**NTNU – Trondheim**
Norwegian University of
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# Life Cycle Assessment of Electricity Transmission and Distribution

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# MASTER THESIS

for

student Ingrid Bjerke Hauan

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## Life cycle assessment of electricity transmission and distribution

Livssyklusanalyse av regionalnett og distribusjonsnett

**Background and objective**

The supply of electricity is responsible for a significant share of environmental impacts in most countries and constitutes a significant share of the carbon footprint of consumers. These impacts are primarily caused by electricity production from fossil fuels. There has hence been a substantial and continuous effort to assess the environmental impacts of different electricity generation technologies from a life-cycle perspective. There has, however, been relatively little attention to electricity transmission and distribution (T&D). While T&D causes fewer impacts than generation, they cannot be neglected and may influence the total impacts per kWh of electricity by consumers to some degree. Knowledge about the environmental impacts of T&D is also relevant because measures to balance generation variable renewable energy sources directed at grid operations and demand control involve the grid. Knowledge of the environmental impacts of electricity distribution is hence important for the environmental design of future electricity systems.

The aim of this project is to provide an assessment of the environmental impacts of electricity delivered to household consumers in the county of Nord-Trøndelag in Central Norway, using life cycle assessment as a method. The assessment should take into consideration power transmission and distribution at all three levels of the Norwegian power grid (main grid, regional grid and distribution grid). The study will build on and extend previous research on environmental impacts of power systems at NTNU, and will be performed in collaboration with the local distribution company in Central Norway, NTE.

**The following elements are to be considered:**

1. Description of the electrical grid in Norway, voltage levels and grid elements.
2. Discussion of power losses in different sections of the grid, and of factors influencing these losses.
2. Detailed inventory of components in the regional and local distribution grid in Nord-Trøndelag.
3. Assessment of $SF_6$ leakages in connection with component manufacturing, use and disposal.
4. Life cycle assessment of electricity delivered to household consumers in Nord-Trøndelag. What are the total impacts of transferring electricity through the main grid, regional grid and local distribution grid, and what are the contributions of individual grid sections? How do the impacts from electricity transmission and distribution compare with impacts from power generation?

5. What lessons can we learn on the environmental impacts of power grids in general based on this case study for Nord-Trøndelag? And what are the important limitations? Include also a brief discussion of how power grids may also help to reduce environmental impacts, for example by raising overall efficiency through enhanced trade and by aiding power grid balancing.

-- ” --

Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

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☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 14. January 2014

Olav Bolland
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# Abstract

As the integration of renewable electricity production progresses and the energy consumption pattern evolves, the transportation of energy is essential for securing sufficient supply while meeting political targets. Power grid renewal and expansion is likely to increase in the future, therefore an understanding of the environmental implications from transmission and distribution (T&D) of electricity is necessary.

This master thesis presents a life cycle assessment (LCA) of the Norwegian power grid, with case-specific data from the Nord-Trøndelag grid, owned and operated by NTE Nett. The aim is to determine the environmental impacts associated with the T&D of electricity, and the functional unit is the delivery of 1 MWh of electrical energy, assuming 2011 conditions. Arda software is used for the impact calculations, applying the ReCiPe midpoint hierarchist method and processes from the Ecoinvent database.

The Norwegian power grid operates with three different voltage levels, namely the distribution grid, the regional grid and the main grid. Each of these grid levels are modelled individually and compared to each other, and three different scenarios for electricity production are run for each model.

When modelling the T&D grid with a Norwegian electricity production, the distribution grid impacts dominate in most of the 18 Ecoinvent midpoint categories. In the case of climate change, the amount from the three grid levels combined is 13.0 kg $CO_2$-equivalents per MWh of delivered energy. Of these, 9.2 kg stem from the distribution grid, 2.9 kg from the regional grid and 0.9 kg from the main grid. With the Nordic and European production mixes, climate change impacts increase drastically in all grid levels.

Attention was also paid to the insulating gas found in the grid components. $SF_6$ is a greenhouse gas with global warming potential 23,900 times higher than that of $CO_2$, and it is utilised in the power grid due to its unique physical properties. In this thesis, leakages of $SF_6$ were found to contribute surprisingly little to the climate change impacts, but it was deemed likely that the model contains an underestimation for this aspect of grid operation.

Comparing the impacts from electricity transmission to the power production showed that in the energy system as a whole, the significance of T&D is relatively small. However, the less fossil fuel based the electricity production is, the more significant are the infrastructure impacts. Therefore, in case of a future transition towards a more renewable electricity production, the environmental strains of the physical grid will become more important.

Even if power grids in themselves strain the environment, this infrastructure makes the exchange of electricity possible. The advantages of a reliable power grid may outweigh the detriment to the environment, as the infrastructure plays a crucial role in phasing in more renewable energy.

# Sammendrag

For å integrere elektrisitet fra fornybare energikilder i kraftsystemet, samtidig som forbruksmønsteret endres, kreves en effektiv og pålitelig transport av kraft. Forsyningssikkerhet skal ivaretas samtidig som politiske mål om fornybarandel og energieffektivisering innfris. Dette vil føre til økt investering i kraftnettet, og miljøaspekter knyttet til kraftoverføring og distribusjon må derfor kartlegges.

Denne masteroppgaven tar for seg miljøpåvirkninger fra kraftoverføring i Norge, med spesifikke data fra nettet i Nord-Trøndelag, som eies og driftes av NTE Nett. Rammeverket som benyttes er livssyklusanalyse (LCA), og beregninger er gjort med den NTNU-utviklede programvaren Arda. ReCiPe "midpoint hierarchist"-metoden anvendes, og prosesser som inngår i systemet hentes fra Ecoinvent-databasen.

Det norske kraftsystemet opererer med tre spenningsnivå, nærmere bestemt distribusjonsnettet, regionalnettet og sentralnettet. Disse modelleres individuelt, hver med tre ulike elektrisitetsproduksjoner, før de sammenlignes.

Når den norske kraftproduksjonen mates inn i overføringsnettet, er distribusjonsnettet den største bidragsyteren til miljøpåvirkninger i de fleste av Ecoinvents 18 påvirkningskategorier. De totale bidragene til klimaendringer fra de tre nettnivåene er 13,0 kg $CO_2$-ekvivalenter per MWh levert energi, hvorav 9,2 kg stammer fra distribusjonsnettet, 2,9 kg fra regionalnettet og 0,9 kg fra sentralnettet. Med nordisk og europeisk kraftproduksjon i systemet øker klimaendringsverdiene drastisk på alle nettnivå.

Isolasjonsgass brukt i kraftkomponenter blir også viet oppmerksomhet, i og med at $SF_6$ er en drivhusgass med globalt oppvarmingspotensial 23 900 ganger kraftigere enn $CO_2$. På grunn av sine helt unike fysiske egenskaper benyttes $SF_6$ likevel i kraftsystemet, og lekkasjer kan oppstå. I denne oppgaven bidro $SF_6$ overraskende lite til potensielle klimaendringer, men dette bunner mest sannsynlig i en underestimering av lekkasjene, når data implementeres i modellen.

Når påvirkninger fra overføringsnettet sammenlignes med tilsvarende verdier fra produksjon av kraft, er førstnevnte relativt ubetydelige. Likevel; jo mindre fossile energikilder som benyttes i kraftproduksjonen, desto viktigere blir påvirkningene fra kraftoverføringen. For kraftproduksjon bestående av mer fornybar energi vil miljøpåvirkninger relativt sett bli mer betydelige.

Til tross for at overføringsnettet utgjør en belastning for miljø og klima, må det bemerkes at denne infrastrukturen muliggjør kraftutveksling. Fordelene med et pålitelig kraftnett mer enn utligner de miljømessige utfordringene, i og med at infrastrukturen er helt essensiell for økt innfasing av fornybar energi.

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# List of Abbreviations

| | |
|---|---|
| 1,4 DB | 1,4-dichlorobenzene |
| EV | Electric vehicle |
| GW | Gigawatt |
| HVDC | High voltage direct current |
| kV | Kilovolt |
| LCA | Life cycle assessment |
| LCI | Life cycle inventory |
| MVA | Mega volt-ampere |
| MW | Megawatt |
| MWh | Megawatt hour |
| NO | Norwegian electricity mix |
| NORDEL | Nordic electricity mix (Sweden, Norway, Finland and Denmark) |
| NTE | Nord-Trøndelag Elektrisitetsverk |
| NTNU | Norwegian University of Science and Technology |
| OHL | Overhead lines |
| PEX | Cross-linked polyethylene |
| PP | Polypropylene |
| PVC | Polyvinyl chloride |
| RER | European average technology (Ecoinvent terminology) |
| $SF_6$ | Sulphur hexafluoride |
| T&D | Transmission and distribution |
| TSO | Transmission system operator |
| TWh | Terawatt hour |

# 1 Introduction

This master thesis presents a life cycle assessment (LCA) of the Norwegian power grid, with case-specific data from Nord-Trøndelag, a county situated in the central region of Norway. The grid includes transmission lines, cables, transformers and switchgear, and the study is done in collaboration with NTE Nett AS, the owner and operator of the modelled grid.

Several LCA studies of the electric power system have been conducted previously, however focus has mainly been on the production of electrical energy rather than the transmission and distribution (T&D) in the high voltage grids.

A quantitative understanding of the environmental impacts of physical grids becomes increasingly important as the development of the future T&D grids progresses. Climate and environmental concerns are a driving force in the development of the next generation of power systems. This transition encompasses many aspects, including increased integration of renewable resources, development of intelligent grids, and increased efficiency of electrical appliances and their respective utilisation.

The regional grid is modelled in Arda, using ReCiPe characterisation and processes from the Ecoinvent database. Bernhard Bolsøy at NTE Nett provided grid data and structural information, and the grid inventory is modelled according to 2011 data.

## 1.1 Goal and Scope

The goal of this project is to explore the environmental impacts associated with the transmission of electric energy in the Norwegian power grid. The grid includes all overhead lines and cables in all grid voltage levels, namely the distribution grid, the regional grid and the main grid, henceforth referred to as the *sentralnett*. Main components are also accounted for, such as transformers and switchgear and masts.

The distribution and regional grid levels are site-specific to Nord-Trøndelag, whereas the *sentralnett* stretches across the entire country. The smallest grid components are found in the distribution grid, however the total length of installed lines and cabling is much longer than what is found in the regional grid, meaning the infrastructure in the two grid levels are structurally different, although both are significant in terms of material requirements.

The distribution grid is responsible for a large fraction of the total losses in the transmission system, 5.0% of energy transfers in the grid are lost, compared to approximately 2.0% in the regional grid and 2.7% in the *sentralnett*. The higher rate of power loss in the distribution grid is due to the low voltages and a more frequent use of underground cables, which is a considerable source of reactive power (OED, 2012).

The functional unit is the delivery of 1 MWh of electrical energy, assuming 2011 conditions. Relating the inventory of the grid to a specific year is necessary, because investments in the physical grid varies from one year to another, although a power grid is relatively constant in its structure. The average lifetime is approximately 40 years. Specifying the time scope of the analysis becomes even more important when considering the fact that the amount of energy delivered by the system also varies from one year to another. Electricity is the main source for heating in Norway. Consequently, the amount of delivered energy in one year is very sensitive to the weather conditions of this particular year, and with the infrastructure being relatively constant, the amount of inventory per unit of delivered energy will therefore depend on which year is considered.

Another important aspect regarding the functional unit is the fact that the regional and distribution grids are assessed in relation to the energy delivered within the region of Nord-Trøndelag. This means the infrastructure is aggregated and divided by the energy consumption in Nord-Trøndelag in 2011. Since the *sentralnett* covers the entire country of Norway, this model is assessed in terms of the energy delivered to the country as a whole. In other words, the entire *sentralnett* infrastructure is mapped, and divided by the energy consumption of Norway in 2011.

A considerable part of this analysis is dedicated to the impacts stemming from different electricity mix scenarios. The power losses are modelled with different origins of electricity production, with different compositions of energy resources. This is done in order to study the impact significance of the electricity production transported in the grid, rather than inspecting the physical grid as a separate and independent system.

# 2 Background

## 2.1 Motivation

According to (da Graça Carvalho, 2012), energy security is alongside climate change and population ageing among the major challenges of the future for the European Union. In order to meet these challenges, energy technology plays a crucial role. The development of new, more efficient and affordable technologies is required to achieve political targets, and in the low carbon economy, electricity has an essential function as energy carrier. Low carbon technologies in the electricity mix are aimed to increase from around 45% to around 60% in 2020. In the words of Carvalho, "energy efficiency is at the heart of European policies for smart, sustainable and inclusive growth".

The European Union has set targets for its ten-year growth plan, commonly referred to as "Europe 2020". By the year 2020, greenhouse gas emissions shall be 20% lower than the emission quantity of 1990. Moreover, 20% of all energy should come from renewable resources, while the energy efficiency increases by 20%. In order to meet the targets, European institutions, member states, local authorities and the civil society must partake, through several flagship initiatives (EC, 2013).

The transmission grid for electricity is crucial both in relation to energy security and climate change, the former through enabling transportation and delivery of electricity. Moreover, the electricity grid allows for the integration of more renewable resources in energy production, which is one of the measures to mitigate emissions of greenhouse gases and in turn global warming and climate change.

An increase in network investments both in terms of kilometres and capacity is required if renewable energy integration is to be satisfactorily achieved (Jorge and Hertwich, 2013). In the future, grid components will continue in their basic structure, meaning the future grid will also consist of overhead lines, cables, transformers and substations, to name a few. Knowledge of the component-related environmental impacts is therefore essential for a thorough understanding of the total impacts from energy systems.

As an example of European grid expansion, offshore wind is part of the EU's renewable target for 2020 (EWEA, 2009).  To accomplish a smooth integration, transnational grids must be built to a greater extent. Not only will these provide grid access to the offshore wind farms, they will also enable more electricity trade within the European region. This will in turn help ensure security of power supply, even when more unpredictable renewable resources are integrated. The offshore grid also requires onshore reinforcement; meaning construction activity of electrical grids will increase with installed capacity offshore.

## 2.2 Previous studies

In the field of environmental impact evaluation of power systems, several studies have been performed, although varying greatly in scope and approximations of the energy system.

Comparisons of underground and overhead power distribution systems were performed by (Bumby et al., 2010). The underground system was found to have higher environmental impacts in all indicators and for all parameter values, and this was analysed to be mostly due to the high material intensity of the cable system. The global warming potential was found to be 1,419 kg $CO_2$-eq for OHL and 7,683 kg $CO_2$-eq for the underground cabling system. These values are given per distribution of power in one circuit over one mile (1.6 km), for one year.

The majority of impacts were found to occur during the production phase. The model included several installation processes for both overhead and underground systems, and the former included hole digging for poles, setting of poles and stringing of lines. The underground system included more processes, namely digging of trenches, the placing of vaults and conduits, mixing and pouring of concrete, backfilling and the pulling of the cable. Although highly detailed in the process perspective, the lifetime of the underground cables is assumed to be 125 years, which exceeds assumptions in similar LCA studies (further discussed in section 4.1.1.1). Also, the failure rate is set to 0.1 events per year per mile for overhead lines, and 0.9 for the underground cables.

