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RELIABILITY ANALYSIS OF THE FINNISH POWER SYSTEM

Master of Science Thesis

Examiner: prof. Sami Repo
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ABSTRACT

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Maintaining power system security and adequacy has become more and more challenging due to the desire to decarbonize the electricity sector promoting renewable electricity. Power inadequacy occurs when the available production capacity does not suffice the demand. Finland wants to phase out coal by 2030 in a bid to drastically cut greenhouse gas emissions and closures of condensing power plants are expected to affect power adequacy during high demand. The main targets of the work are to find out if the power system of Finland will be reliable by 2030, if the decommission of technologies that use traditional energy sources threat the power balance and what impacts will the introduction of renewable technologies cause on the reliability of the power system. The loss of load probability method using a daily peak load variation curve appears to be the most widely accepted technique and used more often than any other approach, where the criterion of adequacy becomes some acceptable risk level at which the load will exceed the probable available capacity. The development of the tool was made using MATLAB. Once the code was finished, first the reliability of the developed program is evaluated testing historical data of electricity consumption in Finland. The results obtained show that the designed tool is very sensitive to changes in the load duration curve, specifically sensitive to the maximum load peaks. Secondly is made a forecast of the reliability of the Finnish power system in 2030, studying how the installed capacities of each technology will change and setting three different scenarios of electricity consumption represented by different load duration curves. The final evaluation considers three cases, one in which the nuclear power plant of Hanhikivi 1 is commissioned, another in which it is not commissioned and a third one considering the unavailability of wind power installed capacity during peak load demand. First two cases give a reduction of the expected load loss in the power system for year 2030, which in the worst case is a 47% lower than the current value. This could indicate that the Finnish power system will be very reliable in the way that the electricity generating facilities will be sufficient to meet the country's electricity demand during most of the year, but in the third case the risk of power inadequacy increases alarmingly due to the intermittent nature of the renewable technologies and the decommissioning of thermal power plants.

PREFACE

This thesis has been made thanks to the motivation experienced in the classes in distributed energy resources, power engineering and smart grids of the Tampere University of Technology. I want to thank my supervisor mainly for the great help he has given me at all times. I also want to thank my family and friends, especially those who have accompanied me in this last year.

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LIST OF SYMBOLS AND ABBREVIATIONS

AC	Alternating Current
BWR	Boiling Water Reactor
CHP	Combined Heat and Power
DC	Direct Current
DH	District Heating
DSO	Distribution System Operator
EPR	Evolutionary Power Reactor
ENSTOE	European Network of Transmission System Operators for Electricity
EU	European Union
FOR	Forced Outage Rate
HV	High Voltage
kV	Kilovolts
kWh	Kilowatt hour
LV	Low Voltage
MV	Medium Voltage
MVA	Megavolt-ampere
MW	Megawatt
PJ	Petajoule
STUK	Säteilyturvakeskus (Radiation and Nuclear Safety Authority)
TOU	Time of Use
TSO	Transmission System Operator
TVO	Teollisuuden Voima Oy
TWh	Terawatt hour
WWER	Water-Water Energetic Reactor

E	Expected load loss
O	Outage
P	Probability
t	Time

1. INTRODUCTION

Energy is the fuel that feeds the engine of modern society. The well-being of our people, industry and economy depends on safe, secure, sustainable and affordable energy. At the same time, dependence on energy entails negative impacts. Energy production and consumption are the largest sources of greenhouse gas emissions in the EU, accounting for 80% of the total. The world is counting to achieve a global agreement that puts us on a more sustainable path. Time is of essence since the cost and difficulty of mitigating greenhouse gas emissions increases every year. The energy sector must play a critical role if efforts to reduce emissions are to succeed.

In 2007 the European Council adopted ambitious energy and climate change objectives for 2020 (Comission, Energy 2020 A strategy for competitive, sustainable and secure energy, 2010)– by 2020, the EU aims to reduce its greenhouse gas emissions by at least 20%, increase the share of renewable energy to at least 20% of consumption, and achieve energy savings of 20% or more. All EU countries must also achieve a 10% share of renewable energy in their transport sector. Through the attainment of these targets, the EU can help combat climate change and air pollution, decrease its dependence on foreign fossil fuels, and keep energy affordable for consumers and businesses. The European Parliament has continuously supported these goals, and while consensus grows among countries to act, we must ensure that the steps taken are adequate and that the commitments made are kept. The European Council has also given a long-term commitment to the decarbonization path with a target for the EU and other industrialized countries of 80 to 95% cuts in emissions by 2050 (Comission, 2050 Energy Strategy, 2018). Greenhouse gas emissions for the EU are expected to decrease further by 2020 to 26 % below 1990 levels as projected by the EU Member States, with the current measures that are already in place. This would surpass the reduction target of 20 %. Additional measures currently planned by Member States could further reduce emissions to 27 % below 1990 levels. A reduction of EU greenhouse gas emissions of between 30 % and 32 % could be achieved by 2030, compared with 1990 levels according to Member States projections reported in 2017.

Nevertheless, the existing strategy is currently unlikely to achieve all the 2020 targets, and it could also be inadequate to the medium and longer-term challenges. Energy investments are needed in every country, both to diversify existing resources and replace equipment and to cater for challenging and changing energy requirements. European economies will suffer structural changes in energy supply, having to choose among energy products and infrastructures. These choices will be felt over the next 30 years and more. The EU energy policy goals are security of supply through the secure operation of the power system, competitiveness regarding market-based investments and sustainability thanks to clean electricity generation. Many recent policies have overemphasized renewable electricity. Proof of this can be found in the search for alternative energies in the light of fossil fuels dependence. In recent years, progress has been made in developing cleaner, more efficient energy technologies. However, this has caused the other two goals to be in jeopardy. On the one hand, subsidies to promote renewable electricity have undermined the role of market-based investments. On the other hand maintaining power system security has become more and more challenging due to the desire to decarbonize the electricity sector promoting renewable electricity. Excess subsidies crowded out market-based investments in the sector. Subsidized production that receives revenues outside the markets pushes conventional generators off the merit order. When conventional electricity generating technologies leave the market power adequacy and power system security are at risk. Power inadequacy occurs when the available production capacity does not suffice the demand and reduced power system security means that the power system becomes less capable of handling the rapid variations in consumption or production.

These threats are also affecting the Nordic power system. The power grids of the Nordic countries face challenges such as keeping the power adequacy and system flexibility. System balancing with controllable production including production curtailment, import/export capacity and demand response are adequacy issues. Due to the policies of promotion of renewable energies, the decommissioning of conventional technologies and the vast subsidies to renewables that pressed electricity prices to historically low levels, a large mount of conventional plants left the market. This means flexibility that the power grid loses, when precisely the increase of renewable technologies should be accompanied by an increase in the flexibility of the power grid to deal with the intermittent nature of these technologies. Also, the increase in renewable technologies arises other problems such as surplus production during low load periods, which puts at risk the adequacy between supply and demand of electricity.

In Finland this had never been a problem thanks to condensing power plants, but now that they are pushed out of the market it means a reduction of supply that could endanger the power balance. Supply and demand need to be balanced at every instant. Inertia is a measure that indicates how large a drop in frequency follows a tripping of a large power plant. Having a lot of inertia slows down the drop of frequency. Low inertia means faster and larger drops in frequency, which increases the risk of blackouts. The largest providers of inertia are the nuclear power plants and the large thermal power plants. Renewable technologies such as wind and solar do not provide inertia.

Finland wants to phase out coal by 2030 in a bid to drastically cut greenhouse gas emissions. The presented “Energy and Climate Strategy for 2030 and Beyond” details plans to stop producing energy from coal within 14 years and replace traditional power sources with bio-fuels and renewable energy so that the power system remains stable

(Sims, 2016). Finland is going to vote for changing legislation and increase the carbon tax by 2018 to phase out coal. Coal produces roughly 10 percent of the energy consumed by Finland. This means the Nordic heaviest coal consumer (Reuters, 2017). Closures of condensing power plants in Finland are expected to affect power adequacy during high demand. Therefore, the need arises to carry out a study capable of measuring the risk faced by the Finnish power grid by closing conventional electricity generation power plants.

1.1 The objectives and the scope of the thesis

The main objectives and research questions formed for this thesis are:

- *Will the power system of Finland be reliable by 2030?*
- *Can decommissioning of technologies that use traditional energy sources threaten the power balance of the Finnish power grid in the future?*
- *How the introduction of renewable technologies will affect the reliability of the Finnish power grid?*

The study is done focusing on the power system of Finland. Specifically, what is going to be analyzed is the Finnish electricity generation system from the point of view of satisfying the demand. Therefore, this study focuses on the analysis of the reliability of the generation system. Even so, it should be noticed that there are more actors participating in the power system. Other analysis could focus on evaluating the reliability of the transmission system.

1.2 Structure of this work

The structure of this work is divided into several stages. First is studied how the Finnish power generation network works today, which resources and technologies are used to satisfy the demand for electricity in Finland. In the second stage a quantitative analysis model known as "Expected loss of load analysis" is studied and developed in the MATLAB program. In the third stage all the necessary data is obtained for testing the designed tool and evaluate its effectiveness. In the fourth stage scenarios for the future are proposed and the expected load loss in each of them is calculated. The idea is visualized in Figure 1.

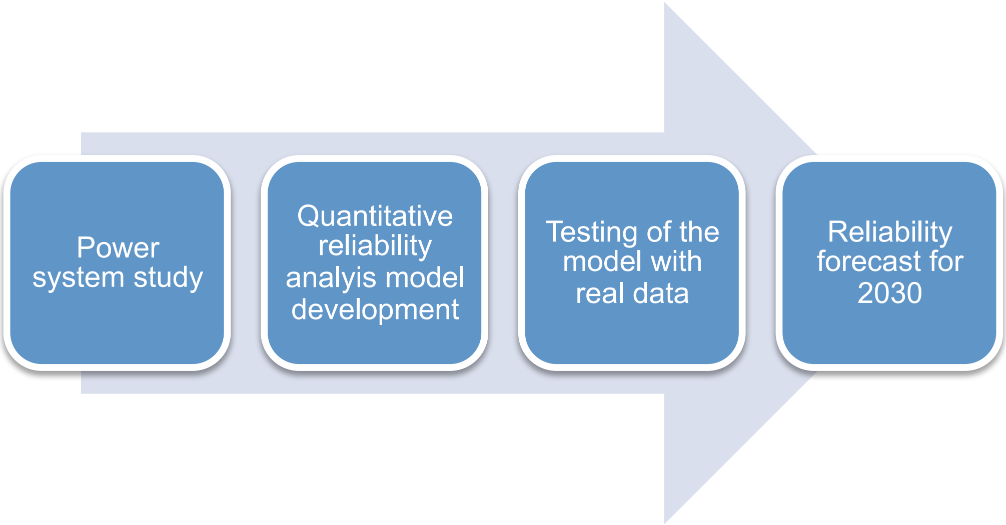


Figure 1. *Foundations of the conducted research*

Chapter 2 makes a study of the prevailing environment of the generating electricity capacity power system in Finland, giving the reader knowledge of the challenges and threats it faces. In chapter 3 a specific type of reliability analysis is studied and the code necessary for its application is implemented in MATLAB. In this chapter, the program is also tested with real data on electricity generation in Finland and the accuracy of the tool is evaluated. In chapter 4, the reliability forecast of the Finnish power system for 2030 is performed. In chapter 5 results and conclusions are extracted.

2. ELECTRICITY GENERATION SYSTEM IN FINLAND

The power system in Finland consists of power plants, nation-wide transmission grid, regional networks, distribution networks and electricity consumers. Finland’s main grid is part of the synchronous inter-Nordic system, which includes the transmission grids of Sweden, Norway and eastern Denmark, in addition to Finland. Moreover, there are direct current transmission links to Finland from Russia and Estonia for the connection of their systems, which work under different principles, to the Finnish power system. Similarly, the inter-Nordic system is connected to the system in Continental Europe by means of direct current transmission links. The Finnish Transmission System Operator (TSO) is Fingrid, who is responsible for the functioning of the Finnish electricity transmission grid. The transmission grid is the high-voltage trunk network that covers the entire Finland. Major power plants, industrial plants and regional electricity distribution networks are connected to the grid. The entire Finnish power system is composed of approximately 4.600 km of 400 kV transmission lines, 2.200 km of 220 kV transmission lines, and 7.600 km of 110 kV transmission lines, 116 substations and 428 power plants (Fingrid, 2017) (Energiavirasto, 2018).

The transmission of electricity refers to the Extra High Voltage network of 440 and 220 kV and the High Voltage (both represented as HV) of 110 kV (Hanninen, 2018) network and its operation is responsibility of the TSO. It is made from high voltage AC feeders that are capable of delivering a large amount of electricity with low losses. The transmission grid serves electricity producers and consumers, enabling trading between them on a nation-wide level and also across national boundaries. The distribution consists of Medium Voltage (MV) of 20 kV and Low Voltage (LV) of 0.4 kV networks, which are usually operated by Distribution System Operators. Their function is to offer sufficient coverage for the benefit of the electricity end consumer. In Finland, the final consumers of electricity are the sectors of transport, construction, services and public sector, industry, agriculture, electric heating for residential buildings and electricity for household equipment.

The electricity generating power plants present a critical role in the engine that makes up the entire power system, since they are the starting points of the long chain that performs the electricity delivery process. Accordingly, it is vitally important that the network of power plants in the country is reliable and safe to meet the needs of consumers.

2.1 Electricity production

The total population in Finland was estimated at 5.4 million people at the end of 2016. According to Statistics Finland's preliminary data, total energy consumption in 2016 amounted to 1,335 PJ (Petajoule) or 371 TWh, which means an increase of two percent over the previous year. A significant fraction of this total energy consumption dissipates due to conversion and transmission losses. Figure 2 shows the difference between the total energy consumption and the final consumption (Vertanen, Total energy consumption rose by 2 per cent in 2016, 2017).

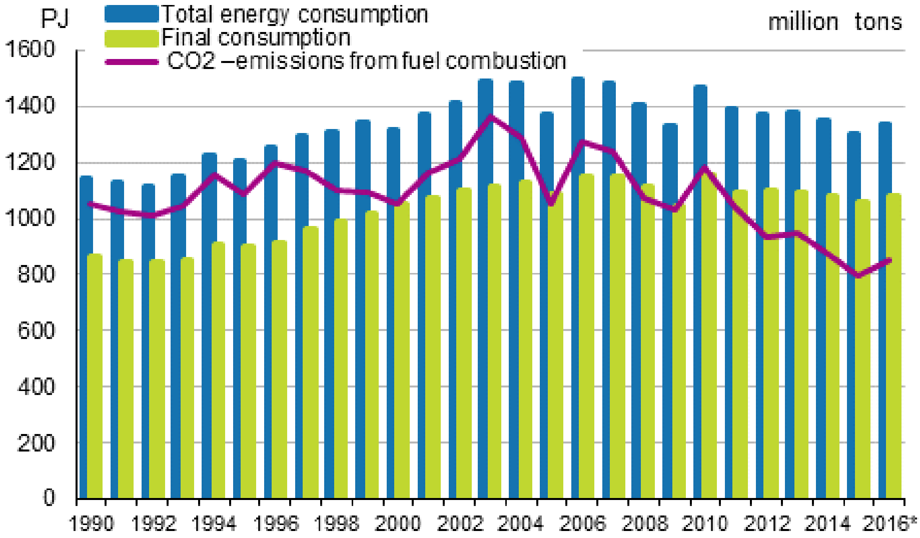


Figure 2.** Energy consumption in Finland during last 26 years **(Vertanen, Total energy consumption rose by 2 per cent in 2016, 2017)

In 2016, electricity production sum up 85,1 TWh of Finland's total energy consumption, up by around three per cent year-on-year. The consumption of electricity per capita in Finland is approximately 15.000 kWh per person per year, being the third highest in Europe, only surpassed by Iceland and Norway. To meet this high demand for electricity the Finnish power system has different technologies that together are able to help achieve the appropriate level of supply. Looking back in time, during the 1970s the Finnish power system was mainly based on hydroelectric power, condensing power and combined industrial heat and power production. During 1975, the first nuclear power plants appeared in Finland, which represented a major change in terms of energy efficiency. By the end of the twentieth century, other technologies appeared such as combined heat and power for district heating and also large interconnection cables connected the Finnish power grid with the neighboring countries for the exchange of electricity. In the twenty-first century, the main technologies that make up the Finnish power system have been consolidated, these are: hydroelectric, nuclear, combined heat and power district heating, combined heat and power for industrial purpose, condensing power, electricity imports and for a few years the wind technology also contributes significantly to the contribution of electricity. The contribution of wind energy is expected to increase during the next decade, and it is also expected that photovoltaic solar energy will be incorporated. Following Figure 3 shows how the contribution to the supply of electricity by technology has evolved during the last 45 years.

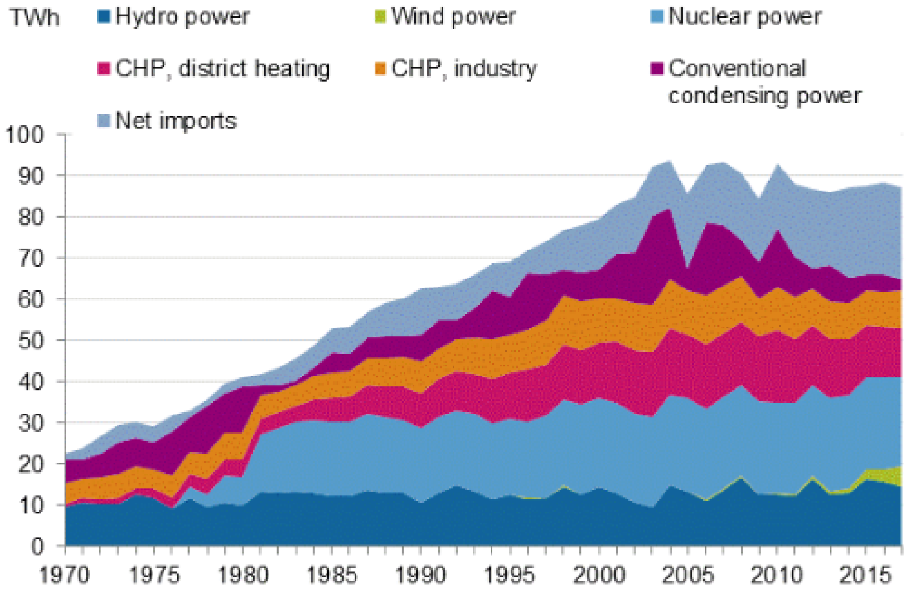


Figure 3. *Electricity supply 1970-2017* ***(Vertanen, Energy supply and consumption, 2018)***

It can be seen how the Finnish power system brings together several technologies, which obtain energy from different renewable and non-renewable natural resources. Based on the information obtained from the Ministry of Economic Affairs and Employment's publications of December 2017 made in the ''Government report on the National Energy and Climate Strategy for 2030'' (Huttunen, 2017), it is shown in Table 1 a breakdown of the different natural sources used during the entire year 2015 for energy production.

Table 1. *Gross inland and final energy consumption in 2015 in Finland* ***(Huttunen, 2017)***

Energy source	**TWh**
Oil	87
Hard coal	17
Coke, blast furnace and coke oven gas	12
Natural gas	22
Nuclear energy	68
Net imports of electricity	16
Hydropower	17
Wind and solar power	2
Peat	15
Wood fuels	93
Others	14

Total energy consumption	**361**
Final energy consumption	**297**

As shown in Table 1, the consumption of fossil fuels is still high and it is necessary to reverse the situation to achieve the established greenhouse gases emissions reduction goals. In a bid to change the situation, the Finnish power system is taking action to help achieve the targets set for 2030.

The country has bet strongly for nuclear energy with the construction of the new nuclear plant Olkiluoto 3, which should start operating in May 2019. There is also another project pending Fennovoima Oy for the construction of another nuclear power plant unit in Pyhäjoki. This would imply a considerable increase in installed capacity since during last years some replacement investments in power generation were made but there was no significant change in total capacity (except wind power). Most of the condensing power plants are closing in Finland and currently many CHP producers are considering whether they should invest for CHP or just heating capacity in the future. Capacity adequacy is a challenge in Finland and it will be a challenge also in the future. Controllable generation capacity has been decreasing and at the same time intermittent renewable capacity is increasing, which means a risk in the power adequacy for the future.

2.2 Non-renewable technologies in Finland

2.2.1 Nuclear power

At 2017 Finland had four nuclear reactors accumulating a total capacity of 2779 MW. Two of them consist of boiling water reactors and are operated by Teollisuuden Voima Oy (TVO). The other two are modified pressurized water reactors (WWER) operated by Fortum Oy. Nuclear power is a fundamental technology for the supply of electricity in Finland. Their average lifetime capacity factor is over 85% and average capacity factor over the last ten years 95% (Association, 2018).

Olkiluoto 1 and 2 (TVO) started up in 1978 and 1980 at 660 MW net each (690 MW gross). Thirty years later it was decided to carry out an upgrade to increase the installed power of the reactors up to 880 MW each and their lifetime was extended to sixty years, subject to safety evaluation every decade. According to TVO, it is possible to continue increasing the installed power up to 1000 MW each. A 25 MW uprate of Olkiluoto 1 over May 2010 was part of this, involving replacement of low-pressure turbines. A similar uprate of unit 2 to almost 910 MW gross was undertaken over June 2011. With uprates, TVO aims “always to have 40 years of remaining technical lifetime”. In January 2017 TVO applied for twenty-year license renewal for both units, and has submitted an extensive periodic safety review the Radiation and Nuclear Safety Authority (STUK) to support this.

The other two nuclear power plants consist of WWER-440 reactors owned by Fortum Oy at Loviisa. Unit 1 started commercial operation in 1977 and unit 2 in 1980 with a design capacity of 420 net MW each (465 MW gross). Later they were uprated 18% from to 496 MW net each (520 MW gross). Their operational life expectancy is fifty years. In 2007 an extension of 20 years was granted by the Radiation and Nuclear Safety Authority, extending its useful life until 2027 and 2030, subject to safety evaluation in 2015 and 2023. In 2008, Areva and Siemens commenced a modernization project to install modern digital instrumentation and controls systems at the plant, expected to take six years, but Fortum terminated this in 2014. The second attempt to renew the automation was transferred to Rolls-Royce, which expects to complete it in 2018. In 2017 Fortum announced a 12 MW uprate due to turbine refurbishments, taking each unit to 502 MW net. Table 2 below shows a summary of the power plants in Finland.

Table 2. *Nuclear power plants in Finland*

	Type	**MW net**	**First power**	**Expected shutdown**
Loviisa 1	WWER-440/ V213	502	1977	2027
Loviisa 2	WWER-440/V213	502	1980	2030
Olkiluoto 1	BWR	880	1978	2038
Olkiluoto 2	BWR	880	1980	2038
TOTAL		**2764**		

The safety and reliability of the nuclear plants in Finland have led the country to keep his bet on this technology. Proof of this is that it is one of the few countries in Europe that is building a new reactor and has another one planned. The most significant generation investment project in Finland is the construction of nuclear power plant unit Olkiluoto 3. The completion of the building of this 1,600 MW unit has been delayed for several years. Originally the commissioning was scheduled for the end of 2009. According to the latest estimates, grid connection is expected in December 2018 and commercial operation in May 2019. The new reactor is rated 1600 MW and the type is a Pressurized Water Reactor (EPR).

Fennovoima Oy is planning to construct the new nuclear power plant of Hanhikivi 1 in Pyhäjoki. The project has received a decision-in-principle from the Finnish Government and the Parliament and is waiting for a construction license, which is expected to be granted in 2018. The unit will be 1.200 MW and it is planned to be in operation in 2024.

A project to further expand Olkiluoto's power plant has been canceled. Table 3 shows a summary of the reactors under construction, planned and canceled.

Table 3. *Nuclear power plants under construction, planned and cancelled* ***(Association, 2018)***

	Type	MW net	MW gross	Construction start	Commercial operation
Olkiluoto 3	EPR	1600	1720	May 2005	May 2019
Hanhikivi 1	WWER-1200/V-491	1200	1250	2019	2024
TOTAL		2750	2920		
Olkiluoto 4	EPR, ABWR, ESBWR, EU-APWR, or APR1400	1500-1700	1550-1830	Cancelled	

2.2.2 Combined heat and power. District heating and Industrial

Combined heat and power plants (CHP) are characterized for being able to produce electricity and heat at the same time. By this method they can achieve much higher efficiencies than generating electricity and heat separately. Combined heat and power plants can use renewable or non-renewable fuels, depending on the power plant type and the region. If it is a renewable CHP then wood and other biomass is used to produce the electricity. In the case of non-renewable, coal, oil, natural gas or peat are used as fuel. Other possibilities are biogas or synthetic gas made from excess wind power or solar power and carbon dioxide from industrial process might be used as well. When choosing the fuel, it is important to consider the security of supply, overall financial and environmental impacts. Storability is important in the selection of fuels for production plants that are only used from time to time. As striving for carbon-neutral heat production, the share of fossil fuels is diminishing. This type of power plants is mainly used in two different technologies for the production of electricity and heat known as CHP District Heating and Industrial CHP.

District heating is a system for distributing heat (hot water or steam on a pipeline network) that has been generated in a separate boiler or a CHP plant. In environmental and energy efficiency terms district heating is an excellent choice, especially if it is generated in a CHP plant. In one district heat network, there are many power plants. This will help to adjust the production to the seasonally variable demand. Reserve capacity guarantees heat production also during maintenance outages and disruptions. A CHP plant is normally used according to the need for district heat, i.e. at full capacity when the heating need is highest. That is when it will generate the highest amount of electricity as well. Electricity demand is normally highest during cold winter days, and that is when heat demand is also at its highest. In the district heating networks, the thermal energy produced at the production plants is transmitted to customers as hot water in a closed district-heating network consisting of two pipes (supply and return pipes). The district heating water circulating in the supply pipes entering the house releases its heat to customers via heat exchangers, and the return pipe conveys the water back to the production plant for reheating. As said before, the heat is produced in combined heat and power plants, which produce electricity burning a fuel. If the fuel the power plants use is renewable, then it can be considered as a renewable technology. The total installed capacity for producing electricity of combined heat and power district heating in Finland according to Finnish Energy Authority, the data from which is collected and kept every year by Statistics Finland, is around 4294 MW with 63 (Energiavirasto, 2018) combined heat and power plants (Tilastokeskus, Electricity generation capacity, nominal capacity of production engines at beggining of year, 2018). These power plants mainly use hard coal to function. Many of them will have to change the fuel they use for a renewable one or those power plants will be decommissioned in the future.

