. This estimation is realistic considering the data from the Alpha Ventus wind farm and the better windmills and turbines of the future. Larger rotors increase the sweep area which

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[7] This wind data shows the monthly production of Swedish wind turbines in the period of January 2002 to April of 2013 and the rated power of these turbines. Peak load hours in 2012 for the turbines with the power of 2MW or greater were calculated. Turbines with missing production data in 2012 were omitted.

in turn boosts the energy yields. Taller towers and increasing the size of the blades allow a turbine to capture more wind, especially at low wind speeds. Advancements in gearboxes, wind predictions (direction, speed, duration) and programming have the potential to improve the reliability of windmills and turbines and prevent them from breaking at higher wind speeds. (EWEA, 2015; EERE, 2015)

At the end of July 2014, about 26% of the Danish wind turbines were offshore turbines (DEA, 2014). In 2020, an additional 1 500 MW of offshore wind capacity will be connected to the grid in Denmark. This would bring the share of offshore wind power to 44% if no new onshore wind power is installed. However, this is unlikely. In the Base scenario of this thesis, the share of offshore wind power in the Nordic countries in 2050 is estimated to be 35%. This value is generally used in the scenarios set to happen in 2050 except for the Similar scenario which uses a lower value of 22%. This lower value is used in order to have a same share of wind power generation from the total generation in 2050 as it was in 2013. For the 2013 scenario, the share of offshore wind power was not needed because the data from 2013 provided real value for peak load hours (2 448 peak load hours). Offshore wind power is more expensive to build and maintain but it also has better power generating values due to better wind conditions than onshore wind power.

The peak load hours for the Nordic wind power production in 2050 were calculated by combining estimated peak load hours and shares of onshore and offshore wind power. With the exception being the Similar scenario, Nordic wind power has 3 265 peak load hours in the scenarios set to happen in 2050. This is 817 hours more than in 2013 and 0.0933 peak load hours were added per hour to the Nordic wind profile. The Similar scenario has 3 018 peak load hours.

4.4 Hydroelectric power

Nordic electricity generation is dominated by hydropower as can be seen from Figure 9 and Figure 20. In 2013, there was about 50.2 GW of hydroelectric power capacity in the Nordic countries, the majority of which was in Norway. This capacity generated 203

TWh of energy in 2013, equivalent to 53% of the overall power generation. In the model, a portion of the total hydroelectric power capacity is dispatchable and the remaining portion non-dispatchable. Some of the Nordic hydropower plants are run-of-river plants with limited water basins and these types of hydropower plants have limited manoeuvring and adjusting capabilities. According to the NETP, around 35 GW of the 60 GW of hydropower capacity in the Nordic countries in 2050 could be considered dispatchable (IEA, 2013). In the Base scenario, 50% of the hydropower capacity in 2050 is considered dispatchable.

Dispatchable hydropower is the flexible element in the model and it responds to the possible electricity deficits with no other limitations than the maximum capacity it has. The peak load hours of dispatchable hydropower are calculated in the model. The non-dispatchable portion of the hydroelectric power produces electricity evenly over the year and its peak load hours are set to 5 500 in the Base scenario. According to the IEA's Hydropower Technology Roadmap (2012), the average capacity factor of a hydropower plant is 50%, equivalent of 4 380 full load hours per year. However, load factors of individual hydropower plants range from 23% to 95%. In this thesis, it is estimated that Nordic hydropower in 2050 has 5 500 peak load hours which equals a higher than average load factor of 63%.

4.5 Nuclear generation

At the time of writing, only Finland and Sweden of the Nordic countries have nuclear generation; 2.7 GW and 9.5 GW respectively (WNA, 2015). It is unlikely that Norway or Denmark will build nuclear power generation in the future. The IEA estimates in the Nordic Energy Technology Perspectives (2013) that the capacity for nuclear generation in Sweden will remain the same in 2050 as it is at the time of writing but they anticipate that Finland's nuclear generating capacity will rise from the current level to 6.4 GW. These same assumptions are used in this thesis and in the Base scenario, meaning that in 2050 Nordic nuclear generating capacity is estimated to be 15.9 GW. Operating licenses for existing nuclear power plants in Finland and Sweden end before 2050. This naturally means that in order to preserve the same level of nuclear generation capacity in Sweden as it is today, new nuclear power plants will need to be build. The same is true for Finland where one new nuclear power plant, Olkiluoto 3, is already under construction.

Peak load hours in 2013 were 7 050 and they were calculated from the Nordic Market Report (2014). Finland's nuclear power plants had much better peak load hours in 2013, at over 8 000, but as the Oskarshamn 2 unit in Sweden has been offline due to modernization and refurbishment, this lowers the overall peak load hours of Nordic nuclear power generation. In the model, peak load hours for Nordic nuclear power generation are set to 7 700. Peak load hours of 8 000 or more would not be too unrealistic. In the Base scenario, nuclear power produces energy evenly throughout the year and nuclear power generation is split evenly over the hours of the year.

4.6 Combined Heat and Power

In the model, all the CHP generation is estimated to be biomass fuelled in 2050. Fossil fuelled CHP is non-existent in 2050, but is present in the 2013 scenario and it is modelled together with biomass CHP. Combined Heat and Power are assumed to follow the heat demand in the Nordic countries and CHP is not flexible in the model. CHP plants feeding different industries are assumed to run evenly throughout the year while district heating is used mainly only in the winter months. Therefore, it is assumed that CHP produces double the amount of energy in winter compared to summer. This essentially means that some of the CHP plants are shutdown during the summer. According to the Nordic Market Report (2014), the Nordic countries had 15.2 GW of CHP capacity (5,2 GW industrial) in 2013.

4.7 Flexible fossil generation

According to the IEA's NETP (2013), there would be 8 GW of operational gas capacity in 2050, but it would be used only at a low load and full hours to provide additional flexibility. In this thesis it is envisaged that in 2050 there will be no fossil generation in the Nordic countries. Flexibility in the Base model is provided by dispatchable hydroelectric power. In 2013 there was 12.1 GW of non-CHP thermal power generation (NMR, 2014). This value is used in the 2013 scenario as the flexible fossil generation capacity. Peak load hours for this capacity are calculated in the model. Deficits after dispatchable hydropower were fulfilled by flexible fossil generation in the 2013 scenario.

5 SCENARIOS ANALYSED WITH THE MODEL

Some basic scenarios were constructed with the model and they are presented in the following chapter. General observations and results are presented in chapter 6. Table 7 presents installed capacities and shares out of total energy for different electricity generation sources. For electricity storage, the installed capacities and number of hours in which they are used are listed. These hours are called deficit hours in this thesis. Consumed energy is deducted from the generated energy and if the result is negative, energy storage is assumed to be available. The amount of energy used from the storage is small compared to the total energy generated in the Nordic energy system, around 0.8 TWh out of 435 TWh in the Storage scenario and 14 TWh out of 474 TWh in the Low Hydro scenario. Storage is not used as a daily source of energy, instead it is used in the hours when the total energy generated is not enough to satisfy the consumption of the energy. Still, the importance of storage in these specific scenarios should not be underestimated even if the share out of the total generated electricity is small because it has an important role in the hours it is needed. After all, society requires that its electricity demand is satisfied every hour of the year.

Table 7. Generation mix in different scenarios. Installed capacities and shares of total energy for different electricity generation sources. Shares are rounded values.

Electricity source	Base scenario	2013 scenario	Similar scenario	Storage scenario	Low Hydro scenario
Wind	40 GW 25.8 %	9.6 GW 6.1 %	10.5 GW 6.4 %	20 GW 15 %	35 GW 24.1 %
Hydro	65 GW 38.1 %	50.2 GW 53.5 %	65 GW 52.9 %	55 GW 51.9 %	1 GW 0.8 %
Nuclear	15.9 GW 24.2 %	12.2 GW 22.3 %	14.4 GW 22.5 %	12.2 GW 21.6 %	30 GW 48.7 %
Biomass	12 GW 11.9 %	5 GW 6 %	6 GW 6.1 %	10 GW 11.5 %	25 GW 26.4 %
Fossil	N/A	22.1 GW 12.1 %	12 GW 12.2 %	N/A	N/A
Storages	N/A	N/A	N/A	Short :0.5 GW Long: 5/10 GW (input/output) 242 deficit hours	Short: 25 GW Long: 25/40 GW (input/output) 2 414 deficit hours

5.1 Base scenario

As mentioned before, the Base scenario in the model is based on the IEA's CNS scenario found in the Nordic Energy Technology Perspectives. In this Base scenario, the Nordic energy system has about 76 % renewable generation and 24 % nuclear and the whole system is carbon free. The only intermittent element in the system is the large share of wind power. A portion of hydropower is considered non-dispatchable and acts as a base load power source in the system. The total energy of the nuclear power is divided evenly throughout the year reflecting its role as a base load power source in the energy system. There is, however, the possibility to use nuclear power as a flexible power source, but this is not analysed in the Base scenario. Combined Heat and Power, or CHP, is assumed to generate 100 % more energy in winter months (November to April) than in summer months. Energy from CHP is divided evenly over hours of the year. The energy generated by CHP in the model is electricity; heat energy or heat flows in the energy system are not modelled. Finally the remaining hydropower is dispatchable and is the only flexible form of power generation in the Base scenario. Dispatchable hydropower is used when there is an energy deficit in the system and it has no flexibility limitations. Hydropower plants have low [8]warm and [9]hot start-up times ranging from seconds to 1-2 minutes and their power change rate (MW/min) is high.

5.2 2013 scenario

The model was also used to recreate the Nordic energy system in 2013 in order to compare the results of the model to the known real-life situation in 2013. This scenario is called the 2013 scenario in the model and it also includes fossil fuel power generation. The scenario was constructed in order to assess whether the model gives realistic outputs or not. Capacities for different electricity generation sources were

[8] warm start-up = from standby to production
[9] hot start-up = turbine is already rotating

obtained from the Nordic Market Report (2014) and the peak load hours were calculated from the same report.

5.3 Similar scenario

In this scenario, the energy system in 2050 has about the same shares for different electricity generation sources as in 2013. Only now, the total energy produced in 2050 is in line with the IEA predictions and close to 500 TWh. The shares are obtained by choosing such capacities for different electricity generation sources that they produce the predetermined shares of the total energy production. Peak load hours are same as in other scenarios happening in 2050, except for wind power. The Similar scenario uses 3 018 peak load hours for wind power which is lower than in other scenarios set to happen in 2050. This is due to an assumed lower share of offshore wind power in this scenario and this assumption is made in order to keep the wind power's share of the total generation the same as it was in 2013. However, these shares may not be in line with the predictions for the future. For example, wind power capacity is only 0.9 GW more than in 2013. It is highly unlikely that the future energy system in 2050 is the one presented in the Similar scenario. However, the purpose of this scenario was to show how much an energy system with the current generation mix would produce greenhouse gas emissions in 2050 when compared to an energy system with no fossil generation i.e. the system found in the Base scenario.

5.4 Storage scenario

In this scenario, the Nordic energy system has electric storages connected to the grid. In the Base scenario the energy system produces a surplus of energy which could be exported. In the Storage scenario, some of the power generation capacity is replaced with electric storage. In this scenario, how much potential power generating capacity is saved by using electric storage is analysed and from which electricity generating sources this capacity is saved from. The capacity values are chosen and are not strictly based on any scenario or situation in any country. The capacities of different electricity generation sources are estimated in such a way that the overall energy production together with electricity storage can answer to the demands of consumption but the surplus of energy is not as high as the IEA estimates or what it is in the Base scenario. The IEA estimates that the Nordic countries will be net exporters of electricity in 2050 and the Base scenario was constructed accordingly. In the Storage scenario the Nordic energy system is more optimised to the consumption of the Nordic countries and does not generate as much surplus as in the Base scenario.

5.5 Low Hydro scenario

The energy system in this scenario is not strictly based on any real life country, region or any IEA scenario. However, the model uses real data for the Nordic electricity load and thus, also this scenario uses the Nordic load pattern. This means that the largest loads are in the winter months.

The Nordic energy system has significant amounts of hydropower generation available and it has the largest impact on the Nordic energy system. In this scenario, the share of hydropower compared to other generation sources is insignificant. The generation mix and shares of different generation sources are chosen and just one possible combination. The Low Hydro scenario includes electricity generation from wind, nuclear and biomass. Hourly balancing and flexibility is ensured by incorporating energy storage into the energy system. The shares and capacities for different generation sources and storage are selected in such a way that there are no deficits in the system after energy storage. The total electricity generated in this scenario is in line with other scenarios happening in 2050.

6 RESULTS AND ANALYSES

This chapter presents the results and analyses of the different scenarios modelled in the thesis. As the model essentially simulates the hourly power balance in the Nordic system, we can obtain hourly and monthly generation profiles. The model returned generation mixes for each scenario and the produced and consumed energies. Generally, nuclear generation works as a base load in the scenarios. It provides energy evenly throughout the year and, together with other electricity generation sources, replaces the fossil generation used currently. Nuclear power is well suited for systems with large shares of intermittent power generation (e.g. wind power) as it ensures that there is a certain amount of base load capacity available throughout the year regardless of weather conditions.

Inputs and outputs on the model are same for every scenario and they are marked in the model. Of course, the values of these inputs and outputs vary depending on the selected scenario. Table 8 gathers some of the inputs and outputs from the model which are used to calculate hourly consumed and produced energies for different scenarios. The numbers inside the red rectangle are outputs and the other numbers are inputs. Wind assumptions for the 2013 scenario differ from the assumptions made in other scenarios because the model uses real life data from the year 2013. The most important outputs in the model are hourly generation and consumption profiles. The generation mix, the total energies and possible deficit hours are all results of these hourly calculations. As there are 8 760 hours in the year, it is not reasonable to present these outputs here.

In short, most of the capacities and peak load hours are inputs in the model and these are used to calculate hourly consumption and generation profiles. This hourly data is in turn used to form the generation mix and total energies in the system.

Table 8. Inputs and outputs for different electricity sources used in the model. Model outputs are inside the red rectangle.

