OULUN YLIOPISTO

FACULTY OF TECHNOLOGY

ENVIRONMENTAL IMPACT RELATED TO ELECTRICITY PRODUCTION: COMPARISON OF FINLAND AND SWEDEN

Salla-Mari Amazdo
ENVIRONMENTAL ENGINEERING

Bachelor’s thesis

December 2019

TIIVISTELMÄ

Sähköntuotantoon liittyvät ympäristövaikutukset: vertailu Suomen ja Ruotsin välillä

Salla-Mari Amazdo

Oulun yliopisto, Energia- ja ympäristötekniikka

Kandidaatintyö 2019, 36 s.

Työn ohjaaja yliopistolla: Caló A., FT

Ilmastoasiat ovat olleet viime aikoina paljon esillä. Etenkin päästöihin pyritään kiinnittämään huomiota entistä enemmän, koska ne vaikuttavat ilmastonmuutokseen. Sähköntuotanto aiheuttaa paljon päästöjä, joten ympäristön kannalta olisi hyvä siirtyä puhtaisiin tuotantomenetelmiin. Mikään menetelmä ei kuitenkaan ole täysin päästötön, mutta päästöt ovat vähäisiä osassa tuotantomuodoista. Näitä ovat esimerkiksi tuulen ja auringon kautta tuotettu sähkö, sekä ydinenergia. Fossiiliset luonnonvarat loppuvat myös ajallaan, joten sähköntuotannon olisi hyvä olla mahdollisimman uusiutuvaa, kuten esimerkiksi tuuli-, aurinko- ja bioenergialla tuotettu sähkö.

Sähköä tuotetaan samaan aikaan kuin sitä käytetään. Tämän takia sähköntuotannon on vastattava sen hetkistä kulutusta. Osa sähköntuotannon menetelmistä riippuu paljolti säästä, eikä siksi ole aina saatavilla. Sähköntuotantoa ja -kulutusta pidetään tasapainossa säätövoiman avulla, näitä ovat esimerkiksi vesivoima ja tuontisähkö. Niillä voidaan reagoida nopeasti muuttuvaan sähköntarpeeseen. Pistorasiasta tuleva sähkö on siis sekasähköä, joka sisältää eri menetelmin tuotettua sähköä. Pohjoismaissa, kuten Suomessa ja Ruotsissa, talvi ovat pitkä ja kylmä, joten sähköntuotannossa on omat haasteensa.

Tässä kandidaatin työssä vertaillaan Suomen ja Ruotsin välisiä eroja sähköntuotannossa, sekä selvitetään, kumman sähkö on puhtaampaa. Lisäksi tutustutaan sähköverkkoihin ja -markkinoihin pohjoismaissa. Kandidaatin työ käsittelee myös lyhyesti erilaisia sähköntuotanto menetelmiä, sekä niiden aiheuttamia päästöjä.

Maantieteellisesti Suomi ja Ruotsi ovat hyvin samanlaisia, mutta sähköntuotannossa on paljon eroja. Suomessa käytetään paljon tuontisähköä. Tuontisähköstä iso osa tulee

Ruotsista, koska Ruotsi tuottaa sähköä yli tarpeidensa. Ruotsissa tuotetaan sähköä enemmän uusiutuvasta energiasta kuin suomessa. Lisäksi, Ruotsin sähköntuotannon päästöt ovat alhaisempia kuin Suomen. Tulevaisuuden Ruotsi on irrottautumasta ydinenergian käytöstä, mutta suomessa sitä ollaan lisäämässä. Molemmat maat pyrkivät vähentämään kasvihuonekaasuja.

Avainsanat: Sähköntuotanto, päästöt, ympäristö

ABSTRACT

Environmental impact related to electricity production: comparison of Finland and Sweden

Salla-Mari Amazdo

University of Oulu, Degree Programme of Environmental Engineering

Bachelor's thesis 2019, 36 pp.

Supervisor at the university: Caló A., PhD

Environmental issues have been on the topic lately. Particular attention is paid to emissions which cause global warming. Electricity production causes significant amount of emissions. Therefore, switching to cleaner production is environmentally beneficial. None of the methods are fully clean but emissions are low in some production modes. These include such methods as electricity produced by the sun and wind, as well as nuclear energy. Fossil fuel resources are in short supply. For that reason, it is important to produce electricity from such renewable sources as wind-, solar- and bioenergy plants.

Electricity production and consumption occur simultaneously. For that reason, electricity production should match with consumption. Some of the electricity production methods depends on the weather and its sometimes unavailable. Electricity production and consumption is balanced by reserve power plants, like hydro power and imported electricity. Therefore, the electricity coming from the outlet is mixed electricity which contains electricity produced by different methods. In such the Nordic countries as Finland and Sweden, winter is cold and long which cause its own challenges to power generation.

This bachelor's thesis compares the differences of Finnish and Swedish electricity production and clarifies which electricity mix is cleaner. In addition, the network and markets in the Nordic countries will be introduced. Bachelor's thesis also explains shortly different electricity production methods and emissions caused by them.

Geographically Finland and Sweden are very identical, however, there are many differences in their power generation. Finland utilize a plenty amount of imported electricity. A large part of imported electricity comes from Sweden, because Sweden generates electricity beyond its needs. Sweden produces more electricity from renewable energy than Finland. Also, emissions from power generation in Sweden are lower than in Finland. Future plans with electricity production are different since Sweden is eliminating the use of nuclear energy, but Finland is increasing it. Both countries aim to reduce greenhouse gas emissions.

Keywords: electricity production, emissions, environment

TABLE OF CONTENTS

1 INTRODUCTION

Electricity production has various environmental impacts. The environmental impacts include, for example, climate change, acidification, water impacts and waste generation. They occur at different stages of the production chain, such part as, the procurement, refining, storage and transport of fuels, process of energy production and the waste treatment. Many laws and regulations govern energy production. (Enegiateollisuus 2019)

Energy production and consumption cause the largest amount of greenhouse gas emissions. The EU environment and energy policy aims to reduce emissions, increase renewable energy and better energy efficiency. Each country has its own strategies to achieve these goals. (Ympäristöministeriö 2015)

In a long term, Finland aims to a carbon-neutral society based on renewable energy sources. By 2030, it is planned to increase the share of renewable energy to over 50% of final consumption, to increase self-sufficiency to over 55%, to abandon the use of coal in energy production and to halve domestic use of imported oils. Electricity markets are planned to develop at regional and European level. Flexibility of electricity supply and demand and system-level energy efficiency will be increased. For the year 2018-2020, technology-neutral tenders will be prepared to support cost-effective new electricity generation based on renewable energy. (Huttunen R 2017 p.3)

In 2030, heat and electricity co-generation would still use some coal (3-7 TWh) in Finland, since coal is a more competitive fuel than natural gas. The utilization of waste in the production of heat and electricity will be increased. Wind power usage will increase and the capacity of pre-licensed wind power projects is estimated to be around 6 TWh/year. The share of solar electricity will be increased in small scale production. The use of nuclear energy will continue in Finland. Olkiluoto 3 unit of Teollisuuden Voima, which is under construction, will significantly improve the self-sufficiency of electricity production in Finland. (Huttunen 2017 p.33-34, 42-44, 71)

According to Government offices of Sweden (2018 p.3), Sweden aims for zero net emissions of greenhouse gases, followed by negative emissions. By the year 2040, electricity production is planned to be 100% renewable. However, this does not mean giving up nuclear energy if some reactors are still operating

By 2020 four oldest nuclear reactors will be taken out of service in Sweden. Other reactors will still be in service until year 2045. By 2040, the amount of wind and solar power will be increased and will replace nuclear power. Production of wind power is estimated to be 50 TWh/year and for solar power 5 TWh/year. However, the replacement of nuclear energy can cause problems with future electricity production. Usage of other energy sources will mostly remain the same. (Government offices of Sweden 2018 p.67)

2 ELECTRICITY NETWORK

Electricity is generated by the power plants. The electricity generated by the power plants is transferred to the nation-wide transmission grid with a voltage of 110, 220 or 400 kV. At the substation, the voltage is converted to the distribution network with a voltage of 0,4 to 110 kV. In the medium voltage network, the voltage is most often 20 kV. In a distribution transformer, the voltage is further converted to 0,4 kV for distribution in a low-voltage network to homes. (Elenia 2017)

Households are connected to a low-voltage power line by a power cord that supplies power to the main switchboard (Elenia 2017). Other consumers and power plants are linked either to a distribution or regional network or to the nation-wide transmission grid depending on the case (Fingrid 2019a).