Industrial CHP power plants arise from the need of many industries to have their own power plant, which produces electricity and heat or steam to the industrial process. This technology has developed very well in Finland and especially in the chemical, steel and forest based industries. The plants typically use residue material or heat for fuel that would otherwise be wasted. Industrial CHP considerably increases the process's material and energy efficiency. Industrial CHP production can also provide heat for the local community through a district-heating network, but still it is considered as two different resources. The installed electrical capacity of industry CHP according to the Energy Authority in 2017 was around 2837 MW (Tilastokeskus, Electricity generation capacity, nominal capacity of production engines at beggining of year, 2018), with 73 (Energiavirasto, 2018) power plants according to the power plant register. The main fuel used by these power plants is wood. Since these power plants do not burn as much coal as CHP district heating, a lower impact is expected from the coal phase out. The following Table 4 shows the use of fuel in the combined heat and power plants in Finland during the year 2016.

Table 4. *CHP District Heating and Industrial CHP fuel consumption 2016 in Finland* ***(Tilastokeskus, Heat and power production and energy sources 2016, 2018)***

	Hard coal	**Oil**	**Natural gas**	**Peat**	**Wood fuels**	**Other renewables**	**Other fossil fuels**	**Other energy sources**	**Total (TJ)**
CHP DH	51523	598	21786	25842	42882	7637	6661	1213	158142
Shares from CHP DH	33%	0%	14%	16%	27%	5%	4%	1%	
I CHP	4086	1996	14938	14708	181842	3187	2399	6494	229650
Shares from I CHP	2%	1%	7%	6%	79%	1%	1%	3%	

CHP total	55608	2593	36725	40550	224724	10999	9060	7707	**387967**
Shares from Total	14%	1%	9%	10%	58%	3%	2%	2%	

This table is of vital importance and will be used later when deducting how many power plants will be decommissioned in the future by the coal phase out.

2.2.3 Separate electricity production

When referring to separate electricity production, it aggregates the power plants that produce electricity through condensing power, peak gas turbines and gas engines and small power plants of less than 1 MVA. These power plants are usually referred to as one electricity generation technology known as separate electricity production. In Finland, many condensing power plants were built for the production of electricity using fossil fuels. Now the condensing power plants are also capable of burning renewable resources. According to Statistics Finland (Tilastokeskus) in 2017 the total installed capacity of condensing power was 1028 MW, the installed capacity of peak gas turbines and gas engines was 1230 MW and 140 MW for small power plants. Following Figure 4 shows the evolution of the installed capacity in the period between 2000-2017.

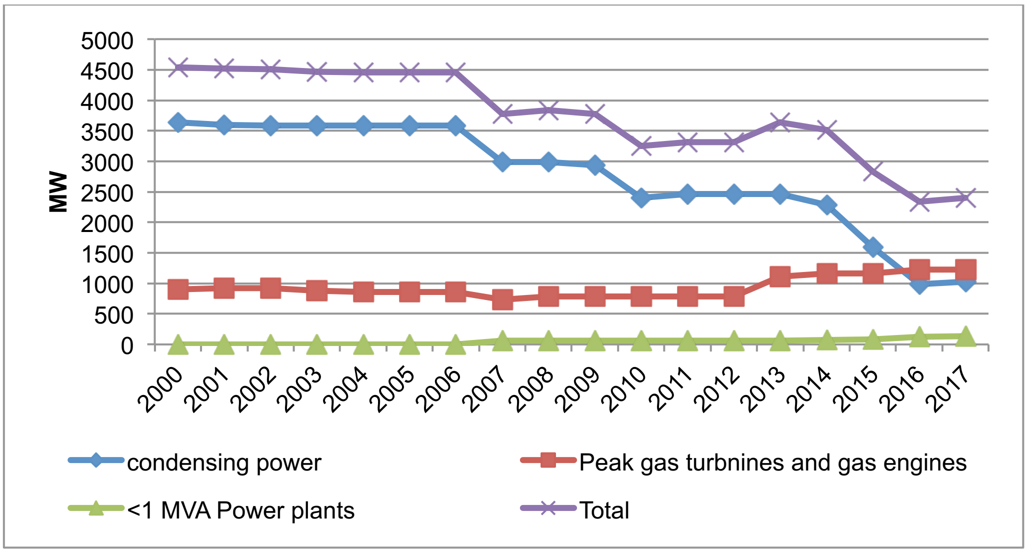


Figure 4. *Separate electricity production installed capacity 2000-2017 in Finland*

It can be clearly seen how the installed capacity of condensing power has been decreasing during the last years while the gas turbines on the other hand slightly increased. Following Table 5 shows the fuel consumption in the condensing power plants during 2016 (Tilastokeskus, Heat and power production and energy sources 2016, 2018).

Table 5. *Fuel consumption in condensing power plants during 2016 in Finland*

	Hard coal	Oil	Natural gas	Peat	Wood fuels	Other renewables	Other fossil fuels	Other energy sources	Total (TJ)
Conventional condensing power	20047	929	269	4782	11239	986	5628	818	**44699**
Shares	45%	2%	1%	11%	25%	2%	13%	2%	

From the table it can be seen that the most used fuel in this power plants is the hard coal, therefore, many of these power plants will be decommissioned before 2030.

2.3 Renewable technologies in Finland

Renewable technologies in Finland began with the construction of the first dams with their corresponding hydroelectric power plants. Afterwards, electricity production power plants started to use biofuels as a resource. In the decade of the nineties the first wind farms of Finland began to appear and since then the wind power installed capacity has increased considerably. Also, the first solar photovoltaic farms are currently being developed in Finland.

2.3.1 Hydropower

With 137 hydropower plants, according to the Finnish Energy Authority, the installed capacity of hydropower plants in Finland in 2017 was around 3201 MW (Energiavirasto, 2018). The largest hydropower plants such as Imatra or Petäjäskoski have installed capacities of almost two hundred megawatts, but usually the rivers in which these power plants are located do not have large height drops, so the vast majority consist of small hydropower plants with small head. Anyway, hydropower plays an important role in electricity production in Finland. In recent years its share of electricity production varied within the range 10-15% (Council, 2018), depending on precipitation levels and other hydrological conditions. For the production of electricity the most common used are Kaplan turbines. It could still be possible to increase Finland's hydropower capacity, though the main potential sources are generally well exploited. The hydropower plants belong to several companies. Some of these companies operate the plant by themselves to produce electricity or delegate it to another specialized company.

2.3.2 Biomass. Wood fuels in CHP and Condensing power

The use of biomass has spread very well in the Finnish power plants that burned fossil fuels for the production of electricity or heat. The fuel most used is wood. The advantage of burning biomass is that the CO_2 emissions that are produced come from a carbon removed from the atmosphere in the same biological cycle, not altering the equilibrium of the concentration of atmospheric carbon, and therefore they do not increase the greenhouse effect. Although, there is a debate ongoing about how much and in which conditions this is really true, since it seem that the dynamics of carbon cycle is more complex than we have thought. Its use helps reduce CO_2 emissions into the atmosphere provided it replaces a fossil fuel. In Finland, this practice has been extended especially in the power plants of Industrial CHP. In the condensing power plants and the CHP district heating is also used although the share is lower.

Following Table 6 shows the consumption of each fuel for CHP District Heating and for Industry CHP during 2016. The data has been extracted from Statistics Finland (Tilastokeskus, Heat and power production and energy sources 2016, 2018).

Table 6. *CHP DH and I CHP biomass consumption in Finland during 2016*

	Hard coal	**Oil**	**Natural gas**	**Peat**	**Wood fuels**	**Other renewables**	**Other fossil fuels**	**Other energy sources**	**Total (TJ)**
CHP DH	51523	598	21786	25842	42882	7637	6661	1213	158142
Shares from CHP DH	33%	0%	14%	16%	27%	5%	4%	1%	
I CHP	4086	1996	14938	14708	181842	3187	2399	6494	229650
Shares from I CHP	2%	1%	7%	6%	79%	1%	1%	3%	
CHP total	55608	2593	36725	40550	224724	10999	9060	7707	**387967**
Shares from Total	14%	1%	9%	10%	58%	3%	2%	2%	

This table shows how the highest consumption of renewable fuel is that carried out by the Industrial CHP, reaching 80% (adding wood and other renewables) and for the CHP district heating it is lower, 32%. In the total, the contribution of renewable resources exceeds the half, with 61%.

Condensing power technology, which traditionally used fossil fuels, has begun to develop power plants that are capable of using biofuels. In Table 5 showed before the share of biofuels of total consumption in 2016, accounting for a total amount of 15%. These data will be of vital importance later when forecasting the decommissioning of power plants due the coal phase out.

2.3.3 Wind power

Wind power is a relatively new mode of electricity generation in Finland and has developed well in the last few years. As with other forms of renewable energy, wind power receives government subsidies. However, if the wind power market is allowed to develop after 2020, and if cost effective methods are used to promote development, wind energy will become competitive in the electricity market without subsidies. There is a lot of potential to develop wind parks along almost the entire west coast and increase wind power capacity considerably. At the beginning of 2017 the installed capacity of wind power was 1533 MW according to Statistics Finland (Tilastokeskus, Electricity generation capacity, nominal capacity of production engines at beggining of year, 2018). By the end of 2017 there was a cumulative capacity between 1995 MW and 2044 MW (Tuulivoimayhdistys, 2017) depending on source. In Figure 5 is seen how the installed capacity of wind power has increased over the last 17 years in Finland.

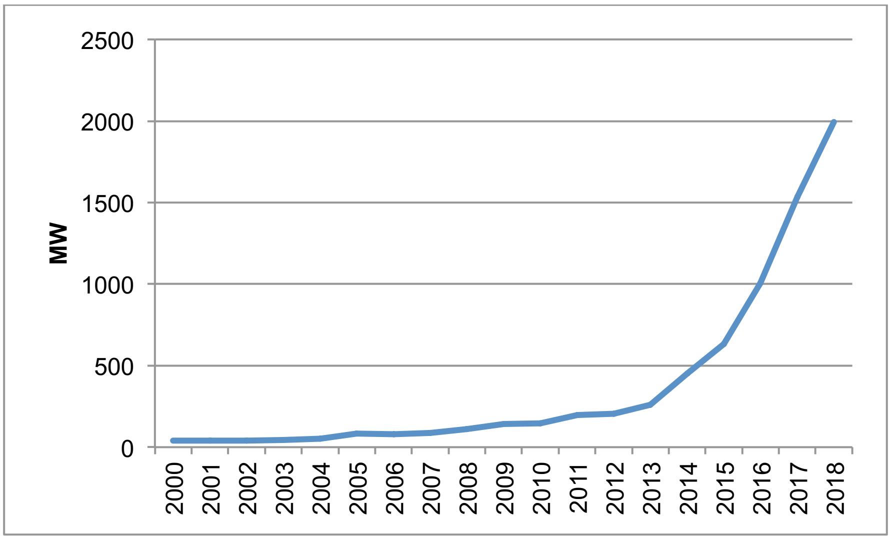


Figure 5. *Installed wind power capacity in Finland 2000-2018(start)*

Wind Energy Europe forecasts that the installed wind power capacity in Finland could achieve the 5000 MW by 2030 (WindEurope, 2017).

2.3.4 Solar photovoltaic power

According to data from the Finnish Energy Authority the installed capacity of solar photovoltaic energy in Finland in the beginning of 2017 was 3,6 MW. This amount is alarmingly low and makes it clear that the solar resource is scarce in the country. This is due to the weather conditions of Finland, which consists of long period in which the solar resource becomes really low or even zero. Even so, it is worth noting that potentially solar photovoltaic technology could be developed since there are periods during the year when there is a lot of solar resource. It would be especially useful in summer season contributing to the production of electricity in the network. This has raised the interest in building photovoltaic parks during the last few years, although there is still much to do to contribute in a significant way to the power system. In the end of 2017 the installed capacity of solar photovoltaic power in Finland was 35 MW (Energiavirasto, 2018), which means an increase in capacity by a factor of almost 10. Even so, the installed capacity is still very low.

2.3.5 Import electricity capacity

To deal with the electricity demand the Finnish power system needs to import electricity from neighboring countries. The country has been interconnected through large projects for many years to achieve an interconnection level of around 29% dealing with the highest rates in Europe (Commission, 2017) (TYNDP, Vision 2020, 2016). To define the installed capacity of the import, it is necessary to look into the interconnections established between Finland and other countries. The transmission grids of Sweden, Norway, Eastern Denmark and Finland form an aggregated grid known as the inter-Nordic system. The Nordic system is interconnected with other countries through several direct current (DC) transmission connections. The ones that involve Finland are DC connections from Finland to Estonia and Russia.

There are two AC 400 kV overhead lines between north Finland and Sweden that account for a total of 1500 MW. Also, there are DC connections between central Sweden and Finland, Fenno-Skan 1 and Fenno-Skan 2. The first one has a maximum rate capacity of 400 MW and the second one of 800 MW. The connections with Estonia are also based on two DC links. One is known as Estlink1 and consists of 350 MW. The other one is called Estlink2 and consists of 650 MW. Together mean a capacity of 1000 MW. The connection between Finland and Russia known as Vyborg consists of three DC links with a sum of 1300 MW. The interconnection capacity between Finland and Norway is quite small and consists of an AC link with a capacity about 100 MW. According to data published by the Finnish transmission system operator, Fingrid, the total electricity import capacity of Finland in 2017 was around 5100 MW. Following Table 7 shows the interconnections between Finland and its neighboring countries.

Table 7. *Interconnections between Finland and neighboring countries*

Interconnections	Type	Location	Capacity MW
North Finland-Sweden	Two AC 400kV	Northern Finland	1500
Central Finland-Sweden	DC	Fenno-skan1 and 2	1200
Finland-Estonia	DC	Estlink1 and 2	1000
Finland-Russia	Three DC 400kV	Vyborg	1300
Finland-Norway	AC 220kV	Ivalo Imatra	100
Total			5100

It shall be clarified that these numbers of capacity are valid during normal conditions. Especially the AC capacity may vary depending on transmission system stability limits.

2.4 Challenges for the power system

2.4.1 Global warming. Phase out coal 2030

Earth's climate has changed throughout history. Most of these climate changes are attributed to very small variations in the Earth's orbit that change the amount of solar energy our planet receives, but the heating trend suffered lately is extremely likely (more than 95 percent probability) of be the result of human activity since the mid-twentieth century and continue at a pace that is unprecedented.

Several indicators collected over many years reveal the evidence of a changing climate. There is no doubt that the increase in greenhouse gas levels should cause the Earth to warm up in response. Some evidences are for example that the average surface temperature of the planet has increased around 1,1 degrees centigrade since the late nineteenth century, a change driven mainly by the increase in carbon dioxide and other emissions produced by man in the atmosphere mostly in the last 35 years. The temperature of the oceans has increased by absorbing part of this heat. The ice sheets of Greenland and Antarctica have diminished in mass and glaciers are retreating almost everywhere in the world. The acidity of surface ocean waters has increased due to the increase in carbon dioxide absorption. Following Figure 6 shows rapid warming data in the past few decades and that the last decade has been the warmest on record (NASA, 2018).

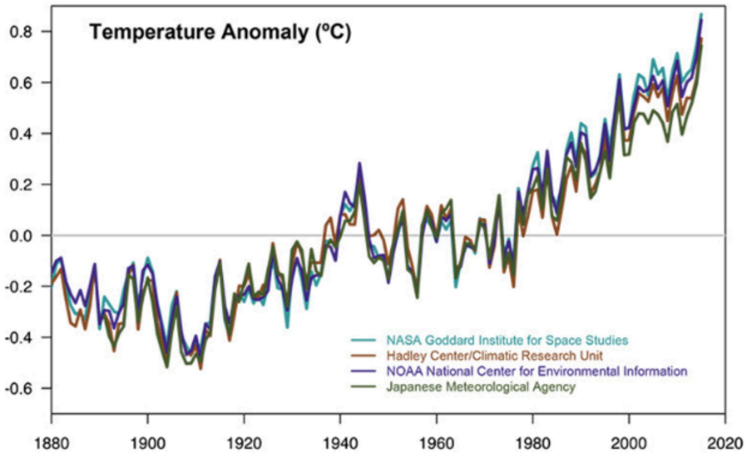


Figure 6. *Rapid warming data from four international science institutions*

Most of the scientific climate community agrees that the main cause of the current trend of global warming is the "greenhouse effect". The greenhouse effect is the warming that occurs when the atmosphere traps the heat radiating from Earth to space. It occurs because certain gases in the atmosphere block the escape of heat. Gases that contribute to the greenhouse effect are water vapor, which is the most abundant greenhouse gas; carbon dioxide (CO2), a minor but very important component of the atmosphere that is released through natural processes and through human activities such as deforestation, changes in land use and the burning of fossil fuels. Methane, nitrous oxide and chlorofluorocarbons (CFCs) are also greenhouse gases.

On Earth, human activities are changing the natural greenhouse. In the last century, the burning of fossil fuels such as coal and oil has contributed to increasing the concentration of atmospheric carbon dioxide (CO_2). This happens because the process of burning coal or oil combines carbon with oxygen in the air to produce CO_2. The most likely consequences of changing the natural atmospheric greenhouse (among many others) are the average warming of the Earth, greater evaporation and precipitation in general, making regions more humid and drier, and the rise in sea level by partially melting glaciers and other ice.

The prevention of dangerous climate change is a key priority for the European Union. Europe is working hard to reduce its greenhouse gas emissions while encouraging other nations and regions to do the same. The "European 2020 Strategy" taken in 2006 was the key 2020 objectives:

- 20% reduction in greenhouse gas emissions compared to 1990.
- Achieve the production of 20% of total energy consumption through renewable technologies
- Achieve a 20% increase in energy efficiency

EU countries have agreed on a new 2030 Framework for climate and energy, including EU-wide targets and policy objectives for the period between 2020 and 2030. These targets aim to help the EU achieve a more competitive, secure and sustainable energy system and to meet its long-term 2050 greenhouse gas reductions target. The key objectives for 2030 are:

- At least 40% reduction in greenhouse gas emissions compared to 1990
- At least 27% of total renewable energy
- At least 27% increase in energy efficiency

By 2050, the EU aims to substantially reduce its emissions, by 80-95% compared to 1990 levels as part of the efforts required by developed countries as a group.

Actions have been taken towards climate targets, especially in regulation, such as the EU emissions trading system, which is the key tool to reduce greenhouse gas emissions in the industry at the lowest cost. EU countries are also required to support renewable energy sources, such as wind, solar and biomass, to achieve green energy targets. Finland wants to phase out coal by 2030 in a bid to drastically cut greenhouse gas emissions. The presented "Energy and Climate Strategy for 2030 and Beyond" details plans to stop producing energy from coal within 14 years and replace traditional power sources with bio-fuels and renewable energy that the power system remains stable (Sims, 2016). Finland is going to vote for changing legislation and increase the carbon tax by 2018 to phase out coal. Coal produces roughly 10 percent of the energy consumed by Finland. This means the Nordic heaviest coal consumer (Reuters, 2017). Hence, closures of condensing power plants in Finland are expected to affect power adequacy during high demand.

2.4.2 Power adequacy

The structure of power generation capacity is changing towards more intermittent renewable energy, less base load generation and fewer flexible power plants. One of the main reasons that have caused this change is the growing participation of wind energy in power systems, which leads to greater variability in energy production.

Due to these changes, the conventional electricity generation power plants are seeing how their profitability decreases due to the low prices offered by renewables and this uncertainty is accelerating the withdrawal of conventional thermal and nuclear power plants. As if that were not enough, the policies that are being taken lately want to finish completely with many conventional power plants because of their emissions. This change means increasing the risks of investing in renewable technology. The changes are seen throughout Europe, returning the concern about the adequacy of the generation.

Making the generation adjust to the demand has always solved the balance between supply and demand. This supply-demand balance is now endangered by the change in the generation mix, and several studies indicate that the risk of capacity shortages is increasing nationally and for certain periods of time (Sihvonen-Punkka, 2016).

Power generation is facing massive changes across Europe since the phasing in of intermittent renewables combined with decommissioning of conventional thermal plants is challenging the operation of the power system. Conventional thermal plants represent a very reliable and safe source of electricity for the Finnish power system as they provide flexibility and inertia. Flexibility means that many of these power plants participate in the balancing system helping to maintain the balance between supply and demand. Inertia means that these plants help keep the frequency stable during tripping of other power plants.

The EU energy policy goals are security of supply, market competitiveness and the generation of clean electricity. The latest policies that have been taken have overemphasized renewable electricity, endangering the other two objectives. The capacity of wind power in Finland has grown rapidly, while a significant amount of thermal capacity has been decommissioned or dismantled. In addition, Finland is increasingly dependent on electricity imports and current electricity prices do not encourage market investments in electricity capacity.

The Ministry of Employment and the Economy prepared the National Energy and Climate strategy for 2030. The report forecasts an estimated consumption of electricity in Finland in the coming years of 88 TWh in 2020 and 92 TWh in 2030, and also shows how it predicts that the maximum peak load demand will continue to grow during the next few years as shown in Table 8.

Table 8. *Short-term forecast maximum peak load demand in Finland*

Winter season	2017-2018	2018-2019	2019-2020
Estimated peak load, MW	15200	15300	15400

As load peak demand is expected to continue increasing over the next few years, the generation capacity available during the load peak demand has been decreasing as can be seen in the table obtained from Statistics Finland of available capacity during peak demand (Tilastokeskus, Statistics Finland, 2018).

Table 9. *Available capacity during peaks in Finland*

	Hydro power	Wind power	Nuclear power	Condensing power	Gas engines and turbines	Industrial CHP	CHP District Heat	Capacity of power plants	Power system reserves
2007	2350	..	2720	2800	10	2450	2790	**13120**	1046
2008	2350	..	2700	2650	..	2450	3150	**13300**	1180
2009	2350	..	2700	2650	..	2450	3150	**13300**	1180
2010	2550	..	2700	2200	..	2300	3350	**13100**	1180
2011	2575	..	2730	2200	..	2365	3490	**13360**	1240

2012	2595	..	2750	2045	..	2370	3490	**13250**	1240
2013	2610	..	2765	2045	..	2330	3550	**13300**	1556
2014	2610	..	2780	1650	..	2330	3430	**12800**	1540
2015	2520	..	2780	1600	..	2250	3350	**12500**	1540
2016	2550	60	2780	960	..	2000	3250	**11600**	1400
2017	2550	100	2792	970	..	1990	3260	**11662**	1400

Table 9 clearly shows how the capacity available during the peaks has been decreasing due to decommission of condensing power plants. It is expected that in the years 2017 - 2019, the electricity generation capacity will not be sufficient to cover the electricity demand during the peak periods. Therefore, it will increase the dependence on the import of electricity, which in winter could reach the top of the capacity for importing electricity. According to the data for 2017, the production capacity of electricity in use in Finland was approximately 11.700 MW in the winter period 2017-2018.

The Finnish power system is taking action against the situation decreasing the dependency on imports once the new nuclear power plant unit (Olkiluoto 3) has been completed. Even so, it is expected that Finland will remain very dependent on electricity import after Olkiluoto 3 has been completed, and it is possible that even more power plants will be decommissioned in near future. As can be seen in the table, during the 2016-2017 winter season the total available generation capacity was approximately 11.600 MW. The peak load reserve is considered a strategic reserve and is not available for the electricity market. According to Statistcs Finland data, the reserve consists of four power plants (707 MW) (Tilastokeskus, Statistics Finland, 2018). The total capacity of installed capacity in Finland was approximately 16,400 MW at the end of 2016. Of that installed capacity, approximately 1.600 MW corresponded to wind generation. However, as seen in the Table 9, the amount of wind generation available in the peak load period in winter is negligible. This is a big problem from the power adequacy point of view for the Finnish power system.

3. GENERATING CAPACITY RELIABILITY EVALUATION

There are two different ways to evaluate the reliability of installed generation capacity, according to static or spinning requirements. These two areas should be examined at the planning level when evaluating different installation alternatives. The static requirements can be considered as the installed power that must be planned and built in advance of the system requirements. The static reserve must be sufficient to satisfy the revision of the generating equipment, the interruptions that are not planned or scheduled and the growth requirements of the load in excess of the estimates. Several excellent papers have been published in this area while the interest in the application of probability methods for the evaluation of capacity requirements increased. The publication "Power System Reliability Evaluation" from R. Billinton should be highlighted for this study, since it is used the loss of load approach presented in it (Billinton, 1970). It must be realized that there is a basic difference between the statistic used in a static study and that used in a spinning study. In a static reserve study, the Forced Outage Rate is defined as the probability of finding the unit in question on forced outage at some time in the future. The criterion of adequacy then becomes some acceptable risk level at which the load will exceed the probable available capacity. The loss of load probability method using a daily peak load variation curve appears to be the most widely accepted technique and used more often than any other approach. The ability to indicate both duration and interval of a given outage condition adds a certain physical significance to the results of the frequency and duration method which is not present in the other approaches.

Therefore, to carry out the reliability analysis of the Finnish power system, it was decided to carry out the static generating capacity evaluation based on the loss of load approach. This analysis is able to determine the expected load loss during the year for which it is calculated, that is, it will give us an idea of the days that the generating technologies that supply electricity to the network will not be able to satisfy the needs established by the demand. This type of analysis takes into account the load that has occurred over a year in what is known as the load duration curve, and then compares it with the probability of failure of each technology at a certain time over the same year, using what is known as forced outage rates.

To compute this model it will be necessary to carry out many operations, so the tool MATLAB will be used, which allows to calculate the operations and obtain the results for several situations by simply changing some inputs.

- How will this reliability analysis help understand how reliable is the modern Finnish power system?

Using a deterministic model this tool allows quantifying the risk of forced outage in the current Finnish power system based on the current profile of the load, the installed capacity and the forced outages that have occurred during the last years. High results of expected load loss in this tool may indicate that the power system is at risk of blackout.

- How well with this tool you can model the different production capacities for the power system?

This tool allows to verify quickly and without costs if the introduction of new installed power capacities to the Finnish power system supposes an increase of outage risk, as for example when planning the insertion of a new wind farm or a PV solar plant, or what is even more interesting, how withdrawing traditional power plants (such as coal), which provided flexibility to the grid, can also contribute to an increase of the outage risk levels even if that removed capacity is being replaced with renewable technologies.