The environmental implications of large-scale adoption of wind power was studied by (Arvesen and Hertwich, 2012), and both onshore and offshore wind power were assessed. The delivery of 1 kWh of electricity from onshore wind energy conversion was found to cause 22.5 g $CO_2$-eq of climate change impacts. For offshore wind power, the corresponding value was 21.2 g $CO_2$-eq. When the analysis was performed with a 5-year extension added to the lifetime, the climate change impacts were reduced by 8%. The total emissions from wind electricity are found to be between 4% and 14% of the emissions caused by fossil-fuelled power plants.

Power transmission in Norway was assessed by (Jorge and Hertwich, 2013), and the transmission of 1 kWh of electricity was found to have climate change impacts of 1.3–1.5 g $CO_2$-eq. The main contributing aspects to the infrastructure impacts were overhead lines, transformers and $SF_6$ losses in components. In order for this study to be performed, two assessments of grid components were done prior to the evaluation of the transmission system as a whole. One targeted power lines and cables (Jorge et al., 2012a), whereas in the other, transformers were assessed (Jorge et al., 2012b).

For the overhead lines, the processes with the most impacts were the materials for masts and conductors, mainly due to their requirement of metals. However, the end-of-life has a negative contribution in all impact categories, meaning the environmental benefits achieved by recycling outweigh the sum of impacts generated by the rest of the end of life processes.

For the transformers and switchgear modelled, the most dominant process for nearly all impact categories was power losses, and of climate change impacts, 96% was due to the losses. However, when inspecting components individually, some substations using $SF_6$ insulation technology were found to have more climate change impacts from $SF_6$ than from power losses.

The transmission network in Great Britain was assessed by (Harrison et al., 2010), and when a static generation mix was assumed, the carbon equivalent emissions (or global warming potential) of the transmission network were approximately 11 g $CO_2$-eq per kWh. These results were obtained when modelling with a 40-year lifetime assumption, and operational losses were estimated to account for most of the $CO_2$-equivalent emissions, with $SF_6$ being also significant. The production of electricity and the ensuing emissions are not included in the study, however network assets include overhead lines, underground cables, substation switchgear and associated civil engineering work.

The entire Danish electricity grid was modelled by (Turconi et al., 2013), and the impacts from the local distribution system were found to be higher than those from the high voltage transmission system. This was due to the fact that energy losses in the former are higher, causing most of the impacts. The highest voltage studied in this system was 50 kV, as opposed to the assessment of the Norwegian grid, which included voltages up to 420 kV. Again cables were found to have larger impacts than overhead lines, and when comparing copper lines to lines of aluminium, the latter had lower environmental impacts.

The suggestion that impacts from electricity distribution may become more significant in the future is explained by the likely increase in renewable energy integration, intertwined with a more decentralised electricity production. Although this study did not include switchgear, $SF_6$ is assumed significant, and therefore inclusion of switchgear in future LCAs is encouraged.

## 2.3 The Norwegian Power Grid

The Norwegian power grid has three levels, determined by voltage levels and function. The highest voltages are found in the main grid (the *sentralnett*). Because of the high voltage levels in the main grid, it consists of the largest components found in the Norwegian power system. Through the transformation to lower voltages, the electricity is delivered to the regional grid, which in turn delivers the electricity to the lower voltage grid, called the distribution grid. The latter feeds electricity to the final consumers, including households. Large-scale consumers are connected to the *sentralnett* or regional grid, depending on the individual power demand. Examples of such consumers in Norway are the aluminium production facilities and other power intensive industry.

Most of the large electricity production facilities, for example hydro power plants, deliver directly to the main grid, whereas small-scale wind production units and other smaller production facilities are connected to the regional grid. The smallest production units feed electricity to the distribution grid.

| | **Voltage levels** | **Total length** |
|---|---|---|
| Main grid/"Sentralnett" | 132-420 kV | 11,062 km |
| Regional grid | 22-132 kV | 18,687 km |
| Distribution grid | 230 V- 22 kV | 98,842 km |

(OED, 2012)

The main function of the *sentralnett* is to transport large quantities of energy across the country. Because the production and consumption of electricity is not equally distributed across Norway, some regions have more production than consumption, and these are considered surplus areas. Other regions are deficit areas, due to insufficient power production compared to the consumption pattern. In order to ensure an optimal flow of energy across the regions while balancing production and consumption, the *sentralnett* is owned and operated by the Norwegian transmission system operator (TSO) Statnett SF.

The regional grid has the same function of transmission as the main grid, although the distances of energy transportation are shorter. System operators of regional grids are appointed based on relative regional dominance within a county, and are referred to as the *concessionaire* of the county. In Nord-Trøndelag, NTE Nett is the concessionaire, providing annually revised reports, in which the county's power supply and transmission situation is evaluated. These reports are delivered to the Norwegian Water Resources and Energy Directorate, and are mandatory for all concessionaires (NVE, 2007).

### 2.3.1 Grid components

The main components found in the grid are wires, transformers and switchgear. Wires are aerial power lines or cables, the latter either under ground or subsea. In addition there is the necessary infrastructure to uphold the grid, including masts, trenches and insulation.

### 2.3.2 $SF_6$ in the Grid

$SF_6$ is a greenhouse gas with global warming potential 23,900 times higher than that of $CO_2$, when applying a time horizon of 100 years (UNFCCC, 2013). The gas was first produced in 1953, and due to its high dielectric strength and ability to quench electric arcs, it quickly became a favoured insulating agent in power electronics (Neumann et al., 2004). Moreover, the gas is non-toxic, non-ozone depleting and non-combustible (Reimueller et al., 2005). Because of its chemical stability - $SF_6$ has an atmospheric lifetime of approximately 3,200 years - the gas is very difficult to break down. In the Kyoto Protocol $SF_6$ is listed as one of the six main greenhouse gases targeted in the first commitment period. Countries ratifying the protocol submit to reducing the use of $SF_6$ (Maiss and Brenninkmeijer, 1998).

As the physical properties of $SF_6$ in power electronics are in a league of their own, there is at present no satisfactory replacement for the gas. To exemplify these properties; substations filled with $SF_6$ gas only requires approximately 20% of the space of an open-air installation of comparable capacity (Schavemaker and Sluis, 2008). The most realistic measure to reduce impacts from $SF_6$ in electrical grid is therefore to reduce leakages in the use of the equipment, in order to stagger some of the emissions to a certain degree (Neumann et al., 2004).

In Norway, a user group for $SF_6$-installations was established in 1991 as a forum for providers and owners of $SF_6$-installations, authorities and other affected parties. As of 2002, the Department of Environment demands annual reports on the accumulation and emissions of $SF_6$ across the installations in the country (SINTEF, 2014).

As remarked in the study of the Danish power grid, the use of $SF_6$ is expected to increase in the future, which is a valid reason for wishing to include this use in life cycle studies (Turconi et al., 2013).

## 2.4 The Energy Situation in Norway

Currently, the Norwegian electricity supply originates mainly from hydropower. 130 TWh of electricity is produced from hydropower in an average year (NVE, 2013a). In 2011, 95% of the electricity produced in Norway was from hydropower, whereas heat plants and wind power covered the remaining 5% (SSB, 2013).

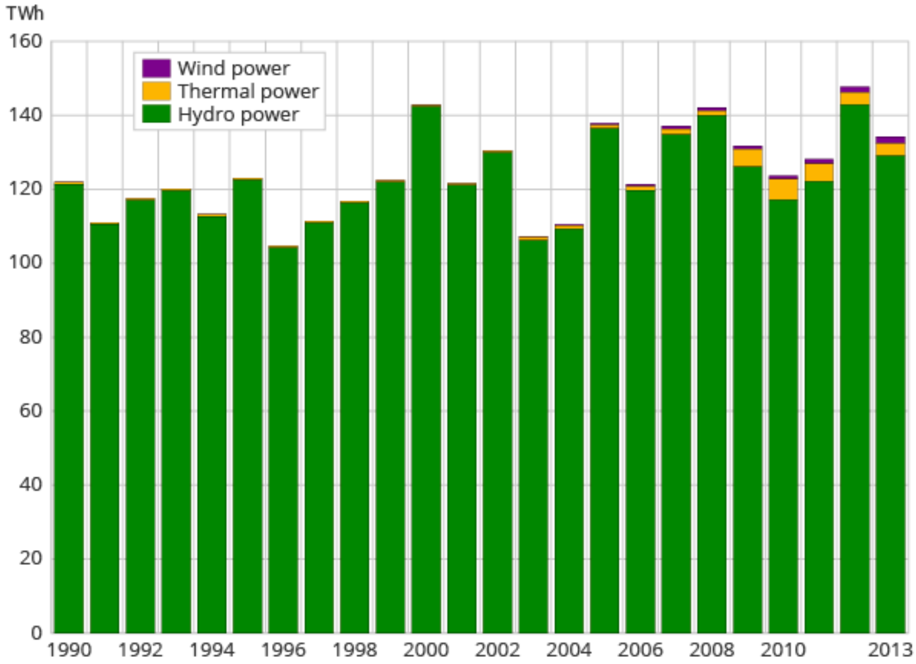

**Figure 1 Energy production in Norway (SSB, 2014)**

When considering capacity increase in the Norwegian energy system, much can be gained through energy efficiency, stabilisation of the load situation, and a conversion to more local power production. In other words, increase in production or physical strengthening of the grid infrastructure are not necessarily the only solutions to scarce capacity issues (NVE et al., 2007).

Due to the dependence on hydropower in the Norwegian production mix, the hydrological cycle and weather conditions will determine the quantity of power generation in Norway from year to year. In order to cope with the fluctuating production, imports and exports are inevitable. These are facilitated through grid connections to the Nordic countries and the Netherlands, with expansion plans towards Germany and Great Britain (Statnett, 2014).

By 2030, Norwegian TSO *Statnett* are planning to progress into the power grid of the future, the so-called "*sentralnett* of the next generation". Investments in power lines are already being made to a great extent, with an estimated annual cost of 5-7 billion NOK for the next ten years (Statnett, 2013). Not only are these grid investments part of an expansion to foreign power markets; emphasis is also being put on domestic security of supply. In order to sustain delivery of power even in the case of failures and fault situations, existing grid infrastructure needs to be supplied with alternative or strengthened pathways.

## 2.5 Characteristics of the Energy Situation in Nord-Trøndelag

Nord-Trøndelag is localised in the central part of Norway, where production of electricity is scarce compared to other regions. Because consumption in this area is high relative to the local production, central Norway is a deficit region, where the Norwegian TSO frequently sets the area price of electricity higher than the system price given by Nord Pool Spot (Statnett, 2011). This price incentive is used in congestion management to avoid technical overload in the grid, all the while providing sufficient amounts of energy to end-point users. As a consequence of the deficiency of local power supply, Nord-Trøndelag is highly dependent on energy import, thus requiring an adequate grid structure to feed the power into the region.

Other than using price regulation and monetary incentives, potential congestion can be avoided through technical upgrading of the grid. The infrastructure in Nord-Trøndelag is not yet considered old, but with potential changes in the production and consumption pattern in the region, upgrading and reinvestments become necessary. Thermal capacities of overhead lines have improved greatly since around the year 2000, meaning new infrastructure may prove very advantageous, since most of the regional grid in Nord-Trøndelag was installed in the period between 1965-1995 (Stubbe, 2012).

The deficiency of power supply in Nord-Trøndelag is significant even in years of large inflow to the region's hydropower stations (Statnett, 2013). This power scarcity threatens the security of supply, which is a main task for any power system operator to ensure. With all the abovementioned aspects of the current energy supply in Nord-Trøndelag, it is evident that investments in the grid infrastructure must be made to meet future demands. However, there are many uncertainties with respect to the development of the future power grid, both in Norway as a whole, and in the different regions, as discussed in section 2.6.

## 2.6 Future Scenario for Power Supply/Demand

There are many reasons why expansion and upgrading of the grid is necessary. Factors influencing the development of the future power grid are related to production and consumption development, which are again determined by technological development, political initiatives and demographic structures.

### 2.6.1 Power supply

Political initiatives, such as the Kyoto Protocol, the EU 2020 goals and Swedish and Norwegian electricity certificates, indicate that a transition towards a more sustainable energy production is expected to gradually take place over the next decades (NVE, Statnett, 2013). This development induces a larger fraction of the electricity production to originate from "new renewable" energy sources, for example solar and wind power. Unlike hydropower, which is a traditional renewable resource, production of solar and wind power is determined by unreliable weather conditions. Additionally, electricity is a commodity that must be consumed instantly, as there currently is no feasible method for storing electrical energy. Many hydropower stations have inflow from reservoirs, which allows for a scheduling of production. This regulation of production enables storage of potential energy, and is a unique characteristic of hydropower when compared to other renewable resources.

As of May 2014, planned installation of hydropower is 2,880 MW, with an expected production of 14,529 GWh. These numbers reflect the sum of the concessions granted by the Norwegian Water Resources and Energy Directorate, and the actual development may therefore turn out differently. However, the intention is clear; some new instalment of hydropower is to be expected. The amount of wind power planned supersedes the concessions given to hydropower, however. Planned installed power totals at 6,478 MW, responding to an estimated 18,131 GWh of energy (NVE, 2014).

An aspect of renewable energy production is the localisation of the production plants. These will often be placed far from settlements or even offshore, which results in a significant transportation distance to the consumption's geographical location. In Nord-Trøndelag licences for new wind power has already been granted to five projects, with a total potential for installed capacity of 450 GW, and these are planned in areas with low population and consumption (NVE, 2013b). In parallel with new plants, license is given to numerous micro-scale power plants, and these will be widespread in location. Both new resource utilisation and production localisation necessitate an efficient and reliable power grid, in order to employ the full potential of renewable energy production (Statnett, 2011).

### 2.6.2 Power demand

As the production system changes, so does the consumption pattern. With an increase in electrification of the petroleum sector, transmission of electricity to offshore installation requires new instalment of grid infrastructure. This tendency was most recently exemplified by the political opposition's resolution to provide the Utsira High oil field with onshore electricity (NTB, 2014). Establishing new power intensive industry also affects the power flow in the grid, and a strengthened grid will be necessary to ensure reliable delivery to industry. Central Norway is likely to have an increase in consumption both to industry and the petroleum sector (Statnett, 2013).

Energy consumption relies on the price of energy, policies and regulatory means like emission quotas, technical specifications, prohibitions and standards. Increased eco-efficiency of household appliances is an example of how electricity consumption can be reduced; however, this reduction is possibly outweighed by the continuous introduction of electricity for new purposes. Other factors inducing an increase in electricity use are population increase, blossoming household economies and economic growth in general (Energiutvalget, 2012).

Determining the future trends of electricity consumption is challenging, especially due to the uncertainties regarding development of use patterns and introduction of electricity as a replacement for traditional household heating. Electric heat pumps are being installed in Norwegian households, both in new houses and as a replacement or substitute for oil and wood. As of 2013, more than 750,000 heat pumps have been sold in Norway, and the number is expected to reach 1 million somewhere between the years 2016 and 2018 (NOVAP, 2013).

Another important factor in the consumption pattern is the expanding market for electric vehicles (EV). Charging of vehicle batteries overnight will, if sufficiently numerous, affect the daily consumption cycle. This cycle is monitored closely by the TSOs in order to schedule production of electricity as appropriately as possible. This challenge will be lessened with a more flexible, i.e. technically stronger power grid (Zdrallek et al., 2013). It is important to note however, that a power grid’s capacity is liable to the way the installed infrastructure is operated, and not merely its physical components’ technical qualities.

All of the abovementioned aspects of the development of future energy systems indicate that new and improved power systems must be installed or rebuilt. Whatever the future brings of increases or reductions of power consumption, the grid will be required to operate in a flexible manner, handling both instantaneous shifts in demand and supply, as well as more long term changes in consumption and production patterns.