Model inputs and outputs				Base	2013	Similar	Storages	Low Hydro
			Peakload hours	GW	GW	GW	GW	GW
Wind			2 448-3 265	40	9.6	10.5	20	35
Non-disp. hydro			4 045-5 500	32.5	35.1	45.5	27.5	0.4
Nuclear			7 000-7 700	15.9	12.2	14.4	12.2	30
Biomass CHP			4 600-5 000	12	5	6	10	25
Fossil CHP			4 000-5 000	0	10	12	0	0
Disp. hydro			**400-4 200**	32.5	15.1	19.5	27.5	0.6
Fossil			**530**	0	12.1	0	0	0
Storage, short			**11-643**	**0**	**0**	**0**	**1.5**	**3**
Storage, long ,input			**266-3 980**	**0**	**0**	**0**	**5**	**5**
Storage, long, output			**80-500**	**0**	**0**	**0**	**10**	**24**

Wind assumptions				Base	2013	Similar	Storages	Low Hydro
Capacity [GW]				40	9,6	10,5	20	35
% of offshore wind				35 %	N/A	22 %	35 %	35 %
Onshore capacity [GW]				26	N/A	8,2	13	23
Offshore capacity [GW]				14	N/A	2,3	7	12
PLH, onshore				2 600	N/A	2 600	2 600	2 600
PLH, offshore				4 500	N/A	4 500	4 500	4 500
PLH, total				3 265	2 448	3 018	3 265	3 265
PLH in 2013, from data				2 448	2 448	2 448	2 448	2 448
Added hours to PLH, total				817	0	570	817	817
Added per hour				0,0933	0,0000	0,0651	0,0933	0,0933

6.1 Results of different scenarios

6.1.1 Base scenario

Figure 16 shows the generation mix in the Base scenario. Hydropower has the largest share with 38%, followed by wind (26%) and nuclear generation (24%). Biomass has the smallest share with 12% and is the only source producing industrial and district heat in the Base scenario.

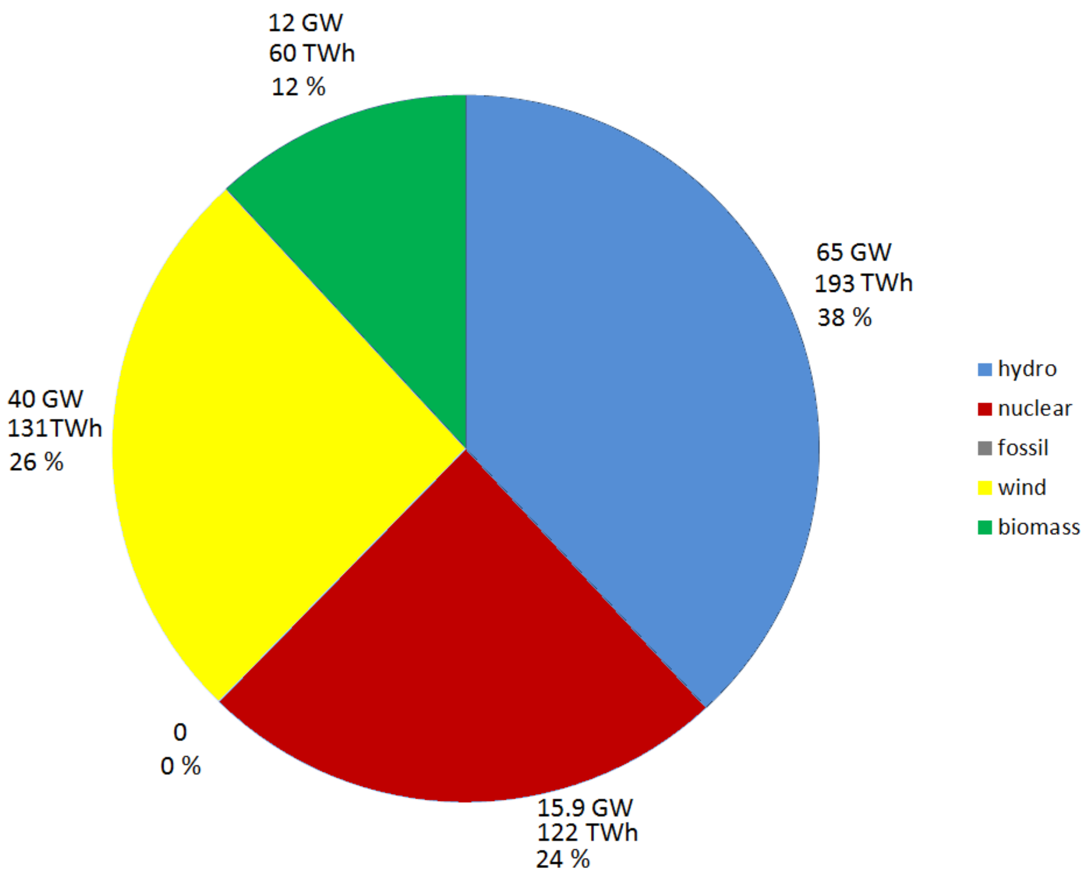


Figure 16. Generation mix in the Base scenario in 2050.

The maximum deficit in the system after wind and base load power sources is about 25 GWh in 16.1.2013 hr. 08-09. The IEA estimates that about 60% of the Nordic hydropower will be dispatchable in 2050. In the model, this value is set to 50% meaning that dispatchable hydropower has a capacity of 32.5 GW. This capacity is enough to fulfil the largest energy deficit in the year. Figure 17 shows the load, dispatchable hydropower and wind generation in a two week period in January.

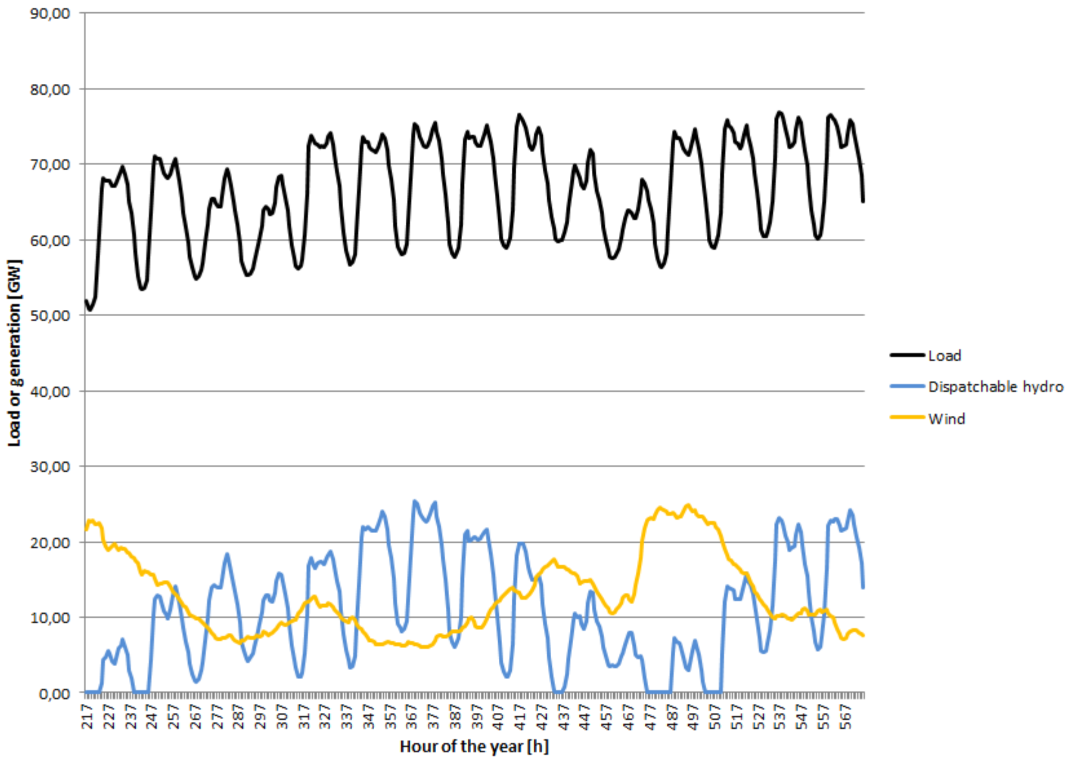


Figure 17. Load, dispatchable hydropower and wind generation in 10.1-24.1.2050 according to the model.

As Figure 17 shows, the dispatchable hydropower follows the demands of the load and wind generation. The load and hydropower curves are similar in shape. The largest deficit of 25 GWh is in hour 369 of the year. The wind generation is low in that hour so the hydropower has to fulfil the load demand. In turn, when the wind generation is better, the need for dispatchable hydropower is reduced. This can be seen for example in hours 217 to 247 and 467 to 507. Overall, Figure 17 shows how dispatchable hydropower works in the model. It compensates for possible deficits which essentially are the combined results of load and wind generation profiles. Other generation sources produce electricity evenly throughout the year. The total generation curve is not shown in the figure because most of it would overlap the load curve. When dispatchable hydropower is not used for generation, there is either an energy surplus in the system or the generation and consumption of electricity are in balance. Figure 18 shows the first week of June, when there is virtually no dispatchable hydropower generation and the energy system produces more energy than the Nordic countries consume. Hours 3 777 to 3 780 show less than 1 GWh of dispatchable hydropower generation each.

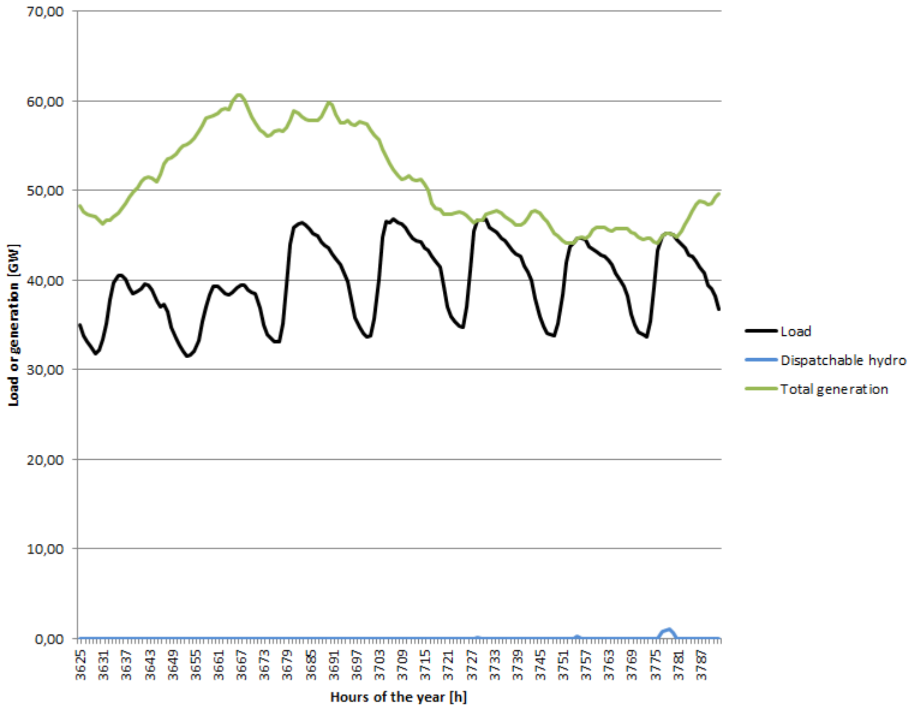


Figure 18. Load, dispatchable hydro and total generation in 1.6-7.6.2050 according to the model.

In the Base scenario for the 2050, the overall electricity generation increases by 30% from 384 TWh to 506 TWh and the generating capacity with about 30 GW. These values are on the same scale as presented in the IEA's Nordic Energy Technology Perspectives. In the Base scenario, the constructed future energy system has a generation surplus of 76 TWh. The IEA estimates that, depending on scenario, the Nordic countries will have a combined net electricity exports between 40 TWh and 100 TWh (IEA, 2013).

In Europe, intermittent wind and solar power are becoming more popular and it is intended that fossil fuelled power generation will be abandoned in many countries, thus the need for regulating power capacity will increase. The large hydropower capacity in the Nordic system is valuable as it can help to regulate the electricity systems in

Northern and Central Europe. Even if overproduction of electricity takes place at the same time in the Nordic countries as well as in Northern and Central Europe, the problem can be alleviated by using energy storage or large dispatchable hydropower capacity in the Nordic countries. Norway has great realisable potential for pumped-storage hydropower (13.3 TWh) and Sweden has potential for 3.1 TWh (Gimeno-Gutiérrez & Lacal-Arántegui, 2013). And as Figure 19 shows, the Nordic energy system has overproduction in most of the months, even in winter. Thus, it seems that the Nordic energy system in the future could produce more energy than it consumes and the surplus energy could be sold to the European market. For example, the regulating power from the Nordic energy system could help the German electricity system which is anticipated to have a major shares of wind and solar power but relatively small shares of hydropower capacity in the future (Paukkeri, 2013).

The monthly generation profile for the Base scenario is presented in Figure 19. The black line represents the load in Nordic countries. The different electricity generation sources are, from bottom to top, in the same order as in the model.

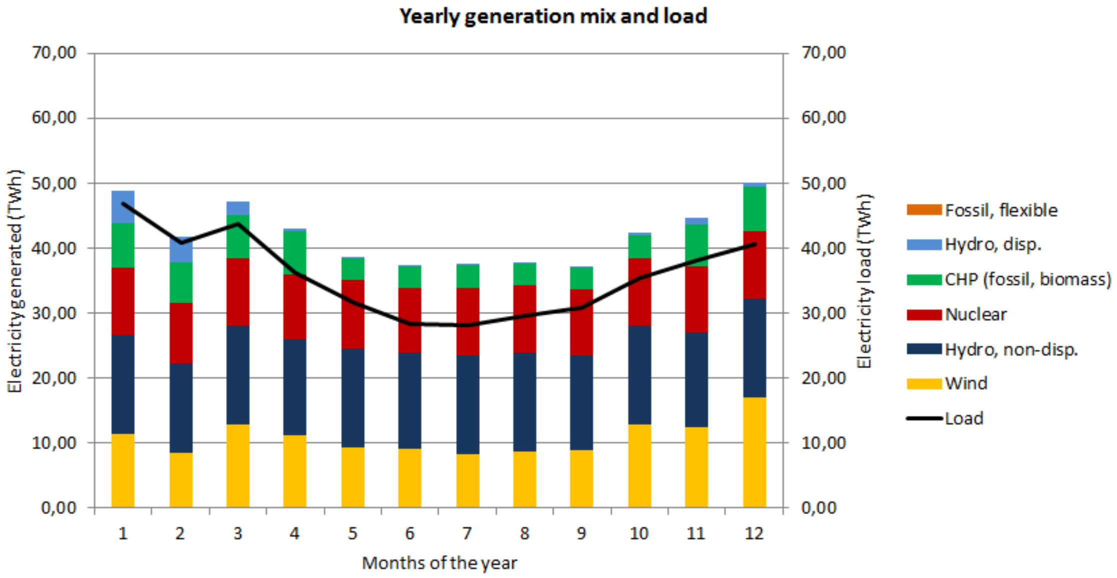


Figure 19. The generation mix and load month to month in the Base scenario.