3.1 The loss of load analysis

In this approach, the applicable system capacity outage probability table is combined with the system load characteristic to give and expected risk of loss of load. Depending on the load characteristic that has been used the units will be in days or hours. Before combining the outage probability table it should be realized that there is a difference between “capacity outage” and “loss of load”. The capacity outage probability table indicates a loss of generation that may or may not result in a loss of load. This condition depends upon the generating capacity reserve margin and the system load level. A “loss of load” will occur only when the system load level exceeds the capability remaining in service.

A particular capacity outage will contribute to the system expected load loss by an amount equal to the product of the probability of existence of the particular outage and the number of time units in the study interval that loss of load would occur if such a capacity outage where to exist. In principle, a capacity outage less than the reserve will not contribute to the system expected load loss. Outages of capacity in excess of the reserve will result in varying numbers of time units during which load loss would occur. Figure 7 shows the relationship between the load duration curve (in blue), the total installed capacity form the system and the reserve.

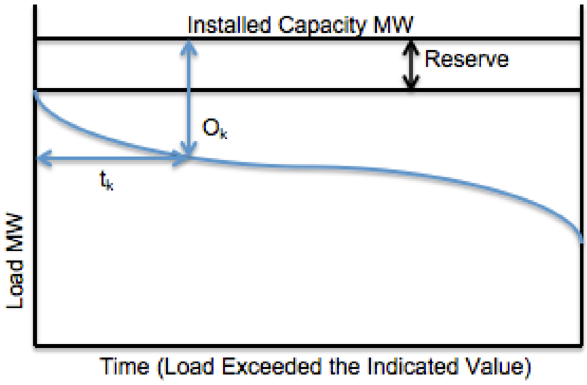


***Figure** 7. Relationship between Load, Capacity and Reserve.*

Figure 7 also shows the time t_k that a certain outage of a given magnitude O_k could produce a blackout of the system. With this information the expected load loss can be obtained by multiplying each probability of an outage event by its corresponding time. Expressed mathematically, if defined O_k as the magnitude of the kth outage in the system capacity outage probability table, P_k as the probability of an outage of capacity equal to O_k and t_k as the number of time units in the study interval that an outage magnitude O_k would cause a loss of load, the contribution to the system loss of load made by capacity outage O_k is $P_k t_k$ time units. The total expected load loss for the study interval is:

$$ELL(t) = \sum_{k=1}^{n} P_k t_k$$

If a daily peak load variation curve is used, the loss of load expectancy is in days for the period of study. The most common application is the use of the curve on a yearly basis. When using a daily peak load variation curve on an annual basis, the expected loss of load is in days per year.

3.2 Mathematical model design

Due to the complexity involved in developing a model like this for a power system, some simplifications and assumptions have had to be made.

- Aggregate all the power plants of the same technology in one block.
  This simplification has been done because otherwise the capacity outage table of outage probabilities would have all the possible combinations among the 428 power plants that are active in Finland, that is 2^{428} combinations. Instead, the power plants that belong to the same technology type have been grouped in one. The result is eight different blocks: Nuclear power, Hydro power, CHP district heating, Industrial CHP, Separate electricity production (sometimes referred to as "Other"), Wind power, Import capacity and Solar photovoltaic. In this way the combinations are reduced to 2^8. This simplification leads to errors such as assuming that when a block suffers from a forced outage all the power plants of

that technology are out of service, which is very significant. In the section of further research, possibilities that can mitigate this error are considered.

- Use average forced outage rates from all power plants.
  After grouping the power plants by technology it was necessary to decide how the forced outage rates were to be defined. The forced outage rates that have been used for each technology are an average of the yearly forced outage rates collected for each power plant that forms the group of that technology. These rates were later used to elaborate the capacity outage probability table.

3.2.1 Operation of the tool

The tool designed in MATLAB performs all the calculations necessary to obtain the expected load loss through the introduction of certain inputs. The data necessary for the operation of the tool are:

- The installed capacities of each technology during the year in which the study is to be carried out
- The forced outage rates of each technology
- The load duration curves of the year in which the study is performed

The tool subtracts from an Excel database the corresponding data of those indicated above according to the year of study requested. The process for calculating the expected load loss is as follows:

1. First the tool subtracts from the database the installed capacities of electrical generation from each year and stores them in a matrix.

2. Then subtracts the forced outage rates of each technology and performs all combinations of capacity out of service together with their corresponding probability, that is, performs the capacity outage probability table and stores it.

3. The next step is to subtract the load duration curve corresponding to the year that has been indicated for the study and perform a linear interpolation to build a function that relates capacity out of service with time. Once the function has been built, for each combination of capacity outage capacity of the capacity outage probability table is obtained its corresponding time value during which a loss of load could have happened according to the load duration curve of that year.

4. Finally the program adds all the results obtained from expected load loss during that year to obtain a final value. The result is shown in days of forced outage per year.

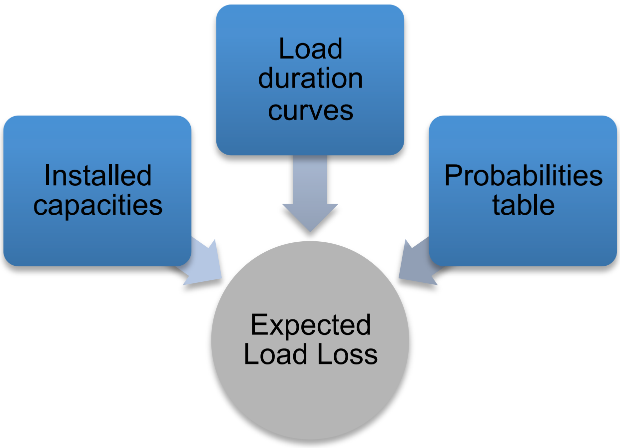


Figure 8. *Operating scheme of the tool*

Figure 8 shows the necessary inputs for the proper functioning of the tool. Once the tool has been developed, the next target is to test it with real data of installed capacities, forced outage rates and load duration curves of previous years to measure the risk of load loss. The following sections explain the process followed to collect all the necessary data to carry out the evaluation.

3.3 Installed capacities data collection

Once data about installed capacity of each technology in Finland has been collected, it is used for the loss of load analysis. The data about the installed capacity of each technology may vary slightly depending on the source consulted. For this study it is used the data published by Statistics Finland (Tilastokeskus, Electricity generation capacity, nominal capacity of production engines at beggining of year, 2018), which does an excellent work collecting all this information every year. These data have also been compared with those published by the Energy Authority in the so-called "Power plant Register", in which all the power plants of Finland appear with all their characteristics: type of technology, installed capacity, fuel, company, etc.

It is important to organize the data according to the year, since the analysis performs the calculations taking for each year the corresponding amounts of installed capacity and load duration curves. Following Table 10 shows the installed capacities of each technology in Finland during the period between 2011 and 2017.

Table 10. *Installed capacities in Finland per technology 2011-2017*

Technology	2011 (MW)	2012 (MW)	2013 (MW)	2014 (MW)	2015 (MW)	2016 (MW)	2017 (MW)
Nuclear	2779	2779	2779	2779	2779	2779	2779
Hydropower	3084	3111	3125	3125	3153	3171	3171

I CHP	3286	3286	3180	2930	2930	2908	2837
CHP DH	4425	4375	4369	4450	4015	4022	4290
Wind power	198	206	259	453	631	1005	1533
Separate electricity production	3308	3308	3640	3514	2834	2335	2398
Import	3850	4650	4650	4650	5100	5100	5100
Solar	7	7	8	9	11	15	35
Total	20937	21722	22010	21910	21453	21335	22143

3.4 Load duration curves in Finland from 2011-2017

The load duration curves for each year of the study have been calculated using Fingrid’s open data (FINGRID, 2018). For this work, Finland's load duration curves have been drawn up from 2011 to 2017, which are the years from which information on the country's electricity consumption is found on the website of the transmission system operator, which means there is no information before 2011. The load duration curves arise from the maximum load peaks of daily demand, that is, only the maximum demand peaks of each day are taken and they are ordered in a time axis from the highest to the lowest. Sorting in this way the peaks of demand allows performing reliability calculations since it relates peaks load demand with time. These curves can be used for determining the requirements that a power system needs for its correct operation. These curves are also used for other types of reliability analysis and not only for the "Expected load loss".

Figure 9 shows the load duration curves obtained for this study. Each of the load duration curves that have been obtained comprise a period of one year and collect the daily demand peaks calculated from Fingrid’s open data. These peaks are ordered from highest to lowest in the graph, showing at the beginning the highest peak during the year and ordering the other daily peaks decreasing until reaching the lowest daily peak.

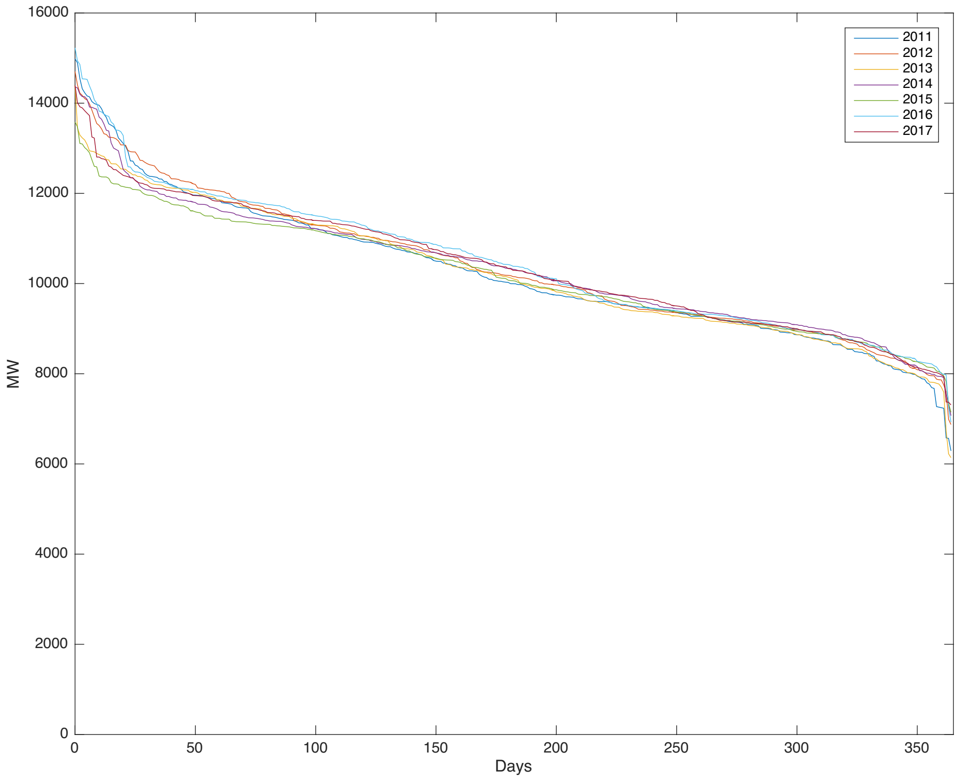


Figure 9. *Load duration curves 2011-2017 obtained from Fingrid Open data*

Some common characteristics can be detected between the curves obtained. Most of the curves are very similar between them, with similar values of maximum peaks. Some of these curves present different profiles in the area of the greatest peaks of demand, as in the case of the years 2011, 2014 and 2016. At first sight it seems that these years had higher peaks. These results will be taken into account later when carrying out the reliability evaluation.

3.5 Calculation of the forced outage rates

The forced outage rate can be defined as the percentage of time that a given point in the supply chain is nonfunctional due to forced outages. Forced outage rates are used when calculating the overall reliability of an energy delivery system. To get the forced outage rates it is necessary to carry out a study of the failure on the different power stations during the last years to create a reliable statistic of the behavior of the technologies by means of frequency and duration of outages. Ideally, information should be gathered about outages of several years ago separated by technology in order to calculate the most accurate forced outage rates, but due to lack of information it has been necessary to make certain assumptions in the study.

The forced outage rates from each power plant from the study have been calculated as follows:

$$Forced\ outage\ rate\ (annual) = \frac{annual\ hours\ in\ forced\ outage}{annual\ hours\ in\ forced\ outage + annual\ hours\ in\ service}$$

The forced outage rates do not have units, since they represent a ratio. Simply, the outage rates calculated for the study have to be in accordance with the time period used for the analysis. In this case consists of a yearly analysis of the expected load loss as represented in the load duration curves of every year.

The information about the hours in forced outage and hours in service has been found in the “Transparency platform” from the European Network of Transmission System Operators known as ENTSO-E (ENTSOE, 2018). When it comes to forced outages, it refers to stops that have not been planned and that are due to a failure of the generating or production facility and not to intentional stops, such as maintenance. Since 2015, it is possible to access information on outages in power plants across Europe displayed by country in the web platform of ENTSO-E called “Transparency platform”. From this information tool has been obtained data on the forced outages that occurred in Finland since 2015, which is the year the tool was ready for operation. This means that there is much information missing from historical data on outages. Only the outages of the nuclear, district heating CHP, industrial CHP and separate electricity production power plants appear, and have been used to calculate the forced outage rates of those technologies.

There are other platforms from other entities but none of them gather as much information as this one. In the section “Unavailability of production and generation units” information can be found about when an outage occurred, how large the cut was, how long it lasted and what generating power plant was responsible for the outage. Even so, using this tool also carries some drawbacks: as said, this platform came on line in 2015 and the power plants are not required to provide prior information, allowing them to give it voluntarily. In addition, the information about different technologies varies according to the country. For example, to calculate the forced outage rates of the hydro power technology, since no information about forced outages in Finnish hydro power plants was found, it was necessary to use the information that appears about hydro power plants outages in other nearby countries, like Norway, which does have information on outages in hydro power plants.

Regarding Finland, there is only data about outages in nuclear power plants, industrial CHP, district heating CHP and separate electricity production. To obtain information about outages in technologies such as hydro power or wind it was necessary to appeal to data published by other countries such as Norway or Denmark.

3.5.1 Force outage rates for nuclear power

The first technology of which the study of the outages has been carried out is nuclear technology. As already indicated above, Finland currently has four nuclear facilities for the production of electricity. In the data published in the platform of the ENTSO-E there are numerous outages of different duration. Classifying the outages according to the year and according to the nuclear power plant to which they correspond, it was possible to obtain the yearly forced outage rates of each nuclear power plant. As the MATLAB tool that has been designed aggregates all the power plants of the same technology in one, it was decided to make an average between all the forced outage rates obtained of the nuclear power plants. This may lead to errors when realizing that not all power plants contribute in the same way to the total installed capacity of the corresponding technology, but the results prove that the fact that a power plant has larger installed power does not mean that its outages are longer than for a smaller power plant. Therefore, for the aggregated value of each installed technology that is going to be used in the analysis, it is considered appropriate to use an average from the forced outage rates of all plants pertaining to that technology. Following Figure 10 shows the results obtained for nuclear technology. Despite specific cases as Olkiluoto 2 during 2016, it seems that the forced outage rates have been decreasing during the last years.

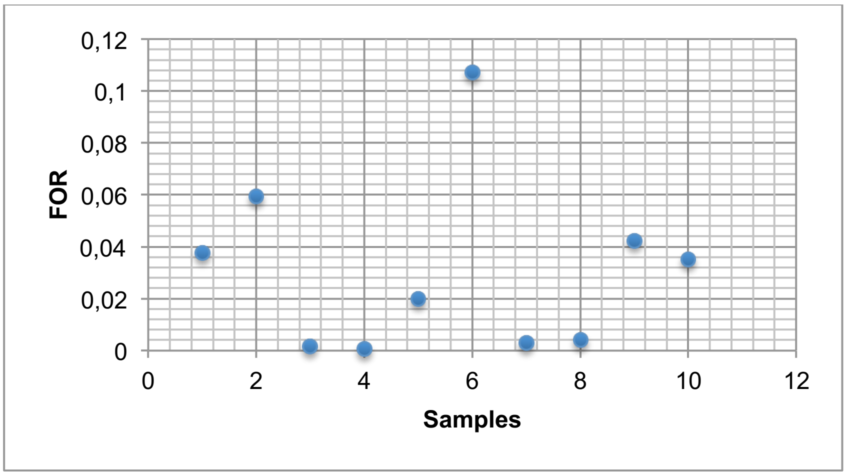


Figure 10. *Distribution of forced outage rates obtained for nuclear power plants*

Table 11 below shows all the forced outage rates obtained. The average of the results gives an average forced outage rate for the nuclear technology of 0,0311 (probability of outage in a year basis).

Table 11. *Forced outage rate values obtained for Finnish nuclear power plants*

Power plant	FOR (2015)	Power plant	FOR (2016)	Power plant	FOR (2017)
Loviisa 2	0,03771	**Loviisa 1**	0,00169	**Loviisa 1**	0,00285
Olkiluoto 2	0,05930	**Loviisa 2**	0,00069	**Loviisa 2**	0,00409
		Olkiluoto 1	0,01992	**Olkiluoto 1**	0,04237

		Olkiluoto 2	0,10722	**Olkiluoto 2**	0,03515

3.5.2 Forced outage rates for CHP District Heating

As explained before, Finland has many power plants of combined heat and power for district heating. The outages of these plants are collected in the same way as for the nuclear plants on the platform of the ENTSO-E association. In order to determine a forced outage rate that fits all the CHP district heating power plants, the forced outage rate of each power plant was calculated individually dividing the time during which the power plant had a forced outage and the time during which the plant was in service in that year. Figure 11 shows the results obtained for the forced outage rates of the CHP district heating power plants in Finland. It can be seen how the values are quite low. The trend of the forced outage rates during the last years is decreasing, except in some specific cases.

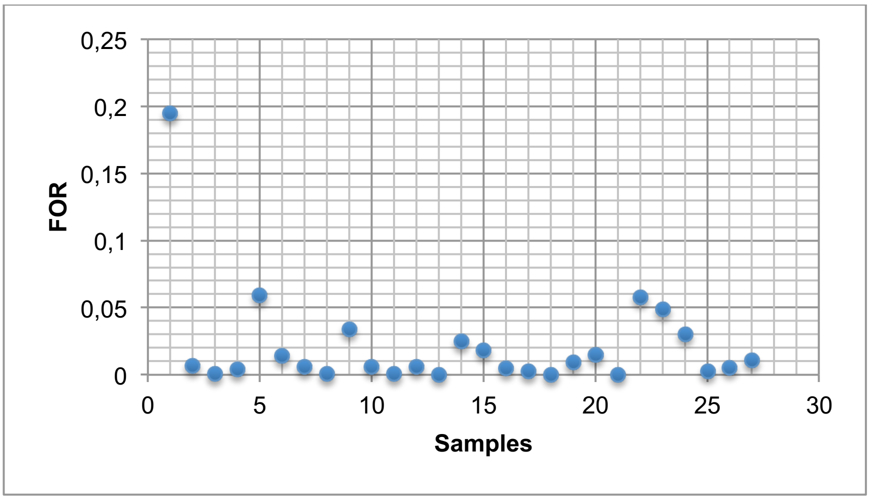


Figure 11. *Distribution of forced outage rates obtained for CHP DH*

Table 12 shows all the forced outage rates obtained for CHP district heating power plants in Finland. The average of the results gives an average forced outage rate for this technology of 0,0208. The outage presented by the power plant Hanasaari during 2015 is clearly an outlier, which could be removed from statistical analysis, although in this study it wasn't removed for calculating the average FOR.

Table 12. *Forced outage rates obtained for Finnish CHP DH power plants*

Power plant	FOR (2015)	Power plant	FOR (2016)	Power plat	FOR (2017)
Hanasaari	0,19453	**Hanasaari**	0,00562	**Hanasaari**	0,05780
Kaukaan	0,00697	**Kaukaan**	0,00011	**Naantali**	0,04860
Keljonlahti	0,00057	**Kymijarvi**	0,02492	**Seinajoki**	0,03020
Kymijarvi	0,00370	**Naantali**	0,01838	**Suomenoja**	0,00257

Naantali	0,05903	**Salmisaari**	0,00482	**Vaskiluoto**	0,00555
Salmisaari	0,01409	**Seinajoki**	0,00230	**Vuosaari**	0,01081
Seinajoki	0,00597	**Suomenoja**	0,00021		
Suomenoja	0,00077	**Toppila**	0,00899		
Toppila	0,03377	**Vaskiluoto**	0,01468		
Vaskiluoto	0,00599	**Vuosaari**	0,00030		
Vuosaari	0,00052				

3.5.3 Forced outage rates for Industrial CHP

Obtaining the forced outage rates of this technology was more complicated than the previous ones. This is because the platform of the association ENTSO-E does not have much information about forced outages in power plants of industrial combined heat and power. Anyway, information was found about a power plant of industrial CHP that suffered forced outages during the years 2016 and early 2017. Due to the lack of information, this case will be taken when calculating the forced outage rate of this technology. Figure 12 shows the forced outage rates obtained for this technology.

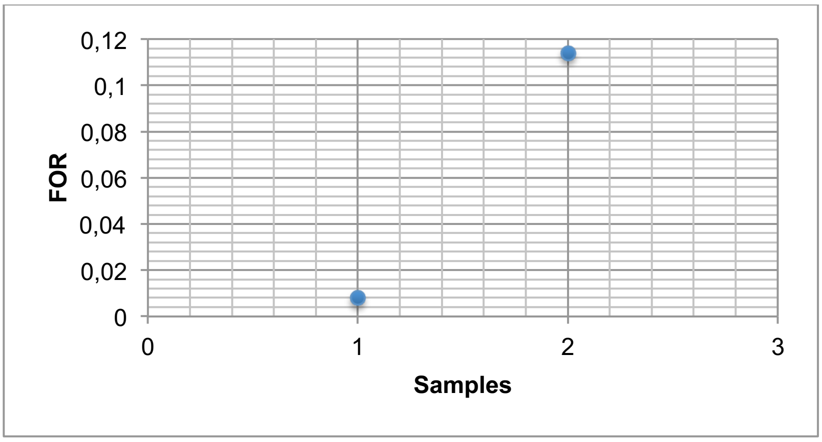


Figure 12. *Distribution of forced outage rates for Industrial CHP*

Table 13 below shows the calculated values of forced outage rates. The average forced outage rate for this technology is 0,061.

Table 13. *Forced outage rates obtained for Finnish I CHP power plants*

Power plant	FOR (2016)	Power plant	FOR (2017)
Äänekoski	0,00810	**Äänekoski**	0,11398

This value is unexpectedly high. Looking for an explanation it was discovered that this power plant came into operation recently, so it is common to suffer forced outages. This trend is known as the “bathtub” curve, in which it is explained how at the beginning the new technology tends to suffer failures. In the first phase the failure rate starts high and decreases over time until it reaches the stage in when the failure rate is considered constant, and in the end there is a stage of increasing failure rate, giving the graph of failure rate over time the shape of a bathtub. This power plant analyzed must probably be on the first stage of the curve, when the failures are rather common.

3.5.4 Forced outage rates for separate electricity production

When talking about separate electricity production, it refers to power plants that are explicitly dedicated to the production of electricity. This aspect differentiates the power plants of this technology from those that belong to combined heat and power. This technology is very reliable from the point of view of response to peak demand and is known as a technology that provides flexibility to the power system. To obtain electricity, fossil resources such as coal or gas are mainly used as fuel, but other renewable resources can also be used. Everything specified above induces a low forced outage rate to be expected. The results of the forced outage rates obtained for the power plants of separated electricity production are shown in Figure 13.

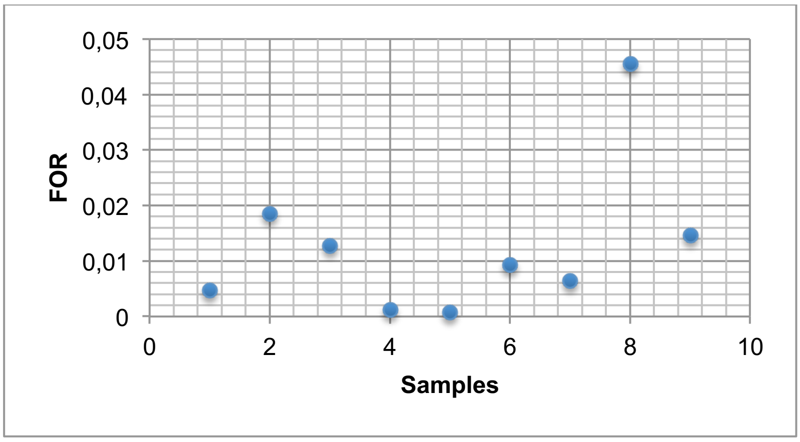


Figure 13. *Distribution of forced outage rates for separate electricity production power plants*

The average forced outage rate for this technology is 0,0126. As expected, the result obtained is a low value, which indicates that it is a very reliable technology that suffers few forced outages. Table 14 shows the results obtained for each power plant.

Table 14. *Forced outage rates obtained for Finnish separate electricity production power plants*

Power plant	FOR (2015)	Power plant	FOR (2016)	Power plant	FOR (2017)
Alholmens	0,00470	**Alholmens**	0,00068	**Alholmens**	0,04549
Kristiina	0,01846	**Forssa**	0,00930	**Meri-Pori**	0,01456
Meri-Pori	0,01268	**Meri-Pori**	0,00642		
Tahkoluoto	0,00118				

3.5.5 Forced outage rates for hydro power plants

The study that has been carried out to obtain reliable values of forced outage rate for hydro power plants has been more complicated since in the “Transparency platform” of the association ENTSO-E no records of forced outages of Finland’s hydro power plants have been published. Given the impossibility of obtaining information about the forced outages of the hydro power plants of Finland by any other means, it was decided to analyze the forced outages suffered by the hydro power plants of other neighboring countries that do present such information published in the "Transparency platform" of the ENTSO-E. This assumption has been carried out taking into consideration the following:

- Only forced outages from power plants from countries that have weather conditions similar to Finland will be studied.
- The countries from which the data is obtained are interconnected through the Nordic power grid by which Estonia, Norway, Finland, Denmark and Sweden are interconnected.

Once this has been clarified the study continues with the calculation of the forced outage rates of the hydropower plants. All the data of forced outages in Norway's hydro power plants were collected during the years 2015, 2016 and 2017. This data was used to calculate plant by plant the hours of forced outage for determining later the forced outage rate of each hydro power facility, which requires a laborious work. Finally, as in the other cases, an aggregate forced outage rate has been calculated for the hydropower technology by averaging all obtained forced outage rate values. The results are shown on Figure 14.