Based on Fingrid (2019a), highest voltages in the system can be up to 400 kV. Using high voltages reduces the losses during long transmission distances. The power grid can be built overhead lines and underground cables. According to Electrical equipment (2019), using underground cables has many benefits compared to overhead lines. They are not easily affected by the nature or can’t be brought down by human or animals. In addition, they have less transmission losses, can’t be seen in landscape and are safer for the environment. Negative sides of the underground cables are their cost, difficultness to repair and install, limited voltage carriage (only up to 33 kV) and shorter life expectancy. For that reason, overhead lines are more commonly used.

The instantaneous balance between consumption and production is reflected in the frequency of the grid. The frequency drops when the consumption is higher than the output. Similarly, the frequency exceeds when output is higher than consumption. In Finland and Sweden, the power grid frequency is 50 Hz and may vary between 49,9 Hz and 50,1 Hz. (Fingrid 2019c)

2.1 Markets

The Nordic electricity market consists of several interconnected markets, all of which have their own significance. Small electricity consumers buy electricity in the retail market from electricity sellers and dealers. In the wholesale electricity market, the electricity is being traded by electricity producers and large electricity consumers and intermediaries. In the wholesale market, prices fluctuate widely daily, especially between seasons, and retail electricity is often sold at a fixed price to consumers. (Ollikka 2017)

Supply and demand determine the wholesale market price of electricity. Demand is influenced by the weather, the time of year, the time of the day and by the general economic situation through industrial electricity demand. Supply is influenced by the weather: for example, the amount of hydro power through rainfall. In addition, the prices of fuels and emission allowances have a significant impact on variable production costs and thus on wholesale market prices. In addition to the wholesale price of electricity, the selling price of electricity includes the selling costs of the electricity seller, marketing, billing and other customer service and administration costs. (Energiateollisuus 2011)

Figure 1 shows the day-ahead price variations EUR/MWh in Finland and Sweden during 2018. The table shows that electricity price in Finland is higher than in Sweden most of the time.

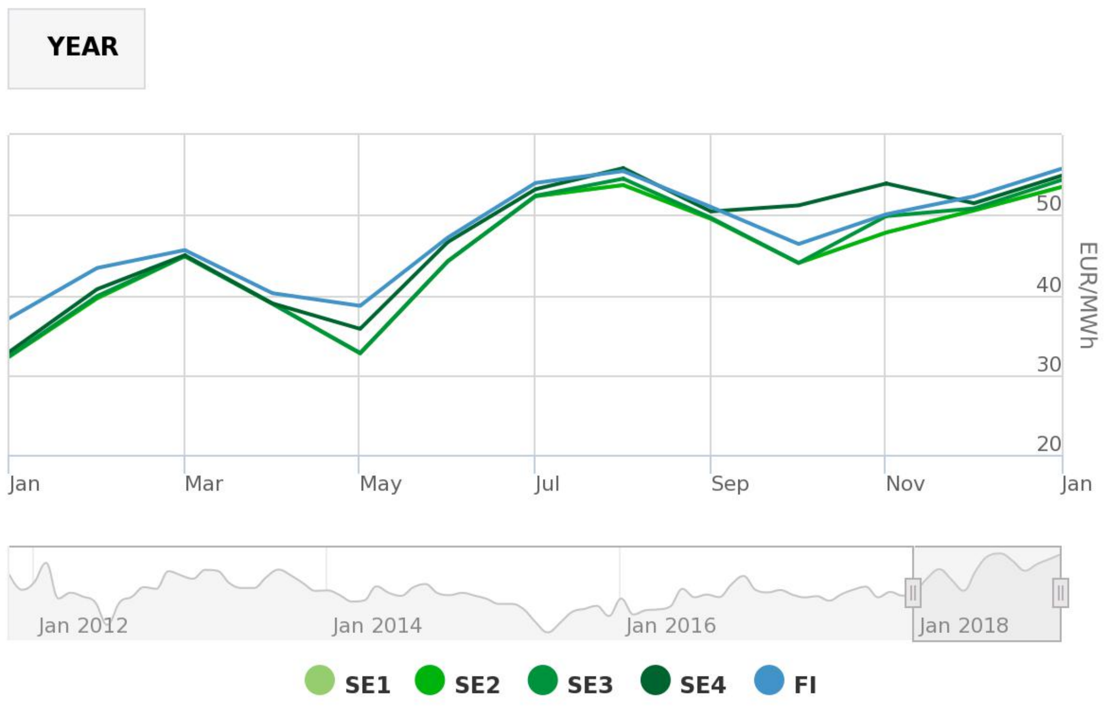

Figure 1. Day-ahead price variations of electricity price EUR/MWh (Nordpool 2019a).

2.2 NordPool

NordPool is in charge of the Nordic Countries electricity wholesale market where 380 companies from 20 different countries trade electricity. Its services are offer trading, clearing and settlement. (Nordpool 2019b)

In NordPool, the electricity is traded in many different markets. The most important of these is Elspot day-ahead market, where every day the electricity needed for every hour of the next day is traded to meet demand. Once the day-ahead market closes the Elbas intra-day market is traded on an hourly basis, where demand and supply match if changes in the fluctuating conditions occur during the day. After Elbas markets follows power and reserve markets managed by national transmission system operators, such as Finnish Fingrid and Swedish Svenska Kraftnät. (Ollikka 2017)

2.2.1 Fingrid and Svenska Kraftnät

Fingrid is a Finnish and Svenska Kraftnät is a Swedish power grid company. They are one of the owners of NordPool. (NordPool 2019b) Planning, system supervision, balance service, maintenance, marketing, constructions and development of the transmission grid is their responsibilities (Fingrid 2019a; Svenska kräftnat, 2018).

Both countries, Finland and Sweden, must renew their grid depending on their targets. Grid must be able to receive new electricity generation, but also investments include other things, for example, changes in the consumption and repairing old systems (Fingrid 2019a; Svenska Kräftnat). In addition, making new connections between countries is one of their targets. In addition, one of their latest investment is new 400 kV AC power line between Finland and Sweden which is supposed to happen at 2025 (Svenska kräfnat 2019).

3 ELECTRICITY PRODUCTION

Generation, transportation, supply and usage of electricity occurs almost simultaneously because electricity moves nearly the speed of light. The energy entering into the washing machine was a moment ago, for example, the water spinning the turbine at the hydropower plant. In power generation, energy is converted from one form to another, most commonly in turbines. First, kinetic energy is developed from heat, wind, hydro or tidal power. After, generator in turbines exchange kinetic energy to electrical energy by electromagnetic induction. In electromagnetic induction, electric conductor rotates in a magnetic field and inducts voltage to produce electricity. (Hillhouse 2019)

Reserve power plants balance electricity production and consumption by keeping the frequency of electric grid stable. They either increase or decrease their power as needed. (Fingrid 2019b) The ability of a system of kinetic energy stored in the rotating masses of an electrical system to resist frequency changes is called inertia. Low inertia means high frequency change and high inertia means low frequency change. If a large power plant suddenly disconnects from the grid, sufficient inertia of the electrical system will ensure that power balance is maintained and electricity is available. (Päivinen 2018)

Figure 2 shows the importance of inertia in power generation. In the event of disruption, inertia resists the change of frequency so that no power failure occurs.