To ensure a sustainable development of the power system and to meet climate targets, knowledge of the impacts and climate aspects associated with the transmission and distribution of electricity is necessary. This study therefore serves as a contributing part in a more widespread research field.

# 3 Methodology

## 3.1 LCA Framework

Life cycle assessment is a renowned method for determining environmental impacts from a product or service system. The mapping of a product's life cycle in its entirety, from raw material extraction to end-of-life treatments like incineration, recycling or landfilling is the foundation of this analytical tool.

The necessity of including the life cycle from cradle to grave stems from the fact that commodities and infrastructures in a society have long lifetimes, meaning consequences of present production and consumption is dealt with by future generations. To include every stage of a product's life cycle, the system borders of the analysis stretches wide, into different technological spheres and time frames.

The objective of LCA is to give a quantified impression of all impacts occurring due to production, use and disposal of a product. In other words environmental consequences of final demand is calculated. Emissions to air, water, soil and ecosystems may occur both in the production phase, the use phase and even in the end-of-life phase. When all the emissions and other impacts, such as resource depletion, land use, deforestation and eutrophication are accounted for in a quantitative manner, the life cycle assessment is an important tool for decision making on many levels.

The mathematics of LCA are based on the linear modelling, and the formulations used were first developed by the economist Wassily Leontief (Strømman, 2010). The open Leontief model equates output ($x$) with intermediate demand ($A*x$) plus final demand ($y$).

$$x = Ax + y \qquad 3.1$$

A is the requirements matrix, where each element $a_{ij}$ shows the required amount from sector $i$ to produce one output unit from sector $j$. When this production structure is combined with data on emissions and other stressors, impacts can be calculated using linear algebra. Equation 3.1 can also be expressed using the Leontief Inverse, $L = (I-A)^{-1}$. From this, output can be defined as $x=L*y$, because the $L$ matrix elements $l_{ij}$ represent the amount of output of process $i$ required per output unit of process $j$.

The stressor intensity matrix $S$ is multiplied with the output vector to calculate the stressors induced by a production output $x$, which again stems from a final demand $y$.

$$e = Sx = SLy \qquad 3.2$$

Equation 3.2 shows the total emissions associated with a production output generated by an external demand. However, if an LCA is to be useful for more than stating the conditions of an entire production system, a more accurate detail level of emissions is necessary. To achieve this, the stressor matrix is multiplied with the diagonalised output vector. This will result in an emission matrix $E$, as expressed in equation 3.3.

$$E = S\hat{x} = S\widehat{Ly} \qquad 3.3$$

To determine the impacts from the production system, the total emissions are multiplied with a characterisation matrix $C$, as is done in equation 3.4. Alternatively, the $C$ matrix can be multiplied with the $E$ matrix, as in equation 3.5, to express the impacts from each process.

$$d = Ce = CSx = CSLy \qquad 3.4$$

$$D_{pro} = CE = CS\hat{x} = CS\widehat{Ly} \qquad 3.5$$

$$D_{str} = C\hat{e} = C\widehat{Sx} = C\widehat{SLy} \qquad 3.6$$

The impact matrix $D_{pro}$ is interpreted as an impact matrix showing how the processes in the production system contribute to the different impact categories, whereas $D_{str}$ expresses how the stressors from $S$ contribute to the total impact.

**Table 1 LCA Nomenclature**

| Variable | Description | Dimensions |
|---|---|---|
| $x$ | Output vector | $processes \times 1$ |
| $y$ | Final/external demand vector | $processes \times 1$ |
| $A$ | Requirement matrix | $processes \times processes$ |
| $L$ | Leontief inverse, matrix of output per final demand | $processes \times processes$ |
| $S$ | Stressor intensity matrix, per unit output | $stressors \times processes$ |
| $e$ | Vector of generated stressors, for a given demand | $stressors \times 1$ |
| $E$ | Matrix of generated stressors from each process | $stressors \times processes$ |
| $d$ | Vector of generated impacts, for a given demand | $impacts \times 1$ |
| $C$ | Characterisation matrix | $impacts \times stressors$ |
| $D_{pro}$ | Matrix of impacts generated from processes | $impacts \times processes$ |
| $D_{str}$ | Matrix of impacts generated from stressors | $impacts \times stressors$ |

## 3.2 Computational Software (Arda)

In this study the NTNU developed tool Arda was used to calculate the impacts of the regional grid. Final results were obtained with the version 17.0 of the program, which applies the Ecoinvent database, combined with ReCiPe Midpoint Hierarchist method (version 1.08). ReCiPe contains the characterisation factors used to calculate the impacts, and the hierarchist perspective is the most commonly used in scientific models (Goedkoop et al., 2008). The method provides a helpful sorting of life cycle inventory results into a list of eighteen endpoint indicators, listed below.

Agricultural land transformation ($m^2a$ (area time))

Climate change (kg $CO_2$ equivalent)

Fossil depletion (kg oil equivalent)

Freshwater ecotoxicity (kg 1,4-dichlorobenzene (DB) equivalent)

Freshwater eutrophication (kg P equivalent)

Human toxicity (kg 1,4-DB equivalent)

Ionising radiation (kg $U_{235}$ equivalent)

Marine ecotoxicity (kg 1,4-DB equivalent)

Marine eutrophication (kg N equivalent)

Metal depletion (kg Fe equivalent)

Natural land transformation ($m^2$)

Ozone depletion (kg CFC equivalent)

Particulate matter formation (kg PM10 equivalent)

Photochemical oxidant formation (kg non-methane volatile organic compounds)

Terrestrial acidification (kg $SO_2$ equivalent)

Terrestrial ecotoxicity (kg 1,4-DB equivalent)

Urban land occupation ($m^2a$)

Water depletion ($m^3$)

The impact categories at midpoint level lead to endpoint damage categories, but these are beyond the scope of this project, partly due to the great uncertainties associated with the transitions from midpoint to endpoint categories. For example climate change is a midpoint category that possibly leads to the endpoint category global warming, however the relationship between these impacts categories is very difficult to quantify.

The Arda software requests input of the $A$ matrix, separated into a foreground and a background requirements matrix ($A_{ff}$ and $A_{bf}$), and a demand vector $y$ to calculate inventory results. Input of additional stressors is also possible.

The calculation results from Arda are presented in terms of total impacts $d$, $D_{pro}$, $D_{str}$ and the emissions $e$ from every possible stressor in the system. There are more than 25,000 different kinds of emissions and other stressors, contributing to the 18 midpoint impact categories. In addition to this, the software provides tools for structural path analysis and Taylor series expansion, which is useful when examining which processes lead to the different impacts. It is also possible to discern the amounts of impacts generated in each tier of the system.

# 4 Life Cycle Inventory

## 4.1 Scope and Functional Unit Assumptions

The life cycle stages inspected are materials for grid construction, grid assembly, the use phase and the end-of-life. Material requirements for grid components and production processing are included in the first stage, whereas the transportation from the production site is included in the grid assembly. The use phase covers maintenance of the infrastructure, as well as power losses that occur throughout the grid system. In the end-of-life phase disassembly of materials is modelled, but recycling is kept out. This is due both to lack of accurate data for recycling for most of the components, but also to the fact that partial recycling is included in some of Ecoinvent background processes. Leaving out recycling ascertains that double counting is avoided, in the sense that recycled materials appear both at the cradle and grave of the life cycle.

As the main, if not sole, function of the grid is to supply electrical energy, the functional unit of the system is delivery of 1 MWh to an end-point user in Nord-Trøndelag. The analysis is based on inventory and usage data from 2011, and these are presented in NTE Nett's power system plan published in 2012 (Stubbe, 2012). Consequently, this life cycle assessment depicts the impacts stemming from delivery of 1 MWh of energy in the power grid of 2011. This limits the scope slightly, however the results may hopefully prove useful in a context of considering new structures for the future T&D system.

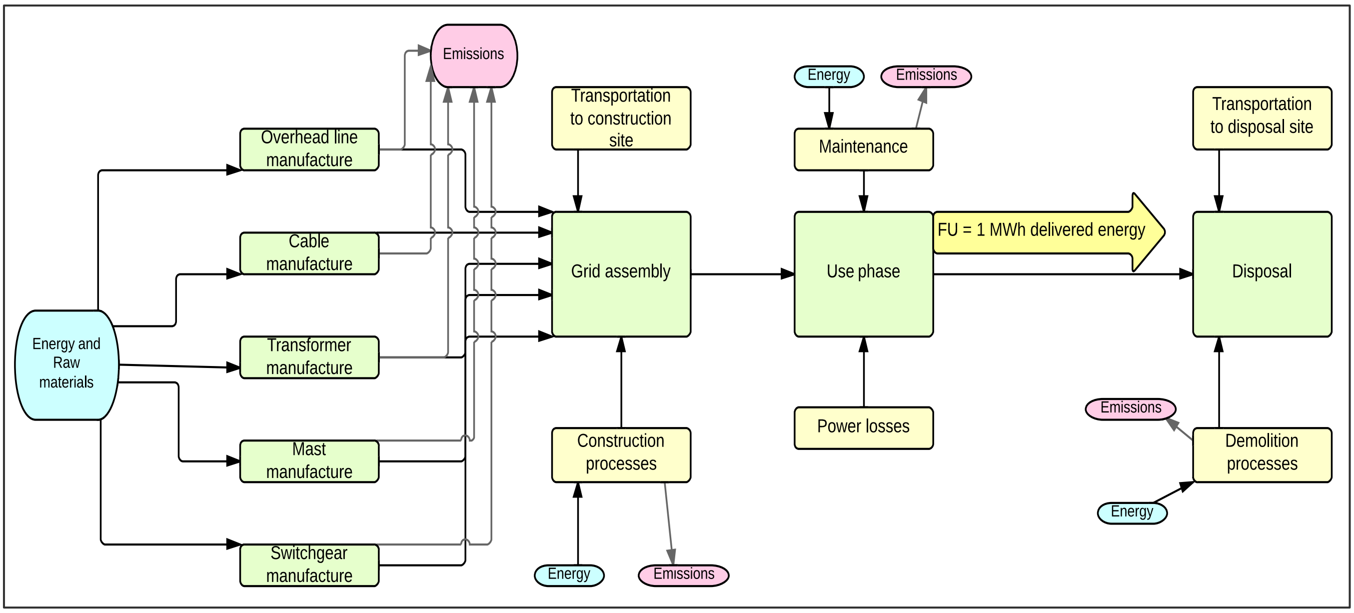

Figure 2 Life cycle flow chart

The three grid levels are modelled individually, with approximately the same life cycle. The main difference between the grid models is the selection of component types and sizes required, determined by the different voltage levels. The life cycle of the T&D grid is illustrated in Figure 2.

Generally, the physical infrastructure of power grids is highly susceptible to the environment where it is situated, meaning the surrounding nature and climate, as well as demography, determines the technical aspects of the grid. Examples of these measures are the installation of underground cables in rural areas, overhead lines spanning fjords, and positioning of transformer stations, to name a few. Therefore, an analysis such as the one presented in this project becomes rather site-specific, but general conclusions may still be drawn from it.

#### 4.1.1.1 Lifetime

The entire grid is assumed to have an average lifetime of 40 years, meaning that for the year 2011, one 40th of a grid life is used in the system. This is modelled in Arda as the entire material and energy inputs used for assembling the grid divided by 40. The 40-year life span is commonly applied in similar studies of the power grid and its components (Harrison et al., 2010, Turconi et al., 2013, Eltra, 1999).

The lifetime of the grid infrastructure is assumed to be 40 years *on average*. However, geographical positioning and the accompanying climate conditions vary greatly within the Nord-Trøndelag region. Especially the coastal part of the grid is subject to rough weather, possibly reducing the expected lifetime to as little as 20 years. To account for this range of lifetimes, the regional grid model is more differentiated with respect to lifetime. 25% of the overhead lines are calculated with inputs corresponding to a lifetime of 25 years, 5% with 20 years, and 10% to 30 years. The remaining 60% have the mentioned average of 40 years of expected functional life. The same lifetime assumptions are applied to the wood masts.

#### 4.1.1.2 Cut-off

Components that are found in the grid, but left out of the model are substations and capacitor banks. Other exclusions are mentioned in the details of each modelled component in sections 4.2 - 4.6.

#### 4.1.1.3 Data acquisition

The inventory data for both the regional and distribution grids are accessed through NTE Nett's grid database NetBas, developed by Powel. In addition, some information stems from the confidential report and personal communications with Bernhard Bolsøy and Kåre Olav Bratberg at NTE Nett (Stubbe, 2012, NTE, 2013). For the *sentralnett*, the data stem from the doctoral thesis of Raquel S. Jorge (Jorge, 2013).

## 4.2 Overhead Lines

The different kinds of lines differ mainly in sizing of the cross section of the conductor. However, the descriptive cross section is not the actual measurements of the wire, but rather the area of aluminium and/or iron, which gives the conductivity equal to a copper wire with the given cross section. Data from cable producers is therefore used to ascertain the correct amount of material input for each of the line types (NTE, 2013).

The process of wire drawing is added to all production of overhead lines, to more correctly include the production processes in addition to the raw material extraction. For this process, the only two metals available as Ecoinvent processes are copper and steel. For the overhead lines therefore, both the aluminium and steel conductors are modelled with a steel wire drawing process.

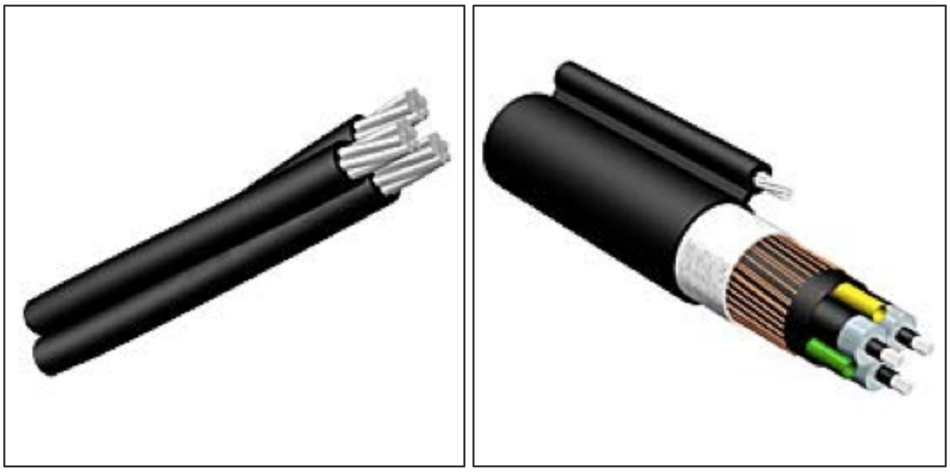

**Figure 3 Nexans illustrations, 230 V (left) and 22 kV (right) (Nexans, 2014b)**

### 4.2.1 Distribution grid

Data for the overhead lines are accessed through NTE Nett's grid database, NetBas. In total, the local distribution in Nord-Trøndelag consists of approximately 7,500 km of overhead lines. The voltage levels for these lines are 230 V, 0.4-6 kV and 22 kV. Only 1% of the total km of installed OHL are of a voltage level between 0.4 kV and 6 kV, therefore these are cut off from the system. At each of the other two levels there are several types of lines installed, with varying materials and cross-sections. For practical purposes, the lines in the model are grouped into two voltage levels (230 V and 22 kV), with two line types for each, and all four are found in Nexans' product catalogue (Nexans, 2014a).