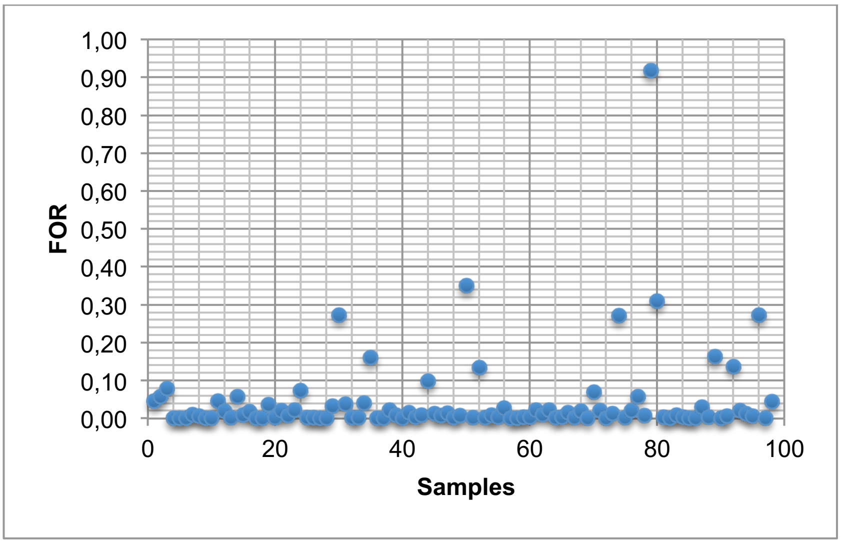


Figure 14. *Distribution of forced outage rates for hydro power plants*

The average forced outage rate obtained is 0,0441. This value matches with the results obtained in other technologies. The comparison is made at the end of this section. Table 15 shows the forced outage rates obtained for all hydro power plants in Norway.

Table 15. Forced outage rates obtained for hydro power plants in Norway

Power plant	FOR (2015)	Power plant	FOR (2016)	Power plant	FOR (2017)
Alta Krvg	0,0467	**Aurland**	0,1603	**Alta Krvg**	0,0008
Aurland	0,0584	**Borgund**	0,0010	**Aurland**	0,0704
Blafal	0,0791	**Brokke**	0,0010	**Borgund**	0,0204
Borgund	0,0002	**Duge**	0,0228	**Brokke**	0,0001
Brokke	0,0005	**Evanger**	0,0091	**Duge**	0,0128
Dale	0,0013	**Gryttenkg**	0,0011	**Evanger**	0,2712
Duge	0,0113	**Holen**	0,0156	**EVM**	0,0022
Evanger	0,0059	**Jostedal**	0,0041	**Holen**	0,0205
EVM	0,0010	**Kobbelv**	0,0084	**Jostedal**	0,0587
Gryttenkg	0,0013	**Kvilldal**	0,0989	**Kobbelv**	0,0076
Holen	0,0460	**Lang Sima**	0,0131	**Kvilldalg**	0,9180
Jostedal	0,0183	**Leirdolag**	0,0070	**Lang Sima**	0,3102
Kobbelv	0,0021	**Mauranger**	0,0137	**Mauranger**	0,0046
Kvilldalg	0,0584	**Myster**	0,0015	**Naddvik**	0,0011
Leirdolag	0,0086	**Nedre Rossaga**	0,0071	**Nedre Rossaga**	0,0094
Mauranger	0,0180	**Nedre Vinstra**	0,3494	**Nedre**	0,0042
Myster	0,0002	**Oksla**	0,0021	**Nedrerosg**	0,0008
Naddvik	0,0013	**Rana**	0,1347	**Oksla**	0,0002
Nedre	0,0368	**Saurdal**	0,0028	**Rana**	0,0290
Oksla	0,0023	**Sima**	0,0086	**Saurdal**	0,0039
Rana	0,0208	**Skjerka**	0,0043	**Sima**	0,1624
Saurdal	0,0070	**Skjomen**	0,0282	**Skjomen**	0,0011
Sima	0,0232	**Songa**	0,0008	**Sonna**	0,0055
Skjomen	0,0728	**Sonna**	0,0003	**Svartisen**	0,1372
Solhom	0,0019	**Sundsbarg**	0,0039	**Tokke**	0,0208
Songa	0,0023	**Svartiseg**	0,0044	**Tonstad**	0,0124
Sonna	0,0003	**Tjodan**	0,0218	**Tyin**	0,0050
Svartiseg	0,0011	**Tokke**	0,0112	**Tysso**	0,2724
Tokke	0,0329	**Tonstad**	0,0223	**Vemork**	0,0004
Tonstad	0,2716	**Trolheimg**	0,0018	**Vinje**	0,0437
Tyin	0,0372	**Tyin**	0,0032		
Tysso	0,0019	**Tysso**	0,0155		
Vemork	0,0031	**Vemork**	0,0022		
Vinje	0,0415	**Vinje**	0,0187		

3.5.6 Forced outage rates for wind power parks

This case has similarities with the previous one of hydro power plants, since there is no information published in the "Transparency platform" of the ENTSO-E about forced outages in wind power farms in Finland. Hence, it has been necessary to access information published by other countries. In this case the data comes from the forced outages of the wind farms of Denmark. This assumption has been made for the following reasons:

- Only forced outages from power plants from countries that have weather conditions similar to Finland will be studied.
- The countries from which the data is obtained are interconnected through the Nordic power grid by which Estonia, Norway, Finland, Denmark and Sweden are interconnected.

Once this has been clarified, the study continues with the analysis carried out on the wind farms of Denmark to determine the forced outage rate of this technology. In this case, the data of the forced outages of certain wind farms have been obtained and the forced outage rate has been calculated for each one of them. The final value of forced outage rate is calculated averaging the individual forced outage rates of each wind power farm. Following Figure 15 shows the values that have been used for the study.

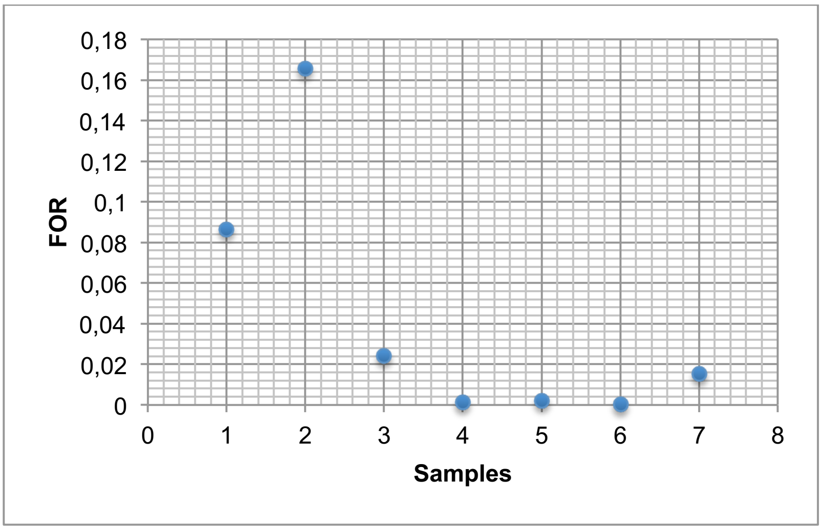


Figure 15. *Distribution of forced outage rates for wind power parks*

The average forced outage rate that has been calculated for wind power technology is 0,0421. It can be seen that this value is similar to the one of hydro power. At the end of this section the possible similarities observed are discussed. Table 16 shows the values obtained of forced outage rates for wind parks.

Table 16. *Forced outage rates obtained for wind parks in Denmark*

Power	FOR (2015)	Power	FOR (2016)	Power	FOR (2017)

plant		plant		plant	
Anholt	0,08655	**Roedsand1**	0,00106	**Anholt**	0,00035
Horns Rev	0,16544	**Roedsand2**	0,00208	**Horns Rev**	0,01542
Roedsand	0,02401				

3.5.7 Forced outage rates for import capacity

Calculating the forced outage rates of the import capacity of Finland is a difficult task to perform. The connections that Finland has with its neighboring countries have different characteristics in terms of length, capacity, outages, etc. Therefore, all connections have been gathered in what will be understood as the total import installed capacity. To find the forced outage rate of this technology it was possible to access data about forced outages in the lines that connect Finland with Norway, Russia, Sweden and Estonia. The information found specified in which lines the outages occurred, how large they were and how long they lasted. It was possible to calculate for each of the lines the yearly forced outage rate of each one and then make the average to obtain a value that reliably represents the forced outage rate of the import capacity. Following Figure 16 shows the forced outage rates and the average obtained for the interconnections of Finland.

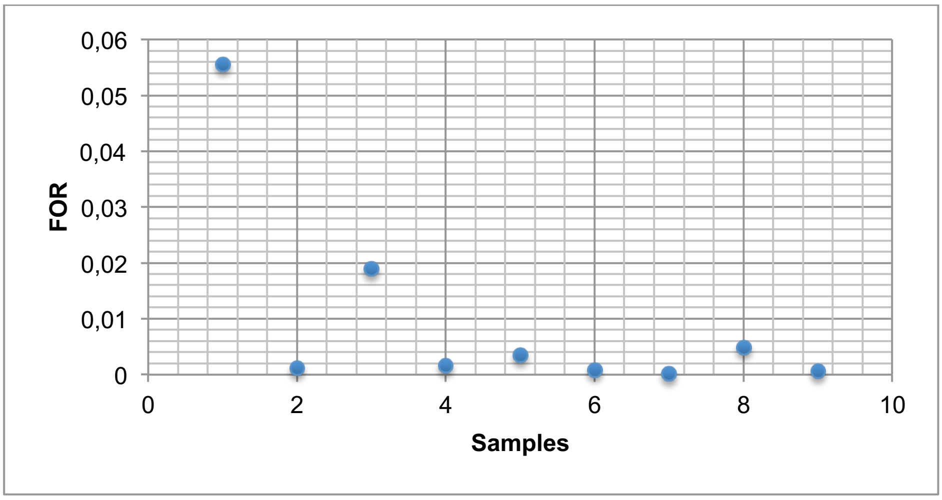


Figure 16. *Distribution of forced outage rates of the import capacity*

The average forced outage rate that has been obtained for this technology is 0,0096. It is a particularly low value. In the last section of this chapter this interesting results are discussed. Following Table 17 shows the values of forced outage obtained for each connection.

Table 17. *Forced outage rates of Finnish interconnections with neighboring countries*

Link	FOR (2015)	Link	FOR (2016)	Link	FOR (2017)
Estonia	0,05559	**Estonia**	0,00162	**Estonia**	0,00016
Russia	0,00114	**Sweden**	0,00343	**Russia**	0,00484

Sweden	0,01889	**Russia**	0,00079	**Sweden**	0,00063

3.5.8 Forced outage rate for solar PV

Solar photovoltaic technology in Finland currently has a very low deployment. The weather conditions have not accompanied the adequate development of this technology, but during the last years interest has grown for developing the technology and become a valid resource for the production of electrical energy in Finland. As has already been specified previously in the section about installed capacities, in Finland there are very few solar PV power plants. No information has been found about forced outages in PV power plants neither in Finland nor in Europe. Therefore, to simplify the programming and calculations that must be done in MATLAB, in this first phase of the study the influence of this technology will not be considered since its contribution is so low that it can be neglected. In any case, once the forecast for the future scenarios is made, it will be considered if it is pertinent to obtain the forced outage rate of this technology, since it is expected that in the future it will have an impact.

3.5.9 Comparison

In this section the results of forced outage rates of each technology are collected to compare them and analyze if the results make sense. The following Figure 17 shows a comparison of the results obtained. It should be clarified that what is shown below is not the forced outage rate itself, but the opposite rate, which is simply calculated by doing one minus the forced outage rate of each technology. This value is used for probabilistic purposes and represents the probability that a certain facility has for not failing during a time period, in this case, a year.

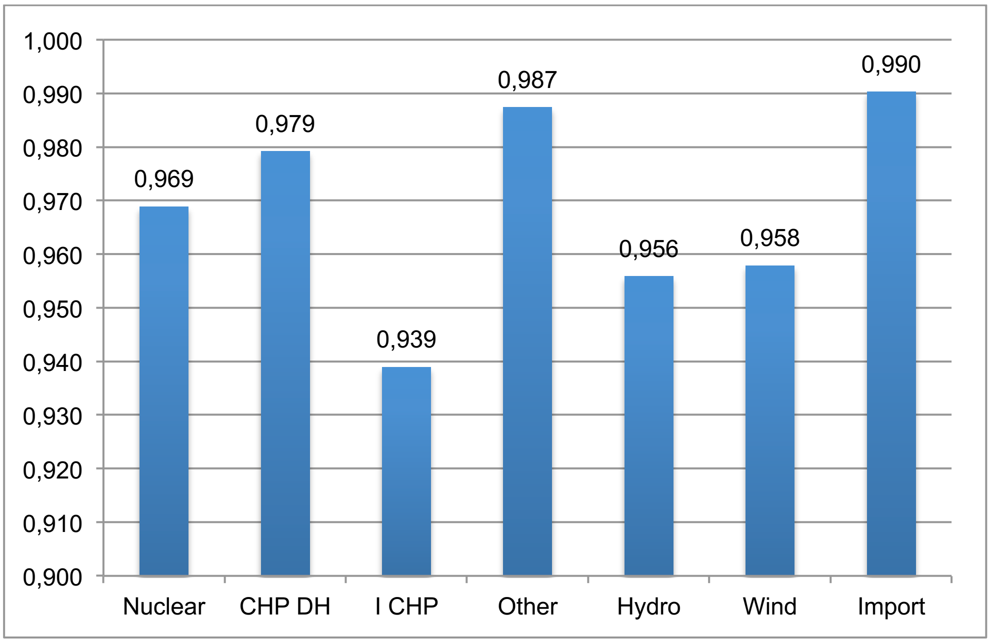


Figure 17. *Annual measure of probability of not suffering a forced outage by technology*

Below, some comments are made about the results shown in Figure 17 that help understand their meaning.

1. The rates obtained for the technologies that use non-renewable resources as sources of energy have values that adjust well to reality (except Industrial CHP, which unexpected value is discussed in point 2.). These are nuclear technology, CHP District Heating and Other (Separate electricity production). In the first place, the value of nuclear technology is slightly lower than that of CHP district heating and separate electricity production. This can be understood as nuclear power plants suffer forced outages longer than the other two technologies, therefore, although nuclear power plants still have a high reliability, power plants that use fossil fuels such as coal, gas, peat or biofuels have an even greater reliability regarding forced outages than nuclear power plants.

2. In the case of Industry CHP the value is unusually low, which suggests that the sample taken for this study does not represent the real behavior of this technology. The reason why it is believed that this value is low is because Industrial CHP uses similar fuels to CHP DH and Separate electricity production. As already indicated above, the sample used is a power plant that came into operation a short time ago and it is common to suffer several forced outages at the beginning of its commissioning.

3. For the CHP district heating and the Separate electricity production the results suggest that these are technologies that suffer few outages or that when they suffer one, it can be solved quickly, lasting a short time. It is the clear definition of reliable technology, fast responding and flexible, which can be controlled easily whenever the power system needs it.

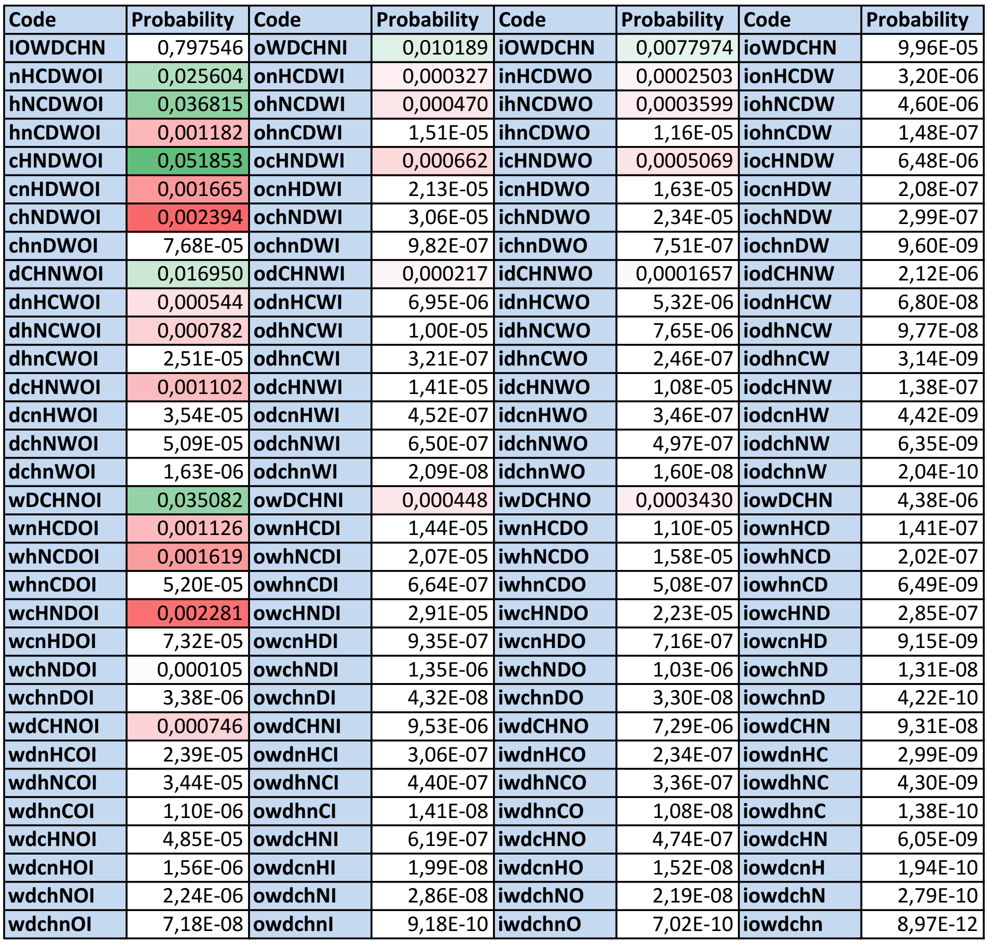
4. When it comes to technologies that use renewable energy resources, as hydro power and wind power, it can be appreciated how the values are quite similar. These values are lower than those corresponding to non-renewable technologies, therefore, it is clear that the hydro and wind power plants suffer forced outages more frequently than the others, or that the forced outages they suffer last longer. The conclusion of these results is that these technologies provide less flexibility to the power system, since they have a slower response to forced outages.

5. The last technology that is analyzed is the import capacity. This result represents in a very realistic way the current situation of the power system in Finland, since the links that connect with the neighboring countries are considered one of the most reliable technologies for electricity supply. According to the results, the links that connect Finland with Sweden, Norway, Estonia and Russia suffer less forced outages and of shorter duration than any other electricity source. This places the technology of electricity import as the most reliable among all.

3.6 Capacity out of service probability table

To carry out the study, it is necessary to create the outage capacity table in which all possible combinations of capacity that are out of service will be represented. Due to the impossibility of evaluating all the possible combinations of all the power plants of Finland for the laborious work, the plants that belong to the same technology have been grouped on a block to simplify the calculations. For calculating the probabilities table all the main technologies in Finland have to be taken into account, so the data from all the power stations has been taken from Energy Authority reports during the last years, which is published in the yearly “Power plant register”. Then, once the forced outage rates of each technology have been determined, the failure probabilities table can be elaborated. This table organizes all the possible combinations of technologies and assigns each of them an occurrence probability. The code used for each combination is the following: for the technologies that are in operation a capital letter is used and for those that are out of service a normal letter. The initials used for each technology are an "N" for nuclear, the "H" for hydro power, the "W" for wind power, the "O" for separate electricity production (other), the "D" for combined heat and power district heating, the "C" for industrial combined heat and power plants and the "I" for the import capacity.

Obviously, in the table the combinations of the greatest number of technologies out of service are those that are less likely to happen, since the forced outage rates of the technologies are very low. Below are the results obtained from the table of failure probabilities. This table does not change for each year since it has been decided to use the forced outage rates calculated in section 3.5. The table is represented in Figure 18. Obviously, the sum of all the probability values of the table equals 1. In green are represented the most probable outage cases due to the failure of a certain technology block, and in red are represented the most likely cases of a combination of blocks of technologies out of service.



Code	Probability	Code	Probability	Code	Probability	Code	Probability
IOWDCHN	0,797546	**oWDCHNI**	0,010189	**iOWDCHN**	0,0077974	**ioWDCHN**	9,96E-05
nHCDWOI	0,025604	**onHCDWI**	0,000327	**inHCDWO**	0,0002503	**ionHCDW**	3,20E-06
hNCDWOI	0,036815	**ohNCDWI**	0,000470	**ihNCDWO**	0,0003599	**iohNCDW**	4,60E-06
hnCDWOI	0,001182	**ohnCDWI**	1,51E-05	**ihnCDWO**	1,16E-05	**iohnCDW**	1,48E-07
cHNDWOI	0,051853	**ocHNDWI**	0,000662	**icHNDWO**	0,0005069	**iocHNDW**	6,48E-06
cnHDWOI	0,001665	**ocnHDWI**	2,13E-05	**icnHDWO**	1,63E-05	**iocnHDW**	2,08E-07
chNDWOI	0,002394	**ochNDWI**	3,06E-05	**ichNDWO**	2,34E-05	**iochNDW**	2,99E-07
chnDWOI	7,68E-05	**ochnDWI**	9,82E-07	**ichnDWO**	7,51E-07	**iochnDW**	9,60E-09
dCHNWOI	0,016950	**odCHNWI**	0,000217	**idCHNWO**	0,0001657	**iodCHNW**	2,12E-06
dnHCWOI	0,000544	**odnHCWI**	6,95E-06	**idnHCWO**	5,32E-06	**iodnHCW**	6,80E-08
dhNCWOI	0,000782	**odhNCWI**	1,00E-05	**idhNCWO**	7,65E-06	**iodhNCW**	9,77E-08
dhnCWOI	2,51E-05	**odhnCWI**	3,21E-07	**idhnCWO**	2,46E-07	**iodhnCW**	3,14E-09
dcHNWOI	0,001102	**odcHNWI**	1,41E-05	**idcHNWO**	1,08E-05	**iodcHNW**	1,38E-07
dcnHWOI	3,54E-05	**odcnHWI**	4,52E-07	**idcnHWO**	3,46E-07	**iodcnHW**	4,42E-09
dchNWOI	5,09E-05	**odchNWI**	6,50E-07	**idchNWO**	4,97E-07	**iodchNW**	6,35E-09
dchnWOI	1,63E-06	**odchnWI**	2,09E-08	**idchnWO**	1,60E-08	**iodchnW**	2,04E-10
wDCHNOI	0,035082	**owDCHNI**	0,000448	**iwDCHNO**	0,0003430	**iowDCHN**	4,38E-06
wnHCDOI	0,001126	**ownHCDI**	1,44E-05	**iwnHCDO**	1,10E-05	**iownHCD**	1,41E-07
whNCDOI	0,001619	**owhNCDI**	2,07E-05	**iwhNCDO**	1,58E-05	**iowhNCD**	2,02E-07
whnCDOI	5,20E-05	**owhnCDI**	6,64E-07	**iwhnCDO**	5,08E-07	**iowhnCD**	6,49E-09
wcHNDOI	0,002281	**owcHNDI**	2,91E-05	**iwcHNDO**	2,23E-05	**iowcHND**	2,85E-07
wcnHDOI	7,32E-05	**owcnHDI**	9,35E-07	**iwcnHDO**	7,16E-07	**iowcnHD**	9,15E-09
wchNDOI	0,000105	**owchNDI**	1,35E-06	**iwchNDO**	1,03E-06	**iowchND**	1,31E-08
wchnDOI	3,38E-06	**owchnDI**	4,32E-08	**iwchnDO**	3,30E-08	**iowchnD**	4,22E-10
wdCHNOI	0,000746	**owdCHNI**	9,53E-06	**iwdCHNO**	7,29E-06	**iowdCHN**	9,31E-08
wdnHCOI	2,39E-05	**owdnHCI**	3,06E-07	**iwdnHCO**	2,34E-07	**iowdnHC**	2,99E-09
wdhNCOI	3,44E-05	**owdhNCI**	4,40E-07	**iwdhNCO**	3,36E-07	**iowdhNC**	4,30E-09
wdhnCOI	1,10E-06	**owdhnCI**	1,41E-08	**iwdhnCO**	1,08E-08	**iowdhnC**	1,38E-10
wdcHNOI	4,85E-05	**owdcHNI**	6,19E-07	**iwdcHNO**	4,74E-07	**iowdcHN**	6,05E-09
wdcnHOI	1,56E-06	**owdcnHI**	1,99E-08	**iwdcnHO**	1,52E-08	**iowdcnH**	1,94E-10
wdchNOI	2,24E-06	**owdchNI**	2,86E-08	**iwdchNO**	2,19E-08	**iowdchN**	2,79E-10
wdchnOI	7,18E-08	**owdchnI**	9,18E-10	**iwdchnO**	7,02E-10	**iowdchn**	8,97E-12

Figure 18. *Capacity out of service probability table*

The most likely situation to happen is when all the technologies are working properly with almost an 80% probability of occurrence among all the possible combinations. Among the outage cases highlighted in green, the most probable is the failure of the Industrial CHP technology with a 5% probability, since it has the highest forced outage rate of all technologies. The second most probable case is the outage of the hydro power capacity, closely followed by the wind power failure. Both outage situations have probabilities of 3,5%. The next outage case with the highest probability of occurrence is the failure of the nuclear power. The lowest outage probabilities of outage cases belong to separate electricity production and import capacity.

Regarding the combination of capacities out of service, which is shown in red in the table, the most likely to happen is the combination of outages in industrial CHP power plants and hydro power plants or industrial power plants with wind power plants. Both cases have probabilities around 0,2%. Other combinations of capacities out of service with high probability are the unavailability of industrial CHP and nuclear power, and the unavailability of wind parks and hydro power plants, both with probabilities around 0,16%.

3.7 Evaluation of the designed program

In this section is analyzed the reliability of the program. The tool that has been designed in MATLAB allows obtaining a measure of the expected loss of load measured in time for a certain year. Therefore, as long as the relevant data from previous years is available, that is, load duration curves, installed capacities and forced outage rates of the different technologies, this tool can be used to obtain how high the risk of outage was. The process for evaluating the load loss in every year is the following:

1. First, the program defines a matrix that stores the values of installed capacities in Finland form 2011 to 2017.
2. Secondly, another matrix is defined in which the forced outage rates of each technology are collected and calculates all combinations of capacities out of service. This generates de capacity outage probability table.
3. Later, it is necessary to insert the year of study to take the right load duration curve, and interpolating it over the time gets a function that assigns a time to each combination of capacities out of service from the outage capacity probability table.
4. When the time units are associated to each of the combinations of the table, multiplying each unit of time of each combination by the probability of happening of that combination gives the final value of expected loss of load for the year studied.