As can be seen from the figure, wind generation and dispatchable hydropower are the only intermittent electricity generation sources. Non-dispatchable hydro, nuclear and CHP generation have no hourly variation. Nuclear generation and non-dispatchable hydro provide the base load to the energy system. The combined heat and power has twice the generation in winter than in the summer. The Nordic countries have more load in the winter months and therefore dispatchable hydropower is needed to compensate for deficits. Figure 19 shows only one year and wind generation differs from year to year. Still, only a fraction of the potential dispatchable hydro is used and it is safe to assume that even with no wind generation in one month, the load demand in the Nordic countries could be fulfilled. Of course this holds true only when other electricity generation sources such as nuclear and biomass are present in the system.

6.1.2 2013 scenario

The 2013 scenario was constructed in order to assess whether the outputs of the model can be trusted or not. If the 2013 scenario gives somewhat similar results as the known real-life situation was in 2013, the model can be considered to work with sufficient accuracy. Figure 20 shows the power generation mixes in 2013.

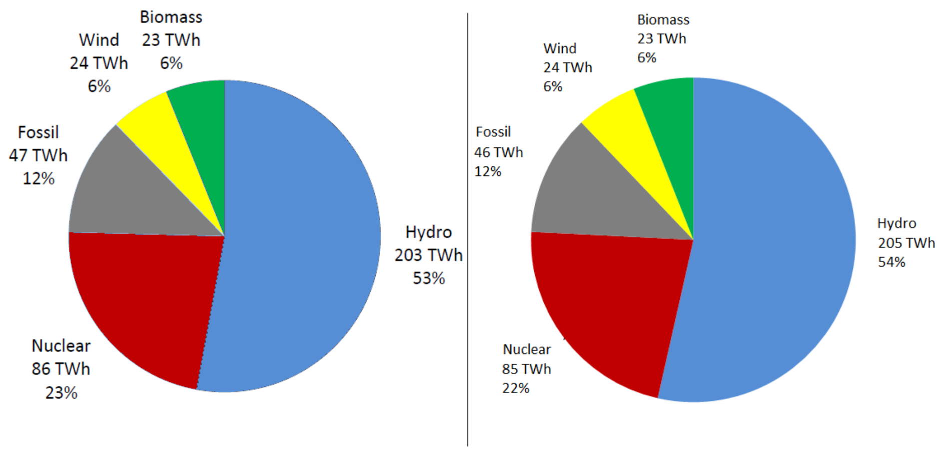


Figure 20. Comparison between generation by source in 2013 (left) and the results of the model (right). (NordREG, 2014)

The diagram on the left represents the real-life situation in 2013 and it is obtained from the publication the Nordic Market Report 2014 by Nordic Energy Regulators. The diagram on the right represents the results obtained from the model by using known capacities in 2013 (NordREG, 2014). The diagrams are almost identical, apart from relatively minor differences with hydro (2 TWh), nuclear (1 TWh) and fossil (1 TWh) generations.

The fossil fuel power generation in the model consists of fossil CHP and flexible fossil generation. Fossil CHP is considered together with biomass CHP and the energy is divided evenly between the hours of the year. Flexible fossil generation is the last electricity generation source in the model and it is used only when there are energy deficits in the system. If there is an energy deficit in the energy system after base load power sources are utilised, it is first fulfilled by utilising dispatchable hydropower and after that flexible fossil power. This results in only 6.3 TWh of flexible fossil energy over the year with peak load hours of 521h. Overall the amount of fossil generation seems realistic and close to the real 2013 situation, but almost all the fossil energy is generated with CHP in the model and only a miniscule amount with flexible fossil generation. This model somewhat differs from the real life, but overall the amount of energy produced by fossil fuelled generation is in line with the statistics from 2013.

In the 2013 scenario, the capacity of dispatchable hydropower is about 15 GW. If the energy deficit in any given hour of the year is more than that, flexible fossil generation is used to attempt to fulfil the deficit. The system has 12 GW of flexible fossil generation. Overall, dispatchable hydro and flexible fossil generation handle the load requirements well; there are only a total of 81 deficit hours in 2013. These can be handled with imports from e.g. Russia. The model gives fairly good results for 2013, but in real-life situations in 2013 there were even more hours in the year when imports were needed. Figure 21 shows load, dispatchable hydropower and flexible fossil generation in January 2013.

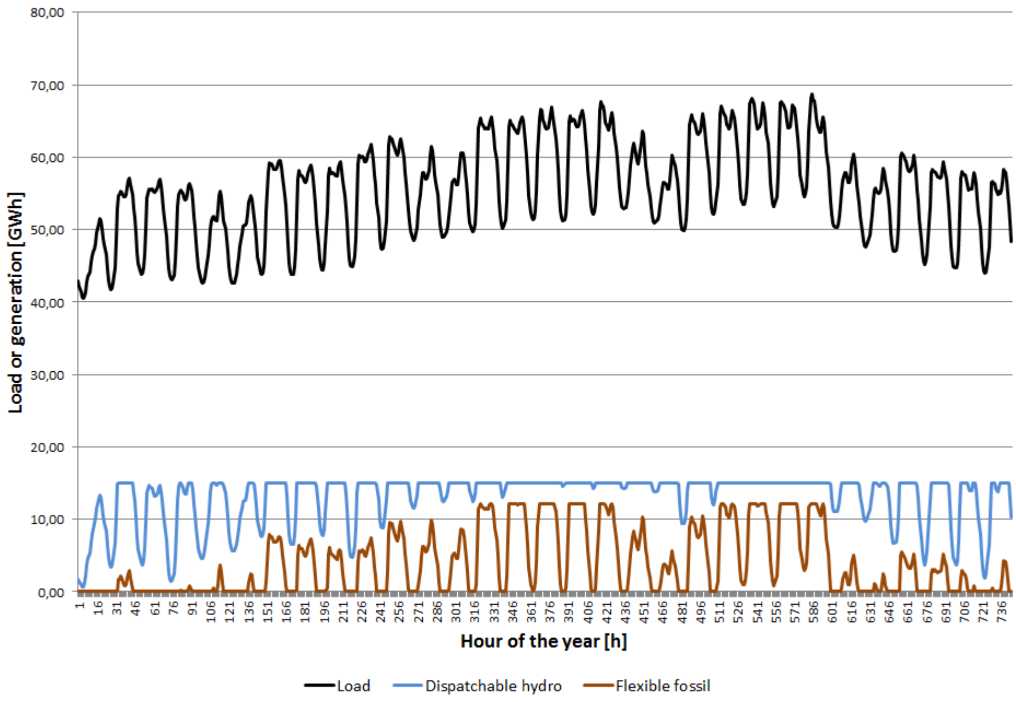


Figure 21. Curves for load, dispatchable hydropower and flexible fossil generation in January 2013.

Figure 21 shows how the balancing elements of the constructed energy system work. If the capacity of dispatchable hydropower is enough to fulfil the deficit, no flexible fossil generation is needed. In instances when hydropower does not generate enough electricity, flexible fossil steps in and tries to answer the load demand. Both of these electricity generation sources have a maximum capacity and if the deficit in any given hour exceeds the sum of these capacities, imports to the energy system are needed. These hours can be observed in figure 24; when both dispatchable hydro and flexible fossil curves have straight horizontal lines in the same hours, they are at their maximum capacities.

6.1.3 **Similar scenario**

This scenario has a similar generation mix in regards to percentages as the 2013 scenario and the real-life situation in 2013. As the Similar scenario happens in 2050, the amounts of produced energies are of course different from those produced in 2013. The total amount of produced energy is about 493 TWh and is in line with the IEA predictions. In the Base scenario and the IEA scenarios presented in the NETP publication, fossil fuelled generation is either non-existent or its share of total energy production is small. Figure 22 shows a comparison between the real-life generation mix in 2013 and the generation mix in the Similar scenario.

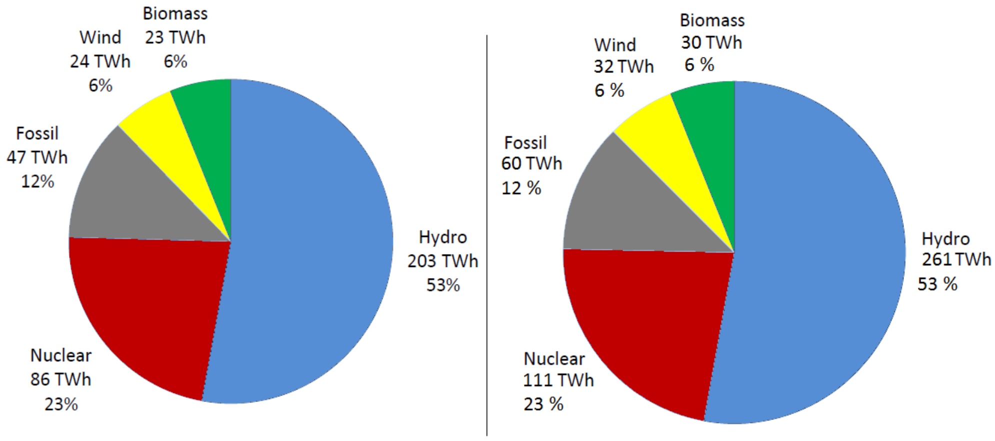


Figure 22. Generation mix in 2013(left) and a similarly structured energy system in 2050 (right). (NordREG, 2014)

As can be seen from the figure above, the shares of different electricity generation sources in 2013 and in the Similar scenario are almost identical but the produced energies are different. In the Similar scenario, fossil fuelled generation produces 60 TWh of energy compared to none in the Base scenario (Figure 16).

The energy system in the Similar scenario works in the same way as in other year 2050 scenarios. Dispatchable hydropower functions as a flexible element in the energy system. As in the Base scenario, dispatchable hydropower's generation greatly depends on the load and the wind generation. Other generation sources function as base load power sources in the system and thus the need for dispatchable hydropower in any given hour is in practice determined by the load and wind power generation.

Table 3 presents carbon dioxide equivalent emissions per kWh of produced energy from different sources. These values are used here to evaluate how much carbon dioxide-equivalent emissions the future constructed energy system in the Base scenario produces carbon dioxide-equivalent emissions compared to the energy system in this Similar scenario. It is important to note that the CO_2-equivalent emissions presented in Table 3 include whole lifecycles, not just emissions from operation.

The model calculates the produced energies from different sources over one year. Table 9 gathers these energies, CO_2-equivalent lifecycle emissions and total average emissions for these energy sources over the year 2050. Lifecycle emissions for fossil fuelled power generation varies greatly as natural gas has lifecycle emissions of 443 gCO_2-eq/kWh, heavy oil 778 gCO_2-eq/kWh and coal 960 to 1 050 gCO_2-eq/kWh. A value 747 gCO_2-eq/kWh is used, an average value between 443 gCO_2-eq/kWh and 1 050 gCO_2-eq/kWh, to calculate average emissions of fossil fuelled power generation in 2050. Average values of lifecycle emissions are also used for other electricity sources.

Table 9. Lifecycle emissions, produced energy and average emissions in 2050 for different electricity sources. Lifecycle emissions values are from Table 3.

		Base scenario		Similar scenario	
Electricity source	**Lifecycle emissions [gCO_2-eq/kWh]**	**Produced energy in 2050 [GWh]**	**Average emissions in 2050 [tCO_2-eq]**	**Produced energy in 2050 [GWh]**	**Average emissions in 2050 [gCO_2-eq]**
Wind	9-11	130 600	1 306 000	31 689	316 890
Hydro	10-13	192 651	2 215 484	260 634	2 997 294
Nuclear	15	122 430	1 836 450	110 880	1 663 200
Biomass	14-41	60 000	1 650 000	30 000	825 000
Fossil	443-1050	0	0	60 000	44 820 000
Total		505 681	7 007 934	492 448	50 622 384

In the Similar scenario, fossil fuelled generation produces only 12% of the total energy but almost 80% of the total CO_2-equivalent lifecycle emissions in 2050. Overall, the energy system in the Similar scenario produces over four times as much CO_2-equivalent emissions than the energy system in the Base scenario.

The IEA estimates that the greenhouse gas emissions intensity for nuclear power is currently about 15 gCO_2-eq/kWh (IEA, 2014e). This value is used in Table 9. In his study, Sovacool (2008) used a lifecycle emission value of 66 gCO_2-eq/kWh for nuclear energy (Sovacool, B., 2008). With this value the average emissions in 2050 for nuclear power would rise from around 1 840 000 tCO_2-eq/kWh to 8 080 000 tCO_2-eq/kWh in Base scenario and from 1 660 000 tCO_2-eq/kWh to 7 320 000 tCO_2-eq/kWh in Similar scenario. The IEA value for nuclear lifetime emissions sets the nuclear energy emissions in 2050 to the same levels as the emissions from renewables. Figure 23 presents average emissions in 2050 with different lifecycle emission values for nuclear and fossil power. Using a higher nuclear lifecycle emissions value of 66 gCO_2-eq/kWh still shows the benefits of replacing fossil power with a combination of nuclear and renewables.