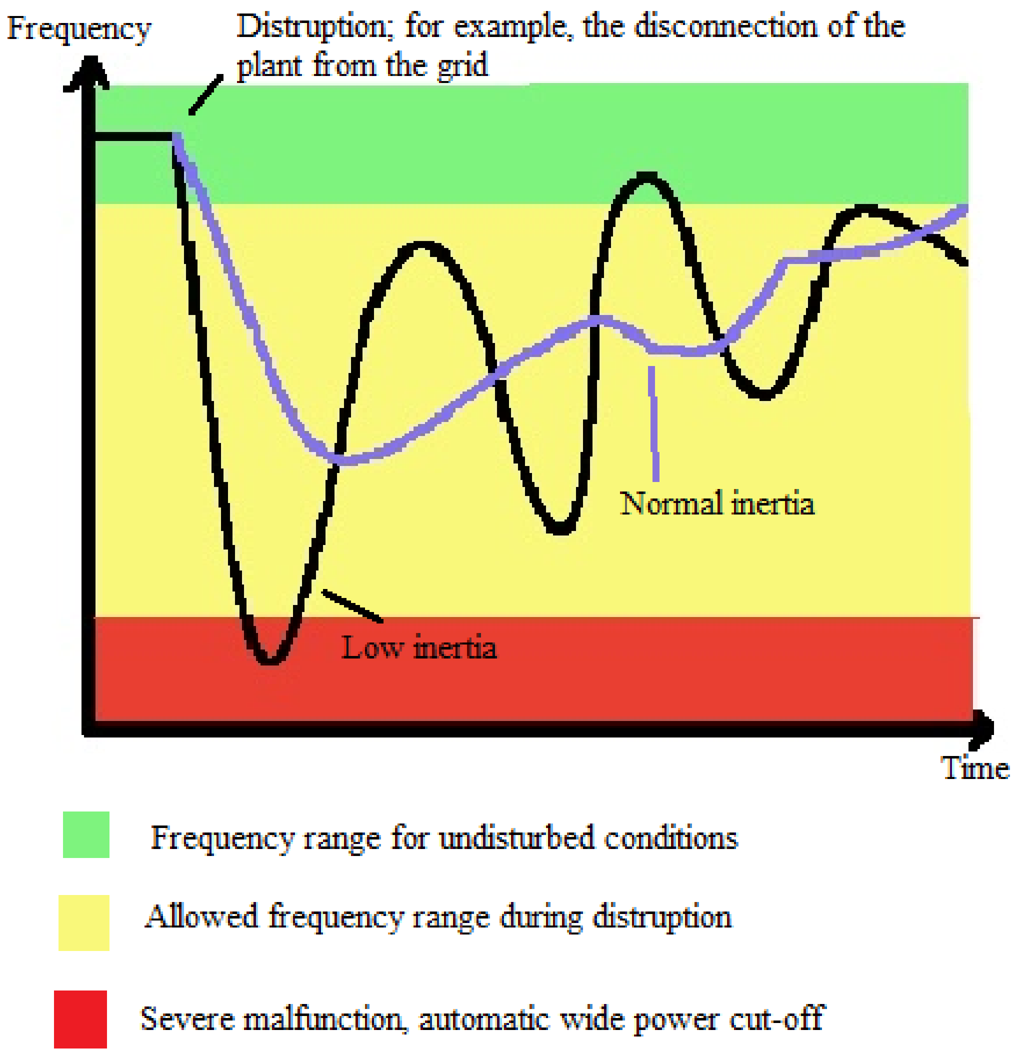

Figure 2. Inertia changes during disruption (retell Päivinen 2018).

3.1 Electricity production in Finland

In Finland, electricity is produced by many methods. There are about 120 electricity companies and about 400 power plants, from which more than half are hydropower plants. Electricity production is diversified and decentralized, which increases the security of electricity supply. Almost one third of the electricity is cogenerated with heat production, whereby the energy content of the fuel is used as precisely as possible. Up to 90% of fuel energy can be converted into electricity and heat. (Kostama 2018)

From 2000 to 2017 use of renewable electricity sources has grown and use of fossil fuels and peat has decreased. Nuclear power and hydro power have remained the same.

(Official Statistics of Finland 2018). Figure 3 shows the variations of electricity production sources from 2000 to 2017.

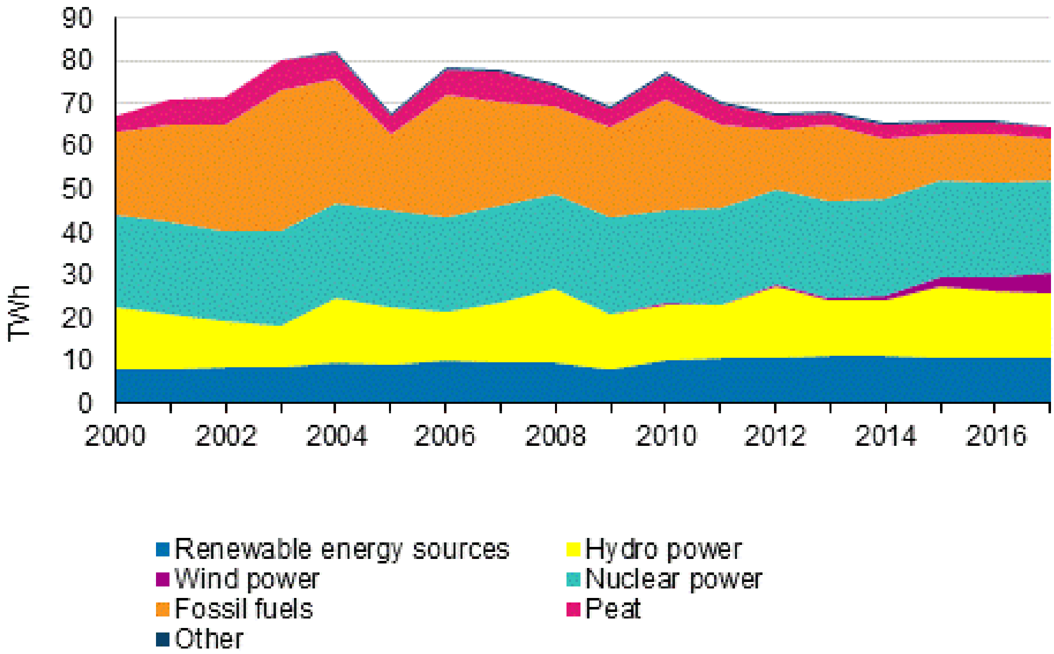

Figure 3. Electricity production by energy source 2000-2017 (Official Statistics of Finland 2018).

In 2018, electricity production was 67 TWh (Kostama 2018). Figure 4 represents the percentage of different electricity production systems in Finland. Oil and solar power are not included since the amount is lower than 1%.

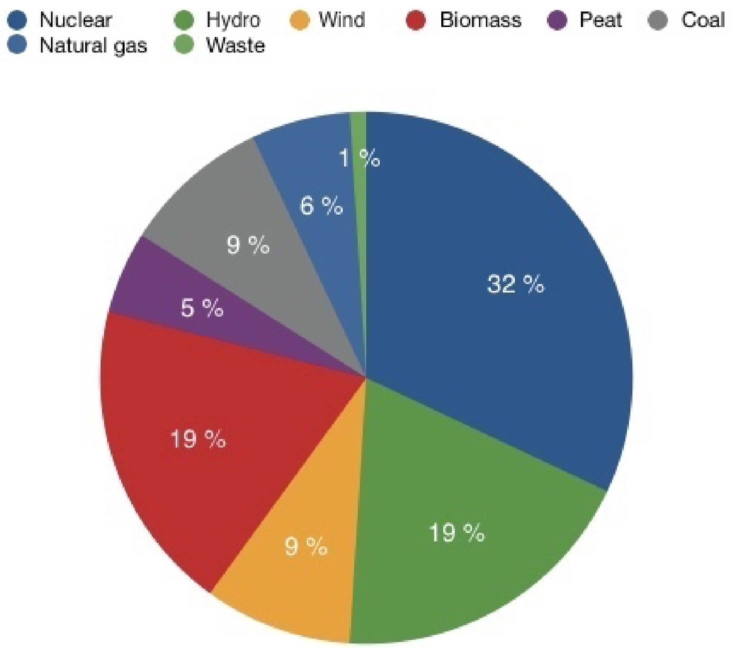

Figure 4. Electricity production by energy source 2018 in Finland (retell Kostama 2018).

In 2018, electricity consumption in Finland was 87,4 TWh. Gab between consumption and production is filled with imports. Finland has electricity transmission connections between Sweden, Russia Estonia and Norway. Finland exported electricity 3,5 TWh and imported 23,5 TWh. Finland exported 1TWh electricity to Sweden and imported 14,5 TWh. Net import was 13,5 TWh. (Fingrid 2018)

3.2 Electricity production in Sweden

Sweden uses domestic renewable energy sources such as water, wind, sun and biofuels. Nuclear energy is in a major part of Sweden's electricity generation since 1975. 9% of the electricity is generated together with heat (Swedish Energy agency 2019a).

In the past 10 year, Sweden has increased wind power production. Figure 5 shows the variations of electricity production sources from 1970 to 2017. In addition, figure 6 shows the amount of different fuels used for electricity production from 1983.