The conductive metal is aluminium, and insulation is modelled as either polyethylene or polyvinylchloride (PVC).

### 4.2.2 Regional grid

In total, there are more than 1,000 km of overhead lines in NTE's regional grid. The conductive metal is aluminium or a combination of iron and aluminium. In the model, there are 12 different types of OHL at this voltage level, with varying cross-sections and masses per kilometre.

### 4.2.3 Sentralnett

The *sentralnett* has aerial lines at four different voltages, meaning there are four OHL types modelled in the system. These are 150 kV, 220 kV, 300 kV and 400 kV. In this grid section, more background processes of the line construction are included in the OHL process; as insulation strings, concrete and cement are also part of the lines in the model. This is done mostly because data was available, but also because at the *sentralnett* voltage level, the dimensioning of components induces larger quantities of materials for the grid framework.

## 4.3 Cables

The installation of cables typically requires extensive underground pathways, thus land modification and excavation ensue. This means heavy machinery and vehicles are used both for construction and maintenance of cables. Due to insufficient data, neither land transformation or construction processes are  included explicitly in this model; however some general construction processes are applied to the grid as a whole to reflect parts of this aspect.

The ratio of cable to OHL in terms of installed kilometres is much higher for the distribution grid than the regional grid. This is because cabling costs are higher due to the mentioned extensive construction and maintenance processes. In order to outweigh these costs, the advantages for society need to be significant, as is the case for rural areas, where cables ensure the grid is unobtrusive and out of common way.

To simulate a part of the cable production process, the Ecoinvent process "wire drawing of steel" is added to all the conductive aluminium in the cable models for the regional and distribution grids.

### 4.3.1 Distribution grid

In the distribution grid there are 4,700 km of cables. These are found to be at either 230 V or 22 kV, with respectively 80% and 20% of the total cable length. For the cables at 230 V, half of the cable length is modelled with PVC insulation, whereas the other half instead has PEX coating. This is to ensure both materials are included in the model, as several cable types are found in the actual grid. The cables at 22 kV were also grouped into two cable types, and although these consist of the same materials for insulation, the conductive surfaces differ. All cable types are modelled according to products found in Nexans' assortment. The selection is as follows:

**Table 2 Nexans cables**

| | Model name | Nexans Product |
|---|---|---|
| 230 V | Aluminium & PVC | PFSP 1kV 3x25A/10 |
| | Aluminium & PEX | TFXP1kV4G 50 |
| 22 kV | Aluminium & PEX | TSLF (HD) 24kV3x1x 95AQ |
| | Aluminium & PEX | TSLF (HD) 24kV3x1x150AQ |

### 4.3.2 Regional grid

In NTE's regional grid, only about 3% of the total wire length is cabled, which equates to approximately 32 km. Of these, only 9 km are sea cables, whereas the rest are found underground (Stubbe, 2012).

There are several types of cables used in the grid, but all have either PEX or impregnated paper (oil) as isolation. The materials in the different layers of the cable structure vary, and materials like lead, aluminium and steel are all used. The outer layer is typically a plastic material such as polyvinyl chloride (PVC) or polypropylene (PP) (Nexans). As there are in total 27 different cables in the grid when including the varying levels of conductivity found in each cable type, the cables are grouped into general categories for the convenience of the LCA modelling. This is justifiable due to the small proportion of cables in the network. To simplify further, all conductive materials are assumed to be aluminium, and all outer isolating materials PVC.

**Figure 4 TSLF Cable (Nexans, 2009)**

To determine the material input to the cables, measurements from the Nexans cable TSLF 72 kV conductor is used for approximation of all cable types except for one where data for TSLF 24 kV is used.

### 4.3.3 Sentralnett

There is only one type of cable included in the *sentralnett* model, and this is a HVDC sea cable. This is the type of cable used to connect the Norwegian power grid to the Danish and Dutch grids. In addition to conductor and insulation materials, asphalt, lead and copper are included for construction materials, and transportation is included in terms of ship freight.

## 4.4 Masts

The mast dimensioning naturally differs greatly between the three grid levels. In the distribution grid, all poles are wood poles, with a height of 8-13 m, whereas in the *sentralnett*, the 420 kV masts are made of steel and are 25-40 m tall (OED, 2012).

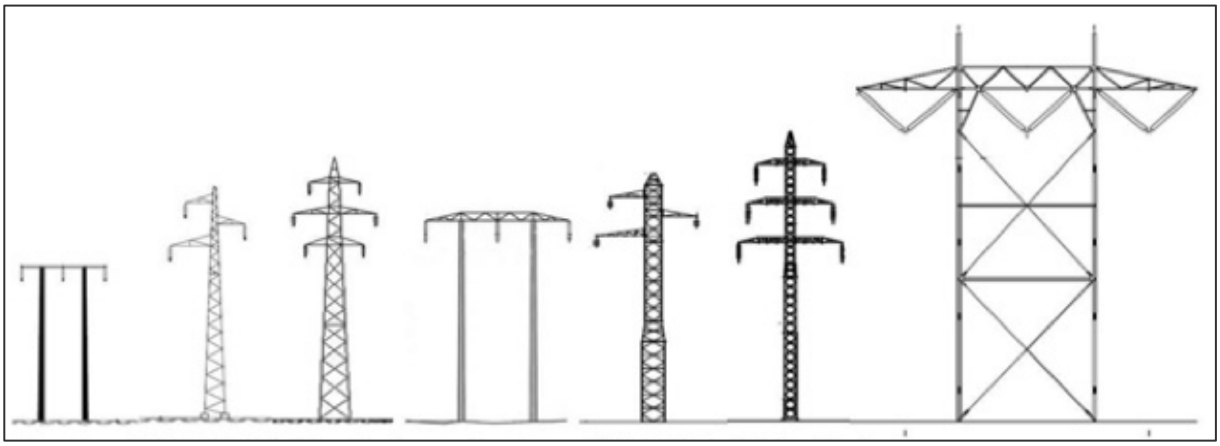

Figure 5 Examples of mast designs (OED, 2012)

Mast dimensions are in this model generally based on assumptions, rather than accurate product data, as was used for components such as cables and overhead lines. Therefore the material requirements are subject to rough estimates, leaving the uncertainty connected with the mast processes significant.

Moreover, all mast points are assumed equal in this study, in contrary to the real life grid, where masts are dimensioned according to local site specifications. Typical factors determining the mast specifications are voltage level, conductor diameter, geographical circumstances (i.e. ground composition, incline, proximity to seas and fjords) and natural conditions, such as weather, air salinity and temperature. Additionally, the time of construction of the masts varies, leading the historically “best practice” to differ between the masts.

### 4.4.1 Distribution grid

The wood poles are modelled according to voltage levels, 230 V, 0.69-6.6 kV and 22 kV, with pole heights as 9 m, 10 m and 11 m, respectively. Other than this difference, the assumptions for the masts in the distribution grid are the same.

### 4.4.2 Regional grid

The masts in the regional grid are mainly wooden poles. Of approximately 6,000 mast points in the grid, only around 30 are steel constructions (NTE, 2013).

To imitate the process of impregnating the wooden poles with creosote, the refinement process of preservative treatment of logs is used in the model. The pressure vessel used for this purpose is thought to resemble the devices used for creosote treatment.

The insulation is assumed to be strings of glass discs, and the amount required per string is as given by (Blackett et al., 2008). However, these steel masts are taller and on a larger scale in general than the masts of NTE's regional grid, the insulation is scaled down in compliance with the tower height. In addition to the foam glass, the insulation string consists of mild steel and some zinc.

The same insulation is added to the wood masts. The number of insulation strings per mast is assumed to be three, as suggested by (OED, 2012).

### 4.4.3 Sentralnett

The *sentralnett* masts' material requirements are incorporated in the data of OHL. The requirements of steel and zinc for the masts are given as mass per km of wire.

## 4.5 Switchgear

Data for the switchgear stems from product sheets by ABB ((ABB, 2004, ABB, 2001, ABB)), and although Siemens manufactures most of the switches in the Nord-Trøndelag grid, the material requirements are thought to be reasonably similar.

### 4.5.1 Distribution grid

The switches included in the distribution grid are circuit breakers at 230 V, 3.3-11 kV and 22 kV, in addition to disconnectors and load breakers. All the switch categories are approximated to match available component data from appropriate ABB switchgear. The determining factors for selecting ABB equivalent component are total weight and whether or not $SF_6$ is used for insulation.

### 4.5.2 Regional grid

In the regional grid the switchgear can be found on voltage levels of both 66 kV and 132 kV. Of the former, 116 are registered as $SF_6$-insulated switches, whereas 75 are either using pressurized air, oil or other technologies. As the number of switches without $SF_6$ at this voltage level is significant, these are modelled with the same material requirements as the $SF_6$ switches, excluding the $SF_6$ gas. Although this simplification is slightly inaccurate, the guessing of excessive material use due to lack of $SF_6$ is considered even more inaccurate.

Thus, the switches are modelled as three types, namely 66 kV with $SF_6$ insulation, 66 kV without $SF_6$ insulation, and 132 kV with $SF_6$ insulation. All are modelled according to an ABB data sheet (ABB, 2004).

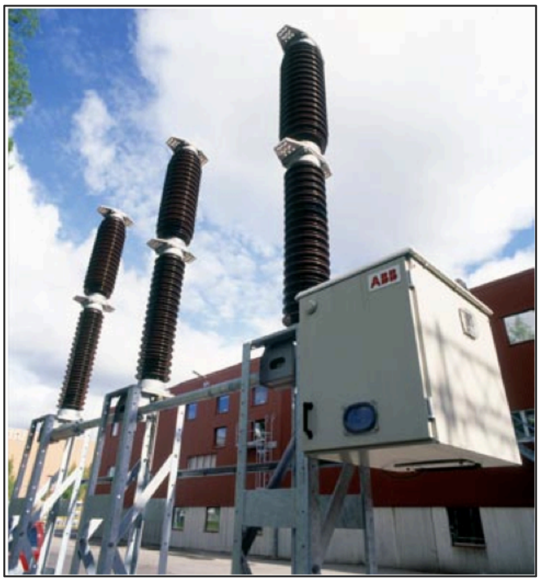

**Figure 6 Live tank Circuit Breaker type LTB 145D (ABB, 2004)**

The requirements of electricity and heat in the production phase of the switches are also assumed linear to the total mass, as are the waste products, emissions and stressors related to production. Further switchgear modelling is detailed in the appendix.

### 4.5.3 Sentralnett

Switches included in the *sentralnett* model are gas-insulated switchgear for 300 and 420 kV, plug and switch system and double break disconnectors. The inventory is as given by (Jorge, 2013).

## 4.6 Transformers

In the Norwegian grid, there are several stages of voltage transformations. Transformation occurs from production to the *sentralnett*, from *sentralnett* to regional grid, from the regional grid to the local distribution grid, to name a few instances. The voltage levels are presented in section 2.3, and the transformers installed have a varying capacity measured in MVA (Jorge et al., 2012b) provides detailed inventory data of different transformers from ABB, with the respective material inputs and wastes during the manufacturing phase of the life cycle. All transformers in all levels of the grid are modelled according to ABB's product data.

The actual transformers found in NTE's grid are approximated to comply with the transformer models provided by Jorge, based on the closest match considering the capacity in MVA.

Production is assumed to take place in Monselice, Italy, as is done in the data collection by Jorge. In reality however, NTE Nett primarily utilise transformers from Siemens or Møre Trafo (NTE, 2013).

For the production of transformers, the electricity and heat consumptions are assumed linearly related to the MVA capacity (Jorge et al., 2012b). Accordingly, emissions from the production of transformers go to both air and water, in addition to the generation of waste. The amounts vary with the capacity of the transformer. These emissions are inserted into the stressor intensity matrix *S* in Arda.

### 4.6.1 Distribution grid

In total there are more than 9,000 low capacity transformers in the Nord-Trøndelag distribution grid. The average capacity for these is approximately 200 kVA, however the lowest available data sheet from ABB is for a 315 kVA transformer. Therefore all the transformers in the distribution grid are modelled as 315 kVA.

### 4.6.2 Regional grid

**Table 3 Transformers in the regional grid**

| Capacity (in MVA) | Numbers found in the regional grid |
|---|---|
| 0.315 | 0 |
| 10 | 11 |
| 16 | 14 |
| 20 | 7 |
| 40 | 4 |
| 50 | 8 |
| 63 | 4 |
| 250 | 2 |
| 500 | 1 |

Because the range of the given transformer capacities is finer for the lower capacities, the approximations are most accurately representing the real-life transformers converting regional grid voltages to distribution grid levels. However, as a further investigation and collection of the actual data is considered too time consuming for this study, the approximation described above is used.

### 4.6.3 Sentralnett

The data inventory data for transformers is as presented in (Jorge et al., 2012b).

## 4.7 Transportation

The components are produced at different locations in Europe before being transported to Nord-Trøndelag for the assembling of the grid. Transportation inputs to the *sentralnett* are as found in the dataset compiled by (Jorge, 2013).

For the regional and distribution grid, transportation of OHL and cables is assumed to be by truck from Halden, as Nexans has a production facility located there. The distance to Hommelvik, which is located at the border between southern and northern Trøndelag, from Halden is approximately 630 km of road, but as the grid assembly is spread across the county of Nord-Trøndelag, an average distance is used for the OHL transportation. Nord-Trøndelag stretches approximately 280 km from the southernmost point, to the very north, meaning $630\ km + \frac{280\ km}{2} = 770\ km$ is a reasonable measure for the transportation distance.

Transformers are assumed to be produced in Monselice, as stated in section 4.6. The distance to a midpoint in Nord-Trøndelag is estimated to be approximately 2,740 km.

Wood poles for masts are assumed to be of Swedish origin, and a transportation distance roughly estimated to be 500 km on average.

As for switchgear, the production facility of Siemens and not ABB is assumed to be the place of origin for all the switches in the distribution and regional grids. The Schaltwerk factory is the world's largest of its kind, and is located in Berlin (Siemens, 2012). The transportation from Berlin to Nord-Trøndelag is assumed to be 1,800 km of road.

All end-of-life processes are assumed to take place within the county of Nord-Trøndelag, and $\frac{280\ km}{2} = 140\ km$ is again used as an average estimate of the necessary transportation distance from grid site to incineration or landfill facility.

## 4.8 Construction

The use of lorries and passenger cars for inspection are included in the regional and distribution grid, whereas in the *sentralnett* these processes are incorporated in the component processes mentioned above. The processes added in the regional and distribution grids are based on the same background data as is used in the *sentralnett*, scaled to the mass per km of overhead lines.

Although this is a very simplified display of grid construction processes, the detailed data required to improve the model is considered excessive compared to the potential accuracy acquired. Moreover the study of 11 kV lines and cables (Jones and McManus, 2010) concluded that the impact due to installation and assembling processes, i.e. use of machinery and vehicles for construction of the grid, was a minor contributor to the overall LCA results.

## 4.9 Maintenance

According to their power system plan, NTE inspect their regional grid by helicopter once every year (Stubbe, 2012). The standard procedure for these check-ups consist of a visual inspection combined with thermographing. Every decade a more thorough inspection is conducted, also by helicopter. The distribution grid is assumed to not demand any helicopter inspection, therefore this process is left out of the model. As compensation however, inspection with a diesel-consuming vehicle is included in the construction phase, possibly slightly overestimated.