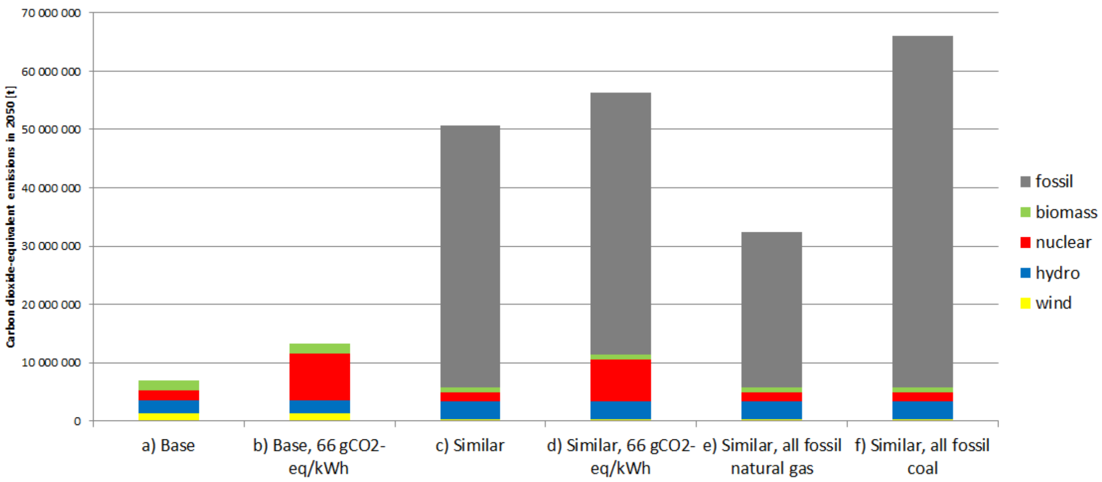


Figure 23. Average carbon dioxide-equivalent lifetime emissions calculated for one year. All the different cases have around same total energy produced, 500 TWh. Cases a), c), e) and f) use the value 15 gCO_2-eq/kWh for nuclear power while cases b) and d) use the value 66 gCO_2-eq/kWh.

As Figure 23 clearly shows, carbon dioxide-equivalent emissions are drastically smaller in the Base scenario compared to the Similar scenario, even if all the fossil fuel used in the Similar scenario is natural gas. The future energy system in the Base scenario not only has lower emissions from greenhouse gases and other air pollutants but it also has some monetary benefits as CO_2-equivalent emissions are likely even more heavily charged and taxed in the future than they are today.

6.1.4 **Storage scenario**

In the Base scenario and in the IEA scenarios, the Nordic countries become net exporters of electricity by 2050. In the Storage scenario, the goal was to construct an energy system which produces just about the same amount of electricity that the Nordic countries consume but at the same time there would be no deficit hours during the year. The constructed energy system is also self-sufficient and does not depend on energy imports from other countries e.g. Russia. In order to ensure that there are no deficits, energy storage is introduced to the system. The storage input and output capacities were chosen by finding the values which bring the hourly production-consumption balance in every hour of the year to zero or positive i.e. the system does not have any deficits.

In the Storage scenario, the capacity of all the different electricity generation sources have been decreased from the values used in the Base scenario. The energy system has short term storage with 1.5 GW capacity and a size of 7.5 GWh and long term storage with 5 GW input capacity, 10 GW output capacity and 2000 GWh storage size. The capacity values for the different electricity generation sources are somewhat arbitrarily chosen. They are not based on any IEA scenarios but can be deemed to be realistic. Overall, the capacities of different electricity sources are lower than in the Base scenario but higher or the same as in 2013.

The amount of nuclear generating capacity was kept same as in 2013 but the capacity is of course renewed in 2050. This differs from the Base scenario in which it was assumed that nuclear generating capacity would increase in Finland compared to present levels. Hydropower capacity is about 5 GW more than in 2013 reaching 55 GW. It is safe to assume that Nordic hydropower will continue to be the most important element in the Nordic energy system but its capacity additions are lower than in the Base scenario as there is no need for as much electricity generation as in the Base scenario. Biomass fuelled CHP capacity is 10 GW which is 3 GW more than in 2013, but at the same time it is 2 GW less than in the Base scenario. This is again due to the lower energy requirements in the Storage scenario compared to the Base scenario. In 2013, there was 15 GW of CHP (biomass + fossil) capacity in Nordic countries. In Storage scenario, biomass CHP capacity is set to 10 GW but an assumption is made that some of the new nuclear generating capacity is providing district heat. The wind power capacity is 20 GW which is double the 2013 capacity. This follows the trend and desire of increasing the share of renewables in the generation mix compared to the shares in the present day. The wind power capacity is lower than in the Base scenario as the whole energy system is designed to produce less energy. 20 GW was the result of keeping the nuclear generating capacity at the same level as in 2013, having an adequate amount of CHP capacity present in the system and wanting the energy system to produce just about the same amount of energy as it consumes. Figure 24 shows the generation mix in the Storage scenario.

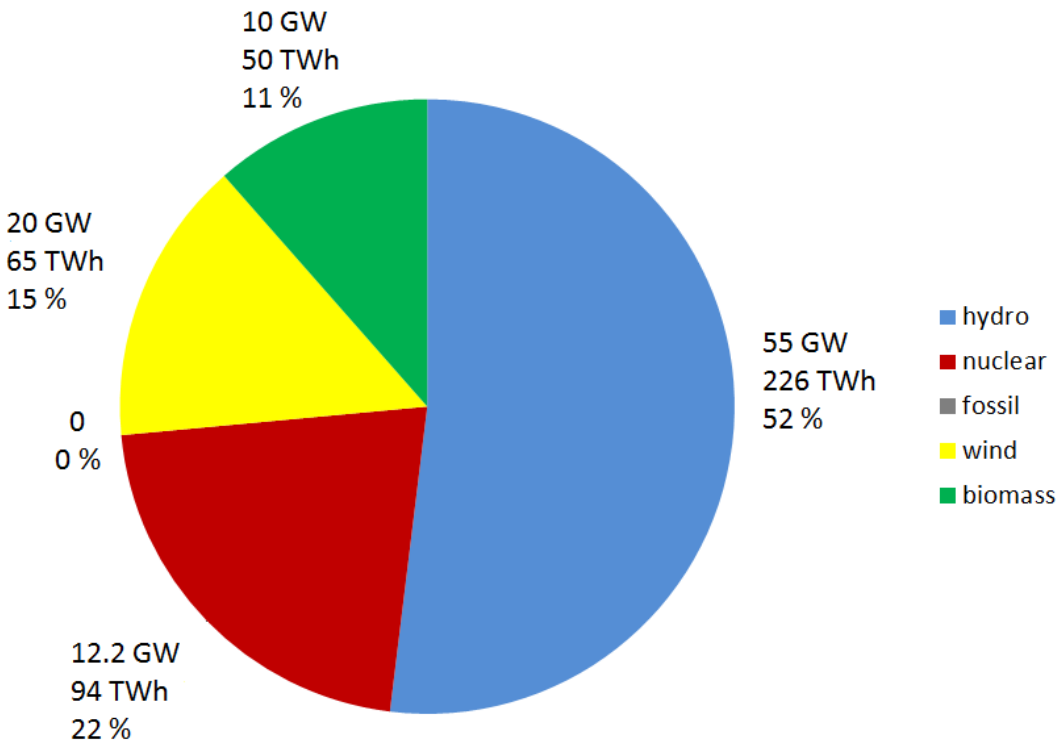


Figure 24. Generation mix in the Storage scenario. Energy storage not included.

Overall, the generating capacity in the Storage scenario is 97 GW while in 2013 it was 99 GW because the energy system in 2013 still includes fossil fuelled generation. Still, the energy system in the Storage scenario produces about 51 TWh more electricity due to an increase of 42 TWh in wind production and 29 TWh in hydro production. Electricity consumption in the Storage scenario is 430 TWh and the system produces 435 TWh of electricity. Without storage there would be 242 deficit hours during the year.

Table 10 shows the capacity values for different electricity sources in the Base and the Storage scenarios. In the Storage scenario, the total generating capacity is 36 GW and the produced electricity is 71 TWh less than in the Base scenario. Hydropower in the Storage scenario produces more energy than hydropower in the Base scenario. Because electricity generation from wind, nuclear and biomass is lower, dispatchable hydropower has to produce more energy.

Table 10. Capacities and corresponding energies and shares for different electricity generation sources in Base and Storage scenarios.

	Base scenario			**Storage scenario**		
Electricity source	Share of total energy	Net electricity generation [TWh]	Capacity [GW]	Share of total energy	Net electricity generation [TWh]	Capacity [GW]
Wind	26 %	131	40	15 %	65	20
Hydro	38 %	193	65	52 %	226	55
Nuclear	24 %	122	16	22 %	94	12
Biomass	12 %	60	12	11 %	50	10
Other	0 %	0	0	0 %	0	0
Total	100 %	506	133	100 %	435	97

The Nordic load is concentrated in the winter months. The system has noticeable deficits only at the start of the year as can be seen in Figure 25. In the figure, the hourly power balance was calculated by subtracting the hourly Nordic load from the hourly Nordic production.

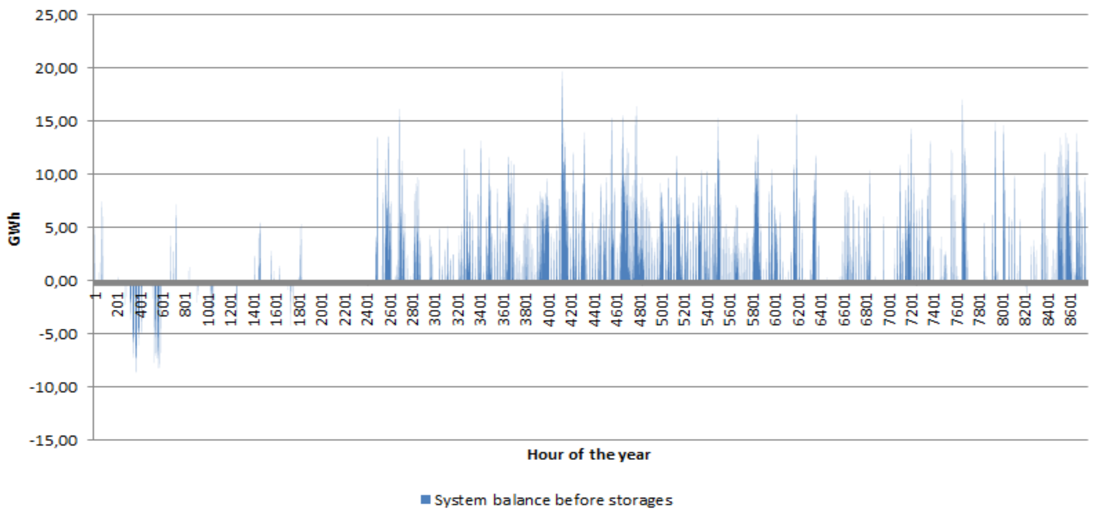


Figure 25. Hourly system balance before introduction of electric storage.

Towards the middle and end of the year, the Nordic energy system produces more energy than the Nordic countries consume. This surplus of energy can be stored in energy storage and used at the start of the year, namely in January and February, shifting the produced energy up to 6 months to match the consumption. As the Nordic energy system has deficit hours at the start of the year, the long term storage level also has to be adequate at the start of the year. The worst case scenario would of course be if all gas in power-to-gas storage is depleted at the start of the year.

Storage capacities and the storage level at the start of the year are a result of testing in the model. The minimum long term storage output capacity and the required storage level at the start of the year was found by following the requirement that no deficit hours can be left in the system after introduction of storages. Basically the value for the output capacity was set in the model and then by changing this value together with the storage level value at the start of the year, a solution was found. Figure 26 presents the sum of hourly deficits with different values for long term storage output capacity and with different storage levels at the start of the year. Short term storage capacity was set to 1.5 GW and the long term storage input capacity to 5 GW.

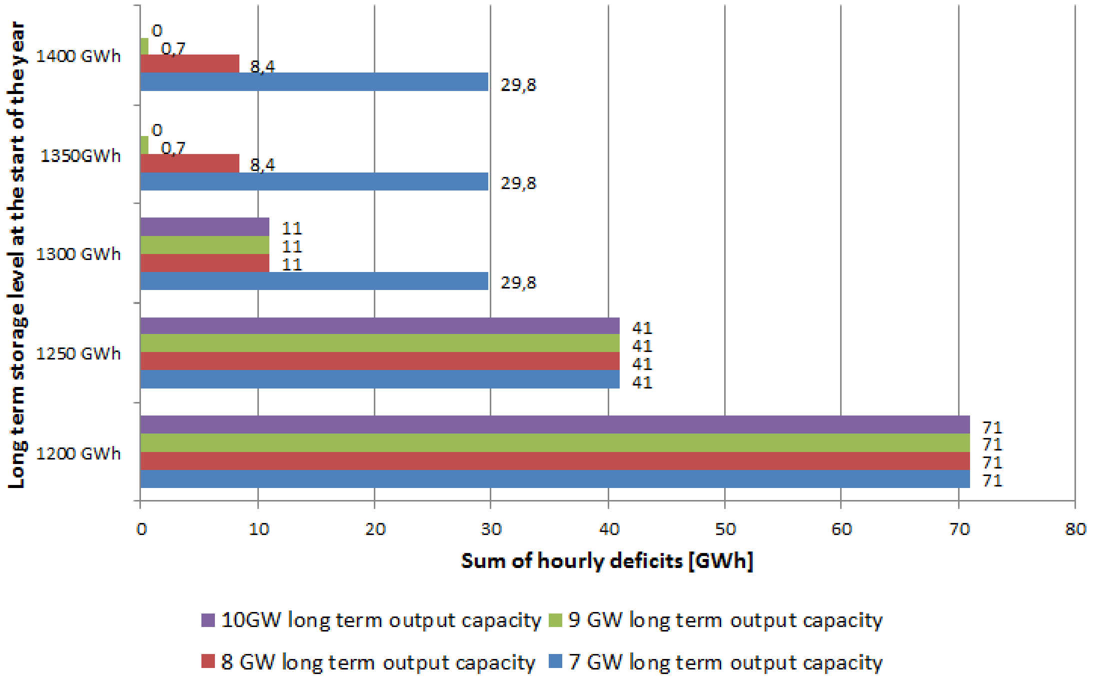


Figure 26. Long term storage output capacity optimisation with different storage levels at the start of the year.