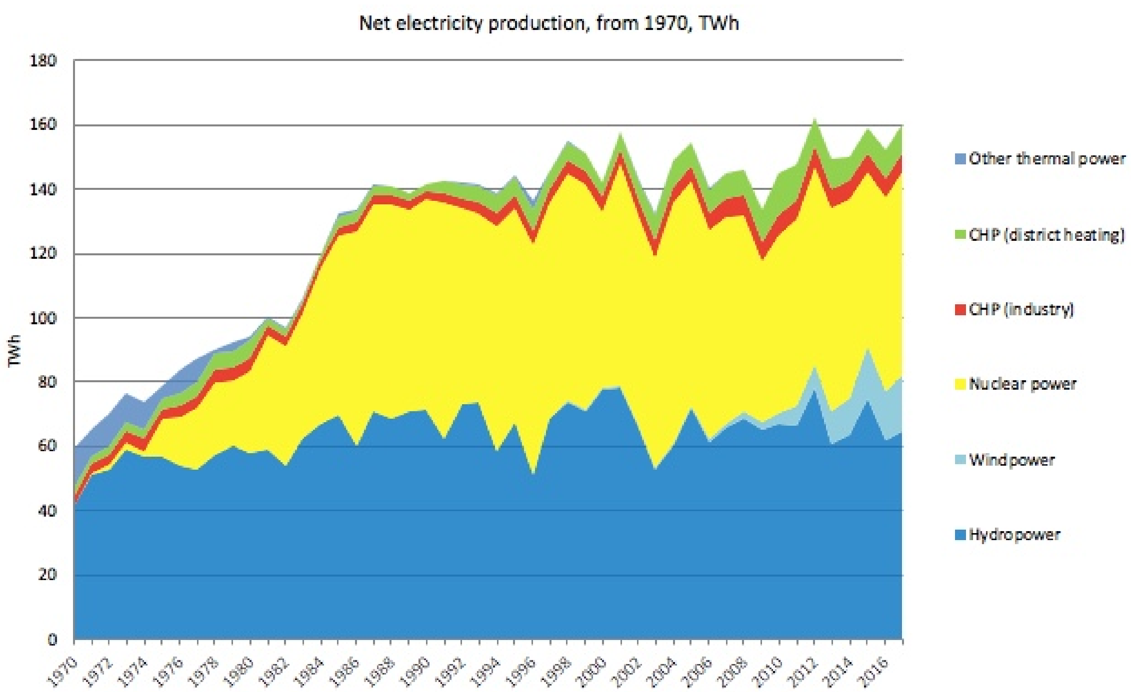

Figure 5. Electricity production (TWh) by energy source 1970-2017 in Sweden (Swedish energy agency 2019b).

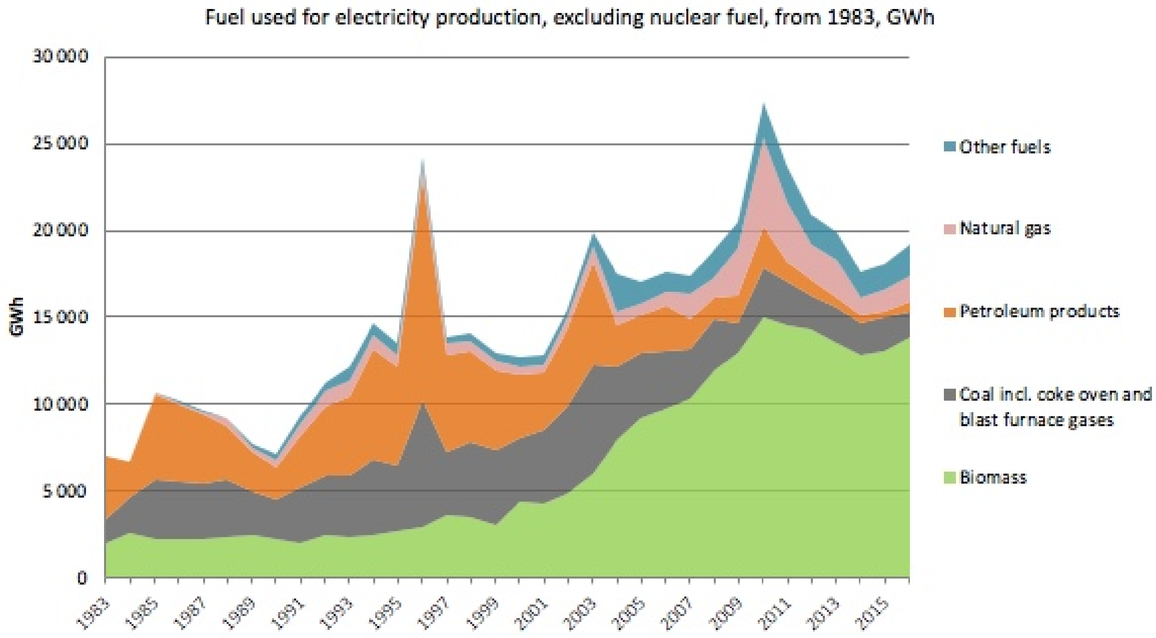

Figure 6. Fuel used for electricity production (GWh) from 1983 in Sweden (Swedish energy agency 2019b).

In 2018, electricity generation in Sweden was 158 TWh (Dellby 2019). Figure 7 represents the percentage of different electricity production systems in Sweden. Solar electricity part is very small (below 1%) so it is not included.

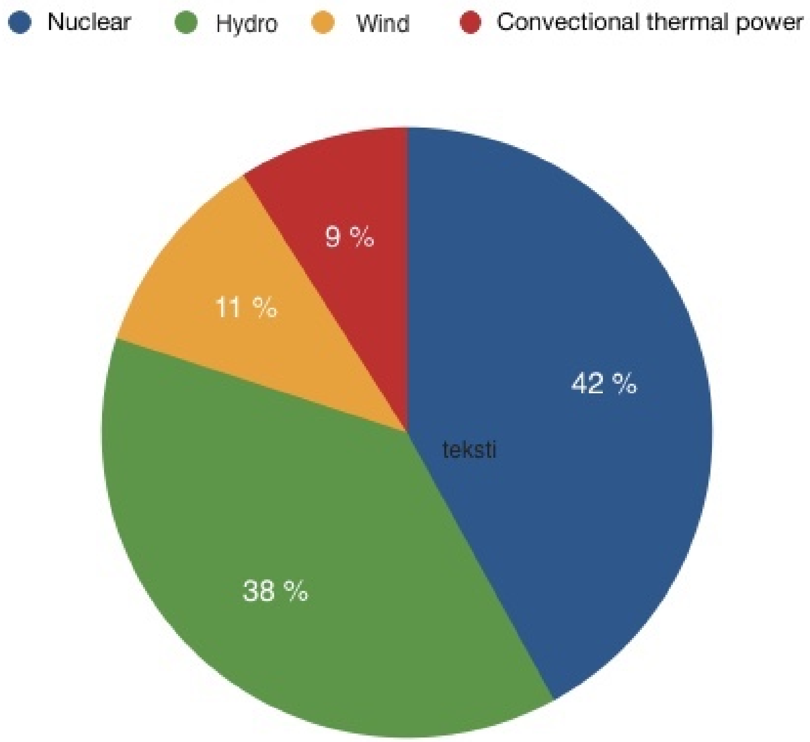

Figure 7. Electricity production by energy source 2018 in Sweden (retell Dellby 2019).

No exact sources were found for convectional thermal power content. According to Energy in Sweden 2019, around 58% of the electricity generated at 2017 comes from renewable sources. Based on Uniper (2019), 2% is from fossil fuels. Based on figure 6, most common fossil fuels are coal, peat and natural gas. Estimation contents for convectional thermal power is 7% biomass, 0,67% coal, 0.67% peat and 0,67% natural gas.

In 2018, electricity consumption in Sweden was 141 TWh. Rest of the electricity was exported to other countries such as Finland, Poland, Denmark, Lithuania and Germany. Imported electricity came mostly from Norway and Denmark. Net export was 17 TWh. (Swedish Energy agency 2019a)

3.3 Renewable energy

Renewable energy comes from renewable sources. Renewable energy production utilizes continuous natural processes such as sunlight, wind, flowing water and air and ground heat - or uses bio-based resources such as wood. Renewable electricity generation is mostly situated where natural processes are available. For that reason, restricts occur for renewable energy electricity production. All renewable energy, except biomass-generated electricity, has no fuel costs. During the manufacturing process, most of the costs, external energy and material inputs take place, which means that renewable energy can be considered as a manufactured energy. (National Research Council (U.S.) et all 2010 p.67-68p)

3.3.1 Hydropower

The hydropower plant utilizes the potential difference between two different water levels. The water is led from a higher level to a lower level through a plant turbine that rotates the generator. Transformer converts the electrical voltage suitable for the grid. (Vattenfall 2019a).