The annual inspection is modelled according to the assumptions of Jones and McManus (Jones and McManus, 2010), where overhead lines are inspected by helicopter with an average time consumption of 4 minutes per km. The decadal helicopter inspections are assumed to take twice as long, as every mast top is photographed for further investigation. Other maintenance processes in the latter study are tree trimming and repairs. Whether the travel distances and fault rates are applicable in NTE's grid is uncertain, thus these maintenance factors are left out of the model.

The *sentralnett* maintenance is modelled according to the data supplied by (Jorge, 2013).

## 4.10 Power Losses

Active power in a three-phase transmission line is defined as:

$$P = |U||I|\cos\varphi \qquad 4.1$$

(Schavemaker and Sluis, 2008)

Here *U* is the voltage, *I* is the current and φ is the phase angle between the voltage and current phasors.

Power losses are calculated according to the following equation:

$$\Delta P = RI^2 \qquad 4.2$$

Where R can be expressed as specific resistance $\rho$ multiplied with the length of the conductor *l*, divided by the cross-section area *A* of the conductor.

$$R = \rho\frac{l}{A} \qquad 4.3$$

Inserting for *I* from 4.1, power losses in a conductor can be expressed as:

$$\Delta P = R \cdot \left(\frac{P}{U\cos\varphi}\right)^2 \qquad 4.4$$

Combining equation 4.3 and 4.4, statements about power losses from *Energiutredningen* (Energiutvalget, 2012) can be confirmed, namely that:

- Losses will increase with the increasing length of a conductor (as length increases the resistance *R*).
- Power losses increase when the amount of power transferred (*P*) increases.
- Losses will decrease when the voltage *U* increases.

Additionally, power losses occur in all parts of the power system, notably when transforming from one voltage level to another. According to *Energiutredningen* the power losses in the regional grid have been averaging below 2.0% in Norway the past decade (Energiutvalget, 2012). As stated in the introduction, the distribution network is generally contributing the most to the total losses in the grid, with above 5.0% power loss, whereas the *sentralnett* only has a loss of approximately 2.7%.

When energy is lost in the T&D system, more power must be produced to satisfy the demand for electricity. This means that all lost energy is inefficient both to the grid companies, and to the environment and society in general. The more electricity is lost, the more impacts will come from the production of replacement electricity. Consequently the composition of resources in the production mix fed into the system will be of great significance.

### 4.10.1 Modelling Power Losses

To evaluate the importance of energy losses for the total impact from the Norwegian grid, three different electricity mixes are inspected in this study, as mentioned in section 1.1. Initially the production mix for Norway was used, as this mix is the most realistic for the actual grid found in Nord-Trøndelag. However, a grid infrastructure similar to NTE Nett's grid will very likely be found in other areas as well, therefore the electricity mix of the northern countries (NORDEL) and the general European mix (RER) were also modelled. Another important reason for including other electricity mixes is the uncertainty regarding the electricity's origin, and the increase in international exchange of energy. There are already HVDC cables connecting the Norwegian power grid to both the Dutch and the Danish grid, and plans of installing cables to Germany and Great Britain are in motion. Expanding the energy market will also result in possible imports of energy from new districts, with a different resource base and power supply than what is found in Norway. Moreover, the Norwegian grid is already closely integrated with the Swedish grid, with an exchange capacity of approximately 3,500 MW (OED, 2012), in addition to overhead line connections to Finland and Russia.

Regarding the incorporation of the power losses in the model, each grid level has been assigned with a percentage of total losses in the grid. Although these values were assigned based on data from (OED, 2012), this generalising term is not reflecting the dynamic power loss situation found in the real-life grid. The different components will be responsible for the losses to a varying degree, some contributing to the total losses more than others. In addition to this, the factors contributing to the power losses described in section 4.10 are not static, and conditions such as temperature and general wear and tear will greatly affect the specific resistance $\rho$, and thus the power loss. All the while the instantaneous load situation will also dictate the losses in the grid.

The simplification is chosen nonetheless, thus there is no differentiating of the causes of power losses in the grid. This is done in part due to the static nature of the corresponding data, for instance in the yearly total of energy delivered. Should the power losses be modelled as a dynamic size, this would have to apply to the rest of the grid, with all the maintenance changes and power delivery situations occurring throughout the year included. Moreover the excessive power electronic analysis and ensuing time consumption this would induce, made this a less appealing option for modelling.

### 4.10.2 Characteristics of Electricity Mixes

As mentioned in section 4.10.1, the power losses in the Norwegian power grid are modelled with three different electricity production mixes found in the Ecoinvent database. Initially, the Norwegian mix is used, and this scenario supplies the grid with a production based almost entirely on hydropower. The other Nordic countries are introduced to the electricity mix with the NORDEL mix, and European average is used in the RER mix.

Table 4 Ecoinvent Production Mixes

| **Production mix** | **Region** | **Composition** | **Origin and characteristics** |
|---|---|---|---|
| NO | Norway | Hydropower – 98% | Hydropower |
| NORDEL | Nordic countries | Swedish production – 39%<br>Norwegian production – 29%<br>Finnish production – 22%<br>Danish production – 10% | Swedish: 51% nuclear, 40% hydro, 13% oil<br>Finnish: 27% nuclear, 19% hard coal, 18% hydropower, 15% natural gas<br>Danish: 46% hard coal, 24% natural gas, 17% wind power |
| RER | Europe | Main contributions:<br>German production – 17%<br>French production – 17%<br>British production – 11% | German: 27% nuclear, 25% lignite, 23% hard coal, 10% natural gas<br>French: 78% nuclear, 11% hydropower, 4% hard coal<br>British: 41% natural gas, 33% hard coal, 20% nuclear |

As presented in Table 4, the fraction of fossil fuels increases as the geographical scope of electricity production is expanded.

The three production mixes are chosen based on their proximity to the Norwegian grid. As international cables are installed, trade of power follows, and thus the production mix will vary based on the instantaneous prices of power generation. It is therefore necessary to view the Norwegian grid not as a separate system with only local production available, as discussed previously.

## 4.11 Disposal and Recycling

Processes are included for disposal of most of the materials found in the distribution grid. However, recycling is not taken into account separately, as the metals used in the grid construction contain a share of recycled material. Therefore, a specific addition of a recycling process for these materials would lead to a double count, or twice the actual environmental benefit, of the material use.

In particular, the steel process is important in this regard. The inventory process used for assembly of different grid components is of a low-alloy type of steel, meaning some recycled steel is integrated into the process.

Detailed information regarding recycling of materials in the grid is considered too time consuming compared to the potential accuracy benefits, therefore, the disposal of 100 % of the materials is included in a 40 year perspective, given the processes have a representative Ecoinvent equivalent. This means not all material processes are modelled in the end-of-life stage, which in turn legitimises setting100% disposal for those that do.

## 4.12 $SF_6$ modelling

In the model of the grid in Nord-Trøndelag, $SF_6$ is found on all voltage levels, although to a varying extent. It is more purposeful and thus more common to use $SF_6$ for the components at the higher voltages, as found in the *sentralnett*. This is because of the high dielectric properties of $SF_6$ when compared to air, thus component sizes can be drastically reduced. The benefits of compromising the size of the stations are more crucial for larger components found at higher voltage levels.

$SF_6$ is modelled both in switchgear and transformers, and where data was available the leakages per year are also taken into account.

# 5 Results and Discussion

In this project, each grid level is represented in an individual Arda model (details are listed in the appendix). Each grid level model is run three times, changing the electricity production mix input for the power losses, as mentioned in section 4.10.2. The resulting differences in impact that originate from changing the electricity mix are studied for each grid level, and the grid levels are also compared to each other. The grid impacts are juxtaposed with impacts associated with production of the electricity fed into the system, meaning three production mixes are studied.

When analysing the models and their impacts, the models are given names according to Table 5, in order to make the discussion more comprehensive.

**Table 5 Model terminology**

| | **NO** | **NORDEL** | **RER** |
|---|---|---|---|
| Distribution grid | *Distr_NO* | *Distr_NORDEL* | *Distr_RER* |
| Regional grid | *Regional_NO* | *Regional_NORDEL* | *Regional_RER* |
| *Sentralnett* | *Sentral_NO* | *Sentral_NORDEL* | *Sentral_RER* |
| Power generation | *Prod_NO* | *Prod_NORDEL* | *Prod_RER* |

For each of the 18 Ecoinvent impact categories, the relative distributions of impacts from the foreground processes are shown in Figure 7. Although the relative importance of the grid categories are a good illustration of which parts of the transmission system are dominating in the different impact categories, conclusions must not be drawn from this alone. This is because the categories cannot be compared to each other without performing a weighting of some sort, which in turn introduces an entire spectrum of uncertainty and subjective interpretation and value choices. For example, the impact categories may vary in severity, but this severity must ultimately be defined, regardless of the defining party being a political authority or a scientific working group. This implies assigning levels of importance to the impacts, which is a subjective and political exercise, hence not attempted in this study.

Another important aspect to keep in mind while comparing the grid levels to each other is that all levels in the Norwegian grid are mutually dependent in order to fulfil their function of delivering energy. Therefore the comparisons are only useful to “place blame”, as there is no possibility of eliminating any grid level from the total delivery system. In other words, no energy delivery can be made from the regional grid unless the *sentralnett* has fed a sufficient amount of energy into the regional grid, and the *sentralnett* cannot deliver energy unless the regional grid receives the energy. This study is not a comparative assessment of alternative technical solutions, even though the three grid levels are modelled and analysed individually.

## 5.1 Impacts from Grid Levels

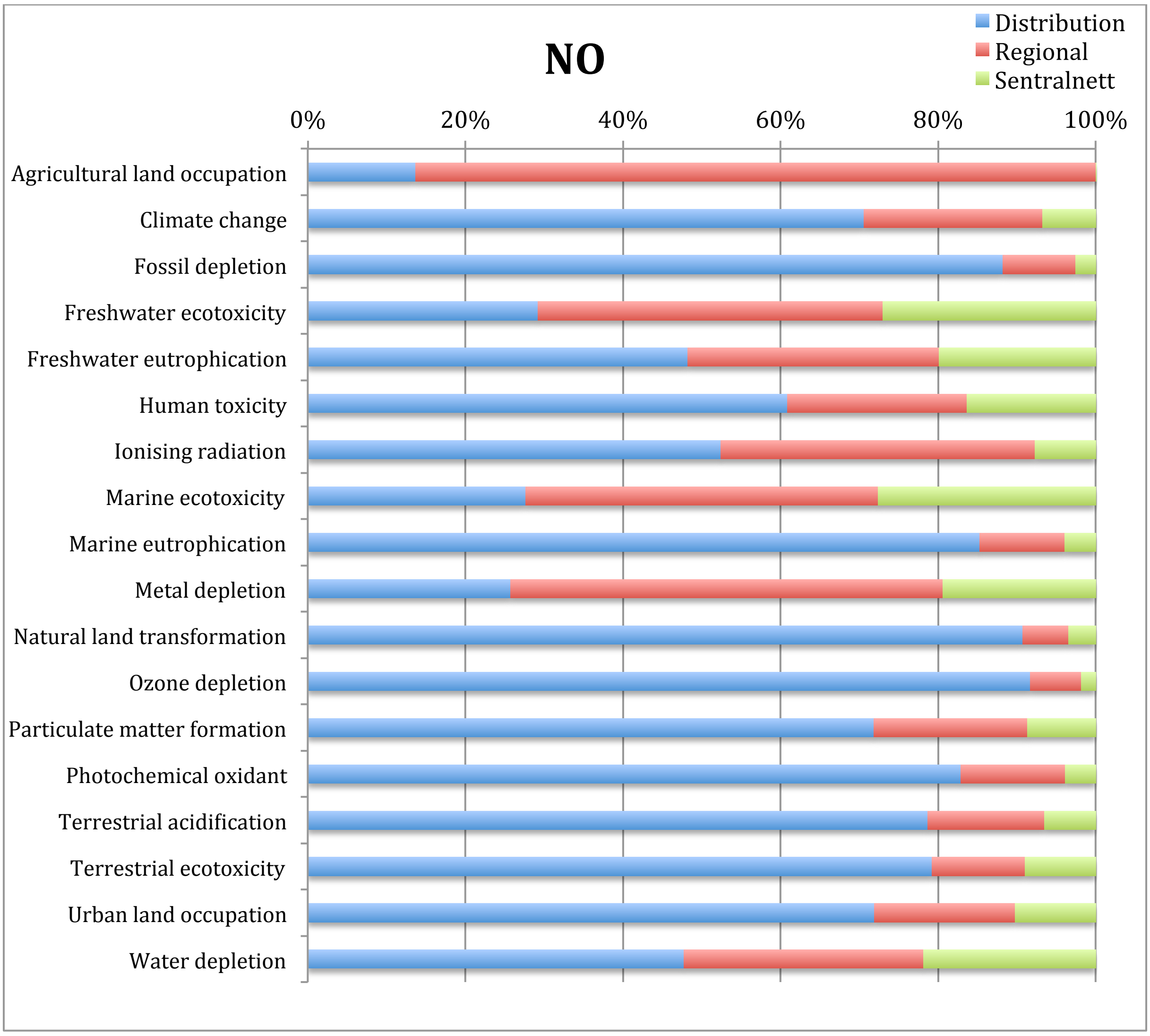

**Figure 7 Impact shares, modelling with NO-mix**

Figure 7 illustrates how the impacts from the three grid levels compare to each other. Overall, the distribution grid is causing the most impacts, when the transmission system is fed electricity from the NO mix. In only four of the 18 midpoint impact categories are the regional grid impacts more dominant. The *sentralnett* is on the other hand consistently contributing the least to the total impacts.

When modelling with the NORDEL and RER mixes, the relative impacts from the three grid levels are roughly the same as with the NO mix, signalling that the production mix fed into the system will not significantly change the allocation of impacts between the grid levels in the Norwegian grid. The plots from the NORDEL and RER mixes are found in the appendix, as are the quantitative impacts calculated in Arda.

## 5.2 Sensitivity of Electricity Mix

To narrow down the impact study, and thereby obtaining a more nuanced discussion, four impact categories will be the focus of the following sections. The chosen impact categories are climate change, freshwater ecotoxicity, human toxicity and metal depletion, as these are considered particularly relevant in the context of power grids.

One way to illustrate the sensitivity to electricity mix used in the power losses is to study the share of total impacts stemming from power losses in each impact category, as is done in Figure 8, Figure 9 and Figure 10.