The bars represent different values for long term storage output capacity. First, the long term storage level at the start of the year was set to 1 200 GWh and the sum of hourly deficits was calculated with different long term output capacity values. The same process was carried out with different values for storage levels at the start of the year. The sum of hourly deficits was more than zero regardless of the value of the long term output capacity until the long term storage level at the start of the year was set to 1 350 GWh. With this value, 10 GW of long term output capacity is needed so that the sum of hourly deficits is zero. More accurately, 1319 GWh was determined to be the point when the sum of hourly deficits reaches zero.

Figure 26 does not show anything about the short term storage capacity or levels. During the long term storage's optimisation it was noted that the short term storage's effect on the sum of hourly deficits is much lower than the long term storage's. If there was no short term storage capacity, 1 331 GWh of energy would be needed at the start of the year in long term storage. With 1 GW of short term storage, the long term storage level at the start of the year has to be 1 322 GWh in order to have no deficits in the system. A value of 2 000 GWh is used in the model as both the storage energy level at the start of the year and as the maximum energy capacity for long term storage. Even though the model shows that the short term storage is not as important for balancing the Nordic energy system as the long term storage, the short term storage capacity was set to 1.5 GW. The short term storage energy storing capacity was restricted by the following rule: for every GW of short term electrical capacity, an energy storage size of 5 GWh is allowed (Paukkeri, 2013). This means that the short term energy storage in the Storage scenario has 7.5 GWh of energy storing capacity.

Pumped-storage hydropower can be used for either short term or long term storage and balancing purposes. PSHs with large reservoirs and storage volumes together with low installed electrical capacity will lead to slow changes in water levels in the lower and upper reservoirs. Small reservoirs with large installed electrical capacity in turn will lead to a more rapid changes in water levels and the pumped-storage hydropower becomes more responsive. Currently in Norway, seasonal pumping is used between very large reservoirs instead of daily or weekly cycle. (Gimeno-Gutiérrez & Lacal-Arántegui, 2013)

Existing PSH energy storage capacity in Norway is reported to be 11 TWh but the pumping/generation capability is limited by the installed electrical capacity of the pumps and turbines. Norwegian water reservoirs for hydropower are very large and also connected to other conventional hydropower generators, not just PSHs and their infrastructure. In 2010, Norway had a pumped-storage hydropower capacity of 1 326 MW and Sweden 99 MW while Finland had zero PSH capacity. In 2010 the Nordic countries had 1.4 GW of long term pumped-storage hydropower capacity while the requirement in 2050 according to the model is 10 GW of long term storage output capacity. Long term storage electrical capacity can be increased by increasing the pumping capacity in Norwegian hydro reservoirs and PSH stations and the possibility of power-to-gas storage also exists. (Gimeno-Gutiérrez & Lacal-Arántegui, 2013)

In the Storage scenario an assumption is made that the installed electrical capacity in Norwegian pumped-storage hydropower stations is better than it is currently and the PSH energy capacity can be better utilized. The required level of long term storage capacity is achieved by 2050. In the model, long term storage has a 2 TWh maximum storage capacity. According to Gimeno-Gutiérrez & Lacal-Arántegui (2013), Norway has realisable PSH potential for a total of 13.3 TWh and Sweden 3.1 TWh. An assumed 2 TWh of maximum long term energy storage capacity and the same amount of stored energy at the start of the year are therefore plausible. Now, the storage level of 2 000 GWh at the start of the year may seem large but as Figure 26 presents, the Nordic energy system produces more energy than it consumes at the middle and end of the year and this energy is stored in the long term energy storage sites. The dourly long term storage level is presented in Figure 27.

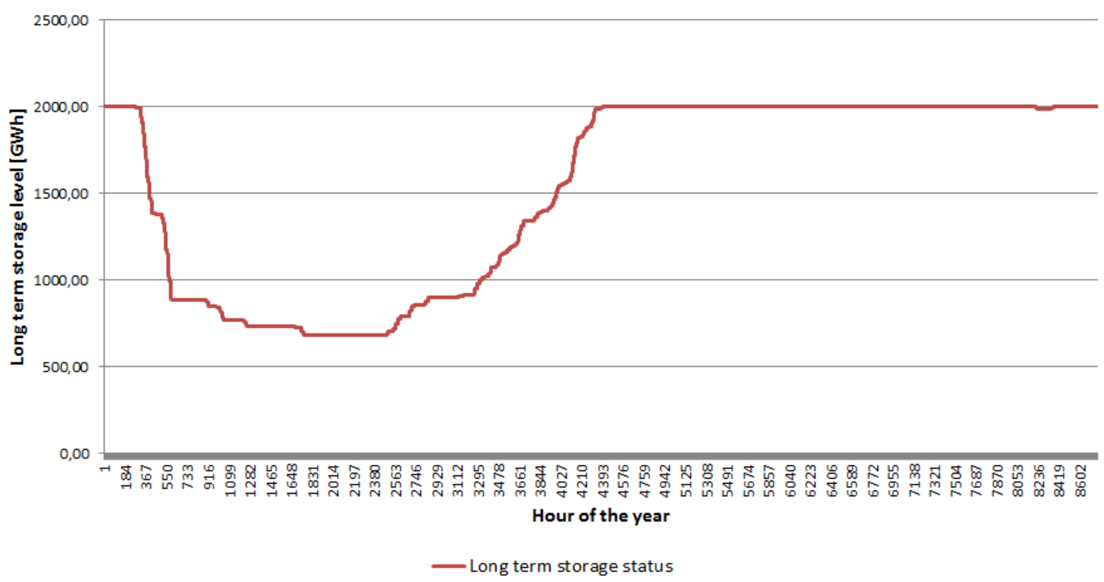


Figure 27. Hourly long term storage level in the Storage scenario.

According to the model, the long term storage is at maximum energy levels at the end of the year thus providing the necessary energy at the start of the next year. Stored energy is generally used from January to March, specifically from hour 282 to 1 763. Of course, this result is based on the consumption of only one year and can somewhat vary from year to year but it is clear that energy storage is needed in winter months and during summer the storage facilities are recharged, so to speak.

6.1.5 Low Hydro scenario

The purpose of this scenario was to construct a carbon free energy system without a large amount of hydropower to see if a system containing only wind, biomass and nuclear power together with energy storage can form a working energy system and to see whether hourly balancing can be achieved with other elements of the system. Balancing elements could consist of energy storage or Demand Side Management in the form of load shifting or indirect control. In the model, hourly balancing in the Low Hydro scenario is done with short and long term energy storage. This scenario resembles the Storage scenario, but as opposed to it, the Low Hydro scenario does not have a large amount of hydropower capacity available. This in turn highlights the importance of energy storage in hourly balancing because the energy flows to and from the energy storage facilities are an order of magnitude higher than in the Storage scenario.

The capacities for different electricity generation sources are arbitrarily chosen. Wind power capacity was set to 35 GW which is 5 GW lower than in the Base scenario and 15 GW higher than in the Storage scenario. The biomass fuelled capacity was set to 25 GW which is the highest in any scenario. The nuclear generating capacity was set to 30 GW. In this scenario, hydropower has only 1 GW capacity. The total generating capacity in the Low Hydro scenario is 91 GW and the total amount of energy generated 474 TWh. The selected electricity generation mix is presented in Figure 28.

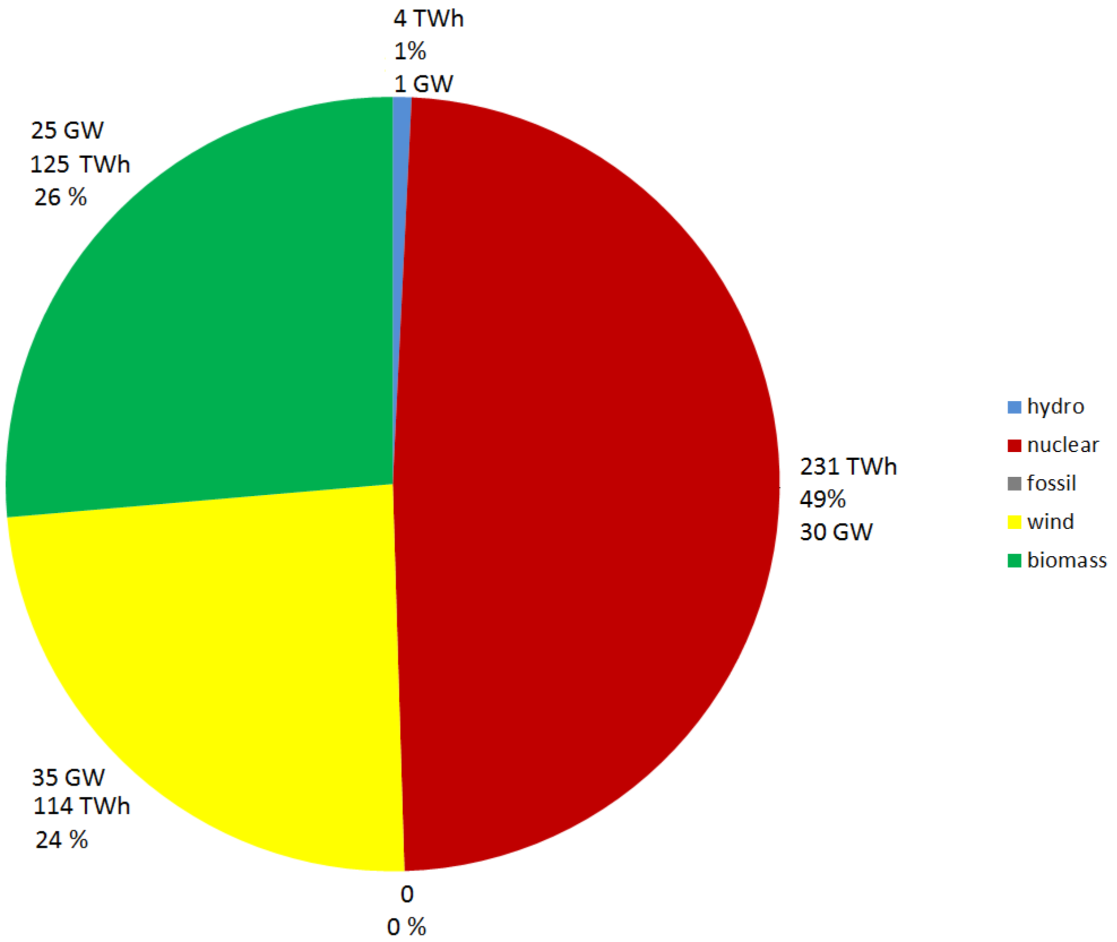


Figure 28. Electricity generation mix in the Low Hydro scenario. Storage not included.

The storage sizes are optimized in the same way as in the Storage scenario i.e. minimum levels for short term storage capacity and long term storage capacities (input and output energy) are found by keeping some of these capacities constant while altering the values for the rest. The solution is found when none of the capacities can be decreased without causing a deficit in the system.

Four variables affect whether the system has a deficit after storage or not: electrical capacity of short term storage, electrical input capacity of long term storage, electrical output capacity of long term storage and energy capacity of long term storage i.e. long term storage size. First, the long term storage size was set to 11 TWh and the minimum capacity levels for short and long term storages were found without causing a deficit in the system. Basically, the short and long term storage capacity values were changed until there was no deficit in the system. It was found that 43 GW of short term storage capacity, 14 GW of long term storage input capacity and 24 GW of long term output capacity were needed in order to have no deficits in the system while the long term storage size is 11 TWh. This was the first result. Next, a new set of capacity values were acquired by increasing the size of the long term storage. Table 11 presents the short and long term storage capacity optimisation with different long term storage sizes. Each row in the table results in a zero deficit in the system.

Table 11. Short and long term storages' capacities with different long term storage sizes. Every set of values/rows result in zero deficit in the system.

Long term storage size [TWh]	Short term storage capacity [GW]	Long term storage input capacity [GW]	Long term storage output capacity [GW]
11	43	14	24
11.5	23	14	24
12	10	11	24
12.5	5	7	24
13	3	5	24
13.5	1	4	24

Table 10 clearly shows that the long term storage output capacity has a distinct minimum value of 24 GW while the minimum values for short term storage capacity and long term storage input capacity depend on the size of the long term storage. Once this had been determined it was only a matter of selecting the preferred size of the long term storage. For reference, the German natural gas grid has 220 TWh capacity at the time of writing (GTI, 2015). In Great Britain, the existing gas storage capacity is 4 727 mcm (million cubic meters) equalling to around 51.2 TWh and new storage projects are planned and some under construction (Le Fevre, 2013). If the long term storage in the Low Hydro scenario is power-to-gas, each value for long term storage size is possible.

The United Kingdom is a good example for this scenario as the UK's electricity generation mix had only 1% of hydropower in 2010 and the total electricity generation in 2010 was at the same level as in the Nordic countries in 2013, 378 TWh and 380 TWh respectively (NordREG, 2014). The United Kingdom also plans to increase the share of renewables, especially wind power, considerably to about 30% in 2020 from 8% in 2010 and the UK nuclear industry has announced ambitions to construct up to 16 GW of new nuclear capacity. This would mean that renewables and nuclear power would have a significant share of the UK's electricity generation mix, just the same as Low Hydro scenario. However, fossil fuelled power still remains an important element in the United Kingdom's energy system. Thus the Low Hydro scenario is not strictly based on the UK as the scenario does not have any fossil fuelled power, not even fossil power equipped with CCS technologies. (IEA, 2012c)

The long term storage size of 13 TWh was selected. This is also the amount of stored energy at the start of the year. Table 11 presents minimum values required in order to have no deficits in the system. The short term storage capacity is 3 GW, the short term storage size is 15 GWh, the long term storage input capacity is 5 GW and long term storage output capacity is 24 GW. With these values, the long term storage has at its lowest point of the year about 41 GWh of stored energy remaining. Figure 29 presents the hourly long term storage level.