3.7.1 Evaluation of results obtained for years 2011-2017

In this section the program designed in MATLAB is used to calculate the reliability of the Finnish power system during the period between 2011 and 2017. The reliability indices obtained are in days of expected load loss per year and in hours of expected load loss per year. Lower values mean more reliability of the power system. Figure 19 shows all the values obtained in order to compare them more easily. Table 18 shows the value of expected load loss in days and hours.

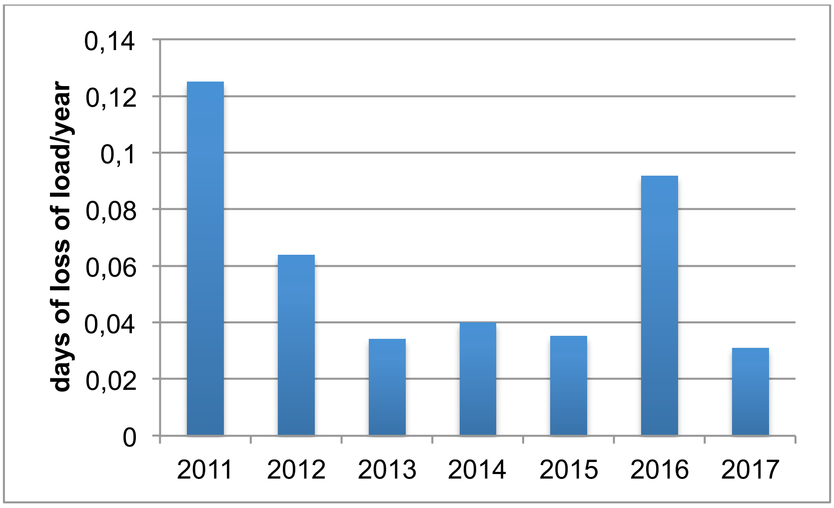


Figure 19. Comparison of expected load loss results for years 2011-2017

Table 18. *Expected load loss in days/year and hours 2011-2017*

		2011	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
Expected Load Loss	**In days**	0,125	0,0639	0,0342	0,04	0,0352	0,0918	0,031
	In hours	3 h	1h 32 min	49 min	57 min	50 min	2 h 12 min	44 min

The values obtained are quite low, clearly indicating that the Finnish power system is very reliable. These values mean the time during a year in which it was jeopardized to maintain the power adequacy in the Finnish power system. As it consists of a unique characteristic of this type of analysis, no records were found of expected load loss in previous years in Finland, but since during the years in the study the Finnish power system always satisfied the demand, this values are going to be taken as good values of reliability in order to compare later the reliability values of the future power system with the ones of the current power system. This means that if the hours of expected load loss obtained with the program on the future scenarios are greater than the values obtained within 2011-2017, the power inadequacy risk will increase.

As for the ability of the tool to detect irregularities the years with the highest expected loss of load are 2011 and 2016, so special attention is given to these two cases. Below some observations are made about the results obtained and it is evaluated if the developed MATLAB tool represents well the real situation of the Finnish power system. To better study the existing correlation between the characteristics that have been analyzed, the installed capacities, the expected load loss and maximum peak loads from every year have been compared in the following Figure 20 which compares the evolution of the installed capacities with the results obtained of expected load loss, and Figure 21, which compares the expected load loss obtained with the maximum load peaks of each year.

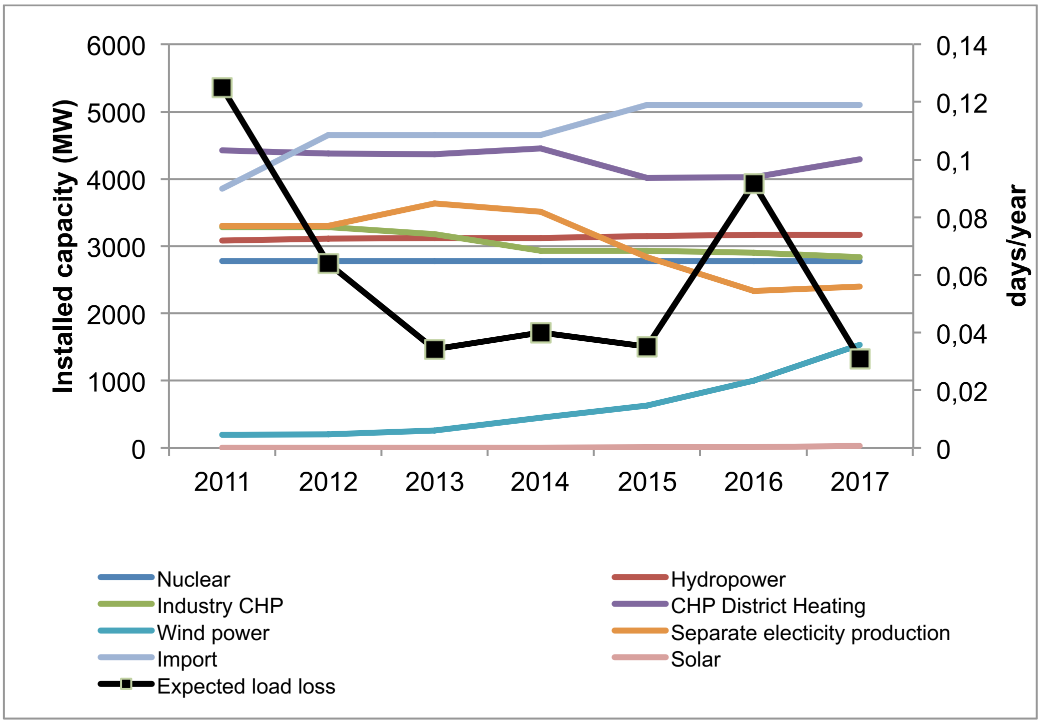


Figure 20. Evolution of installed capacities in Finland vs Expected load loss

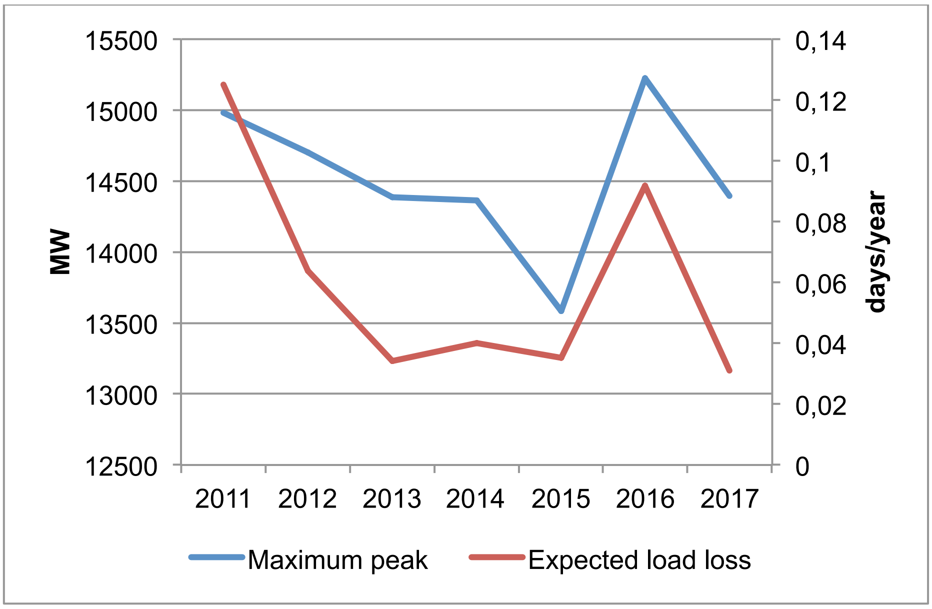


Figure 21. Annual maximum load demand peaks in Finland vs Expected load loss

Another information that has been considered relevant for the study is the total electricity consumption during these years, since the maximum load peak of each year could not represent properly the weather conditions of the entire year. Even so, it is known that the change in total supply of electricity may not be explained completely with weather conditions, since there are other factors, such as the economic crisis in 2008 that affected consumption during 2009, as it can be seen in Figure 22. The electricity consumption has been taken from Statistics Finland (Tilastokeskus, Statistics Finland, 2018), as it is represented in Figure 22. In Figure 23 the total electricity consumption of the years 2011-2017 is compared with the expected load loss obtained for each year.

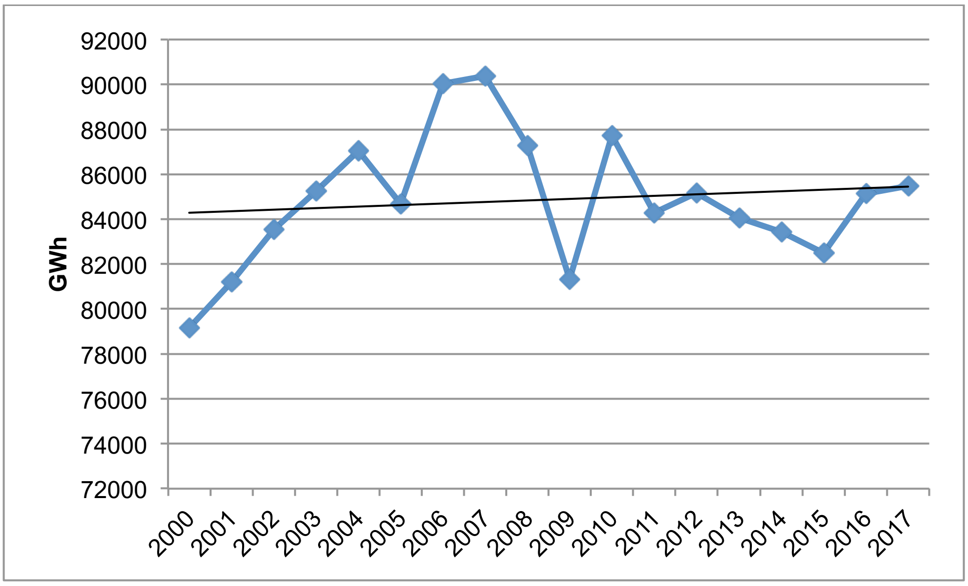


Figure 22. *Total supply of electricity in Finland from 2000-2017*

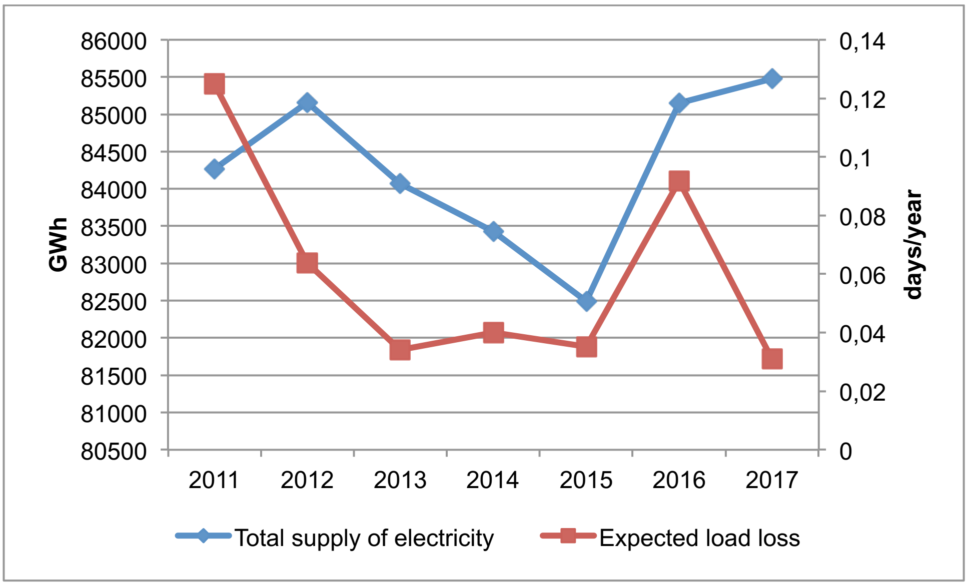


Figure 23. *Total supply of electricity in Finland vs Expected load loss*

1. Analyzing Figure 20, 2011 starts with a very high load loss value. The nuclear capacity is the same as there is currently, with all four nuclear power plants in operation. The capacity to import in the year 2011 was much lower than nowadays, since some of the existing connections with neighboring countries had not yet been carried out. The installed capacities of separate electricity production and industry CHP were similar and slightly higher to the installed capacity of hydropower and nuclear. The installed capacities of renewables such as wind power was very low and that of solar PV almost non-existent. Given that the dominating technologies in this year had low results regarding the probability of

forced outage, it is considered that this high value of load loss obtained must be due to a year in which the load demand was high with remarkable peaks due to weather conditions. In Figure 21 it can be seen how the peak load of that year was quite high. In the other hand, Figure 22 shows how the total electricity consumption during 2011 was under the average. By these results it is concluded that the high expected load loss is due to either the low installed import capacity or the pronounced load peak.

2. In 2012 there was a pronounced decrease in the expected load loss with respect to the previous year with an increase in the installed capacity of import technology. As expected, the increase in import technology, which, as previously calculated, is the one with the lowest outage probability rate, may have influenced the expected load loss for that year to decrease a lot with respect to the previous year. On the other hand, it is also possible that the year 2012 had weather conditions more relaxed than the previous year, decreasing the peak load demand, but this possibility is ruled out since in Figure 23 it is observed that the total electricity consumption in 2012 increases with respect to the 2011 and Figure 21 shows a similar peak values between the two years. These results indicate that the decrease in expected load loss is due to the increase in import capacity.

3. In 2013 there was a decrease in the expected load loss compared to the previous year. The reasons for this decrease can be either an increase in the installed capacity of separate electricity production, which has a very low forced outage rate, or due to the decrease in the load of that year with respect to the previous one. It can be seen in Figure 23 that the total electricity consumption decreased with respect to the previous year and also in Figure 21 the load peak was lower in 2013 than 2012.

4. In the next year, 2014, some interesting observations can be made. While the peak load remains at a very similar value to year 2013 and electricity consumption also stays similar, even a little lower than 2013, the expected load loss increases slightly in 2014. Among the changes in installed capacities that can be seen, all remain constant compared to 2013 except the separate electricity production, CHP district heating, wind power and industry CHP. From these four, the variation that is understood to have a negative impact, that is, to increase the expected load loss, is the decommission of separate electricity production, which removes flexibility from the network. The impact of wind power is considered non-existent because there is still very little installed capacity compared to the other technologies. This result may mean that the tool responds properly to changes in installed capacities.

5. The expected load loss in 2015 decreases slightly compared to 2014. The main changes in installed capacity are a great decommission of separate electricity production plants and a decrease in CHP district heating. The last connections with neighboring countries are also built and the import capacity lines reach the maximum that is currently available. Everything indicates that the decrease in the expected load loss is due to the increase in the import capacity, which is very reliable, and the sharp decline of the load peak during 2015, which indicates that the weather conditions were more relaxed than other years. This observation is

confirmed after checking in Figure 23 that the total electricity consumption in Finland in 2015 was much lower than usual.

6. In 2016, there is a large increase in the expected load loss. With regard to installed capacities, the greatest decrease is suffered by the separate electricity production. For the rest, all the other capacities remain almost constant, except wind power, which increases, but without having enough weight yet. Clearly this result is due to the great increase in the load suffered during 2016 due to hard weather conditions. A very interesting observation shows that although the load peak is higher in 2016 than in 2011, the expected load loss is higher in 2011 than in 2016, and also the total consumption of electricity was higher in 2016 than 2011, as it is shown in figure 23. This could be due to a change in the installed capacities towards more reliable technologies, especially it seems that the increase in import capacity is responsible for this situation.

7. For the last case, in 2017 the expected load loss decreases with respect to 2016. Mainly it seems that it is due to the decrease in load compared to the previous year, due to better weather conditions, but after checking Figure 23 it is observed that the total electricity consumption was even higher than the previous year, which means the opposite. The reason why the situation makes sense is explained in Figure 21. It can be seen how the load peak decreases, which may be perfectly possible even if the electricity consumption is higher during that year. On the other hand, most technologies maintain similar installed capacities, except for a considerable increase in wind power, which begins to approach the others and also a slight increase in CHP district heating. The result in this year clearly indicates that the tool is very sensitive to the maximum load peaks

Some conclusions taken from this section about the reliability of the designed tool are that according to the results obtained, it seems that the designed tool is very sensitive to changes in the load duration curve, particularly sensitive to the maximum load peaks. This result can be useful because if the most influential factor is the maximum load peaks, it could be studied what happens if the installed capacity that is not usually available during peak load demand is removed to see if the risk of load loss increases. To evaluate this, one should simply remove the unavailable capacity of the installed capacity matrix of the program.

The program designed has also shown to be sensitive to variations in installed capacity, although to a lesser extent than in the case of changes in the load duration curve. Therefore, the program is able to provide a measure of the risk of losing load sensitive to changes in installed capacities and electrical consumption profile, so it is considered convenient to use it to continue with the reliability evaluation of the Finnish power system in 2030.

4. RELIABILITY ANALYSIS FOR POWER ADEQUACY IN 2030

The next phase of the study tries to forecast the expected load loss of the Finnish power system in 2030. For this, three different load scenarios are proposed. The analysis performed uses the same MATLAB tool that was previously used to evaluate the expected load loss of previous years. In this case, it is needed:

- The installed capacities of the different technologies that will be commissioned in the future. These data have to be extracted from projects that are currently being carried out and planned decommissions.
- The forced outage rates of technologies. To simplify the calculations in this study we will use the same ones that have been calculated previously considering that they will not change.
- The load duration curves of possible scenarios in the future. Three different scenarios with load duration curves will be considered.
    a. Same load
    b. Development of storage and demand response
    c. Increase load peaks

Performing the evaluation of expected load loss for each of these scenarios will lead to the final results of reliability of the Finnish power system in 2030.

4.1 Forecast of installed capacities in 2030

It is expected that the installed capacities of each technology used for the production of electricity in Finland in 2030 will be very different from what currently exists.

4.1.1 Changes in nuclear installed capacity

Currently there are four nuclear power plants active in Finland. The construction of a nuclear power plant, Olkiluoto 3, has been underway for years. The construction started in 2005 and it was foreseen that this plant would start the commercial operation in 2010, but it has been delayed multiple times. According to the company owner of the plant, Teollisuuden Voima Oy (TVO), it is currently expected to start operating commercially in May 2019 (Tanhua, 2018).

There is another approved project, the nuclear power plant of Hanhikivi 1. It consists of a Russian design of VVER-1200 pressurized water reactor with a net capacity up to 1200 MW. The construction was approved by the parliament in July 2010. The company in charge of the execution is Fennovoima. The plant is expected to start the commercial operation in 2024.

Collecting the information obtained for the evolution of the nuclear power technology installed in Finland, following Table 19 can be elaborated to know the installed capacity that will be available in 2030. Also Figure 24 shows the evolution of installed capacity.

Table 19. *Expected shutdown and commissioning of nuclear power plants in Finland*

	Type	MW net	First power	Expected shutdown
Loviisa 1	VVER-440/ V213	502	1977	2027
Loviisa 2	VVER-440/V213	502	1980	2030
Olkiluoto 1	BWR	880	1978	2038
Olkiluoto 2	BWR	880	1980	2038
Olkiluoto 3	EPR	1600	May 2019	-
Hanhikivi 1	VVER-1200/V-491	1200	2024	-
Total		**4560**		

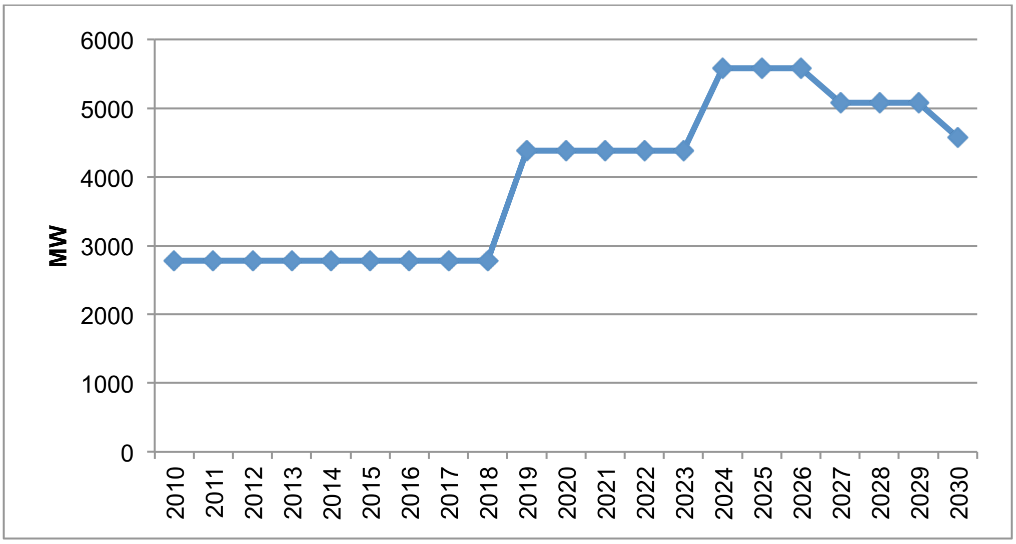


Figure 24. *Forecasted installed nuclear power capacity in Finland until 2030*

4.1.2 Changes in hydro power installed capacity

In the background of this work, the current situation of hydropower in Finland has already been described. According to the World Energy Council, it could still be possible to increase Finland’s hydropower capacity, though the main potential sources are generally well exploited. It is unlikely that hydropower developments could be launched along any remaining totally unharnessed rivers, for conservation reasons. For this reason, it is considered that the installed capacity of hydropower energy in 2030 will be very similar to the one that currently exists. Figure 25 below shows the evolution of how the installed capacity of hydropower technology has increased during the last ten years, which is mainly due to upgrade of the existing hydro power plants in Finland. The value in 2030 is expected to be approximately the same as in 2017, around 3200 MW.

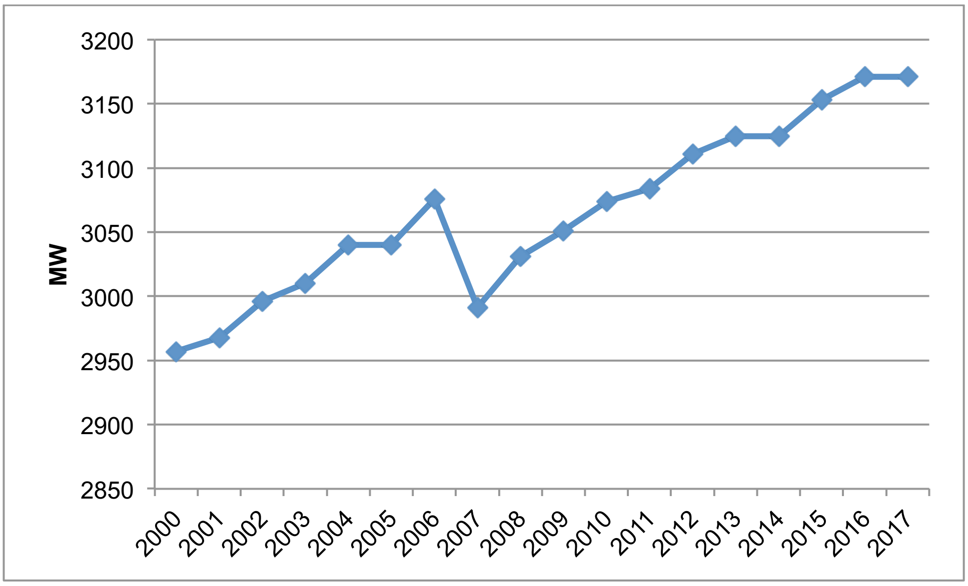


Figure 25. *Evolution of hydropower installed capacity in Finland 2000-2017*

4.1.3 Changes in separate electricity production, industrial CHP and CHP district heating.

These three technologies are studied in the same section because they use similar fuels to obtain electricity. This will simplify the calculations when it comes to foresee the decommissioning of coal power plants by 2030. First, it focuses on the separate electricity production. As it is shown in Figure 26, the trend in installed capacity is decreasing. The main reason is the commitment to other technologies that produce fewer emissions and that use renewable resources. In Finland this technology can be divided into three groups: one refers to the power plants of condensing power, which mainly use hard coal; another is formed by peak gas turbines and gas engines, which use natural gas; the third is made up of small power plants of less than 1 MVA, which can use several different types of fuels.

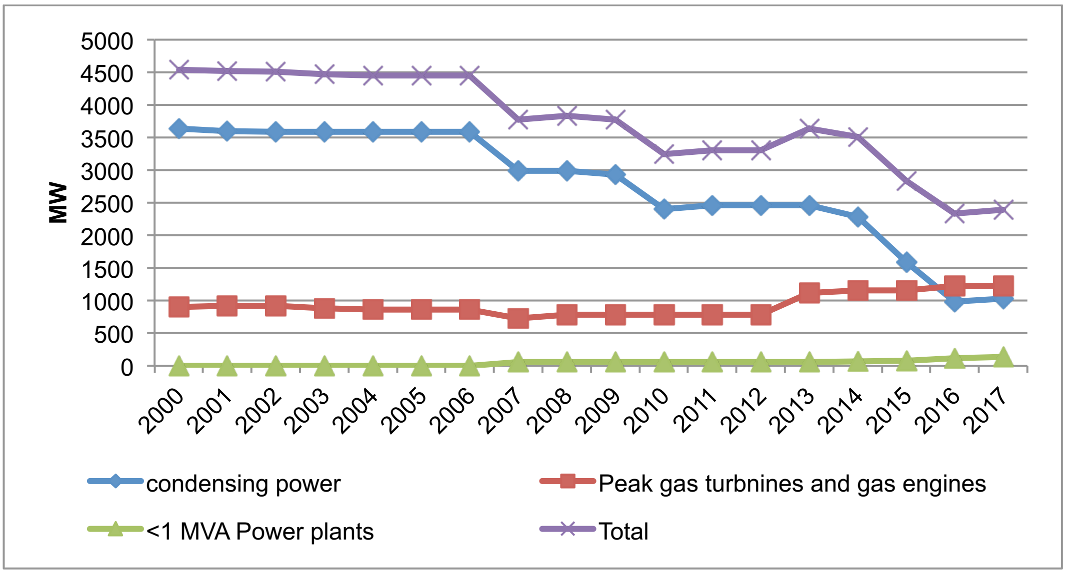


Figure 26. *Evolution of separate electricity production installed capacity in Finland 2000-2017*

As can be seen, the installed capacity of condensing power plants has suffered a large decrease during the last few years, as a result of the commitment to renewable energies. The installed capacities of separate electricity production in year 2017 are shown in Table 20.