Hydropower can be used as a basic energy and reserve power. Water is stored when there is enough water and electricity consumption is low and then is used when electricity consumption is at its highest. Financial investments in hydropower plants are expensive, but at the same time they are long-term, safe and reliable power generating plants. (Vattenfall 2019a)

Hydropower production generates no carbon dioxide and produces neither solid waste nor emissions to air, water or soil. Also, the water does not diminish or spoil when flowing through the power plant. Hydropower has some negative environmental impacts. The environmental impacts are local and the most significant are the construction of dams and control basins. Dams prevent the movement of fish, which affects fish stocks and fishing. The effects are mitigated by fish stocking and other fish management measures. (Vattenfall 2019a)

3.3.2 Wind power

In wind turbines, kinetic energy of the wind is converted into electricity by the rotating blades. A wind turbine converts about a third of the force of wind hitting the blades into electricity. During cold weather the amount is greater since air is denser. A wind farm generates more energy in 3 to 9 months than it takes to manufacture, transport, plant and dismantle it. (Vattenfall 2019b).

Wind power generation depends on the weather and requires at least 3,5 m/s wind speed. In strong winds, over 25 m/s, the turbine shuts off to avoid damage. The plants are built to turn automatically in the wind direction and thus the wind can be utilized regardless of the wind direction. (Vattenfall 2019b)

Wind power is a pollution-free, requires no fuel and creates no greenhouse gases. Moreover, it produces no toxic or radioactive waste. The negative impacts consist the noise caused by wind turbine rotor blades and they sometimes kill birds. Careful planting of wind turbines, as well as technical progress, can reduce these problems. (Jaber 2013)

3.3.3 Solar

Although solar power generation is very small related to total power production, it is important to consider it. The use of solar energy is constantly growing and under development, both in Sweden and Finland.

Solar electricity is produced by a solar panel. The panels consist of solar cells where the energy of the rays generates electrical voltage. Crystalline, polycrystalline or amorphous silicon is the most commonly used raw material for cells. A solar cell is an electronic semiconductor. Solar radiation generates a voltage between the lower and upper surface of the cell. The amount of power generated by the solar panel depends on the intensity of the solar radiation, which is dependent on the weather. Energy can be stored in battery and used when there is no solar radiation. (Alm 2018 p. 57-58)

Solar energy does not produce emissions during operating. Indirect emissions and environmental impacts are caused by the materials needed to produce the panels, the energy involved in the production, the transportation and the installation. Solar cells are manufactured using materials that are expensive and rare, which means that the production of solar cells also consumes limited resources. (Vattenfall 2019c)

3.3.4 Biopower

Biopower is electricity generated form biomass. Biomasses are organic materials such as wood and logging waste. Material comes mostly from three sources: forests, agriculture and waste. Peat is not classified as a bioenergy or a renewable energy source because it regenerates slowly. Biopower plants are often direct-fired systems. The biomass is burned in a boiler that produces high pressure steam. The steam rotates turbines that are connected to electric generator. (Dahiya et all 2015 s.6-7)

Transporting biomass over long distances is not profitable. Therefore, production is most commonly local. It consumes water and other resources such as land locally. It can also cause noise, odors and traffic. The environmental impact is largely dependent on such factors as raw materials, forms of production and transportation. Biofuel is an excellent maintainer of carbon dioxide balance. As it grows, it absorbs the amount of atmospheric carbon dioxide it releases when its burned. Production of biomass cause some particle emissions, which can be reduced by filters. (Dahiya et all 2015 s. 23-25)

3.4 Non-renewable energy

Sources of energy that run out on time or are renewed very slowly are called non-renewable energy. Fossil fuels: petroleum, coal and natural gas, and nuclear energy are most common non-renewable energy sources. They can be easily transported so electricity can be generated anywhere. The electricity produced from them can also be utilized throughout the year and is not depended on weather. (Morse 2013)

3.4.1 Fossil fuels

Main sources of fossil fuels are petroleum, coal and natural gas (methane). They are the product of the remains of prehistoric plants that have rotted underground. Fossil fuels have been formed over millions of years ago and will not be renewed during our lifetimes. Peat, which is used a lot in Finland, is considered as a fossil fuel since it renews very slowly. (Morse 2013)

Fossil fuels are burned in power plants to generate electricity. The main source of energy for fossil fuels is carbon. When consumed and produced, carbon is released into the atmosphere. Globally, carbon dioxide from fossil fuels burning raises the temperature of the earth's atmosphere. Natural gas is the cleanest of the fossil fuels available, though it also releases a lot of carbon dioxide. Burning oil and coal releases harmful gases and pollutants to atmosphere. The surrounding region can suffer from soot and toxic gases. Continuous high emissions from incineration cause environmental damage and disease. Drilling and mining fossil fuels can cause environmental issues. Also transporting them can make damages, for example, oil accidents cause major damage to both water system and aquatic animals. (Morse 2013)

3.4.2 Nuclear power

Nuclear energy is considered a non-renewable energy because the material used is non-renewable. The most common source is uranium and its type U-235. (Morse 2013) At current consumption, uranium reserves will last around 85 years. However, there is still unexploited uranium reserves in the earth's crust which are expected to be high. (Vattenfall 2019d)

Nuclear energy is generated in a nuclear reactor through nuclear fission. In the process, the nucleus of the atom splits. The production method otherwise is similar to other power plants. Nuclear power can produce large amounts of electricity evenly and fuel availability is stable. (Vattenfall 2019d)

The production of nuclear power itself does not cause greenhouse gas emissions. However, carbon dioxide emissions are caused during other parts of production chain:

the purchase of materials and fuels, equipment manufacturing, transportation, and construction and dismantling of plants. Natural uranium is a little radioactive and toxic. In addition, uranium is usually enriched in the mining area, which damages the region. The production generates radioactive waste, which has to be reliably isolated from the environment for over 100 000 years. In addition, nuclear waste can be processed into nuclear weapons. If nuclear accident occur, large areas can become contaminated and uninhabitable. (Vattenfall 2019d)

4 EMISSIONS FROM ELECTRICITY PRODUCTION

Life cycle assessment (LCA) can be used when calculating environmental impact from electricity production. It includes emissions from the construction of the power plant to dismantling them, fuel production, operations and waste treatment. (Vattenfall 2012 p. 10) Because of these variables, emissions vary between LCA studies. One study has been chosen for this thesis to compare emissions from two different countries. The calculated values are not actual emissions from the country but can be used for this comparison. Figure 8 shows LCA's different stages based on International Standards ISO 14040 and 14044. (Vattenfall 2012 p.11)