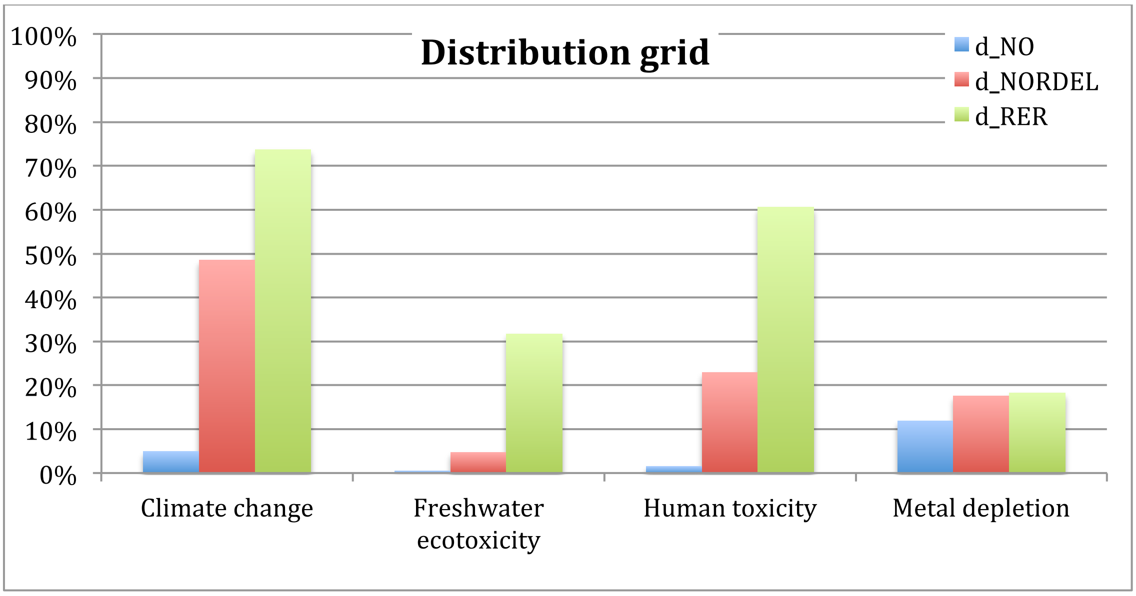

**Figure 8 Relative impacts from power losses – Distribution grid**

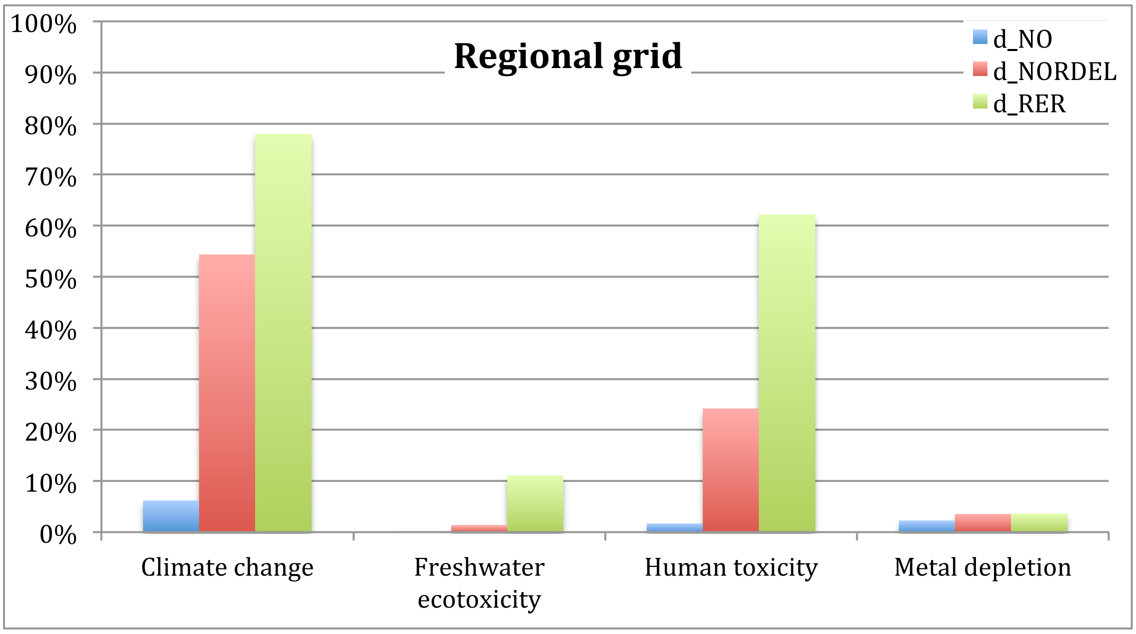

**Figure 9 Relative impacts from power losses – Regional grid**

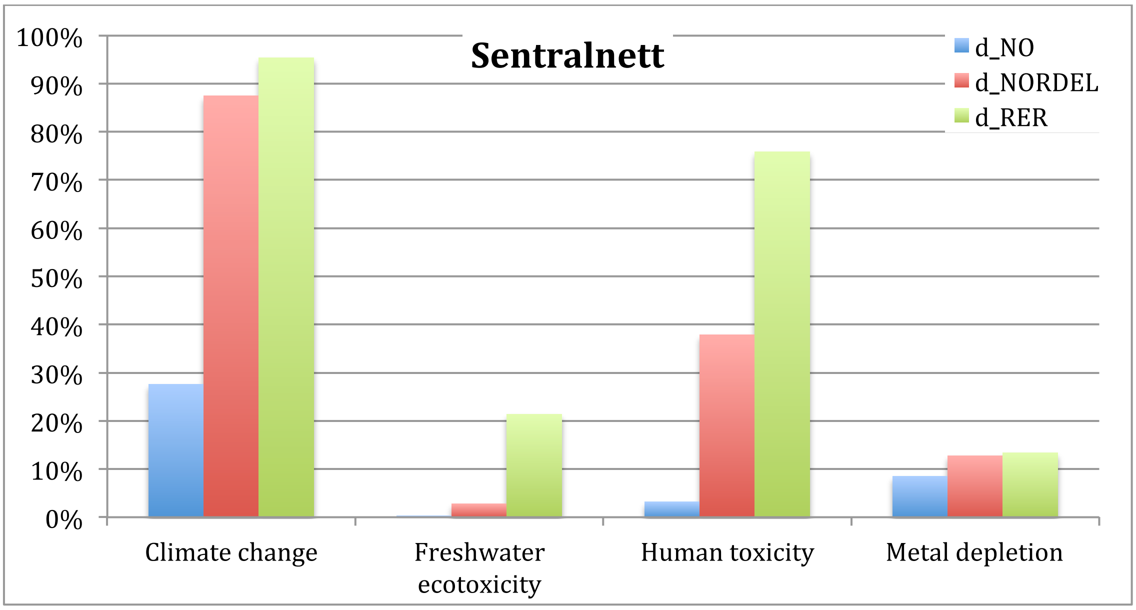

**Figure 10 Relative impacts from power losses -** ***Sentralnett***

Here, the grid levels are presented separately, displaying the relative impacts from power losses with each of the three electricity mixes.

The general conclusion from these figures is that impacts originate from power losses to a greater degree when less renewable energy is found in the production mix. Although this is far from surprising, it is a very important aspect, because it means the environmental impacts from a power system cannot be evaluated independently from the electricity transported in the grid. The delivery of electricity is in its nature dynamic, as the composition of resources used for the electricity production changes constantly. As is the case for most LCA studies, the terms of use is significant to the conclusions of environmental influence.

## 5.3 Closer Examination of Impact Categories

### 5.3.1 Climate Change

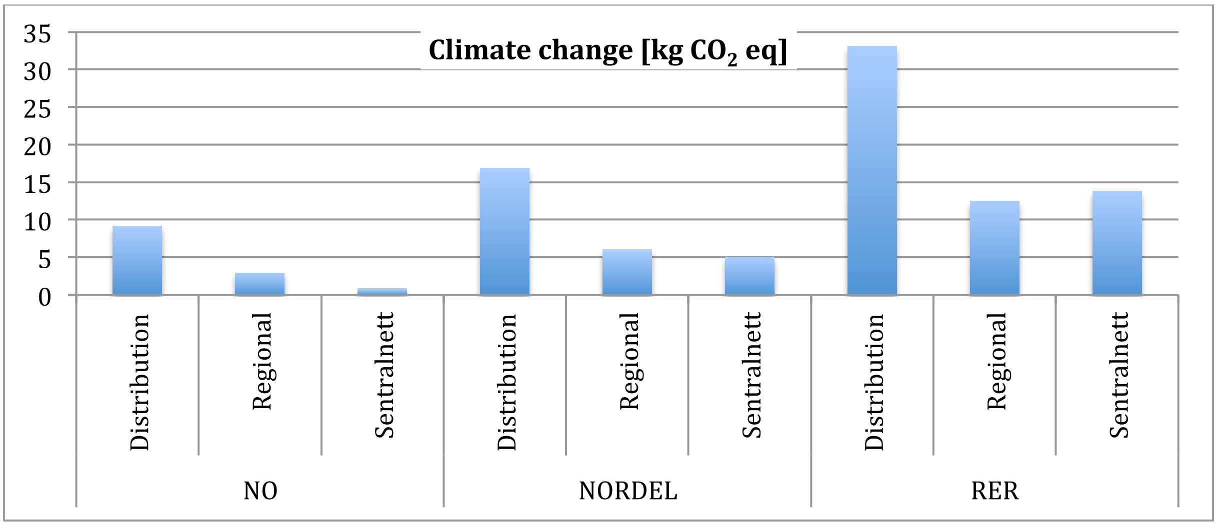

**Figure 11 Climate change impacts, all scenarios**

In the case of climate change, the distribution grid is responsible for the highest impacts in all the production mix scenarios. This is probably due in part to the higher power losses in this segment of the grid, as stated in section 4.10. Based also on the findings in section 5.2, it is reasonable to believe that a significant part of the climate change impacts stem from the power losses. All grid levels have higher impacts with RER-mix than with NO-mix.

A surprising result however, is the fact that higher impacts are found in *Sentral_RER* than *Regional_RER*, when the opposite relationship is the case for the NORDEL and NO mixes. From structural path analysis, it is evident that the climate change impacts in *Sentral_NO* originate from a broad spectrum of background processes, all linked to power losses. In *Regional_RER* on the other hand, climate change impacts stem from both power losses *and* other processes, meaning the increase in fossil fuels in the production mix will not alter the total impacts as much as it did in *Sentral_RER*. The distribution grid has the most power losses, and the highest climate change impacts. The *sentralnett* has a higher fraction of lost power than the regional grid, and thus the climate change impact from the *sentralnett* is higher than from the regional grid. Alas, when applying the RER mix, the impacts from power losses are so dominant that the relative loss percentages modelled are reflected in resulting impacts of the grid levels in Figure 11.

### 5.3.2 Freshwater Ecotoxicity

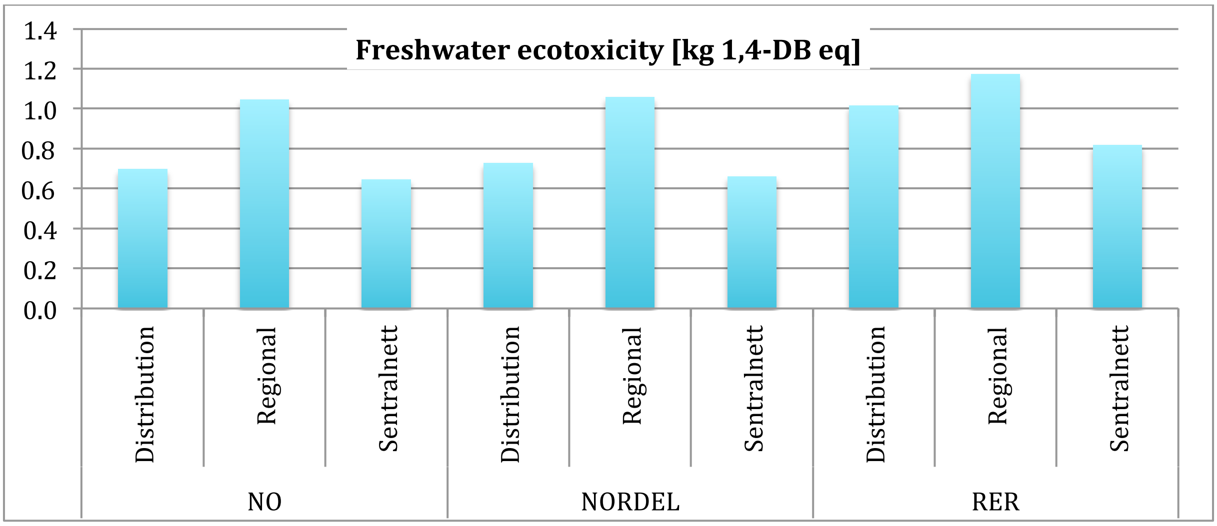

Figure 12 Freshwater ecotoxicity impacts, all scenarios

Freshwater ecotoxicity impacts are always highest in the regional grid, and the relative severity of the impacts between the three grid levels is maintained regardless of electricity mix. Interestingly, the structural path analyses reveals that the main contributing background process is the same for all grid levels. The copper disposal, albeit introduced through different components, is responsible for 38% of the freshwater ecotoxicity impacts in the *Distr_NO*, 41% in *Regional_NO* and 48% in the *Sentral_NO*. This also explains why the increase in impacts with RER-mix compared to the other two is moderate; the freshwater ecotoxicity is less dependent on power losses, and more on infrastructure, which remains constant throughout all electricity mix scenarios.

### 5.3.3 Human Toxicity

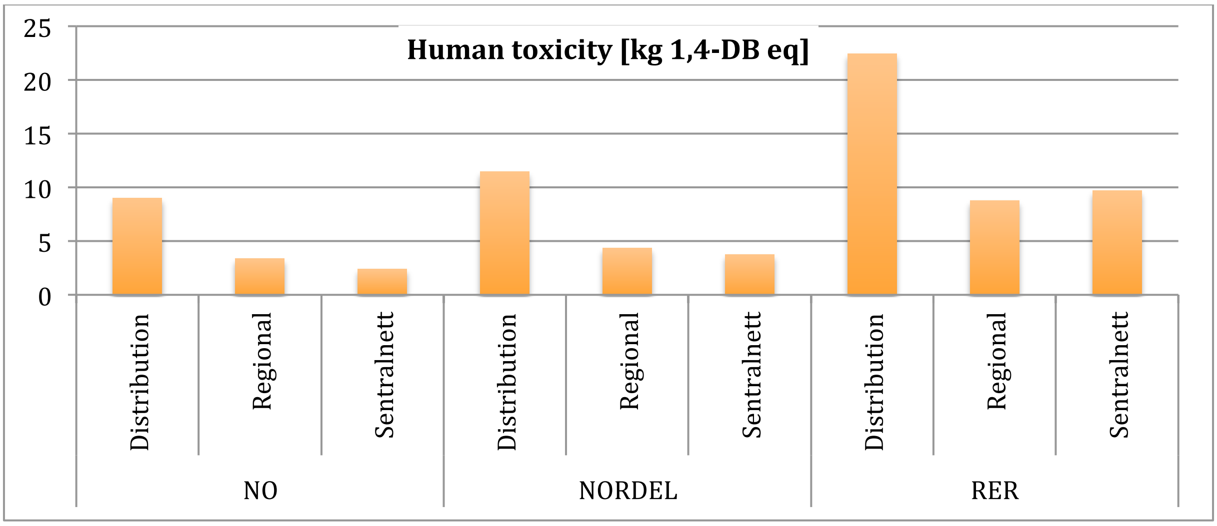

Figure 13 Human toxicity impacts, all scenarios

Human toxicity is much more severe in the distribution grid than in the two other grid levels, especially when using the RER-mix. Although in *Distr_NO* 62% of the human toxicity impacts stem from the transformer production, the impacts from power losses become significantly more dominant when modelling with RER-mix. This is due to the electricity now originating to a greater degree from fossil resources. Examples of this is lignite and coal, which is introduced to the RER-mix through British, Polish, French and German production mixes, to name a few.

The shift in the grid levels' relative impacts is the same as for climate change, when the use of RER production replaces the NO and NORDEL mixes. This signifies that although human toxicity and climate change are two very different impact categories, both are highly susceptible to power losses.