Table 20. *Installed capacities of separate electricity production in 2017 in Finland*

	Condensing power	**Peak gas turbines and gas engines**	**< 1 MVA Power plants**	**Total (MW)**
2017	1028	1230	140	2398

The evolution of the installed capacity of industry CHP and CHP district heating during the last seventeen years has not followed a definite increasing or decreasing trend, rather, it seems that they oscillate around the current values of 3130 MW of installed capacity for Industry CHP and 4230 for CHP district heating (Tilastokeskus, Electricity generation capacity, nominal capacity of production engines at beggining of year, 2018), as it is shown on Figure 27.

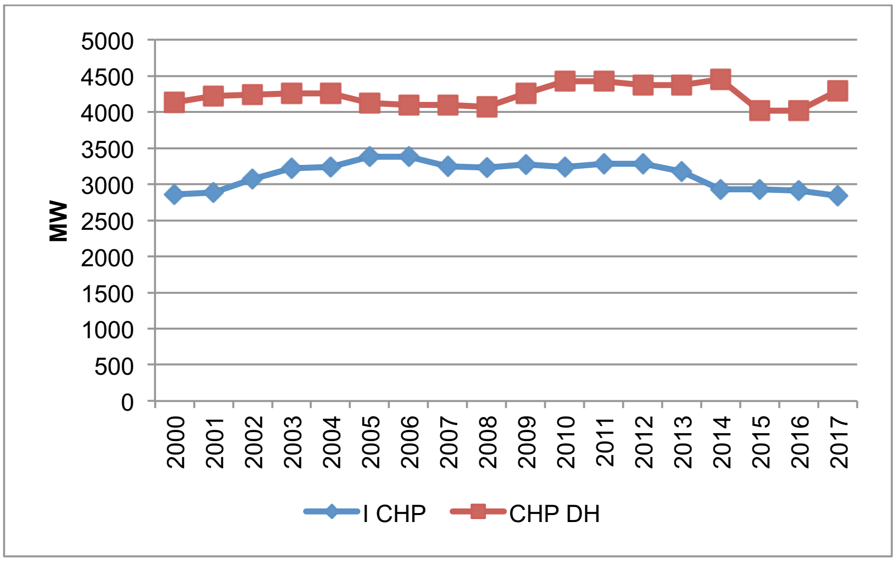


Figure 27. *Industry CHP and CHP district heating installed capacity in Finland 2000-2017*

Therefore, it is considered that the installed capacity that will exist in 2030 of these technologies will stay around these values except for one thing, and it is that some power plants of this type use coal as fuel, so those must be decommissioned by 2030. The installed capacity corresponding to coal in Finland is found in the tool "Transparency platform" of the ENTSO-E. Following Table 21 and the Figure 28 show the installed capacities of each production type during the last four years. It can be seen how the installed capacities have changed. The association ENTSO-E officially publishes all the information (ENTSO-E, 2018).

Table 21. *Installed capacities in Finland by fuel source*

Production Type	2015 (MW)	2016 (MW)	2017 (MW)	2018 (MW)
Biomass	2051	1534	1663	1813
Fossil Brown coal/Lignite	-	-	-	-
Fossil Coal-derived gas	-	-	-	-
Fossil Gas	1611	482	1795	1865
Fossil Hard coal	2792	3416	2854	2278
Fossil Oil	1705	893	1427	1386
Fossil Oil shale	-	-	-	-
Fossil Peat	1685	1024	1077	1135
Geothermal	-	-	-	-
Hydro Pumped Storage	-	-	-	-
Hydro Run-of-river and poundage	3264	3112	3107	3149
Hydro Water Reservoir	-	-	-	-
Marine	-	-	-	-

Nuclear	2752	2782	2782	2782
Other	45	1305	563	362
Other renewable	19	82	85	257
Solar	-	-	-	-
Waste	72	47	126	157
Wind Offshore	-	-	-	-
Wind Onshore	496	1082	1432	1908
Total Grand capacity	16492	15759	16911	17092

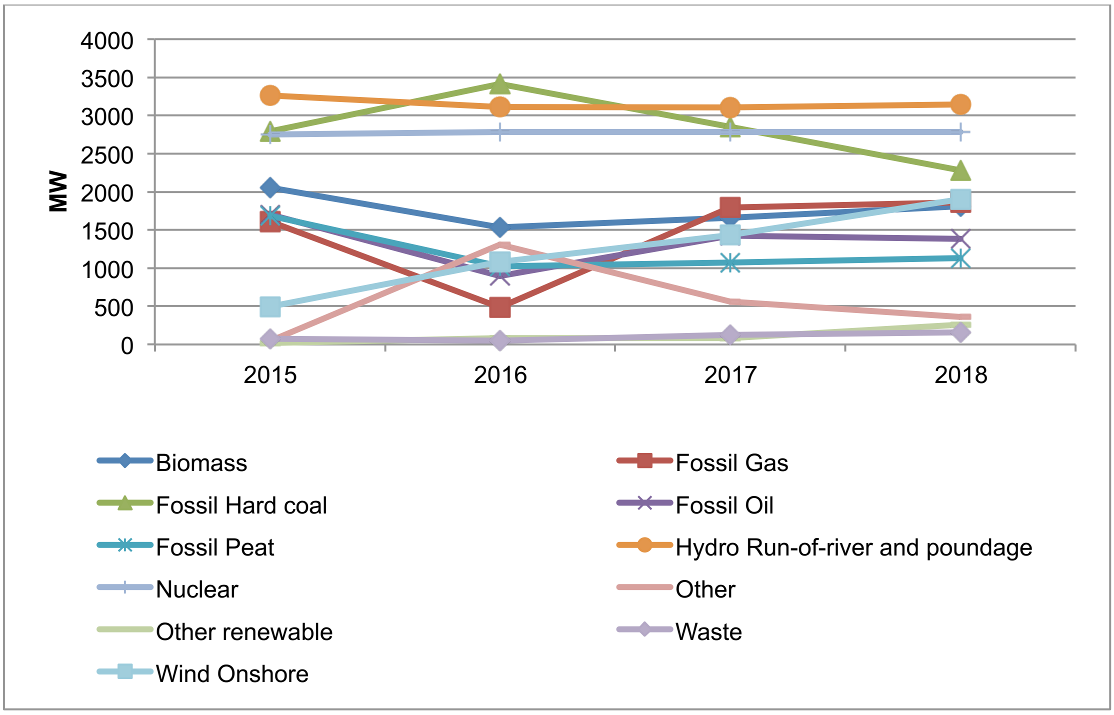


Figure 28. *Evolution of installed capacities per production type in Finland 2015-2018* ***(ENTSO-E, 2018)***

In Figure 28 it can be seen how the hard coal installed capacity reached a maximum in 2016, surpassing even the installed capacity of nuclear and hydropower. Since then, the trend of the number of power plants using hard coal has been clearly decreasing. It seems that the disuse of hard coal has benefited other fuels, such as fossil gas, which installed capacity has increased considerably during the last two years.

Therefore, phasing out hard coal will mainly affect CHP district heating, industry CHP and separate electricity production power plants, since they are the ones that use this resource to a greater extent. Next, he wants to make an estimate of how the installed capacities of these technologies will be reduced by the prohibition of the use of hard coal. The 2278 MW of installed capacity that appear in the "Transparency platform" of the ENTSO-E should disappear from power plants corresponding to these three technologies. Between the CHP district heating, industrial CHP and separate electricity production, it has been proven that the participation of the industrial CHP in terms of hard coal use is much lower than that of the other two, so it is not going to extract capacity from this technology. In terms of separate electricity production, hard coal is used by power plants that are dedicated to condensing power, thus excluding the installed capacity that refers to peak gas turbines and small power plants of less than 1 MVA. Form the 1028 MW available of condensing power in 2018, in section 2.2.2 it has been shown already that approximately 45% of the fuel used in these power plants is hard coal. Assuming that these power plants can only use hard coal to operate, this would imply withdrawing by 2030 around 463 MW of installed capacity of condensing power.

Regarding CHP district heating, in section 2.2.2 it is shown that 33% of the fuel used in the CHP district heating power plants is hard coal. Assuming that this fraction of power plants can only use hard coal to operate, this would represent 33% of the installed capacity of CHP district heating, which is approximately 1417 MW.

As for the installed capacity of industry CHP, the use of hard coal is very low. Only 2% of the fuel used by the power plants of this technology is hard coal. Assuming that this small fraction of power plants can only operate with hard coal, it would mean a withdrawal of 57 MW of installed capacity by 2030. Summarizing the calculations that have been made in Table 22 explains the situation of these three technologies expected for 2030.

Table 22. *Expected phase out coal installed capacity in Finland for 2030*

	Capacity installed 2018 (MW)	Removed (MW)
Separate electricity production	2398	-463
CHP District Heating	4290	-1417
Industry CHP	2837	-57
Total	9525	-1937

Of the 2278 MW of hard coal installed capacity that appear in the official data of the ENTSO-E presented in Table 21, 1937 have been identified among these three technologies. It is possible that due to errors in the calculations of the fuels used by these technologies, the remaining 341 MW still belong to condensing power plants, CHP district heating and industry CHP. Therefore, some corrections have been made to the previous table to fully adjust to the capacity of hard coal that will be faced out in Finland. Most likely the remaining MW of hard coal installed capacity belong to condensing power plants and CHP district heating, therefore, half of the amount will be subtracted from each of them, this means 170 MW less for each. The final values that will be used for the study are represented in Table 23, the corrections are represented in blue.

***Table 23.** Corrected phase out coal installed capacity in Finland for 2030*

	Capacity installed 2018 (MW)	Removed (MW)	Expected installed capacity 2030 (MW)
Separate electricity production	2398	-463 -170	1765
CHP District Heating	4290	-1417 -170	2703
Industry CHP	2837	-57	2780
Total	9525	~2278	7588

4.1.4 Changes in wind power installed capacity

The progression of the installed capacity of wind power in Finland during the last years has been very promising. There are numerous studies carried out on how the installed capacity of wind power in Finland will evolve over the next few years. For this work it has been decided to use the study carried out by WindEurope during September 2017 named "Wind Energy in Europe: Scenarios for 2030". The study makes its projections on installed capacity with a bottom-up approach, collecting data at country level, considering experts from all the relevant national wind energy associations as well as with industrial stakeholders including turbine manufacturers and wind project developers. There are three possible scenarios for the future: low, central and high. In this thesis the predictions made for the central scenario will be used. To describe the scenario used by WindEurope, the description given in his study is used explicitly as follows: *"In the central scenario, a clear 2030 governance structure with reporting mechanisms on Member States' progress to 2030 is implemented, and effective regional cooperation mechanisms are established. Member States implement detailed National Energy and Climate Plans in line with the EU's binding targets. The Renewable Energy Directive is implemented as proposed by the European Commission. As a result, the EU achieves a 27% renewable energy target. Significant progress on system integration allows for higher penetration of wind energy and other renewables, and power interconnection infrastructure is strengthened to allow the EU to reach the 15% interconnection target. Wind energy provides balancing and other ancillary services in all Member States. Policy commitments on electrification drive demand for renewable power."*

In the scenario described, the evolution of installed capacity of wind power in Finland is expected to reach 5000 MW. Figure 29 below shows the installed capacity of wind power during the last years and how it is expected to evolve up to 5000 MW by 2030 (WindEurope, 2017).

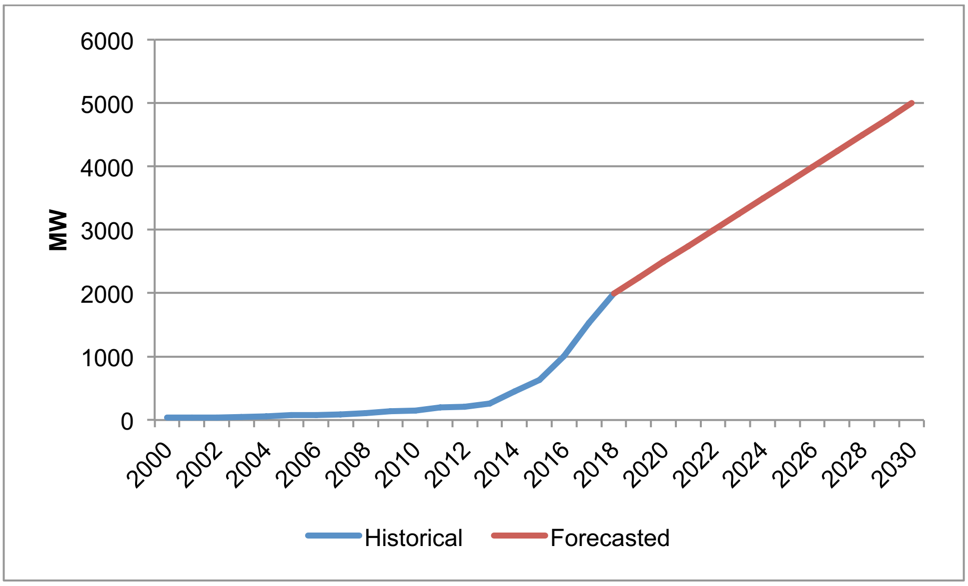
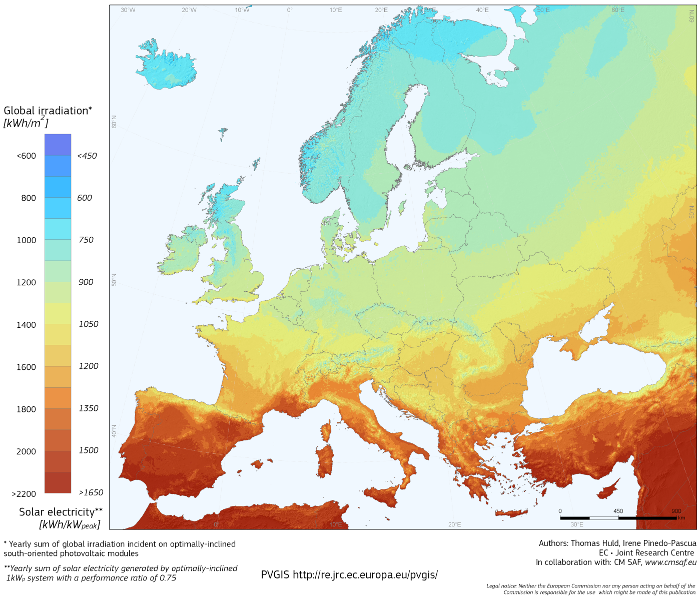


Figure 29. *Forecasted wind power installed capacity growth in Finland*

4.1.5 Changes in solar PV

Photovoltaic solar installed capacity in Finland is very low, probably because it has one of the lowest irradiations in Europe. As it can be seen in the map of Figure 30, yearly solar irradiation in Finland is low, around 1000 kWh/m^2/h.



* Yearly sum of global irradiation incident on optimally-inclined south-oriented photovoltaic modules

**Yearly sum of solar electricity generated by optimally-inclined 1kWp system with a performance ratio of 0.75

PVGIS http://re.jrc.ec.europa.eu/pvgis/

Authors: Thomas Huld, Irene Pinedo-Pascua
EC • Joint Research Centre
In collaboration with: CM SAF, www.cmsaf.eu

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Figure 30. *Irradiation in Europe* ***(Huld & Pinedo-Pascua, 2017)***

In the previous section of this work, in which the installed capacities of each technology were presented, the current installed capacity of solar PV in Finland was shown. Information has been searched in many studies about the development of the installed capacity of photovoltaic solar energy in Finland, especially publications of the Renewable

Energy Policy Network for the 21st century (REN21, 2017) and the European Photovoltaic Industry Association (Masson, Latour, Rekinger, Theologitis, & Papoutsi, 2017), which has published many market reports during the last years, but no explicit numbers have been found about how much installed capacity is expected to be by 2030, nor specific targets to reach. For this reason, the historical evolution of solar PV in Finland has been studied to do a conservative estimation of the possible installed capacity that can be expected for 2030. Figure 31 shows the evolution of the increase rate of solar photovoltaic installed capacity in Finland from 2000 to 2017.

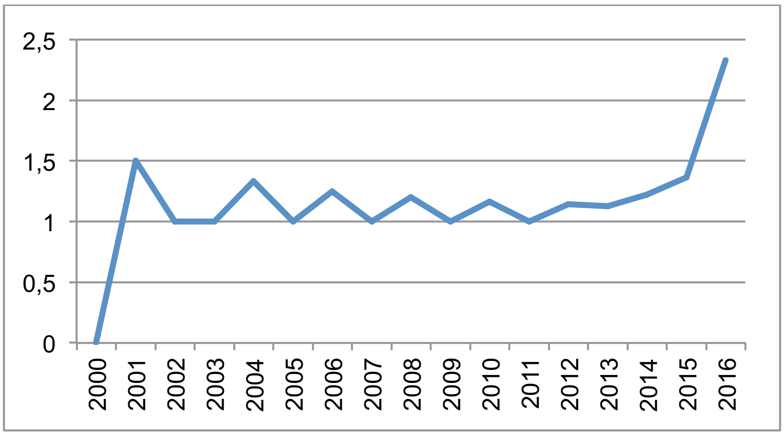

Figure 31. *Increase rate in solar PV installed capacity in Finland 2000-2016*

The average value of this evolution gives an increase ratio of 1,23. This ratio will be used to predict the installed capacity in the following years. Figure 32 shows the forecasted growth of solar PV in Finland until 2030.

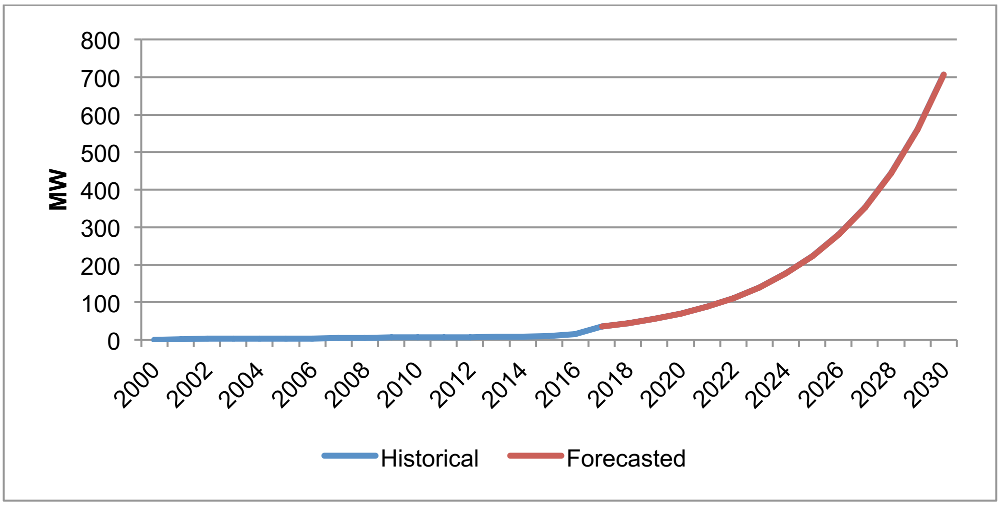

Figure 32. *Forecasted solar PV installed capacity in Finland for 2030*

The calculation of the forecast of installed capacity has not been very rigorous since the main objective of this work is not to obtain an absolutely reliable forecast of the installed capacity of solar photovoltaic by 2030, simply look for reasonable values with the evolution experienced during the last years. The regression that has been made has arisen from applying factors of growth of 23% in each year until 2030. According to this forecast, it is assumed that the installed capacity of solar photovoltaic power will be approximately 700 MW.

4.1.6 Changes in import capacity

Currently, the European Commission has set a target of reaching 15% of cross-border electricity interconnection in all countries of the European Union to achieve its climate and energy goals set for 2030 on it's "Communication on strengthening Europe's energy networks" (Commission, 2017). This will help to secure the security of supply and integrate the renewable energies in the electricity markets. When a power plant fails, the countries need their neighbors to import the electricity they need. Regarding cross border projects within the Nordic areas, a project planned for 2025 to build the third AC connection between Sweden and Finland has been published in the "Nordic grid development plan 2017" carried out by the TSO's of Norway, Sweden, Finland and Denmark. It is a new line of 400 kV across the northern border between Sweden and Finland (Statnett, 2017). The line can increase the trading capacity by approximately 500 MW (TYNDP, Project Third AC Finland-Sweden North, 2015). On the other hand, the report published by the TYNDP (Ten Year Network Development Plan) of the ENTSO-E (TYNDP, Vision 2020, 2016) shows that the interconnection of Finland will decrease from 29% in 2017 to 19% in 2020, probably because the first HVDC connection between Finland and Sweden is already quite old so perhaps it considers its decommission. Even so, it would continue to meet the targets of 15% planned for 2030.

No information has been found on the decommissioning of any of the lines that connect Finland with its neighboring countries. Since the project for the third single circuit 400 kV AC OHL between Finland and Sweden is still under consideration (TYNDP, Project Third AC Finland-Sweden North, 2015) and the country already meets the interconnection targets set by the European commission, it is assumed that the installed capacity of import electricity in Finland will be maintained in the current 5100 MW.

4.1.7 Recap of installed capacities in 2030

Following Table 24 summarizes the results obtained for each technology. These results will be used later in the MATLAB tool to calculate the expected load loss in 2030. The increase in total installed capacity forecasted for 2030 is about 17% compared to the current situation in 2017. This increase is mainly due to the commissioning of large nuclear power plants and the increase in installed capacity of renewable technologies such as wind parks and solar power photovoltaic power plants. The technologies that have been considered to decline its installed capacity to a larger extent are those that use fossil fuels.

Table 24. Summary of forecasted installed capacities in Finland for 2030

	Nuclear	Hydro	Wind	CHP DH	I CHP	Other	Solar	Import	Total
2030 (MW)	4560	3200	5000	2700	2780	1765	700	5100	25805

4.2 Forced outage rates

To simplify the work, the outage rates that will be used for the forecast in 2030 will be the same as those calculated based on the data provided by the "Transparency platform" tool of the ENTSO-E. Since no information has been found about forced outages in solar photovoltaic power plants neither in Finland nor in Europe, it is assumed that the forced outage rate of solar photovoltaic technology will be the same as the wind power, since in chapter 3 it has been seen that it is common to find similar values of forced outage rates between renewable technologies (Figure 17). Even so, this approach is not very realistic since wind farms and solar parks have many technical and operational differences. Although both have similarities like the use of inverters for changing DC to AC and AC to DC currents, Wind turbines have more rotating parts and perhaps should have higher FOR compared to solar. Similarities are also found on the resources that they use, since both come from the sun and have an intermittent nature, but this fact doesn't impact much on the similarities between the forced outage rates. Due to the lack of information about forced outages in solar power plants it was taken the same forced outage rate that has been obtained for wind power for the solar photovoltaic installed capacity. The fact that the installed capacity of solar power in 2030 in Finland is expected to remain relatively low will minimize possible errors.

4.3 Load forecast for 2030

In this section is carried out a forecast of three possible scenarios regarding the load in Finland in 2030. For this purpose, historical data of total energy consumed, electricity consumption, load profiles occurred during the last years and possible future policies are taken into account.

In order to develop the load duration curves profiles needed for the reliability analysis, it is necessary to know if the total consumption of energy and electricity in Finland will vary greatly in the future compared to the current. With information published by Statistics Finland it is easy to observe and analyze how Finland's energy and electricity consumption has historically evolved. The trend is clearly growing, although during the last few years it seems to begin to saturate. Several studies have been carried out on this subject, for example, the calculations made by VTT on the "Energy report on the national energy and climate strategy for 2030" (Huttunen, 2017). As seen in Figure 33, it is expected that the total energy consumed per year does not increase keeping around 310 TWh.

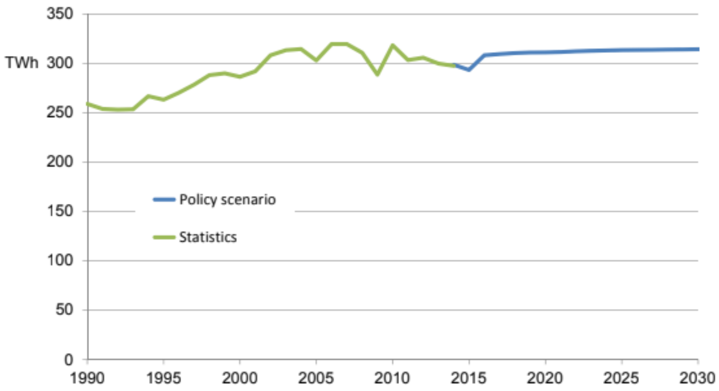

Figure 33. *Total energy consumption forecast in Finland for 2030*

The study also considers the total electricity consumption of Finland in the year 2030. Looking at these results it can be concluded that the demand for electricity in Finland by 2030 will remain around 90 TWh per year, as seen in Figure 34. Since it is not a very high increase, the load duration curves calculated for previous years will be used, making small changes according to the scenario that is being evaluated. Therefore, the load duration curve of the year 2016 will be taken as a reference for developing the curves of the different scenarios, since it has the electrical consumption closest to the expected for 2030.

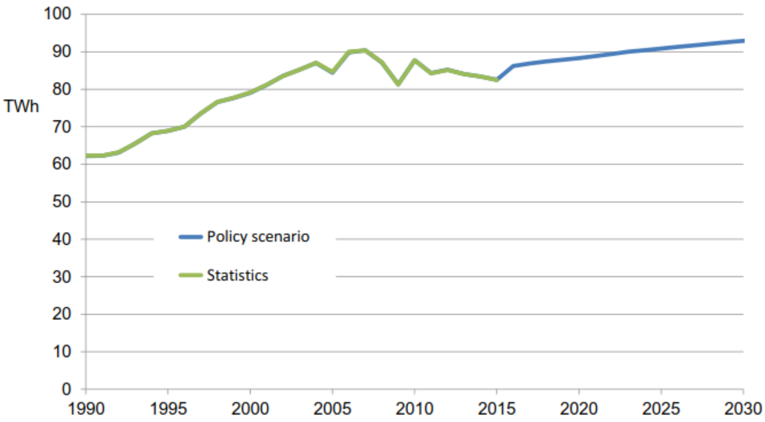

Figure 34. *Total electricity consumption in Finland in 2030*

Once reliable electricity consumption has been set for 2030, the next step is to define three possible scenarios that could arise from load profiles in the future. The characteristic elements that are going to be taken into account for each scenario are the following:

A. Electricity demand: The development of the electricity demand advances driven by different forces. While innovations lead to greater efficiencies of consumers and therefore to a reduction in demand, the same innovation also leads to a fuel switch towards a higher electrification. Higher electrification of heating might even further increase peaks. Not only the heating, the cooling is also becoming more popular in Finland during hot summer days, although there are not many of those. Improved insulation in new houses however increases the cooling need, since houses are not cooled down naturally during nights. This could increase the load demand in the profile.