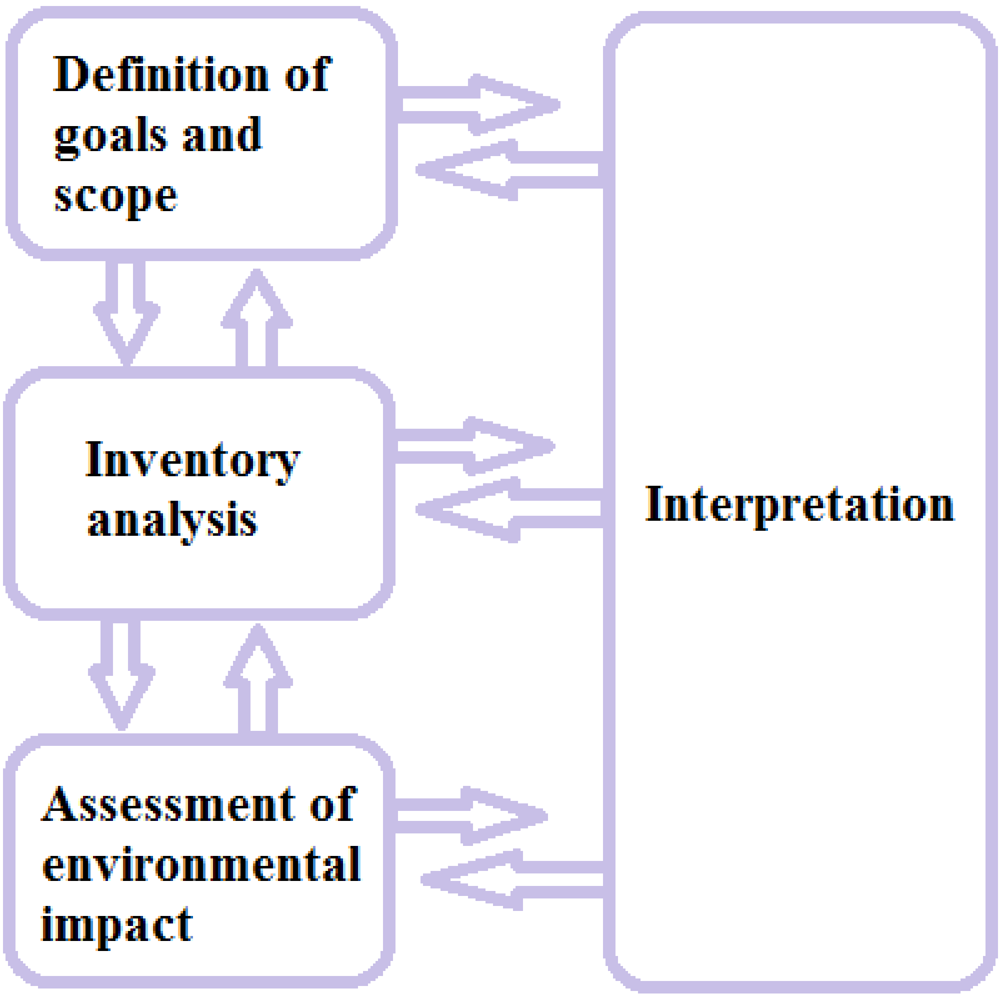

Figure 8. Different stages of life cycle assessment (retell Vattenfall 2012 p.11).

This thesis utilizes Vattenfall's LCA calculations. It is based on the international ISO 14040 and ISO 14044 standards. Emissions are calculated during normal production. Failures or accidents are not included in the calculations. Product Group Regulation (PCR) and Environmental Product Information System (EPD®) have set the system boundaries and allocation principles in which the Vattenfall LCA is based on. (Vattenfall 2012 p.10-11) It is suitable because its calculations cover all electricity production methods used in Finland and Sweden. Solar energy is not included in the calculations because its portion is still small in electricity mix and therefore, does not impact a lot to results. The percentage is also almost the same in both countries.

Vattenfall's LCA include greenhouse gases as a carbon dioxide equivalents (CO_2eq), nitrogen oxides (NOx) and sulphur dioxide (SO_2). The carbon equivalent represents the climate impact of greenhouse gases. The effect of other greenhouse gases has been modified to correspond to the climate effect of carbon dioxide. For example, methane emissions contribute 25 times more to global warming than carbon dioxide. Environmental impact of nitrogen oxides are acidification, eutrophication and ground-level ozone formation. Sulphur dioxide cause acidification. Both, Sulphur dioxide and nitrogen oxides, cause health problems if inhaled. (Vattenfall 2012 p.11)

Table 1 represents CO_2eq, NOx and SO_2 emissions from different forms of electricity production. Biomass is calculated as an average of wood chips and straws. Straws cause more emissions than wood chips because the process before power generation with straws use more energy. For all sources, emissions are caused by fuel production and transportation, operations, infrastructure such operations as construction, maintenance and dismantling, and radioactive waste management. (Vattenfall 2012 p.16-17)

Table 1. Emissions from electricity production g/kWh (retell Vattenfall 2012 p.16-17).

Source	**CO_2 eq (g/kWh)**	**NOx (g/kWh)**	**SO_2 (g/kWh)**
Nuclear	5	0,03	0,03
Hydro	9	0	0
Wind	15	0,03	0,03
Biomass	57,5	0,905	0,195

Peat	636	0,87	0,96
Coal	781	1,46	0,71
Natural gas	503	0,29	0,34

According to Vattenfall's LCA and table 1, the most harmful environmental impact is from coal. Coal has the highest greenhouse gas and nitrogen oxide emissions. The cleanest production with greenhouse gases is nuclear power. Highest sulphur dioxide emissions are caused by peat and lowest by hydro power. Natural gas is the cleanest from fossil fuels and biomass is the dirtiest from renewables. Table 2 explains the main source of emissions from different electricity production methods. Technical service life used in Vattenfall's LCA is also presented.

Table 2. Main sources of emissions and technical life (retell Vattenfall 2012 p. 14-15, 18).

Source	**The main source of emissions**	**Technical service life**
Nuclear	Fuel production covers most of emissions. Testing of backup power, chemicals production and transportation of radioactive waste cause major emissions from operations.	50 years
Hydro	Construction and reinvestments: production of steel and concrete. Operation has low emissions.	Machinery 60 years, concrete structures and dams 100 years
Wind	Construction: production of steel, concrete and composites. Around half of greenhouse gases from steel production.	20 years
Biomass	Carbon dioxide emissions mainly from production of biomass. Other emissions from combustion of biomass.	Straw pellets 20 years, wood chips 40 years
Peat	Drying and combustion are main sources. Vattenfall regards peat as a fossil fuel and includes CO_2 in greenhouse gas emissions.	40 years

Coal	Combustion is major cause. Also mining and transportation has significant affect.	Around 30 years
Natural gas	Combusition is major source for greenhouse gases and NOx. SO_2 emissions are low, since it does not contain any sulphur. Leakages from pipelines can occur.	40 years

The technical service life is 20 years for straw pellets and 40 years for wood chips. This explains partly why emissions are higher for straw pellets in the study.

4.1 Emissions from Finnish electricity production

Table 3 shows the grams of emissions released per kWh from the finnish electricity mix. The values are calculated by multiplying table 1 values with the percentages of the electricity sources used in Finland.

Table 3. Emissions released from Finnish electricity mix g/kWh

Source		**CO_2 eq (g/kWh)**	**NOx (g/kWh)**	**SO_2 (g/kWh)**
Nuclear	**0,32**	1,6	0,0096	0,0096
Hydro	**0,19**	1,71	0	0
Wind	**0,09**	1,35	0,0027	0,0027
Biomass	**0,2**	11,5	0,181	0,039
Peat	**0,05**	31,8	0,0435	0,048
Coal	**0,09**	70,29	0,1314	0,0639
Natural gas	**0,06**	30,18	0,0174	0,0204
Total		**148,43**	**0,3856**	**0,1836**

Coal is the largest source for greenhouse gases. Oil and natural gas also produce a significant amount of greenhouse gases. CO_2eq emissions from biomass are also high, but growing biomass absorbs carbon. Coal and biomass burning releases NOx emissions a lot compared to other sources. SO_2 emissions are high from coal, peat, natural gas and biomass.

According to Eurostat (2019), population in Finland was around 5,5 million at 2018. Electricity production was 67 TWh (Kostama 2018). Therefore, electricity production per capita was 12,18 MWh/year. Emissions from electricity production per capita are calculated in table 4. The values are calculated by multiplying table 3 values with the amount of electricity produced per capita in Finland

Table 4. Emissions per capita from electricity production kg/year in Finland

Source	**CO_2eq (kg)**	**NOx (kg)**	**SO_2 (kg)**
Nuclear	19,488	0,116928	0,116928
Hydro	20,8278	0	0
Wind	16,443	0,032886	0,032886
Biomass	140,07	2,20458	0,47502
Peat	387,324	0,52983	0,58464
Coal	856,1322	1,600452	0,778302
Natural gas	367,5924	0,211932	0,248472
Total	**1807,877**	**4,696608**	**2,236248**

Electricity consumption was higher than production in 2018: 87,4 TWh. Electricity consumption per capita was then 15,9 MWh. If the electricity mix consist only electricity produced in Finland, emissions from electricity consumption per capita are calculated in table 5. The values are calculated by multiplying table 3 values with the amount of electricity consumed per capita in Finland.

Table 5. Emissions per capita from electricity consumption kg/year in Finland.

Source	**CO_2eq (kg)**	**NOx (kg)**	**SO_2 (kg)**
Nuclear	25,44	0,15264	0,15264
Hydro	27,189	0	0

Wind	21,465	0,04293	0,04293
Biomass	182,85	2,8779	0,6201
Peat	505,62	0,69165	0,7632
Coal	1117,611	2,08926	1,01601
Natural gas	479,862	0,27666	0,32436
Total	**2360,037**	**6,13104**	**2,91924**

4.2 Emissions from Swedish electricity production

Table 6 shows the grams of emissions released per kWh from the Swedish electricity mix. The values are calculated by multiplying table 1 values with the percentages of the electricity sources used in Sweden.