### 5.3.4 Metal Depletion

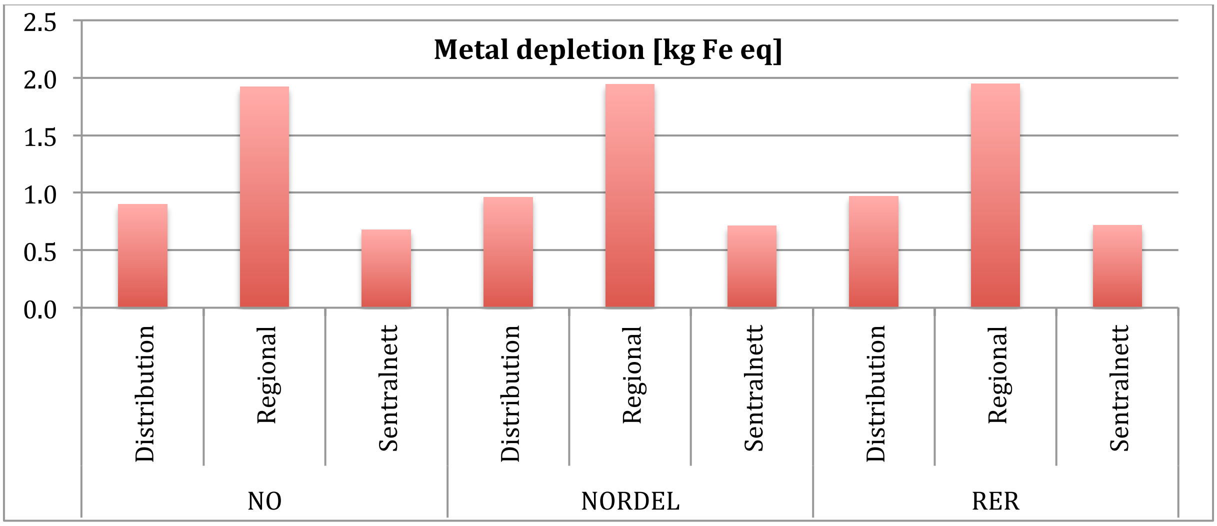

**Figure 14 Metal depletion impacts, all scenarios**

The metal depletion remains fairly constant regardless of the electricity mix used. As this impact stems mostly from the physical infrastructure of almost all components in the grid, the representation of impacts in Figure 14 should come as no surprise. Alas, the conclusion could be drawn from studying the electricity mix dependencies (or lack thereof) for metal depletion in Figure 8, Figure 9 and Figure 10.

Interestingly, the regional grid is the main contributor to the total impacts in this impact category. From structural path analysis it is revealed that the main contributor is manganese through the production of foam glass insulators for the masts. The dimensioning and corresponding material use of insulator strings stem from scaling down of equipment intended for higher voltages. Therefore, a slight inaccuracy is to be expected in the related impacts. It should be generally remarked that the unequal data foundations for the modelling of the three grid levels diminishes the use of studying the impacts in comparison to each other. This is because there are plenty of methodological differences between the three system models, although the choice of Ecoinvent processes applied for the system requirements are the same.

The distribution and regional grid models are fairly homogenous, both based on inventory data retrieved from NTE Nett's database. The *sentralnett* on the other hand is secondary data with respect to this study, as explained in section 4.1.1.3.

## 5.4 Comparing Transmission and Production

Although the study of impacts from the transmission grid is interesting in its own regard, a more rewarding perspective is obtained by comparing the transmission impacts to the impacts from electricity production.

### 5.4.1 NO Production Mix

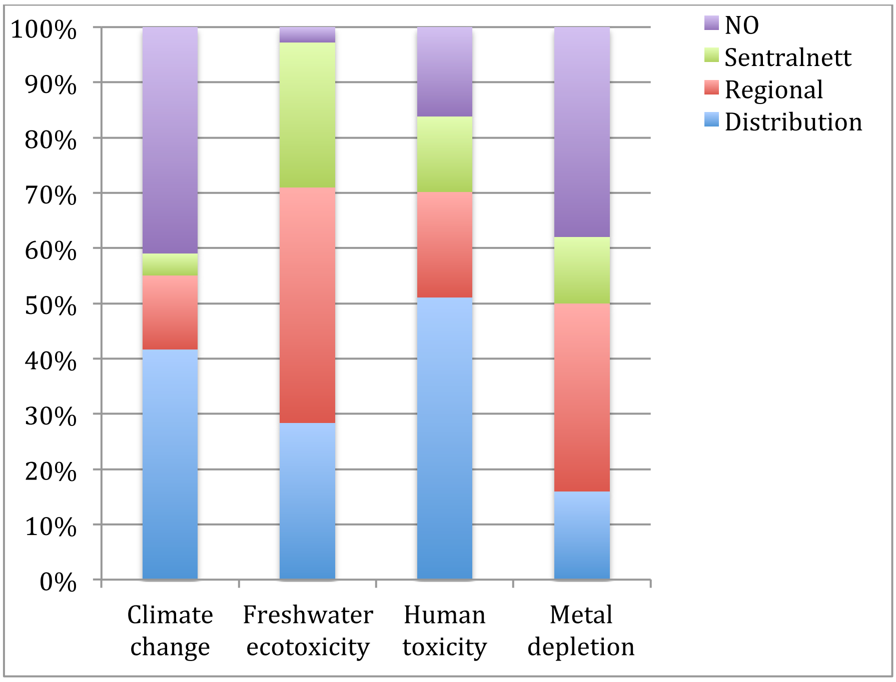

**Figure 15 Comparing grid impacts to power generation impacts, NO**

When the grid system is modelled with NO production mix, the impacts from the infrastructure (i.e. the three grid levels combined) are the most significant. This implies that with an electricity mix based mainly on renewable resources, the most environmental improvements can be gained in the transmission part of the system. With this electricity mix there are few impacts from the energy losses, meaning the total impact quantities are rather static, as they do not vary according to load situations. This is even more apparent when the impacts from the NO-mix are compared to other electricity scenarios.

### 5.4.2 NORDEL Production Mix

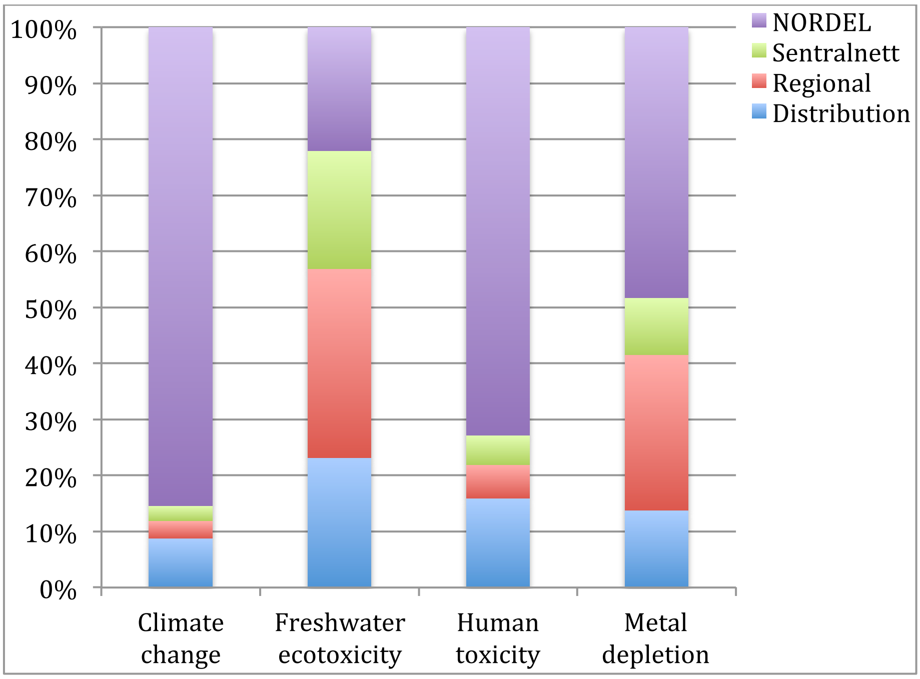

**Figure 16 Comparing grid impacts to power generation impacts, NORDEL**

Figure 16 differs from Figure 15, as the production impacts here are very large when contrasted with the transmission-induced impacts. Again the impacts are explained by the production technologies that comprise the electricity mix. The NORDEL-mix consists of Swedish, Danish and Finnish production in addition to the Norwegian production found in the NO-mix. Therefore, the impacts from production of electricity are very likely linked with the introduction of hard coal as a resource for electricity production. Hard coal is introduced to the model through the other Nordic counties' electricity production. As seen from Table 4, 10% of NORDEL consists of Danish production, where 45% is hard coal in the Ecoinvent process. Additionally, Finnish production contains 17% hard coal, and since Finland accounts for 22% of the NORDEL mix, the quantity is significant.

### 5.4.3 RER Production Mix

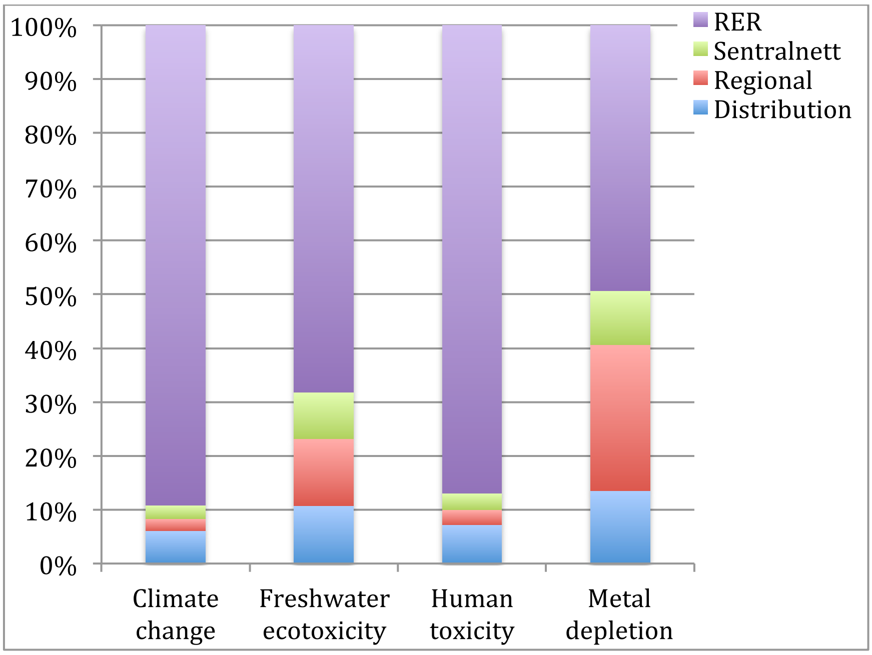

**Figure 17 Comparing grid impacts to power generation impacts, RER**

Similarly to Figure 16, Figure 17 shows a dominance of impacts from electricity production, although in the case of the RER-mix this dominance is even stronger than for the NORDEL-mix.

In the potential process of political or technological prioritising, it seems clear that action should be taken on improving environmental performance of the electricity production, for example by factoring in more renewable production. More can be gained from investments in the production segment of the energy system, as the total impacts would remain relatively similar even if the entire impacts from the grid levels were eradicated.

## 5.5 Closer Inspection

In this section the figures show the total transmission grid impacts modelled with the three different production mixes, compared to the production impacts.

### 5.5.1 Climate Change

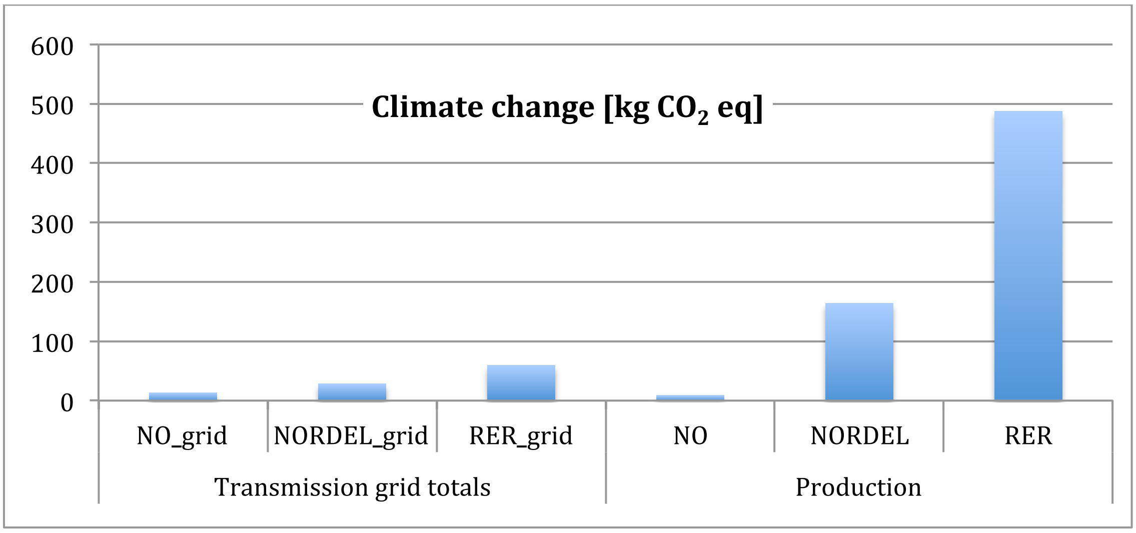

Figure 18 Transmission vs. production - Climate Change

When inspecting the climate change impacts presented in Figure 18, the impacts from production mix RER tower above the other transmission and production scenarios. Again it is essential to remark that the production mix and transmission grid are interdependent, and one cannot function without the other. Therefore, the reality of impacts will be *the sum* of grid impacts and production impacts, and the relative share of blame are visualised in Figure 19.

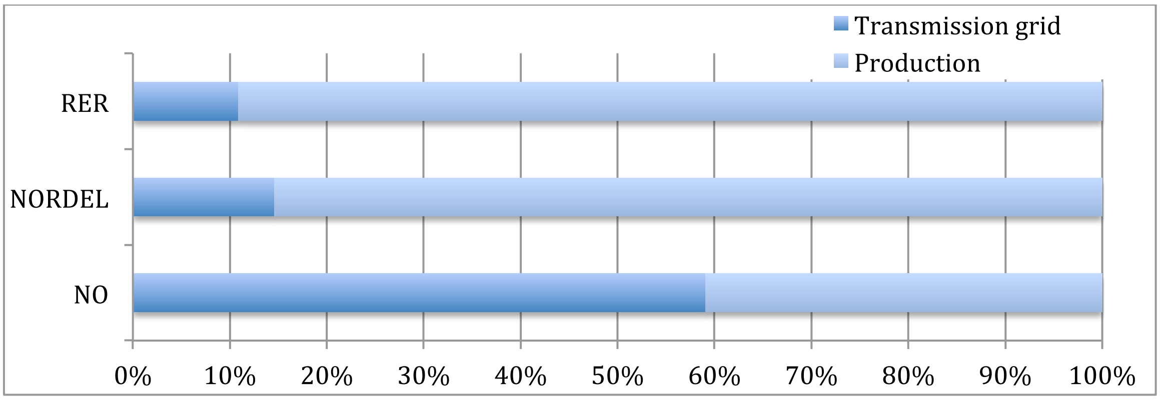

Figure 19 Impact shares of production and transmission - Climate change

In the case of climate change impacts, the production mix determines whether the majority of impacts occur in the transmission or production part of the energy system. The RER and NORDEL models are dominated by impacts from the production of electricity, whereas almost 60% of the impacts in the NO scenario stem from the transmission grid.