B. Demand response: Historically the generation has adapted to the demand of energy. This traditional model may change in the future with the inclusion of distributed energy resources in the power system. Development of distributed energy resources, demand response based on smart metering and actuation systems, home automation, development of smart grids, Internet of things, etc.
C. Electric vehicles: As an alternative transportation option to the combustion engine vehicle the development of smart grids in power grids has advanced the role of electric vehicles. Vehicle to grid technology allows bidirectional energy exchange between electric vehicles and the power grid. It can be used as a spinning reserve, peak load shaving, load leveling, power grid regulation or reactive power compensation. Other possibilities to realize demand response with electric vehicles are by time-of-use tariffs, electricity market price based tariff and combination of retail and grid tariffs. By the end of 2017, the Finnish vehicle fleet accounted 6.474.783 vehicles (Tilastokeskus, Motor vehicle stock, 2018), of which 5.045.365 where in use. The target set for 2030 is to reach 250.000 electric vehicles in Finland (Aarhus, 2017), which means multiplying by a factor of 76 the current deployment, around 3285 (Virta, 2017), of electric vehicles in 2017 in Finland according to the Finnish Transport Safety Agency. This study does not go into details of what exact increase would imply the deployment of this amount of electric vehicles, it is simply used to argue reasons that could lead to an increase in the load peaks as it is shown later in scenario 3.
D. Weather conditions: The weather conditions are perhaps the most influential factor in the profile of the load duration curve. A year of low temperatures easily causes more pronounced demand peaks, while warm years have smoother profiles.
E. Storage: The role of energy storage technology is vital in the development of the power grid to mitigate the challenges it faces regarding power adequacy, security of supply and variability of renewable electricity. Increased deployment of energy storage devices in the distribution grid will help to save the electricity produced during peaks of renewable generation to be used during periods of scarcity and will also help the demand side management.

Table 25 shows how each one from the characteristic elements described before have been defined for each scenario, which will determine the different load duration curves. As it can be seen in Table 25, it is going to be considered that the electricity demand remains constant between the three scenarios. Therefore, the three load duration curves consist of the same area, which is equivalent to the total energy consumption. This assumption is made to simplify the comparison of scenarios. While scenario 1 presents some conservative characteristics without changes, the other scenarios vary some of them. As it is seen in Table 25 scenario 2 is characterized by a very high demand response and the development of large storage capacities. In the case of scenario 3, the characteristics that define it are an increase in the electrification of transportation systems and challenging weather conditions more likely for the appearance of bigger load peaks.

Table 25. *Characteristics for each load scenario*

	Scenario 1	**Scenario 2**	**Scenario 3**
Electricity demand	Normal	Normal	Normal
Demand response	Low	High	Low
Electric vehicles	Low	Normal	High
Weather conditions	Normal	Normal	Bad
Storage	Low	High	Low

To develop the load duration curves in Finland in 2030 is used the load duration curve of 2016, since it was a challenging year to meet electrical energy consumption and peak demand requirements. Hence, the curve obtained for each scenario is the product of applying small changes to the 2016 curve.

4.3.1 Scenario 1: Same load

The first scenario raises the situation that the load remains exactly the same as during the last years. The characteristics that describe this scenario are the following:

a. Electricity demand: In the same load scenario, electricity demand remains at the same levels as there are currently. The industry would continue to be the main consumer of electricity followed by household and services and public sector, as can be seen in Figure 35 where is shown the evolution of electricity consumption in Finland between the years 2000 to 2016 (Tilastokeskus, Statistics Finland, 2018). The sudden change in household equipment is due to the lack of data previous to year 2008 in Statistics Finland.

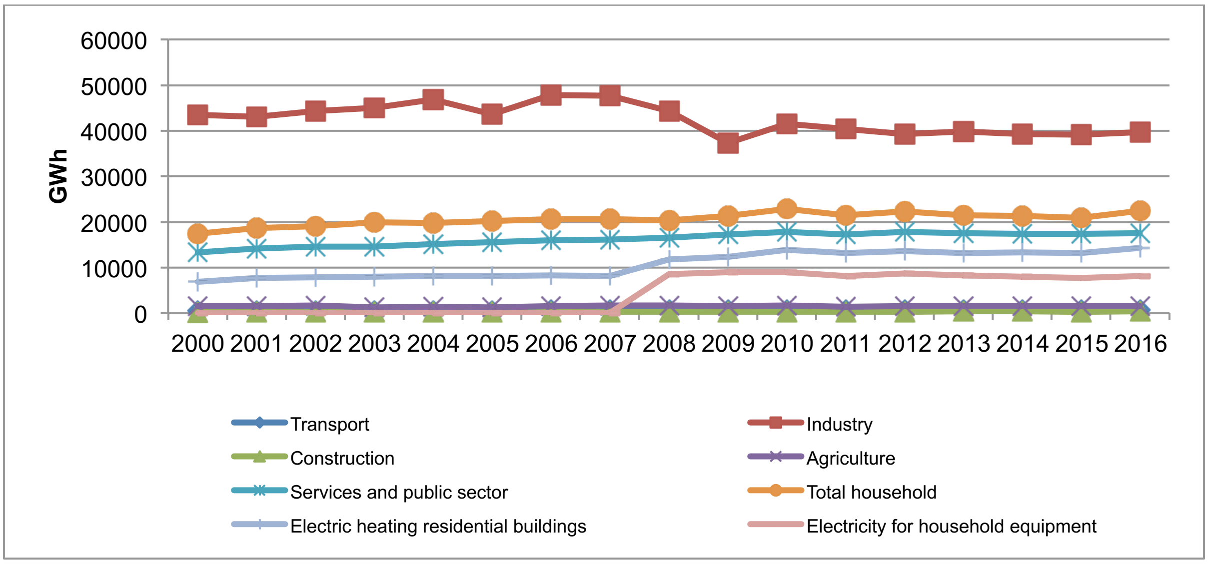

Figure 35. *Electricity consumption by sector in Finland 2000-2016*

b. Demand response: In this scenario, demand response has not been developed beyond the measures currently taken for demand side management such as financial incentives (Time Of Use tariffs), energy efficiency, etc.
c. Electric vehicles: The electric vehicles have not been deployed much among the Finnish fleet. Are still used mostly combustion engine vehicles. The technology has not been developed to introduce electric vehicles into the power system.
d. Weather conditions: The weather conditions during the year are moderate, assuming no peak of demand outside the common.
e. Storage: The necessary technology has not been developed to include storage in the power grid. Therefore, it is not possible for individual costumers to take advantage of the renewable energy produced in peaks when the generation exceeds the demand.

The load duration curve is the same one used for year 2016. This was a challenging year to meet electrical energy consumption and peak load demand requirements, since both characteristics were high. While the maximum peak was 15227 MW, the total electricity consumption was 85150 GWh. The load duration curve used is shown in Figure 36.

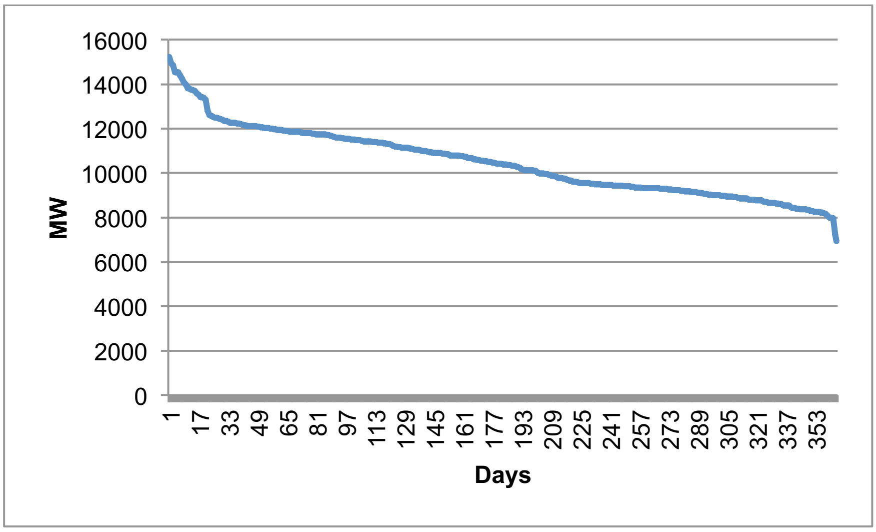

Figure 36. *Load duration curve scenario 1*

4.3.2 Scenario 2: Development of storage and demand response

The second scenario raises the possibility of maintaining conditions similar to the first one, except for new characteristics as a combination of large storage capacity and the development of a good demand response. The characteristics are the following:

a. Electricity demand: In this situation the electricity demand remains the same as in the previous case. It does not assume a much greater electrification than currently exists, posing a profile similar to first scenario, with the industry at the head followed by household and services and public sector.
b. Demand response: The key factor of this scenario is a complete development of the demand response. This means that in addition to the measures currently used

for demand side management such as TOU tariffs and energy efficiency, it will be possible to control (so that they consume more or less during peak hours) the demand for electricity by industrial facilities, household and also of services and public sector, like hospitals and healthcare facilities, universities, etc.

c. Electric vehicles: The electric vehicles have not been deployed much among the Finnish fleet, or if they have been deployed, the necessary technology has been developed to interact in the power system in a positive way, used as a spinning reserve, peak load shaving, load leveling, power grid regulation or reactive power compensation.
d. Weather conditions: The weather conditions during the year are moderate, assuming no peak of demand outside the common.
e. Storage: Storage technology has been developed to help improve demand side management. All facilities like industries, public services and even houses will be equipped with batteries capable of storing electrical energy from the network that could be originated when the electrical generation of renewable technologies exceeds the demand for electricity, being able to use that electricity later in peaks of demand requiring less electricity from the grid, decreasing load peaks.

Below it is explained in more detail the changes that occur in the load duration curve of this scenario with respect to the previous ones. The electricity consumption is much higher in cold seasons than in warm ones. The days of the coldest weather conditions are those that appear on the left side of the load duration curve and those that appear at the end usually have relaxed climatic conditions. This scenario raises the possibility of shifting the load from the electricity consumption of the days with the highest electricity demand in winter to the days of lower energy demand in summer. Figure 37 shows the situation described.

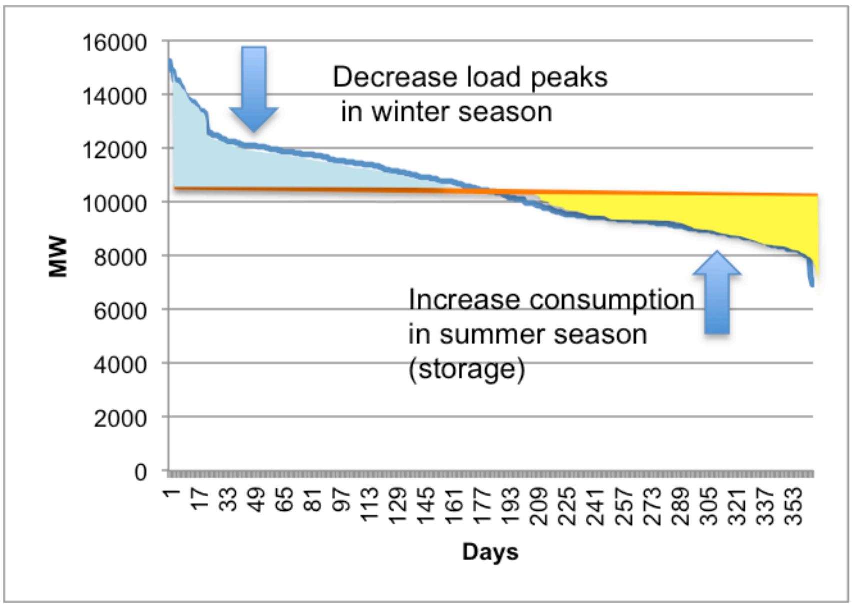

Figure 37. *Load shifting from winter peaks to summer valleys*

This situation may seem impossible, but the way to achieve it is through the development of large energy storage systems, such as improved pumped hydraulic storage systems. Another possibility that is being studied at present to achieve this objective is the photovoltaic solar energy with storage, since the electricity produced in summer when there is a lot of solar resource and low consumption could be stored to be consumed in winter. Although it is unlikely, this scenario raises the possibility that this technology could be developed in Finland.

To calculate the load duration curve of this scenario, the load duration curve of 2016 has been used, applying some changes. As shown in Figure 38, because of the load shifting this scenario would bring the peak values during the year closer to the average value. The average of the load peaks during 2016 gives a value of 10474 MW. To draw the curve, this value has been set for the midpoint of days, that is, 182. Considering that in this scenario there is still a possibility that larger peaks may occur, it has been applied a gradual growth factor to the left until reaching a peak of 10% over the mean value. On the right side of the curve, a gradual decrease factor has been applied until reaching a peak of 10% lower than the average value. It should be clarified that the area below the curve is still the same as in scenario 1. The resulting load duration curve is shown in Figure 38.

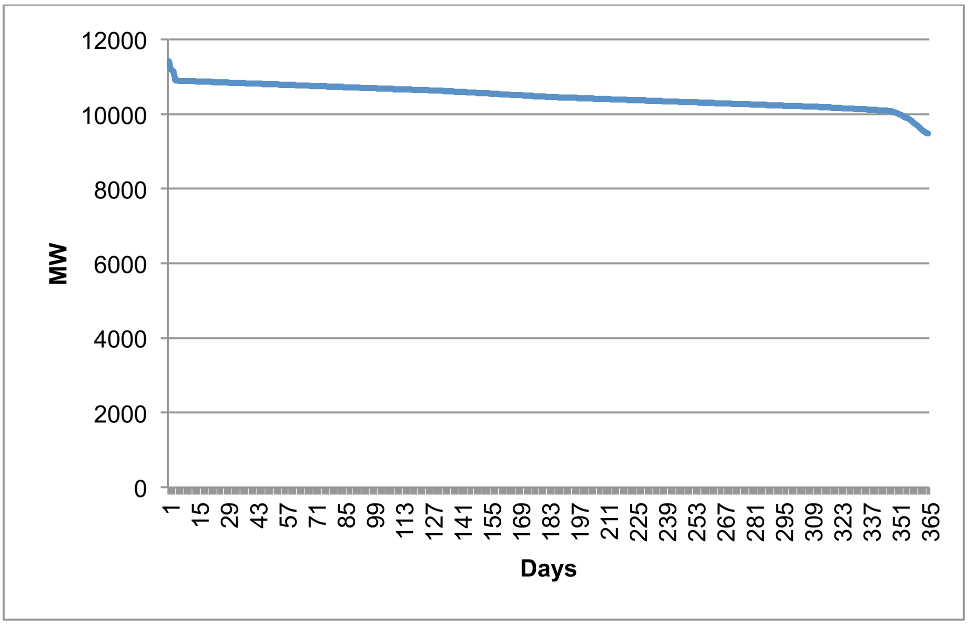

Figure 38. *Load duration curve scenario 2*

4.3.3 Scenario 3: Increase load peaks

This scenario would lead to load peaks even more pronounced than at present, so it is a clearly unfavorable situation for the reliability of the power system. The reasons that can lead to this scenario are the following:

a. Electricity demand: There is an increase in the potential use of electricity. This means that the total amount of electrical energy consumed remains the same as the other scenarios, because at the same time as electrification increases, the energy efficiency increases, but the risk of higher electricity demand peaks also increases.

b. Demand response: In this scenario, demand response has not been developed beyond the measures currently taken for demand side management such as financial incentives (Time Of Use tariffs), energy efficiency, etc.
c. Electric vehicles: There is a very high electrification of the Finnish automobile fleet, completely replacing the combustion engine vehicles. The deployment of electric vehicles has not been accompanied by the development of technology that allows the use of vehicles to perform tasks as spinning reserve, peak load shaving, load leveling, power grid regulation or reactive power compensation.
d. Weather conditions: In this scenario, more severe weather conditions are contemplated than in the two previous cases. It is considered that in the year of study the peaks of electrical demand are more pronounced due to lower temperatures.
e. Storage: The necessary technology has not been developed to include storage in the power grid. Therefore, it is not possible to take advantage of the renewable energy produced in peaks when the generation exceeds the demand.

To calculate the load duration curve profile of this scenario, real information about electricity demand peaks will be used. The load peaks are fundamental information for the design of reliable power systems. Statistics Finland (Tilastokeskus, Statistics Finland, 2018) has published the peaks of demand for more than 30 years. In the statistics appears the value of the maximum load, the day and the time in which it occurred. The peaks have been obtained during the last twenty-seven years to see how they have evolved.

Table 26. *Annual maximum peak load demand in Finland from 1990-2017*

Operating year	Peak power (MW)	Date	Time
1990	10450	15.1.1990	8–9
1991	10270	30.1.1991	8–9
1992	10400	20.1.1992	8–9
1993	10380	27.1.1993	8–9
1994	11300	11.2.1994	19–20
1995	10860	31.1.1995	19–20
1996	11220	9.2.1996	19–20
1997	11320	19.12.1996	8–9
1998	12190	2.2.1998	8–9
1999	13080	29.1.1999	8–9
2000	12400	25.1.2000	8–9
2001	13310	5.2.2001	8–9
2002	13550	2.1.2002	16–17
2003	14040	3.1.2003	17–18
2004	13570	11.2.2004	18–19
2005	13475	28.1.2005	19–20
2006	14849	20.1.2006	8–9
2007	14921	8.2.2007	7–8
2008	13816	4.1.2008	17–18
2009	13342	16.1.2009	8–9
2010	14624	28.1.2010	8–9

2011	14965	18.2.2011	9–10
2012	14441	3.2.2012	18–19
2013	14170	18.1.2013	8–9
2014	14388	20.1.2014	8–9
2015	13567	22.1.2015	8–9
2016	15149	7.1.2016	17–18
2017	14374	5.1.2017	17–18

As can be seen in Table 26, the trend over the last few years is clearly growing. In the scenario presented below it is foreseen that the load peaks continue to grow. A linear regression is proposed for the forecasting of the peak load in 2030 based on values from 1990 to 2017. Figure 39 shows the results obtained and in Table 27 are shown the expected peak load values for the next twelve years in Finland.

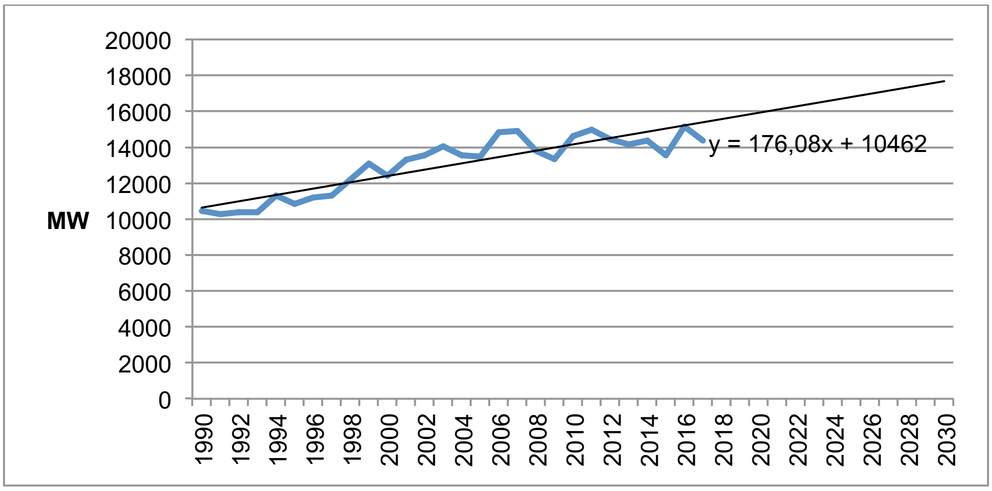

Figure 39. *Peak power linear trendline*

This case supposes an increase of 16% on the highest value of peak happened until 2017, which could very likely happen if is followed the same increasing rate as during last years.

Table 27. *Expected peak load demand increase in Finland 2020-2030*

Year	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Peak load (MW)	15920	16097	16273	16449	16625	16801	16977	17153	17329	17505	**17681**

Next step is to design the load duration curve that represents these peak demand conditions well. For this, it would not be appropriate to apply an increase factor of 16% over a whole load duration curve of those obtained for previous years, since the increase in the maximum peak does not have to suppose an increase in the peaks of the remaining days of the year. Therefore, it has been studied how the two-year load duration curves can be different with different weather conditions. The years 2016 and 2015 are the ones that presented load duration curves more different. While the year 2015 had low peaks, 2016 has much higher consumption peaks. It has been represented in Figure 40 how is the difference of load duration curves throughout the year to separate in three different stages.

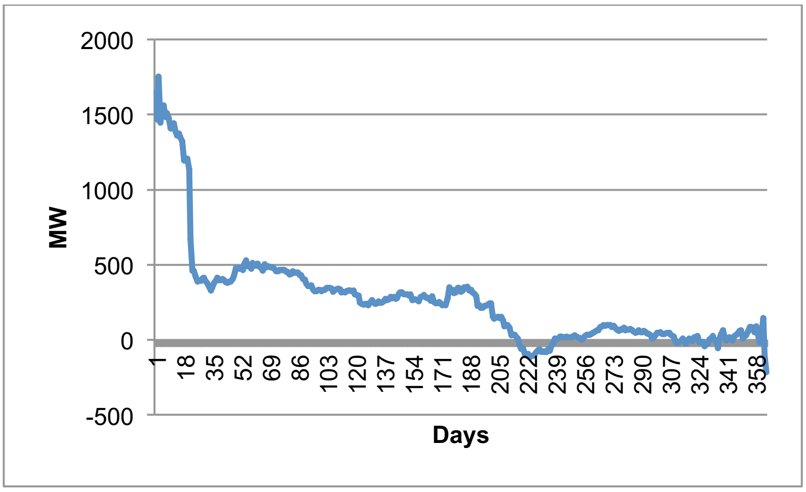

Figure 40. *Difference in daily peaks between 2015 and 2016*

In the first stage is where the large peaks take place. It has duration of approximately 20 days and that is when the higher increase factor can be applied. In the second, the difference is smaller, so the factor of increase will be smaller. In the third the load duration curves are very similar so no factor needs to be applied. In fact, the increase that occurs in the peaks must decrease elsewhere in the curve shown in Figure 41 to maintain the area representing the total energy. This assumption is made to simplify the comparison of scenarios.

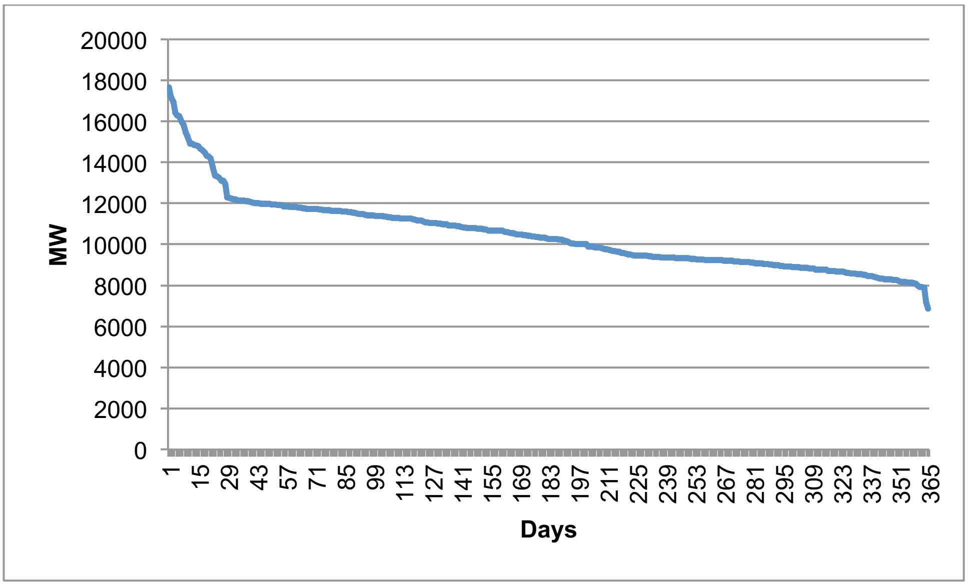

Figure 41. *Load duration curve scenario 3*

The three load duration curves calculated are shown in Figure 42. These three load duration curves have been obtained so that the area below the curve remains constant in all cases, which means different distribution profiles of the load for the same total electricity consumption.

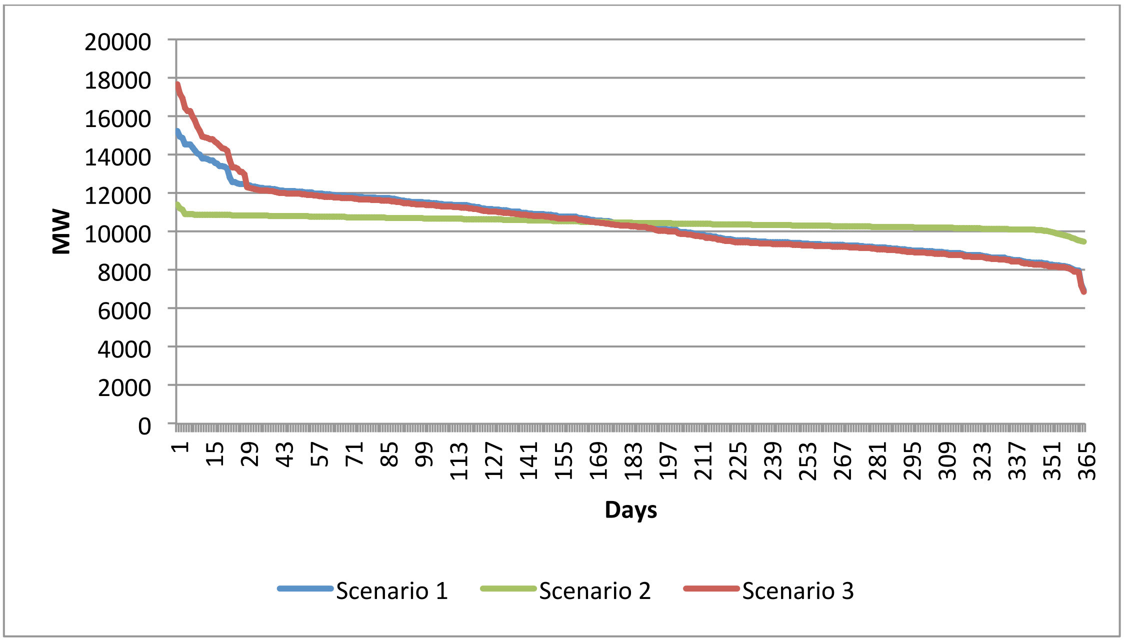

Figure 42. *Comparison of load duration curves from all three scenarios*

4.4 Reliability test in 2030

The tool designed in MATLAB has been tested with the different load duration curves from the scenarios, introducing the expected values of installed capacity in Finland for 2030. The results are shown in Table 28.