Table 6. Emissions released from Swedish electricity mix g/kWh.

Source		**CO_2 eq (g/kWh)**	**NOx (g/kWh)**	**SO_2 (g/kWh)**
Nuclear	**0,42**	2,1	0,0126	0,0126
Hydro	**0,38**	3,42	0	0
Wind	**0,11**	1,65	0,0033	0,0033
Biomass	**0,07**	4,025	0,06335	0,01365
Peat	**0,0067**	4,2612	0,005829	0,006432
Coal	**0,0067**	5,2327	0,009782	0,004757
Natural gas	**0,0067**	3,3701	0,001943	0,002278
Total		**24,059**	**0,094861**	**0,043017**

According to Eurostat (2019), population in Sweden was around 10,1 million at 2018. Electricity production was 158 TWh (Dellby 2019). Therefore, electricity production per capita was 15,6 MWh. Emissions per capita are calculated in table 7. The values are calculated by multiplying table 6 values with the amount of electricity produced per capita in Sweden.

Table 7. Emissions per capita from electricity production kg/year in Sweden.

Source	CO_2eq (kg)	NOx (kg)	SO_2 (kg)
Nuclear	32,76	0,19656	0,19656
Hydro	53,352	0	0
Wind	25,74	0,05148	0,05148
Biomass	62,79	0,98826	0,21294
Peat	66,47472	0,090932	0,100339
Coal	81,63012	0,152599	0,074209
Natural gas	52,57356	0,030311	0,035537
Total	**375,3204**	**1,510142**	**0,671065**

Electricity consumption was lower than production: 141 TWh. Electricity consumption per capita is then 13,97 MWh. If the electricity mix includes only electricity produced in Sweden, emissions from electricity consumption per capita are calculated in table 8. The values are calculated by multiplying table 6 values with the amount of electricity consumed per capita in Sweden.

Table 8. Emissions per capita from electricity consumption kg/year in Sweden.

Source	CO_2eq (kg)	NOx (kg)	SO_2 (kg)
Nuclear	29,337	0,176022	0,176022
Hydro	47,7774	0	0
Wind	23,0505	0,046101	0,046101
Biomass	56,22925	0,885	0,190691
Peat	59,52896	0,081431	0,089855
Coal	73,10082	0,136655	0,066455
Natural gas	47,0803	0,027144	0,031824
Total	**336,1042**	**1,352352**	**0,600947**

5 DISCUSSION AND CONCLUSIONS

Table 9 shows the difference of Finnish and Swedish electricity mix emissions g/kWh. It can be seen that the greenhouse gas emissions produced by Finland are about 6 times higher per kWh, and nitrogen oxides and Sulphur dioxides about 4 times higher per kWh. Therefore, the Swedish electricity mix is much cleaner. The main reason for this is the high share of fossil fuels in Finnish electricity production.

Table 9. Comparison of electricity mixes g/kWh.

	CO_2 eq (g/kWh)	**NOx (g/kWh)**	**SO_2 (g/kWh)**
Finland	148,43	0,3856	0,1836
Sweden	24,059	0,0948	0,043017
Difference	124,371	0,290739	0,14058

Comparison of the electricity production and consumption per capita per year is represented in table 10. Finnish production is 2,8 MWh lower than Swedish. Consumption, in turn, is 1,93 MWh higher. Finland electricity deficit per capita is 3,1 MWh and Swedish surplus is 1,63 MWh. For Sweden it is possible to decrease electricity production, but Finland should increase it so that the countries are balanced in terms of production and consumption.

Table 10. Comparison of electricity production and consumption per capita MWh/year.

	Production per capita (MWh/a)	**Consumption per capita (MWh/a)**	Balance
Finland	12,8	15,9	-3,1
Sweden	15,6	13,97	1,63
Difference	-2,8	1,93	

Table 11 represents the emissions in kg from electricity production and consumption per capita per year. For Finland, with the current mix it would not be good to fill Finnish energy requirement since emissions are higher with consumption. For Sweden, however, emissions are lower with consumption and mix is profitable.

Table 11. Comparison of emissions from electricity production based on consumption and production per capita kg/year.

	CO_2eq (kg)		**NOx (kg)**		**SO_2 (kg)**	
	Product	Consum	Product	Consum	Product	Consum
Finland	1807,877	2360,037	4,696608	6,13104	2,236248	2,91924
Sweden	375,3204	336,1042	1,510142	1,352352	0,671065	0,600947
Difference	1432,5566	2023,9328	3,186466	4,778688	1,565183	2,318293

2018, Finland produced 67 MWh electricity. Net import from Sweden was 13,5 MWh. That all together make 80,5 MWh where Finnish part is 83,2% and Swedish 16,8% of the electricity production. Table 12 presents Finnish mix's emissions compared to Finnish/Swedish mix's emissions in g/kWh.

Table 12. Comparison of emissions from Finland and Sweden/Finland electricity mix.

	CO_2 eq (g/kWh)	**NOx (g/kWh)**	**SO_2 (g/kWh)**
Finland 83,2% **Sweden 16,8%**	127,53	0,3369	0,1599
Finland	148,43	0,3856	0,1836
Difference	-20,9	-0,0487	-0,0237

From table 12 can be seen that the electricity from Sweden decreases emissions noticeably. Therefore, it is profitable to buy electricity from Sweden based on emissions.

In the future, Finland plans to reduce fossil fuels and increase nuclear power, as well as other renewable energy sources. This significantly reduces emissions and it may be even possible to get the same readings with Sweden or near the same. However, it is still a long way to go, so Finland has a lot to do to achieve its goals.

Sweden's plans for the future are the complete abandonment of fossil fuels and the exclusion of nuclear energy. These will be replaced by renewable energy sources. Substitution of fossil fuels is profitable in terms of emissions, but Table K shows that replacement of nuclear energy increases emissions, specially greenhouse gases.

Especially the construction of new power plants produces emissions, as well as dismantling them. Therefore, in the future, Swedish emissions from electricity production will increase even if its 100% renewable.

Solar power generation will continue to increase in both countries in the future. Based on Turconi et all (2013 p.8), greenhouse gases vary between 13-190 g/kWh, nitrogen oxides vary between 0,15-0,40 g/kWh and Sulphur oxides vary between 0,12-0,19 g/kWh. The amount depends on the study. Therefore, replacing fossil fuels with solar energy is profitable based on emissions.

When new power plants are being built, there is also a need to renew electricity distribution network. This also cause its own emissions.

Modifying electricity production also affects the inertia of the electricity grid. Condensing power and nuclear power are good sources for inertia. If these are replaced by solar power and wind power, the inertia will be reduced. The power system of the future may have to limit the power of the largest power plants if there is not enough inertia. (Päivinen 2018)

6 REFERENCES

Alm, M., 2018. Toimialaraportit - Uusiutuva energia. Työ- ja elinkeinoministeriön julkaisuja 42/2018. Helsinki: Työ- ja elinkeinoministeriö. 101p. ISBN 978-952-327-366-9

Dahiya, A, Porter, P., Williams, C., 2015. Bioenergy, biomass to biofuels. Chapter 1: Introduction to bioenergy. Elservier Inc. 670 p. ISBN 978-0-12-407909-0

Dellby, C., 2019. Så påverkades elproduktionen av den varma sommaren 2018 [online document]. Stockholm: Energimyndigheten. Available from: https://www.energimyndigheten.se/nyhetsarkiv/2019/sa-paverkades-elproduktionen-av-den-varma-sommaren-2018/ [cited 13.10.2019].

Electrical equipment, 2019. Comparison of overhead and underground transmission cables [online document]. Available from: http://engineering.electrical-equipment.org/others/comparison-overhead-underground-transmission-cables.html [cited 2.10.2019].

Elenia, 2017. Sähköverkko tutuksi, sähköverkko tuo sähkön kotiisi [online document]. Available from: https://www.elenia.fi/yritys/sähköverkko-tutuksi [cited 2.10.2019].

Energiateollisuus, 2019. Energiantuotannon ympäristövaikutukset [online document]. Helsinki: Energiateollisuus ry. Available from: https://energia.fi/perustietoa_energia-alasta/ymparisto/energiantuotannon_ymparistovaikutukset [cited 5.10.2019].

Energiateollisuus, 2011. Sähkön hinta pähkinänkuoressa [online document]. Helsinki: Energiateollisuus ry. Available from: https://energia.fi/files/624/Sahkon_hinta_-esite.pdf [cited 2.10.2019].