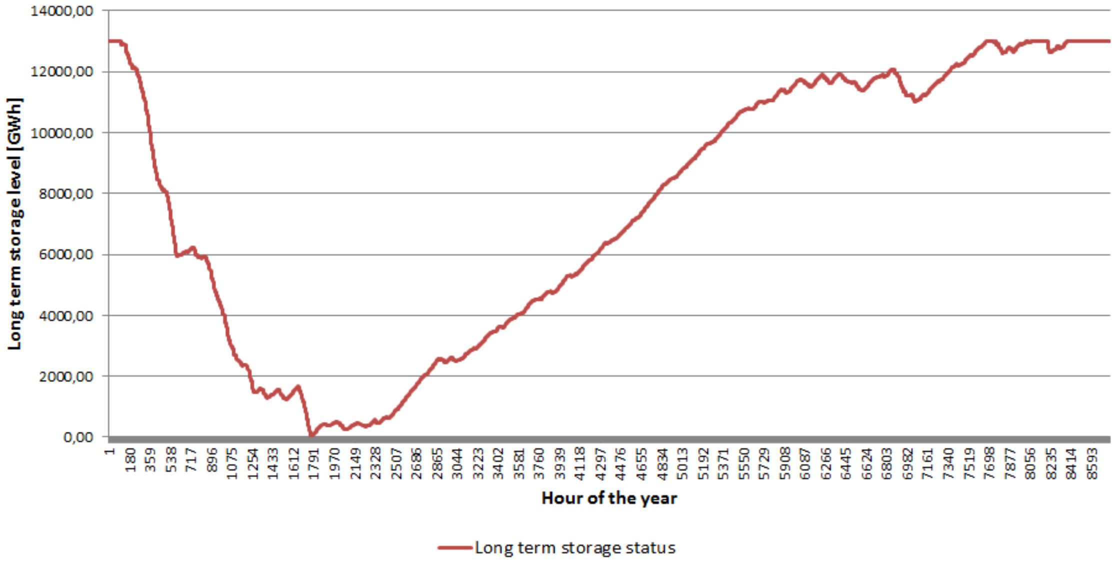


Figure 29. Hourly long term storage level in the Low Hydro scenario.

Figure 28 shows the long term storage level throughout the year. The long term storage level is at its lowest on the night between 15 and 16 of March. The lowest amount of energy stored is about 41 GWh and the general trend for the long term storage's level after this point is upwards. The short term storage level varies much more rapidly as it responds to deficits before the long term storage and the figure for the short term storage level over the whole year is too congested to present. Figure 29 shows the energy balance of the system after all the electricity generation from different sources, long term storage output and short term storage output in January.

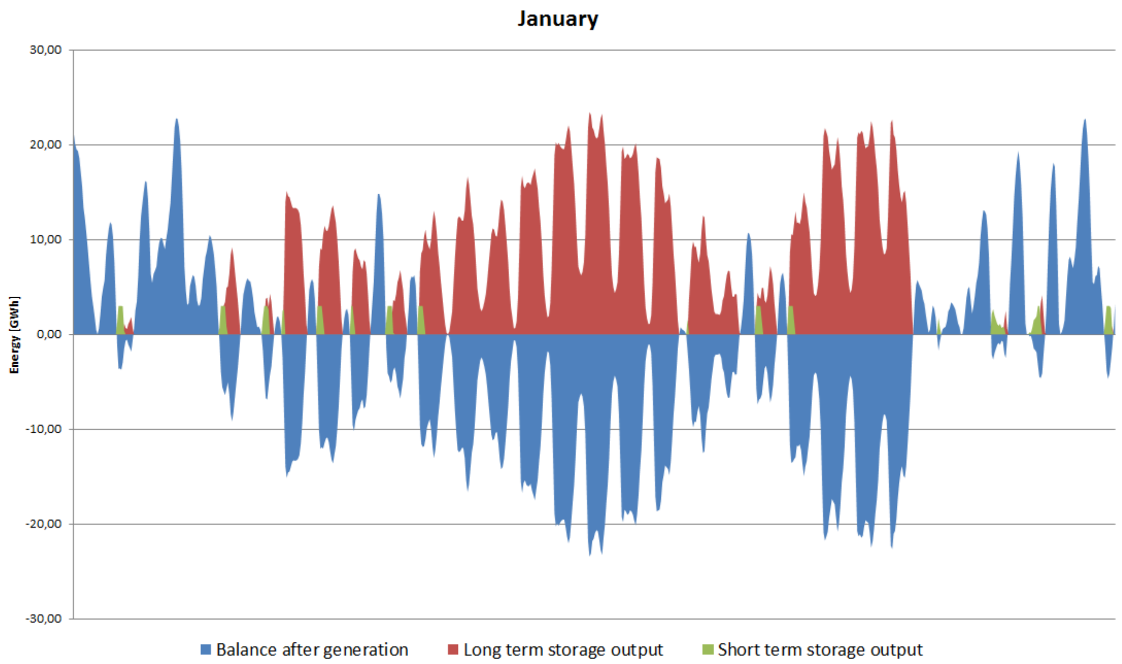


Figure 30. Storage outputs and system balance after generation in January.

Figure 29 clearly shows how the energy storages balance the system. When the energy balance after generation is positive, energy storage outputs are zero. If there are deficits in the system and the balance after generation is negative, energy storage is used to offset the deficit. This is how the energy system in this scenario is balanced throughout the year.

The Low Hydro scenario shows that a carbon free energy system can work without a large amount of hydropower. The Low Hydro scenario has three electricity generation sources, of which nuclear power produces the most energy per installed capacity. For the system to work without a large amount of hydropower, an abundance of generating capacity is required to ensure that enough electricity is generated even in the hours with most demand or using energy storages to balance the difference between electricity generation and demand. The ability to use load following nuclear power plants is not modelled in this thesis but these have been used successfully at least in France. As it stands, the Low Hydro scenario uses energy storages which are the only flexible element in the Low Hydro scenario. If biomass or nuclear power were also somewhat flexible, they would improve the functionality of the system and naturally the overall flexibility.

6.2 Specific situations and sensitivity analyses

Constructed scenarios provide basic outputs of the energy system such as produced energy, consumed energy and generation mix in the system. These factors help to form a basic picture of the energy system. In this chapter, some specific situations are constructed and analysed in order to better understand how important each electricity generation source in the chosen future energy system are. The role of nuclear power is especially considered including; whether the chosen future energy system could function without nuclear power, how it would be replaced and what the effects of nuclear energy's possible dismissal would be on the energy system.

6.2.1 Zero wind situation

Wind generation is the fastest growing source of electricity production in the envisioned future energy system. It is also the only intermittent electricity source in the system and it has the second largest share of total energy production. Feasibility of the constructed future energy system can be somewhat analysed by examining how the system behaves regarding some extreme cases related to wind generation.

The wind power in the model is based on real-life wind data from 2013 and there are no windless hours in the Nordic region in 2013. This is understandable as the region is fairly large. Still, wind power cannot be considered an entirely reliable source of electricity as its output is highly dependent on weather conditions. One way to analyse the feasibility of the envisioned future energy system with large share of wind power is to set the wind power production to zero in some hours of the year and analyse whether the system can handle such a situation i.e. are the remaining electricity generation sources capable of responding to the situation. This is a highly unlikely and extreme situation, but if the system can handle such a scenario, then it can be deduced that the system can also handle smaller disturbances regarding smaller than anticipated wind generation.

The largest need for dispatchable hydropower in scenarios occurring in 2050 is in hour 369 of the year which is January 16 at 8 to 9. Figure 31 shows the power balance curve in that hour in the Base scenario when the wind blows according to the real-life data. The curve starts at a negative load value and each different electricity generation source adds energy to the system until the balance reaches zero after dispatchable hydropower. The dispatchable hydropower needed in this particular hour is 25.40 GWh.

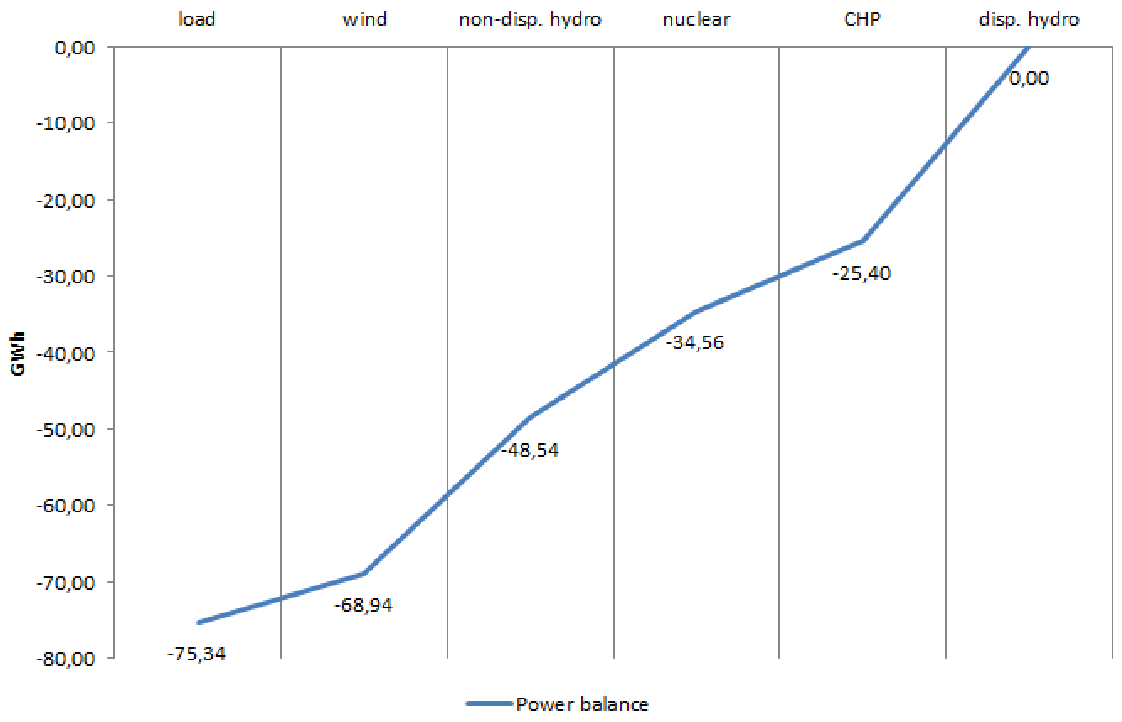


Figure 31. Hour 369 in the energy system in the Base scenario.

The next step is to set the wind generation in hour 369 to zero and see if the other elements in the system can still bring the balance to zero. The result is presented in the Figure 32.

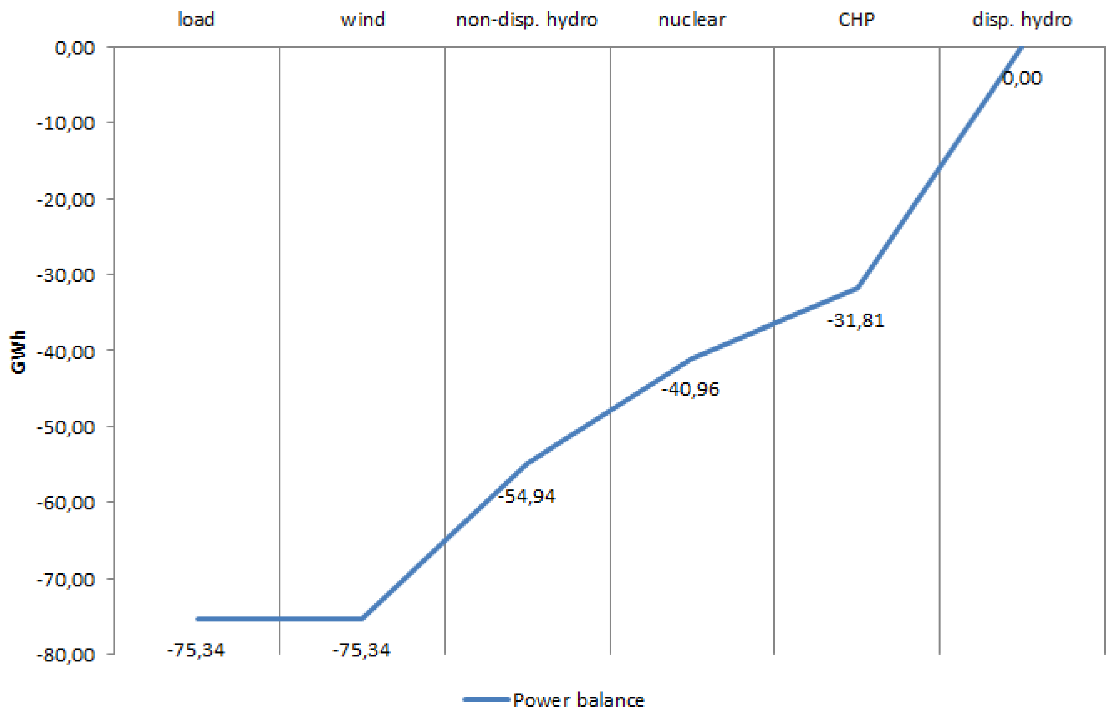


Figure 32. Hour 369 in the energy system with zero wind generation.

Even if there is no wind generation when the energy system has the largest deficit, the remaining generation sources bring the balance to zero. Dispatchable hydropower has 32.5 GW of capacity in the Base scenario and as can be seen in Figure 32, the largest deficit even without wind generation is 31.81 GWh. Even though the dispatchable hydropower is the last generation source that brings the balance to zero, other sources are equally important. If there were no nuclear generation or biomass fuelled generation, the hydropower capacity in the Nordic countries could not answer to the demands of the load by themselves. One could argue that this could be avoided by adding even more hydropower. However, in the Base scenario the total hydropower capacity in 2050 is set to 65 GW, which is already more than the IEA estimates. Figure 33 shows the power balance curves when there is no nuclear or CHP generation in a zero wind situation. In both of these cases, the energy system does not reach zero and there is more consumption of energy than there is production.