Table 28. *Expected load loss in 2030 with Hanhikivi 1*

		Scenario 1	Scenario 2	Scenario 3	(2016)
Expected loss of load	**In days**	0,0094	0,0032	0,0252	0,0918
	In hours	0 h 13 min	0 h 4 min	0 h 36 min	2 h 12 min

It has also been considered convenient to evaluate the expected load loss of the three scenarios in the event that the nuclear power plant Hanhikivi 1, which is expected to start commercial operation in 2024, will not be carried out. This is evaluated by removing the installed capacity corresponding to this nuclear power plant from the forecasted capacity of the nuclear power technology in 2030 in Finland that has been used in the MATLAB. The results are shown in Table 29.

Table 29. *Expected load loss in 2030 without Hanhikivi 1*

		Scenario 1	Scenario 2	Scenario 3	(2016)
Expected loss of load	**In days**	0,018	0,0036	0,0496	0,0918
	In hours	0 h 26 min	0 h 5 min	1 h 11 min	2 h 12 min

Given the ease of evaluating the expected load loss with the program developed in the face of variations in installed capacity, another case has also been considered to take into account the intermittency of renewable technologies, specifically to assess how the unavailability of wind power capacity affects to the reliability of the power system. As previously mentioned, the program is sensitive to the maximum load peaks, so even if it is an annual analysis, the installed capacities that are available during peak demand according to Statistics Finland have been established as annuals.

In Table 9 it was seen that the available capacity of wind power during the peak load in Finland in year 2017 was 100 MW, which corresponds to approximately 6.5% of the total installed capacity of wind power in Finland in 2017, which was 1533 MW as shown in Table 10. The expected increase in installed capacity of wind power in Finland by 2030 could lead to a slight increase in the capacity available during peaks compared to the 6.5% in 2017, therefore is taken a value of 10% of availability of wind power installed capacity in Finland in 2030. The available capacity in this case would be 500 MW, according to the 5000 MW of installed wind power capacity expected in Figure 29. The results of expected load loss are represented in Table 30.

Table 30. *Expected load loss in 2030 without Hanhikivi 1 and 10% availability of wind power during maximum peaks.*

		Scenario 1	Scenario 2	Scenario 3	(2016)
Expected loss of load	**In days**	0,2296	0,0448	0,6069	0,0918
	In hours	5 h 30 min	1 h 4 min	14 h 34 min	2 h 12 min

4.5 Discussion of results

First of all, in the case of the calculation of the expected load loss for 2030 in Finland with the presence of the nuclear power plant Hanhikivi 1, very low values are obtained in the three scenarios when compared with the value obtained of expected load loss in 2016. In scenario 1 the expected load decreases by 90%, with the load duration curve being exactly the same as that of 2016. In case that the nuclear power plant Hanhikivi 1 wasn't commissioned the expected load loss decreases by 80%. In scenario 2 the values obtained from expected load loss are even lower than for scenario 1, reducing by up to 97% with respect to 2016. This result indicates that the lack of large demand peaks significantly reduces the risk of load loss for the power system.

Scenario 3 showed the highest expected load loss results among the three scenarios. Given that the distinctive feature of this scenario was the presence of higher load peaks, it is clearly shown that the MATLAB program designed is very sensitive to changes in the load duration curve, specifically to changes in the maximum load peaks. However, although the load duration curve of scenario 3 has maximum load peaks greater than 2016, the expected load loss has decreased. In the case of the operation of Hanhikivi 1, it was reduced by 73% and in the event that the nuclear power plant did not enter into operation in 2024 the reduction of the expected load loss is 47%. This indicates again that the change in the installed capacities of the technologies in Finland foreseen for 2030 would help to reduce the expected load loss of the power system even if the maximum load peaks increase at the same rate of the last years.

Since the study always keeps the same forced outage rates, it is understood that this risk reduction of loss of load in the three scenarios is due to the change in installed capacities between 2016 and 2030. Table 31 shows the differences in installed capacities between the two years. The increase of the installed capacity of wind power could make it become one of the prevailing technologies, competing with nuclear and import. Phasing out coal would especially impact the installed capacity of CHP district heating and of separate electricity production (Other), decreasing installed capacity in comparison with 2016.

Table 31. *Expected difference in installed capacities between 2016 and 2030*

	Nuclear	Hydro	Wind	CHP DH	I CHP	Other	Solar	Import	Total
2016	2779	3171	1005	4022	2908	2335	15	5100	21335
2030	4560	3200	5000	2700	2780	1765	700	5100	25805

It has been calculated that the CHP district heating and separate electricity production technologies have a very low forced outage rate, only surpassed by import technology. It is expected that the decommissioning of power plants of CHP district heating and separate electricity production using hard coal will have a negative impact on the power system, reducing flexibility by increasing expected load loss, since in chapter 3 it has been calculated that wind power has a forced outage rate higher than other technologies. The results obtained in Tables 28 and 29 show the opposite, decreasing the expected values of expected load loss, but this is not entirely true because it is not taking into account the intermittent nature of renewable technologies, which might vary the expected load loss, so it cannot be said that the expected commissioning of nuclear power plants will provide enough flexibility to the power system. Therefore, it is expected that the increase of wind power installed capacity in substitution of hard coal decommissioned power plants will increase the expected load loss of the system. That is why some further studies with wind power availability are carried out as shown in Table 30.

As can be seen in Table 30, the results obtained of expected load loss are much higher compared to those obtained in Tables 28 and 29. In scenario1, which considers that the load duration curve remains the same as in 2016, the expected load loss is 2.5 times higher than the calculated in 2016. In scenario 3 the situation is even worse, since the expected load loss is multiplied by 6 times the value obtained in 2016. These results could indicate that the power adequacy would be at greater risk than current, and the expected commissioning of nuclear power plants would not be sufficient to deal with the intermittent nature of the wind power.

5. CONCLUSIONS

5.1 Meeting with the research objectives

- *Will the power system of Finland be reliable by 2030?*

Based on the results obtained from expected load loss for the year 2030 it can be said that the Finnish power system will be reliable in the way that the electricity generating facilities would be sufficient to meet the country's electricity demand during normal operation, not ensuring reliability during maximum peaks of demand.

- *Can decommissioning of technologies that use traditional energy sources threaten the power balance of the Finnish power grid in the future?*

The decommissioning of technologies that use fossil resources such as hard coal will not increase the risk for the Finnish power system in terms of keeping the power adequacy during most time of the year, but it could affect the ability to maintain power adequacy during periods of peak demand. The expected commissioning of nuclear power plants might not be enough to provide enough flexibility during load peaks to compensate the loss suffered by the decommission of hard coal power plants.

- *How the introduction of renewable technologies will affect the reliability of the Finnish power grid?*

According to the results that have been obtained with the tool designed, it can be said that the introduction of renewable technologies will not have negative impacts in terms of the expected load loss during the normal operation of the system during the year. Even so, considering the negative impacts that the intermittent nature of renewable technologies would have on the power system, during peaks of demand the risk of power inadequacy could be seen alarmingly increased.

5.2 Limitations of the model

At first it was thought that the analysis of “Expected load loss” would be sufficiently complete to be able to evaluate the risks that the intermittent nature of renewable technologies entails for power adequacy, but this has not been possible due to certain limitations of the model. The tool that has been developed in MATLAB has helped to relate the demand with the installed capacity taking into account the probability of suffering forced outages of each technology, but is not able to consider the availability of each technology at every time. Availability refers to the amount of installed capacity of a technology that was operational at a certain time due to factors such as weather conditions or maintenance. Even so, it has been possible to simulate some case in which there is less available capacity than the installed one, as it is the case of the last analysis in which the capacity of wind power is reduced.

Also, when aggregating all the power plants of the same technology in a block with value the sum of all the installed capacities and assigning a forced outage rate to the block, it is considered that when the block fails all the power plants of that block are out of service, which doesn't represent well reality. The power plants that belong to the same technology may be able to keep producing electricity even if one of them suffers a forced outage.

5.3 Suggestions for further research

The study that has been carried out can continue to be expanded. There are many areas in which improvements can be made. The main interest would be to get the program developed to be able to consider the impact produced by the intermittent nature of renewable technologies on the power system in the way the last case of unavailability of wind power has been designed. Since it has been seen that the program tool is especially sensitive to the maximum peaks of annual demand, the research could continue analyzing what happens in the particular case of the maximum peak load of the year depending on the availability of renewable technologies. The procedure would begin by identifying when the highest demand peaks occur during the year in Finland. With the data published by Statistics Finland, it is easy to know the day and time at which the highest electricity demand peaks occurred from 1970 to 2017. Once known when the highest electrical consumption occurs set different scenarios of availability of the installed capacity of each technology during the peak time. It would be of special interest to know how available where the renewable resources to assess the risk of load loss if these technologies where not operational. To build the scenarios of available technologies, public information about weather conditions and available capacity during peaks in Finland could be used. The different configurations of installed capacities can be tested in the program modeled to get values of expected load loss and continue performing other types of reliability analysis.

One possibility would be to use the expected load loss values obtained as random events for performing a Monte Carlo simulation for system reliability analysis, commonly used for probabilistic safety assessments of power plants (Matsuoka, 2013). This method generates events and repeats the process many times and counts the occurrence number of a specific condition. In this way it could be known which expected load loss is the most probable among all the combinations of technologies available in the load peak. The basic procedure of Monte Carlo method is defining a domain of possible events, generate events randomly, perform deterministic judgments of system states based on the events, and count the occurrence number of a specific system state among total observations. Knowing which expected load loss is the most repeated among all combinations of available technologies improves the accuracy of the analysis. A weakness of the Monte Carlo method is the computing time expended particularly when dealing with a large complex system.

Other possibilities for future studies could focus on improving the program implemented in MATLAB. The code could consider more combinations of operational technologies expanding the program developed by disaggregating the power plants from each installed technology block to get all outage possibilities in the capacity out probability table. In addition, the accuracy of the calculated forced outage rates can be increased by collecting more information about forced outages in power plants of each technology.

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APPENDIX 1: MATLAB CODE FOR THE LOAD LOSS EVALUATION IN 2011-2017

```
%Matrix of the installed capacities between years 2011-2017
ins_year_matrix=zeros(7,7);
ins_year_matrix(1,:)=xlsread('instcap2011.xlsx');
ins_year_matrix(2,:)=xlsread('instcap2012.xlsx');
ins_year_matrix(3,:)=xlsread('instcap2013.xlsx');
ins_year_matrix(4,:)=xlsread('instcap2014.xlsx');
ins_year_matrix(5,:)=xlsread('instcap2015.xlsx');
ins_year_matrix(6,:)=xlsread('instcap2016.xlsx');
ins_year_matrix(7,:)=xlsread('instcap2017.xlsx');
year=input('year: ');
if year==2011
i_year=1;
end
if year==2012
i_year=2;
end
if year==2013
i_year=3;
end
if year==2014
i_year=4;
end
if year==2015
i_year=5;
end
if year==2016
i_year=6;
end
if year==2017
i_year=7;
end
installed(1,:)=ins_year_matrix(i_year,:);
%forced outage rates matrix
out_rates_matrix=zeros(7,7);
out_rates_matrix(1,:)=xlsread('outrates2011.xlsx');
out_rates_matrix(2,:)=xlsread('outrates2012.xlsx');
out_rates_matrix(3,:)=xlsread('outrates2013.xlsx');
out_rates_matrix(4,:)=xlsread('outrates2014.xlsx');
out_rates_matrix(5,:)=xlsread('outrates2015.xlsx');
out_rates_matrix(6,:)=xlsread('outrates2016.xlsx');
out_rates_matrix(7,:)=xlsread('outrates2017.xlsx');
%do the out_rates vector
out_rates(1,:)=out_rates_matrix(i_year,:);
out_rates(2,:)=1-out_rates(1,:);
%create the code and prob vectors
code_nuc=[0 installed(1,1)];
prob_nuc=[out_rates(2,1) out_rates(1,1)];
code_hyd=[0 installed(1,2)];
prob_hyd=[out_rates(2,2) out_rates(1,2)];
code_ichp=[0 installed(1,3)];
prob_ichp=[out_rates(2,3) out_rates(1,3)];
code_chpdh=[0 installed(1,4)];
prob_chpdh=[out_rates(2,4) out_rates(1,4)];
```

```
code_wind=[0 installed(1,5)];
prob_wind=[out_rates(2,5) out_rates(1,5)];
code_oth=[0 installed(1,6)];
prob_oth=[out_rates(2,6) out_rates(1,6)];
code_imp=[0 installed(1,7)];
prob_imp=[out_rates(2,7) out_rates(1,7)];
% NOW CALCULATE THE PROBABILITIES TABLE
%n=nuclear h=hydro c=ICHP d=CHPDH w=wind o=other i=import
prob_n_h=zeros(1,4);
   n=1;
   for j=1:2
        for k=1:2
          prob_n_h(1,n)=prob_hyd(1,j)*prob_nuc(1,k);
          n=n+1;
        end
   end
prob_n_h_c=zeros(1,8);
n=1;
   for i=1:2
       for j=1:4
           prob_n_h_c(1,n)=prob_n_h(1,j)*prob_ichp(1,i);
           n=n+1;
       end
   end
%now with CHPDH
prob_n_h_c_d=zeros(1,16);
n=1;
   for i=1:2
       for j=1:8
           prob_n_h_c_d(1,n)=prob_n_h_c(1,j)*prob_chpdh(1,i);
           n=n+1;
       end
   end
%now with Wind
prob_n_h_c_d_w=zeros(1,32);
n=1;
   for i=1:2
       for j=1:16
           prob_n_h_c_d_w(1,n)=prob_n_h_c_d(1,j)*prob_wind(1,i);
           n=n+1;
       end
   end
%now with other
prob_n_h_c_d_w_o=zeros(1,64);
n=1;
   for i=1:2
       for j=1:32
           prob_n_h_c_d_w_o(1,n)=prob_n_h_c_d_w(1,j)*prob_oth(1,i);
           n=n+1;
       end
   end
%now with import
prob_n_h_c_d_w_o_i=zeros(1,128);
n=1;
   for i=1:2
       for j=1:64

prob_n_h_c_d_w_o_i(1,n)=prob_n_h_c_d_w_o(1,j)*prob_imp(1,i);
           n=n+1;
       end
   end
%NOW CAP OUT TABLE
%first nuclear and hydro
```

```
co_n_h=zeros(1,4);
   n=1;
   for i=1:2
        for j=1:2
          co_n_h(1,n)=code_hyd(1,i)+code_nuc(1,j);
          n=n+1;
        end
   end
%with CHP I
co_n_h_c=zeros(1,8);
n=1;
   for i=1:2
       for j=1:4
           co_n_h_c(1,n)=co_n_h(1,j)+code_ichp(1,i);
           n=n+1;
       end
   end
%now with CHPDH
co_n_h_c_d=zeros(1,16);
n=1;
   for i=1:2
       for j=1:8
           co_n_h_c_d(1,n)=co_n_h_c(1,j)+code_chpdh(1,i);
           n=n+1;
       end
   end
%now with Wind
co_n_h_c_d_w=zeros(1,32);
n=1;
   for i=1:2
       for j=1:16
           co_n_h_c_d_w(1,n)=co_n_h_c_d(1,j)+code_wind(1,i);
           n=n+1;
       end
   end
%now with other
co_n_h_c_d_w_o=zeros(1,64);
n=1;
   for i=1:2
       for j=1:32
           co_n_h_c_d_w_o(1,n)=co_n_h_c_d_w(1,j)+code_oth(1,i);
           n=n+1;
       end
   end
%now with import
co_n_h_c_d_w_o_i=zeros(1,128);
n=1;
   for i=1:2
       for j=1:64
           co_n_h_c_d_w_o_i(1,n)=co_n_h_c_d_w_o(1,j)+code_imp(1,i);
           n=n+1;
       end
   end
%PROBABILITIES TABLE
prob_table=[co_n_h_c_d_w_o_i; prob_n_h_c_d_w_o_i];
%load curve
l_c_matrix=zeros(7,365);
l_c_matrix(1,:)=xlsread('peaks2011.xlsx');
l_c_matrix(2,:)=xlsread('peaks2012.xlsx');
l_c_matrix(3,:)=xlsread('peaks2013.xlsx');
l_c_matrix(4,:)=xlsread('peaks2014.xlsx');
l_c_matrix(5,:)=xlsread('peaks2015.xlsx');
l_c_matrix(6,:)=xlsread('peaks2016.xlsx');
```

```
l_c_matrix(7,:)=xlsread('peaks2017.xlsx');
l_curve(1,:)=l_c_matrix(i_year,:);
%sorted load curve
sorted_lcurve=fliplr(sort(l_curve));
day=0:1:364;
total_ins=0;
for i=1:7
total_ins=total_ins+installed(1,i);
end
for i=1:365
co_for_outage(1,i)=total_ins-sorted_lcurve(1,i);
end
load_curve_t=[sorted_lcurve;co_for_outage; day];
%sorted cap out
[B,I] = sort(prob_table(1,:));
ordered = prob_table(2,I);
sorted_co = [B; ordered]
%time
for i=1:128
    if sorted_co(1,i)<load_curve_t(2,1)
    time(1,i)=0;
    end
    if sorted_co(1,i)>=load_curve_t(2,1) && sort-
ed_co(1,i)<=load_curve_t(2,365)
        y=day;
        nodes=load_curve_t(1,:);
        nod=total_ins-nodes(1,:);
        x=nod;
         for n=1:1:364
           if x(1,n)>=x(1,n+1)
              x(1,n+1)=x(1,n)+1;
           end
         end
         xx=[sorted_co(1,i)];
         yy=interp1(x,y,xx,'linear');
         time(1,i)=yy;
    end
    if sorted_co(1,i)>load_curve_t(2,365)
    time(1,i)=365;
    end
end
%time_percentage
time_p(1,:)=(time(1,:)/365)*100;
%expected load loss
exp_l=0;
for i=1:1:128
exp_l=exp_l+sorted_co(2,i)*time_p(1,i);
end
exp_load_loss=(exp_l/100)*365
```

APPENDIX 2: MATLAB CODE FOR THE LOSS LOAD FORECAST IN 2030

```
%Matrix of the installed capacities between years 2000-2017
ins_cap(1,:)=xlsread('instcap2030.xlsx');
scenario=input('Scenario: ');
i_scenario=scenario;
installed(1,:)=ins_cap(1,:);
%forced outage rates matrix
out_rates_matrix=zeros(1,8);
out_rates_matrix(1,:)=xlsread('outrates2030.xlsx');
%do the out_rates vector
out_rates(1,:)=out_rates_matrix(1,:);
out_rates(2,:)=1-out_rates(1,:);
%create the code and prob vectors
code_nuc=[0 installed(1,1)];
prob_nuc=[out_rates(2,1) out_rates(1,1)];
code_hyd=[0 installed(1,2)];
prob_hyd=[out_rates(2,2) out_rates(1,2)];
code_ichp=[0 installed(1,3)];
prob_ichp=[out_rates(2,3) out_rates(1,3)];
code_chpdh=[0 installed(1,4)];
prob_chpdh=[out_rates(2,4) out_rates(1,4)];
code_wind=[0 installed(1,5)];
prob_wind=[out_rates(2,5) out_rates(1,5)];
code_oth=[0 installed(1,6)];
prob_oth=[out_rates(2,6) out_rates(1,6)];
code_imp=[0 installed(1,7)];
prob_imp=[out_rates(2,7) out_rates(1,7)];
code_sol=[0 installed(1,8)];
prob_sol=[out_rates(2,8) out_rates(1,8)];
% NOW CALCULATE THE PROBABILITIES TABLE
%n=nuclear h=hydro c=ICHP d=CHPDH w=wind o=other i=import
prob_n_h=zeros(1,4);
   n=1;
   for j=1:2
        for k=1:2
          prob_n_h(1,n)=prob_hyd(1,j)*prob_nuc(1,k);
          n=n+1;
        end
   end
prob_n_h_c=zeros(1,8);
n=1;
   for i=1:2
       for j=1:4
           prob_n_h_c(1,n)=prob_n_h(1,j)*prob_ichp(1,i);
           n=n+1;
       end
   end
%now with CHPDH
prob_n_h_c_d=zeros(1,16);
n=1;
   for i=1:2
       for j=1:8
           prob_n_h_c_d(1,n)=prob_n_h_c(1,j)*prob_chpdh(1,i);
           n=n+1;
```

```
       end
   end
%now with Wind
prob_n_h_c_d_w=zeros(1,32);
n=1;
   for i=1:2
       for j=1:16
           prob_n_h_c_d_w(1,n)=prob_n_h_c_d(1,j)*prob_wind(1,i);
           n=n+1;
       end
   end
%now with other
prob_n_h_c_d_w_o=zeros(1,64);
n=1;
   for i=1:2
       for j=1:32
           prob_n_h_c_d_w_o(1,n)=prob_n_h_c_d_w(1,j)*prob_oth(1,i);
           n=n+1;
       end
   end
%now with import
prob_n_h_c_d_w_o_i=zeros(1,128);
n=1;
   for i=1:2
       for j=1:64
          prob_n_h_c_d_w_o_i(1,n)=prob_n_h_c_d_w_o(1,j)*prob_imp(1,i);
           n=n+1;
       end
   end
 %now with solar
prob_n_h_c_d_w_o_i_s=zeros(1,256);
n=1;
   for i=1:2
       for j=1:128

prob_n_h_c_d_w_o_i_s(1,n)=prob_n_h_c_d_w_o_i(1,j)*prob_sol(1,i);
           n=n+1;
       end
   end
%NOW CAP OUT TABLE
%first nuclear and hydro
co_n_h=zeros(1,4);
   n=1;
   for i=1:2
        for j=1:2
          co_n_h(1,n)=code_hyd(1,i)+code_nuc(1,j);
          n=n+1;
        end
   end

%with CHP I
co_n_h_c=zeros(1,8);
n=1;
   for i=1:2
       for j=1:4
           co_n_h_c(1,n)=co_n_h(1,j)+code_ichp(1,i);
           n=n+1;
       end
   end
%now with CHPDH
co_n_h_c_d=zeros(1,16);
n=1;
   for i=1:2
```

```
        for j=1:8
            co_n_h_c_d(1,n)=co_n_h_c(1,j)+code_chpdh(1,i);
            n=n+1;
        end
    end
%now with Wind
co_n_h_c_d_w=zeros(1,32);
n=1;
    for i=1:2
        for j=1:16
            co_n_h_c_d_w(1,n)=co_n_h_c_d(1,j)+code_wind(1,i);
            n=n+1;
        end
    end
%now with other
co_n_h_c_d_w_o=zeros(1,64);
n=1;
    for i=1:2
        for j=1:32
            co_n_h_c_d_w_o(1,n)=co_n_h_c_d_w(1,j)+code_oth(1,i);
            n=n+1;
        end
    end
%now with import
co_n_h_c_d_w_o_i=zeros(1,128);
n=1;
    for i=1:2
        for j=1:64
            co_n_h_c_d_w_o_i(1,n)=co_n_h_c_d_w_o(1,j)+code_imp(1,i);
            n=n+1;
        end
    end
  %now with solar
co_n_h_c_d_w_o_i_s=zeros(1,256);
n=1;
    for i=1:2
        for j=1:128

co_n_h_c_d_w_o_i_s(1,n)=co_n_h_c_d_w_o_i(1,j)+code_sol(1,i);
            n=n+1;
        end
    end
%PROBABILITIES TABLE
prob_table=[co_n_h_c_d_w_o_i_s; prob_n_h_c_d_w_o_i_s];
%load curve
l_c_matrix=zeros(3,365);
l_c_matrix(1,:)=xlsread('peaks1.xlsx');
l_c_matrix(2,:)=xlsread('peaks2.xlsx');
l_c_matrix(3,:)=xlsread('peaks3.xlsx');
l_curve(1,:)=l_c_matrix(i_scenario,:);
%sorted load curve
sorted_lcurve=fliplr(sort(l_curve));
day=0:1:364;
total_ins=0;
for i=1:8
total_ins=total_ins+installed(1,i);
end
for i=1:365
co_for_outage(1,i)=total_ins-sorted_lcurve(1,i);
end
load_curve_t=[sorted_lcurve;co_for_outage; day];
%sorted cap out
[B,I] = sort(prob_table(1,:));
```

```
ordered = prob_table(2,I);
sorted_co = [B; ordered];
%time
for i=1:256
    if sorted_co(1,i)<load_curve_t(2,1)
    time(1,i)=0;
    end
    if sorted_co(1,i)>=load_curve_t(2,1) && sort-
ed_co(1,i)<=load_curve_t(2,365)
        y=day;
        nodes=load_curve_t(1,:);
        nod=total_ins-nodes(1,:);
        x=nod;
         for n=1:1:364
           if x(1,n)>=x(1,n+1)
              x(1,n+1)=x(1,n)+1;
           end
         end
         xx=[sorted_co(1,i)];
         yy=interp1(x,y,xx,'linear');
         time(1,i)=yy;
    end
    if sorted_co(1,i)>load_curve_t(2,365)
    time(1,i)=365;
    end
end
 %time_percentage
time_p(1,:)=(time(1,:)/365)*100;
 %expected load loss
exp_l=0;
for i=1:1:256
exp_l=exp_l+sorted_co(2,i)*time_p(1,i);
end
exp_load_loss=(exp_l/100)*365
```