Eurostat, 2019. Population projections, statistics illustrated [online data]. European Commission. Available from: https://ec.europa.eu/eurostat/web/population-demography-migration-projections/statistics-illustrated [cited 29.10.2019].

Fingrid, 2019a. Electricity Transmission and Use of Electricity System [online document]. Helsinki: Fingrid Oyj. Available from: https://www.fingrid.fi/en/grid/electricity-system-of-finland/ [cited 2.10.2019].

Fingrid, 2019b. Reservimarkkinat, Ylläpidämme ja kehitämme reservi- ja säätösähkön markkinapaikkoja [online document]. Helsinki: Fingrid Oyj. Available from: https://www.fingrid.fi/sahkomarkkinat/reservit-ja-saatosahko/ [cited 9.10.2019]

Fingrid, 2019c. Maintenance of power balance [online document]. Helsinki: Fingrid Oyj. Available from: https://www.fingrid.fi/en/grid/electricity-system-of-finland/maintenance-of-power-balance/ [cited 9.10.2019].

Fingrid, 2018. Vuosikertomus 2018, sähköjärjestelmä [online document]. Helsinki: Fingrid Oyj. Available from: https://annualreport.fingrid.fi/liiketoiminta/sahkojarjestelma.html [cited 9.10.2019].

Government offices of Sweden, 2018. Sweden's draft integrated national energy and climate plan [online document]. Ministry of Environment and Energy. Available from: https://www.government.se/48ee21/contentassets/e731726022cd4e0b8ffa0f8229893115/swedens-draft-integrated-national-energy-and-climate-plan [cited17.10.2019]. 79p.

Hillhouse, G., 2019. How electricity generation really works [online video]. San Antonio: Practical engineering. Available from: https://www.youtube.com/watch?v=AHFZVn38dTM [cited 9.10.2019].

Huttunen, R., 2017. Valtioneuvoston selonteko kansallisesta energia- ja ilmastostrategiasta vuoteen 2003. Työ- ja elinkeinoministeriön julkaisuja 4/2017. Helsinki: Työ- ja elinkeinoministeriö. 116 p. ISBN 978-952-327-189-0

Jaber, S., 2013. Environmental impacts of wind energy [online document]. Journal of Clean Energy Technologies, Vol. 1, No. 3 Available from: http://www.jocet.org/papers/057-J30009.pdf [cited 15.10.2019]. 4p.

Kostama, J., 2018. Sähköntuotanto, sähköntuotanto energialähteittäin 2018 [online document]. Helsinki: Energiateollisuus ry. Available from: https://energia.fi/perustietoa_energia-alasta/energiantuotanto/sahkontuotanto [cited 9.10.2019].

Morse, E., 2013. Non-renewable energy [online document]. Washington, D.C.: National Geographic Society. Available from: https://www.nationalgeographic.org/encyclopedia/non-renewable-energy/ [cited17.10.2019].

National Research Council (U.S.), National Academy of Sciences (U.S.), National Academy of Engineering, 2010. Electricity From Renewable Resources: Status, Prospects, and Impediments [online document]. Washington, DC: National Academies Press. Available from: http://web.a.ebscohost.com.pc124152.oulu.fi:8080/ehost/ebookviewer/ebook/bmxlYmtfXzMxOTE0OF9fQU41?sid=94561335-660f-49d5-8954-0d532466b4ef@sessionmgr4006&vid=0&format=EK&lpid=ncx62&rid=0 367p. ISBN 9780309137096

Nordpool, 2019a. Day-ahead prices [online document]. Lysaker: Nord Pool AS. Available from: https://www.nordpoolgroup.com/Market-data1/Dayahead/Area-Prices/ALL1/Monthly/?view=chart [cited 2.10.2019]

Nordpool, 2019b. About us [online document]. Lysaker: Nord Pool AS. Available from https://www.nordpoolgroup.com/About-us/ [cited 5.10.2019].

Official Statistics of Finland (OSF), 2018. Production of electricity and heat, use of renewable energy sources grew in electricity and heat production in 2017 [online document]. Helsinki: Statistics Finland. Available from: http://www.stat.fi/til/salatuo/2017/salatuo_2017_2018-11-01_tie_001_en.html [cited 9.10.2019].

Ollikka, K., 2017. Miten sähköverkot toimivat? [online document]. VATT: Smart energy transition. Available from: http://smartenergytransition.fi/fi/miten-sahkomarkkinat-toimivat/ [cited 2.10.2019].

Päivinen, R., 2018. Sähköjärjestelmän inertia [online document]. Helsinki: Fingrid Oyj. Available from: https://www.fingrid.fi/globalassets/dokumentit/fi/yhtio/toimikunnat/4_sahkojarjestelman_inertia.pdf [cited 9.10.2019].

Svenska Kräftnat, 2019. Messaure – Keminmaa, New line between Sweden and Finland [online document]. Sundbyberg: Svenska kräftnat. Available from: https://www.svk.se/en/grid-development/grid-projects/messaure---keminmaa/ [cited 5.10.2019].

Svenska Kräftnat, 2018. Our activities [online document]. Sundbyberg: Svenska kräftnat. Available from: https://www.svk.se/en/about-us/our-activities/?id=865 [cited 5.10.2019].

Svenska Kräftnat, 2016. We are developing our national grid [online document]. Sundbyberg: Svenska kräftnat. Available from: https://www.svk.se/en/grid-development/driving-forces/?id=838 [cited 5.10.2019].

Vattenfall, 2019a. Tuotantomuodot, vesivoima [online document]. Helsinki: Vattenfall Oyj. Available from: https://www.vattenfall.fi/sahkosopimukset/tuotantomuodot/vesivoima/ [cited 15.10.2019].

Swedish Energy agency, 2019a. Energy in Sweden 2019, an overview. Stockholm: Swedish Energy Agency. ISSN 1404-3343 14p.

Swedish Energy Agency, 2019b. Energy in Sweden Facts and Figures [excel document]. Stockholm: Swedish Energy Agency. Available from: https://www.energimyndigheten.se/globalassets/statistik/energilaget/energy-in-sweden-2019.xlsx [cited 15.10.2019]

Turconi, R., Boldrin, A., & Astrup, T. F., 2013. Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations [online document]. Lungby: Technical University of Denmark. Available from: https://doi.org/10.1016/j.rser.2013.08.013 25p.

Uniper, 2019. El istället för fossila bränslen [online document] available from: https://www.uniper.energy/sverige/go-electric/el-och-klimat [cited 29.10.2019].

Vattenfall, 2019a. Tuotantomuodot, vesivoima [online document]. Helsinki: Vattenfall Oyj. Available from: https://www.vattenfall.fi/sahkosopimukset/tuotantomuodot/vesivoima/ [cited 15.10.2019].

Vattenfall, 2019b. Tuotantomuodot, tuulivoima [online document]. Helsinki: Vattenfall Oyj. Available from: https://www.vattenfall.fi/sahkosopimukset/tuotantomuodot/tuulivoima/ [cited 15.10.2019].

Vattenfall, 2019c. Tuotantomuodot, aurinkovoima [online document]. Helsinki: Vattenfall Oyj. Available from: https://www.vattenfall.fi/sahkosopimukset/tuotantomuodot/aurinkovoima/ [cited 16.10.2019]

Vattenfall, 2019d. Tuotantomuodot, ydinvoima [online document]. Helsinki: Vattenfall Oyj. Available from: https://www.vattenfall.fi/sahkosopimukset/tuotantomuodot/ydinvoima/?gclsrc=aw.ds& &gclid=EAIaIQobChMIxJiP85-j5QIVVsayCh2ELgszEAAYASAAEgJGMvD_BwE [cited17.10.2019].

Vattenfall, 2012. Life cycle assessment, Vattenfall's electricity generation in the Nordic countries [online document]. Available from: https://group.vattenfall.com/siteassets/corporate/who-we-are/sustainability/doc/life_cycle_assessment_2012.pdf [cited 29.10.2019] 26p.

Ympäristöministeriö, 2015. Suomen ympäristöpolitiikka, kohti vähähiilistä ja energiatehokasta yhteiskuntaa [online document]. Available from: https://ilmasto-opas.fi/ilocms-portlet/article/8a54c390-fed4-42da-a2c2-4bab74993ebd/r/193d4fa4-49ed-4639-aab0-a30e52813f8e/suomen_ilmastopolitiikka_cmyk.pdf [cited 5.10.2019].