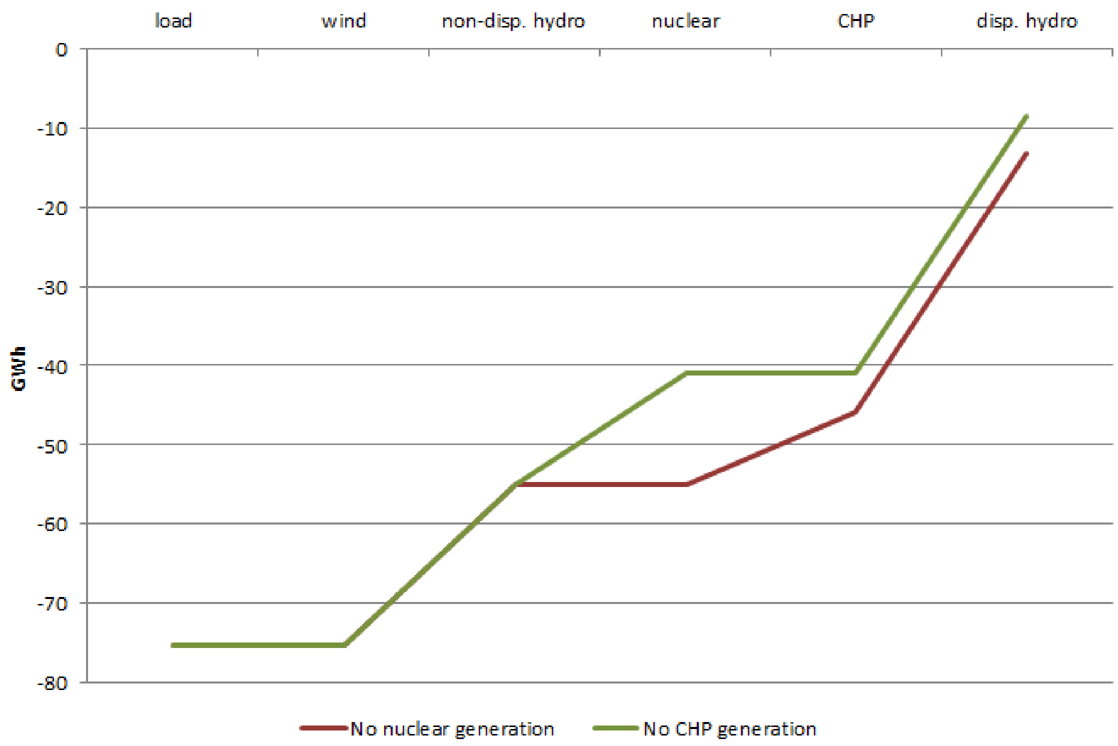


Figure 33. The power balance in hour 369 when there is no nuclear generation (red) and no CHP generation (green).

The zero wind generation in hour 369 is highly unlikely, but it shows that nuclear generation has an important role as a base load source of energy. Some of the nuclear power capacity could be replaced by biomass fuelled generation but from the energy security point of view, it would be better to have a few alternative electricity generation sources. In the Base scenario, nuclear energy produces over 122 TWh of energy in a year which is about one quarter of the total energy produced. If nuclear power was removed from the system, it would require around 25 GW of additional biomass fuelled capacity with peak load hours of 5 000 to produce the same amount of energy as in the Base scenario. This would bring the biomass fuelled generating capacity to 37GW and the strain on the biomass production and transportation system would be greatly increased.

6.2.2 System without nuclear power

Next we set the nuclear power production to zero over the whole year. In order to achieve the same levels of production as with the nuclear power in the system, the capacities of other electricity generation sources need to be raised. As mentioned before, the hydropower capacity in the Base scenario is already higher than anticipated by the IEA and thus the hydropower capacity remains at 65 GW. Wind power has large potential in the Nordic and it is currently a popular and trending source of electricity. If the biomass and hydropower capacities remain the same as in the Base scenario and there is no nuclear of fossil generation, the capacity of wind power would have to be 73 GW, 33 GW more than in the Base scenario in order to produce the same amount of energy, which is about 506 TWh. As mentioned before, biomass fuelled generating capacity would be 37 GW if it was solely responsible for replacing the nuclear generating capacity from the Base scenario.

Of course some kind of combination of biomass and wind power capacity increases would be responsible for replacing the missing energy production from nuclear generation. For example, a system with 65 GW of hydropower, 55 GW of wind power and 26 GW of biomass fuelled generation would produce 505 TWh of energy, about the same as the system in the Base scenario. When compared to the Base scenario, 15 GW of additional wind power capacity and 14 GW of biomass fuelled generating capacity is needed to replace 15.9 GW of nuclear generation.

The cost of different generation sources are naturally different. The U.S Energy Information Administration (EIA, 2013) lists estimates of power plant capital and operating costs. Table 12 gathers nominal capacities, capital costs and operating costs for nuclear, wind and biomass power plants. Listed capital costs exclude financing-related costs such as fees and interest during construction and can also be referred to as overnight costs as if the construction project was completed overnight. Fixed operation and maintenance (O&M) expenses exclude the owner's costs such as insurance fees, property taxes and asset management fees. Variable O&M expenses include major maintenance costs.

Table 12. Capital cost, fixed O&M cost and variable O&M cost of different technologies with a certain nominal capacity. (data from EIA, 2013)

Technology	Nominal capacity [kW]	Capital cost [$/kW]	Fixed O&M [$/kW-yr]	Variable O&M [$/MWh]
Advanced nuclear	2 234 000	5 530	93.28	2.14
Wind, onshore	100 000	2 213	39.55	0
Wind, offshore	400 000	6 230	74.00	0
Biomass, BFB[10]	50 000	4 114	105.63	5.26
Biomass, CC[11]	20 000	8 180	356.07	17.49

Using the information presented in the Table 12, capital and operating costs of 15.9 GW for nuclear power is compared to capital and operating costs of 15 GW of wind and 14 GW of biomass power. Table 12 presents cost values for certain nominal capacities. For example 15.9 GW of nuclear power equals 7.1 nuclear power plants with a nominal capacities of 2.234 GW each. As one cannot build 7.1 nuclear power plants, this value is rounded to lowest whole number which is 7. This is acceptable because the constructed energy system produces more energy than it consumes so 7 instead of 8 power plants is enough. Same logic is applied to the other technologies. It is important to remember that both the wind power and biomass capacity is needed to replace nuclear power. The

[10] Bubbling Fluidized Bed
[11] Combined Cycle

results are presented in Table 13. In the calculations it is assumed that the offshore wind power capacity is 35 % of the total wind power capacity.

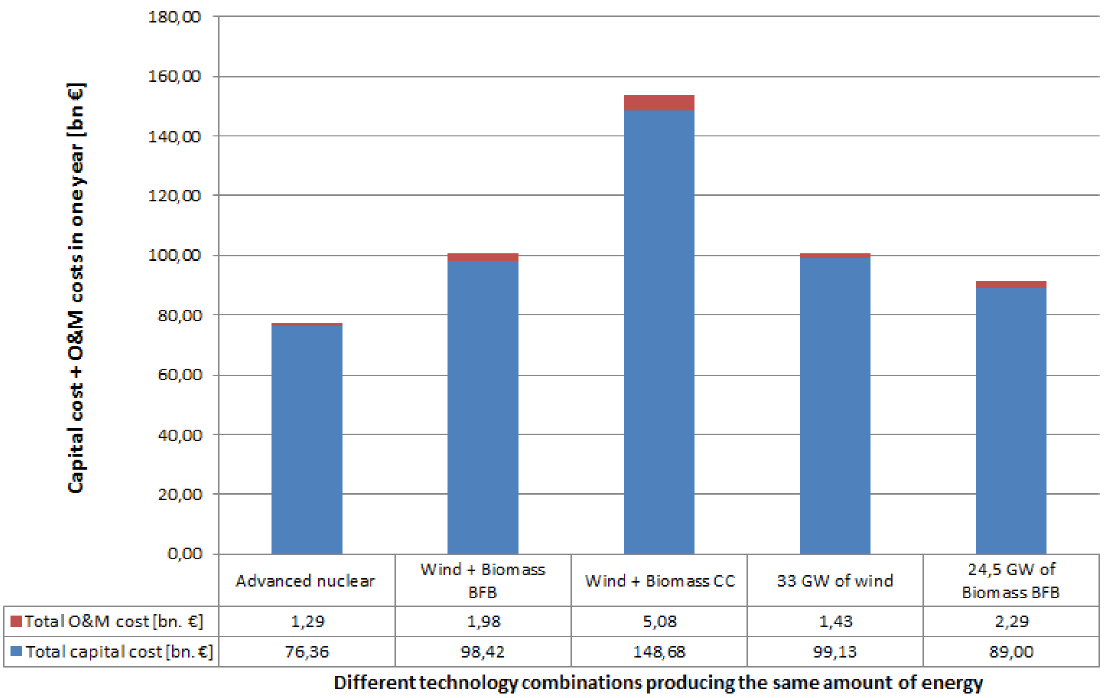
Table 13. Capital and O&M costs of nuclear power in the model and corresponding values for wind and biomass capacity replacing it. The cost values are changed from United States dollars to euros with an exchange value of 1 $ equals to 0.883 €.

Technology (capacity)	Number of units with nominal capacity	Total capacity [GW]	Total capital cost [€]	Total O&M cost per year [€]
Advanced nuclear (2 234 MW)	7	15.6	76.36 bn.	1.29 bn.
Wind, onshore (100 MW)	97	9.7	18.95 bn.	0.34 bn.
Wind, offshore (400 MW)	13	5.2	28.61 bn.	0.34 bn.
Biomass, BFB[12] (50 MW)	280	14.0	50.86 bn.	1.31 bn.
Biomass, CC[13] (20 MW)	700	14.0	101.12 bn.	4.40 bn.

Figure 30 presents the total capital cost and O&M costs of the technologies presented in Table 13. Onshore and offshore wind power costs are summed together with different biomass technologies. Also the cases where nuclear generation is replaced with an additional 33 GW of wind power and 24.5 GW of biomass are included in the figure. The capacity values in the figure are the capacity additions required to the system in

[12] Bubbling Fluidized Bed
[13] Combined Cycle

order to produce about the same amount of energy as the Base scenario's system produces, but without nuclear power.



	Advanced nuclear	Wind + Biomass BFB	Wind + Biomass CC	33 GW of wind	24,5 GW of Biomass BFB
Total O&M cost [bn. €]	1,29	1,98	5,08	1,43	2,29
Total capital cost [bn. €]	76,36	98,42	148,68	99,13	89,00

Figure 34. Total capital cost and O&M costs in one year of different technology combinations.

Figure 30 and Table 13 clearly show that in order to produce the same amount of total energy in the system of about 505 TWh, constructing and operating nuclear power is cheaper than constructing enough wind and biomass power. Constructing and operating biomass power plants are much more expensive than wind power plants but as the last bar in the Figure 34 shows, nuclear power is still the cheapest option when comparing purely total capital costs and operation & maintenance costs.

The challenge with nuclear power is the large unit sizes which require substantial initial investments compared to other generation sources. This can change if and when SMRs are made widely commercially available. SMRs have smaller unit sizes and can be deployed in increments which respectively lowers the initial investments and capital costs.

If the goal is to produce the same amount of energy without nuclear power that the energy system in the Base scenario produces, some substantial additional investments would be needed. Also the large amount of renewable energy may prove to be problematic in respect of grid regulation. For example, wind power does not produce any necessary inertia for the electric grid unlike the nuclear power.

6.2.3 Emission comparisons

Some greenhouse gas emission comparisons were made in chapter 6.1.3 between the Base and Similar scenarios. Here, the emission comparisons are extended to include also the Storage and Low Hydro scenarios as well as a case, where nuclear energy in the Base scenario is replaced by fossil fuelled power generation. For nuclear energy, the IEA's lifetime emission value of 15 gCO_2-eq/kWh was used (IEA, 2014e). Emissions of the energy systems in different scenarios were calculated using the values found in Table 3. These values are lifetime emission values and here they are multiplied by the energies generated from different sources during one year. Figure 35 shows the emission comparisons between different scenarios.

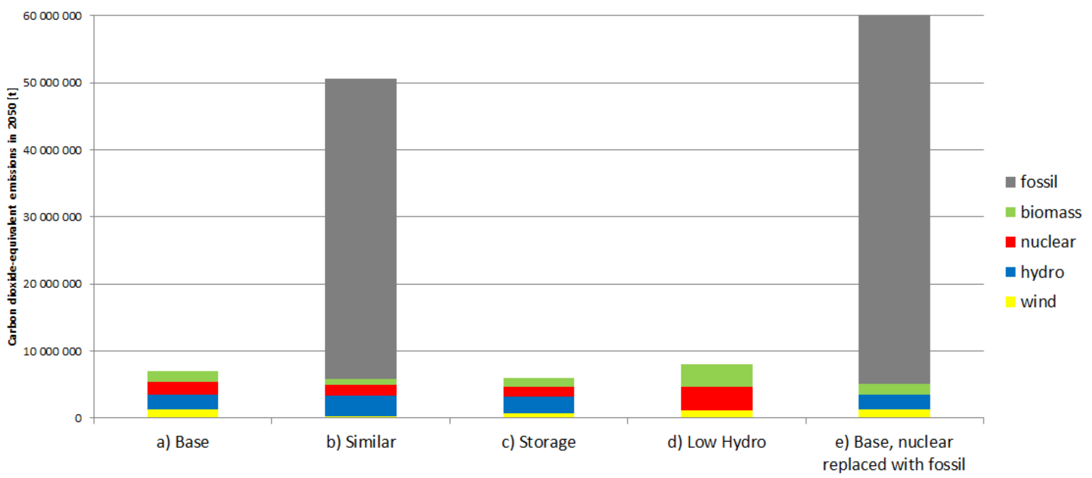


Figure 35. Carbon dioxide equivalent lifetime emissions calculated over one year. All the different cases have about the same total energy produced, which is 500 TWh.

The results are predictable; energy systems containing fossil fuelled power generate much more CO_2 equivalent emissions than the systems with no fossil fuelled power. The last graph exceeds the scale as its emissions are over 90 million tonnes. The Storage and the Low Hydro scenarios use energy storages which are not visible in Figure 35. The Base scenario has around 7 010 000 t of total CO_2 equivalent emissions, the Storage scenario 6 040 000 t and the Low Hydro scenario around 8 090 000 t. If the CO_2 equivalent lifetime emissions related to the energy storages were also considered, the Base scenario would most likely have the lowest total CO_2 equivalent lifetime emissions over the year 2050.

Nuclear energy produces relatively little greenhouse gas emissions and combined with its reliability (high capacity factors) and favourable costs shown in Figure 34, nuclear energy is an attractive option for low carbon power generation.

7 CONCLUSIONS

7.1 Scenario summaries and conclusions

All the future scenarios constructed in the model have working energy systems where there are no deficits after all the different elements of the systems have made their contributions. Conclusions regarding the different future scenarios and the roles of different elements within these systems are presented in this chapter. A broad general conclusion from the scenarios is that nuclear power provides stable and affordable base load generation for the energy system without direct greenhouse gas emissions. Nuclear power generally has high capacity factors and peak load hours and its high stable electricity output helps to offset the intermittent profile of wind power. Nordic hydropower is an excellent electricity generation source and the main element which balances the fluctuating nature of wind power in the model, but most of the potential hydropower capacity has already been built, at least in Finland, Denmark and Sweden.

7.1.1 Base scenario

The energy system in this scenario has four electricity generation sources: wind, hydro, nuclear and biomass. The energy system is based on the IEA's CNS scenario, which estimates that the Nordic countries will become net exporters of energy in the future. Wind power is the only intermittent electricity source in the scenario as its electricity output depends on the weather conditions. A portion of the hydropower is dispatchable and is the only flexible electricity source in the Base scenario. The role of hydropower is to offset the possible hourly deficits in the system. Nuclear and biomass provide the base load to the system and their outputs are stable throughout the year. Biomass also provides heat in the form of CHP production.

In chapter 6.2.2 the Base scenario's generation mix was modified to exclude nuclear power and replace it with wind and biomass generation. Nuclear power can of course be replaced by other electricity generation sources than the ones presented in this scenario, but these were selected as the objective was to create a carbon free energy system using renewables. Increasing the hydropower capacity was not an option as it was deemed that it already was at least close to its maximum capacity at 65 GW while the IEA estimates that there will be around 60 GW of hydropower capacity in the Nordic countries in 2050 (IEA, 2013). As chapter 6.2.2 showed, replacing nuclear power with wind and biomass is not a trivial matter. Nuclear power generates more energy per installed capacity than wind or biomass and is also cheaper to construct.

In chapter 6.2.1 a situation with zero generation from wind power was studied. The Base system could handle this with dispatchable hydropower but as soon as yet another generation source was removed, the system had deficits. This is an unrealistic situation, but shows that all the different electricity generation sources serve a purpose in the constructed energy system; they provide base load energy to the grid. Consumers demand a certain amount of electricity and the energy system has to provide that.

The Base scenario and the modified Base scenario show that the nuclear power has an important role as a base load providing generation source in the future energy system. It provides the most energy per installed capacity and produces hardly any air pollutants during its operation. As the Nordic countries have aspirations to achieve a carbon free energy system in the future, nuclear energy can offer a significant contribution towards this target.

7.1.2 Similar scenario

The energy system in this scenario has a similar generation mix in 2050 as the real life Nordic energy system had in 2013 but the overall electricity generation and consumption was scaled up to the levels that IEA anticipates in their Nordic Energy Technology Perspectives publication. It is highly unlikely that the future energy system will be the one described in this scenario. The purpose of this scenario was to show how the Base scenario's energy system compares to the current one scaled up to 2050 in regards to emissions of CO_2 equivalent air pollutants. The Base scenario's energy system performs favourably in this comparison. Figure 23 shows the CO_2 equivalent lifetime emissions calculated over one year in the Base and Similar scenarios. The Base scenario has significantly lower emission levels. Values for the lifetime emission per kWh of produced energy vary greatly depending on the source. Using the IEA lifetime emission value for nuclear energy shows that the nuclear energy's lifetime emissions calculated over the year 2050 are at the same level as wind, biomass and hydropower.

The Similar scenario shows that if the aim is to replace fossil fuelled generation with low carbon technologies, nuclear energy is a viable option.. Nuclear energy provides large-scale low carbon electricity at stable production costs and its electricity generation is not dependant on the weather conditions.

7.1.3 **Storage scenario**

In this scenario, the Nordic energy system utilizes energy storage and this in turn allows lower capacity values for different electricity generation sources. The total energy produced in this scenario is less than in the Base scenario and the Nordic countries are neither importers nor exporters of energy in the Storage scenario. The energy system is more optimised to produce just the amount of energy that the consumers demand. The total generating capacity is 36 GW less than in the Base scenario but the Storage scenario has the following storage capacities: 1.5 GW short term, 5 GW long term input and 10 GW long term output. These storages values ensure that the energy system has no deficits during the year.

The energy system in this scenario still has a large amount of hydropower capacity which handles the majority of hourly flexibility needs of the grid. Wind power is the only intermittent generation source in the system while nuclear and biomass provide base load power. This scenario was constructed in order to demonstrate that hydro, wind, nuclear, biomass and energy storage can form a functioning energy system. The introduction of energy storage lowers the amount of installed generating capacity and also somewhat enhances the reliability of the grid; if some generating capacity were to suddenly drop from the grid, the stored energy could temporarily replace it.

7.1.4 Low Hydro scenario

The Low Hydro scenario was constructed in order to demonstrate that the carbon free energy system can function without a large amount of hydropower. The Nordic countries benefit from the large amount of Norwegian hydropower available as hydropower is an excellent generation source for balancing and controlling the electric grid. If the energy system has large amount of hydropower capacity, the challenges that arise from large shares of intermittent renewable generation, such as wind and solar, are more easily mitigated. Also when water levels are adequate, hydropower is generally one of the cheapest sources of electricity generation.

In the Low Hydro scenario, the capacity of hydropower was only 1 GW meaning that the balancing and flexibility needs of the grid had to be satisfied with energy storage. Wind, nuclear and biomass capacity values were chosen to generate around 500 TWh of energy over the year, which is at the same level as in the Base scenario. If the energy system had surplus energy in any given hour that energy was stored in long and short term storage facilities. Energy stored in these facilities was utilized in the hours when electricity generation from wind, nuclear and biomass was not enough to satisfy the demand. The constructed energy system has no deficit hours during the year and shows that a carbon free energy system can function without hydropower. Nuclear energy has an important role in this system as it produces almost 49% of the total energy while its generating capacity is only 33% of the total capacity connected to the grid. Replacing this much nuclear generating capacity with other low carbon technologies, such as wind, biomass and solar, would require significant investments.

7.2 Future research

The model constructed for this thesis is quite simple and has relatively few elements. Smart grids, advanced supply side management, demand side management, electricity trade with neighbouring countries and load following with nuclear power plants are just some of the possible elements in the future energy system which are not directly modelled here. In this thesis, only the power sector is considered. In the future energy system, transport, heat, building and industry sectors are interlinked and they will communicate with each other.

A wider variety of electricity generation sources could be added to the model and be further separated and modelled individually, for example different rows for Swedish and Finnish nuclear generation could be included. Load following nuclear power plants and SMRs could be modelled as now the nuclear power in the model provides just base load power to the grid.

The model does not take economic factors in to account. Capital and O&M costs between nuclear, wind and biomass are briefly studied in the theory section of this thesis, but not in the model itself. Electricity prices and market models affect how different electricity generation sources and power plants are run. Taking these factors into account, the generation mixes and merit order could be somewhat different. Profitability and total costs of the future energy system would also be interesting topics for future research.

8 SUMMARY

Currently environmentally friendly power generation and reduction of greenhouse gases are popular and widely adopted targets. For example, The European Union has set different CO_2 emissions reduction and renewable generation targets for its member states. The current energy system in place in the Nordic countries is already one of the most carbon free globally, but there is room for improvement. Nordic countries have set their ambitions and energy targets at CO_2 emissions in the Nordic region being reduced by 85% by 2050 compared to emission levels in 1990. In this thesis, the energy systems of 2050 in different scenarios are 100% carbon free. In the Base scenario, the majority of the energy is produced with renewables (hydro, wind, biomass) and around 24% by nuclear power.

Nuclear power seems to have many attractive properties in regards to carbon free energy system aspirations. Nuclear power is a proven technology and future reactor designs promise even safer, more efficient and versatile reactors. During operation, nuclear power plants have practically zero air pollutant emissions and their lifecycle emissions are also much lower than emissions of fossil fuelled power plants. According to some literature sources, lifecycle CO_2 emissions of nuclear power plants are at the same level as those of renewable generation. Construction and investment costs for new nuclear are competitive with other low carbon technologies. The challenge with nuclear power are the large unit sizes which require substantial initial investments compared to other generation sources. Small modular reactors can alleviate this problem as they have smaller unit sizes and can be deployed in increments.

Nuclear power enhances energy security because the uranium resources and fuel are available from many different sources, both geographically and politically. Using current nuclear technology, conventional uranium resources are expected to last up to 200 years at today's consumption rate. Nuclear power has clear advantages when comparing its energy security to fossil fuelled power plants. Especially oil and natural gas have limited supply sources. The oil crises of 1970s showed that it is important to have various fuel supply sources and dependency on imported fuels from only a few sources is a real problem. In addition to nuclear power's more diverse fuel supply sources, nuclear energy also benefits from the very high energy density of uranium fuel. Uranium fuel is much easier to stockpile than say, coal or oil.

Traditionally nuclear power has been a reliable form of electricity generation. Generally nuclear power plants have high capacity factors, at least when compared to other low carbon technologies. Most shutdowns are planned well in advance and generally they are scheduled to take place when demand is expected to be lower than normal. Nuclear power is a predictable and stable form of generation and this is emphasized when compared to intermittent low carbon generation, namely wind and solar power.

Nuclear power offers grid management services which traditionally are not offered by wind or solar power. These include primary and secondary frequency control, predictable and controllable availability and rotating inertia. All of these are needed in order to have a functioning energy system making an energy system with 100% share of renewables hard to realise. As of now, these grid management services are performed by fossil fuelled generation, nuclear generation and hydropower. The Nordic countries are in the fortunate position that they can utilize the vast hydropower capacity of Norway. Hydropower is an excellent form of power generation for regulating power and for grid balancing purposes, but there is natural limit for hydropower capacity. As future energy systems abandon the use of fossil fuelled generation, nuclear power can replace it as a low carbon technology while maintaining grid stability.

The model and scenarios in this thesis show that it is possible to form a functioning, 100% carbon free energy system by combining GHG-free renewables and nuclear energy. Wind power has large share of the total produced energy, but its generation profile fluctuates. Production from wind turbines is highly dependent on the prevailing weather conditions. The Nordic countries utilize a large hydropower capacity which offers both stable electricity output and flexibility to the grid. Dispatchable hydropower works as the major stabilising element in most of the scenarios. In the Low Hydro scenario, this flexibility and stabilisation is achieved by using energy storage. Nuclear power produces electricity evenly and predictably throughout the year. Biomass fuelled CHP also produces electricity and heat evenly throughout the year. Their roles are equally as important as hydropower is; however wind and hydropower capacities cannot satisfy the consumption demand by themselves. Out of these generation sources, nuclear power produces the most energy per installed capacity.

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APPENDIX 1. THE GENERALISED SUPPLY AND DEMAND INDEX

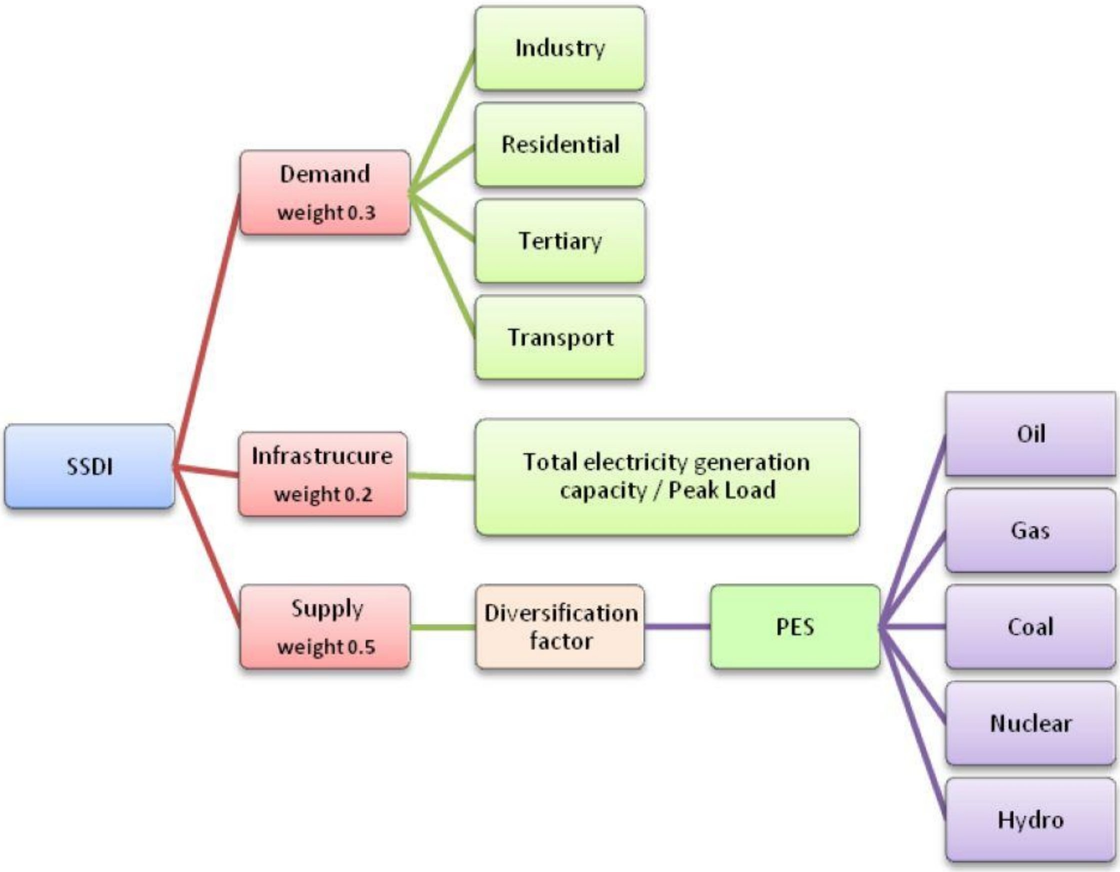

Figure A1. The basic structure of the SSDI.

The Simplified Supply and Demand Index in this thesis is from the Nuclear Energy Agency's (NEA) publications. The SSDI has three weighted contributions: energy demand, energy infrastructure and energy supply. Each of these contributions have different weights based on the perceived vulnerability to a nation's energy security. The given weights take into account:

- the degree of diversity and supply origin of different energy carriers in the nation
- the efficiency of energy consumption
- the state of the electricity generation infrastructure.