### 5.5.2 Freshwater Ecotoxicity

The total impact quantities are graphed in Figure 20. Unlike climate change, the freshwater ecotoxicity impacts from the three grid scenarios are relatively equal in quantity, as seen in Figure 12. The production mixes vary greatly in impacts, on the other hand. This results in the attribution of impact origins as shown in Figure 21.

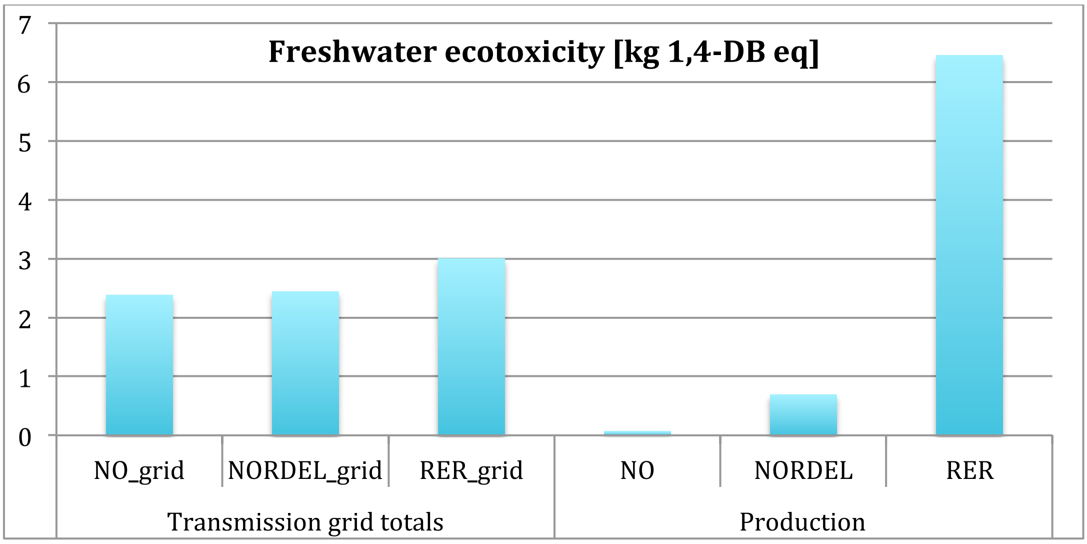

Figure 20 Transmission vs. production - Freshwater ecotoxicity

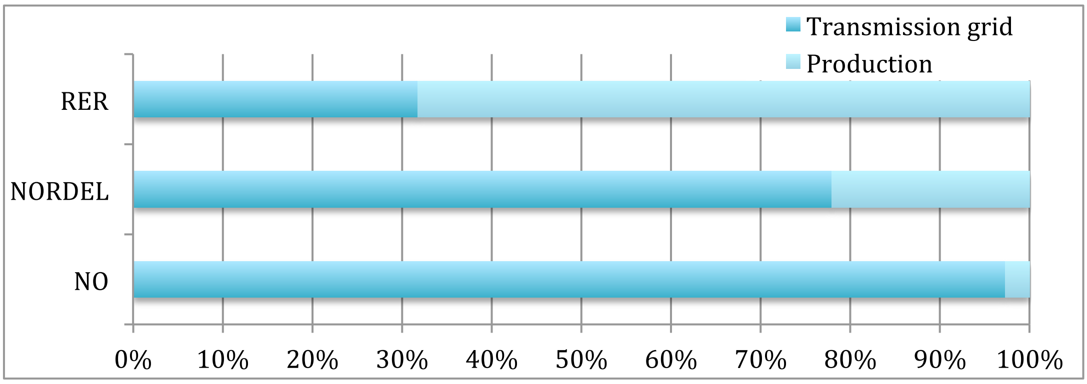

Figure 21 Impact shares of production and transmission - Freshwater ecotoxicity

As was the case for climate change impacts, the freshwater ecotoxicity impacts are split between transmission and production origin according to which production mix is considered. For the RER-mix, the impacts from electricity production dominate, whereas when modelled with NO, production is only an insignificant fraction of the total impacts.

### 5.5.3 Human Toxicity

Again the highest impacts stem from the RER production mix, as was the case for climate change and freshwater toxicity. Judging from these three impact categories, if there is a wish to reduce impacts from the energy system, the most crucial aspect to address is the production of electricity mixes dominated by non-renewable resources.

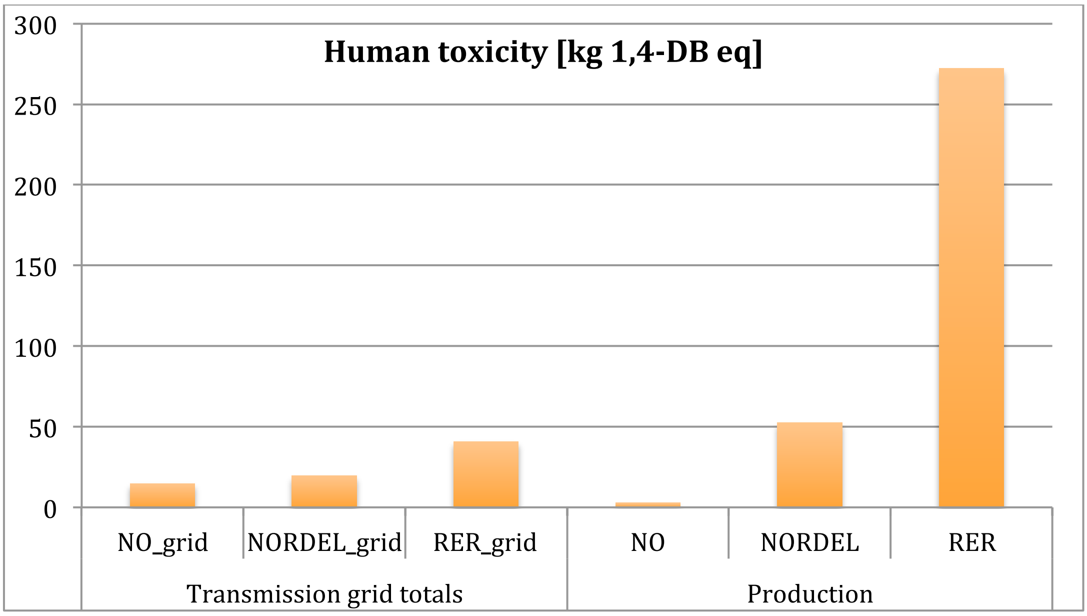

**Figure 22 Transmission vs. production - Human toxicity**

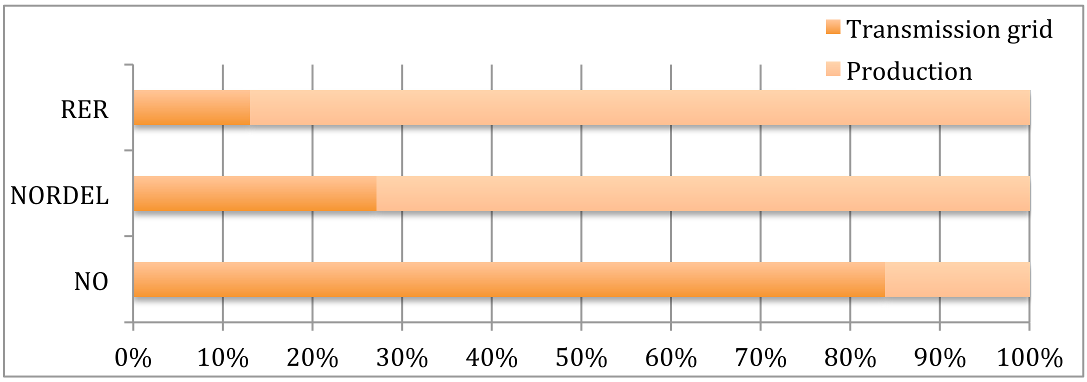

**Figure 23 Impact shares of production and transmission, Human toxicity**

A closer look at the relationship between transmission and production caused impacts reveals that the NO model is again dominated by impacts from the transmission grid, while the human toxicity impacts in the RER and NORDEL scenario originate from the production of electricity. The more renewable the electricity mix, the more can be gained from infrastructure improvement.

### 5.5.4 Metal Depletion

Unlike the three other impact categories examined, metal depletion is more severe in the transmission grid than in the production of electricity. As clarified in section 5.3.4, metal depletion is fairly independent of power losses, meaning the infrastructure is the most significant contributor to this impact category.

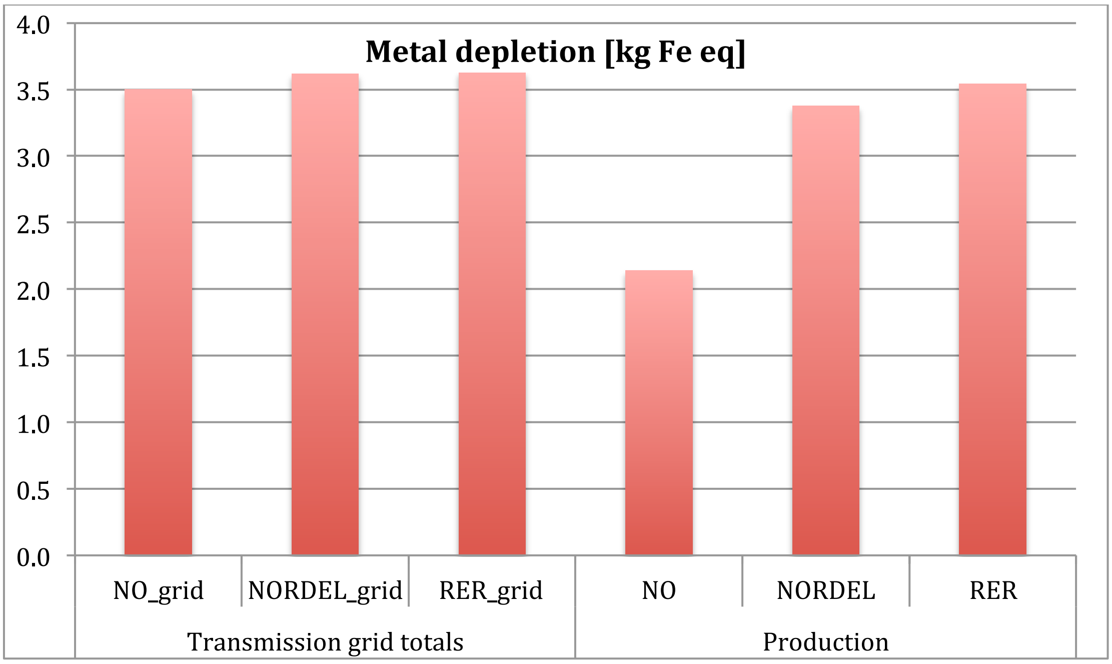

Figure 24 Transmission vs. production – Metal depletion

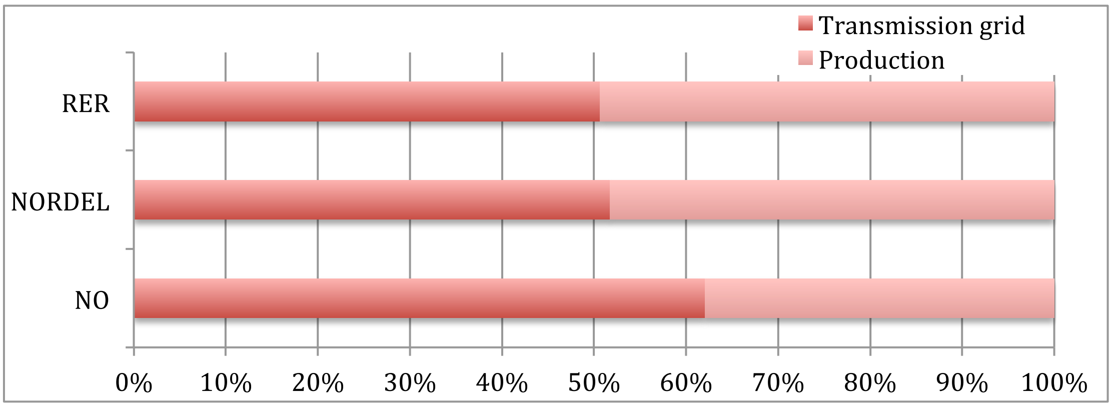

Figure 25 Impact shares of production and transmission - Metal depletion

Metal depletion is different from the other impact categories, because the impacts originate almost equally from the transmission grid and the production of electricity in the cases of the RER and NORDEL models. For the NO scenario however, the transmission grid is responsible for approximately 60% of the impacts from the entire energy system.

## 5.6 $SF_6$ significance

**Table 6 $SF_6$-emissions**

| Model | $SF_6$ emitted [kg/MWh] | Relative importance in Climate Change |
|---|---:|---:|
| *Distr_NO* | 6.49E-06 | 1.61% |
| *Distr_NORDEL* | 6.50E-06 | 0.88% |
| *Distr_RER* | 6.51E-06 | 0% |
| *Regional_NO* | 8.33E-07 | 0.65% |
| *Regional_NORDEL* | 8.38E-07 | 0% |
| *Regional_RER* | 8.43E-07 | 0% |
| *Sentral_NO* | 3.49E-07 | 0.91% |
| *Sentral_NORDEL* | 3.56E-07 | 0% |
| *Sentral_RER* | 3.63E-07 | 0% |

Absolute value of emitted $SF_6$ remains fairly constant in all three grid levels when changing the electricity mix. This indicates that the infrastructural use of $SF_6$ is responsible for almost all $SF_6$-emissions from the power grid, and power losses play an insignificant part. Also, $SF_6$ is responsible for the highest relative share of climate change impacts when the NO-mix is fed into the grid. As mentioned in section 5.4 the Norwegian electricity mix is the scenario where most impacts stem from infrastructure and not from power losses. Carbon dioxide is by far the most contributing stressor to the climate change in all nine models.

The impacts from $SF_6$ are surprisingly small, especially when considering (Jorge et al., 2012b) found that in some high voltage equipment, $SF_6$ leakages contributed more to impacts than power losses. It is necessary to remark that the $SF_6$ leakages are not modelled according to accurate data, as the regional and distribution grid stressors of $SF_6$ are a scaled version of the data from the *sentralnett*. Therefore, it is possible that the leakages modelled in this system are underestimated, and are more significant than what Table 6 indicates. On the other hand, much political attention has been paid to the problem of $SF_6$ leakages, and in 2002 the electric power sector signed an agreement drawn up by the Ministry of Climate and Environment. The purpose was to reduce emissions of $SF_6$ gas by voluntary efforts by 30% by 2010, compared to the situation in year 2000. Although this may have seemed to be an ambitious and perhaps unattainable target, the first annual report revealed that targets were not only met, but the industry had managed to cut their emissions by 60%. The total emissions shrank from 2,000 kg in 2000 to a mere 570 kg in 2003 (Miljødirektoratet, 2004). Alas, this rapid development may promise a low contribution of $SF_6$ from the power system in the future, although it is unlikely to be as completely insignificant as implied in Table 6.

## 5.7 Data Evaluation and Methodological Limitations

As noted by (Arvesen et al., 2011), LCA as a methodology has certain limitations, although it is the preferred method for a holistic quantification of impacts from a product's or system's life cycle. Conventional LCA methodology is known to suffer from underestimation of impacts, because the coverage of product systems is somewhat incomplete. Also, changes in the background economy are not accounted for, which is especially interesting in the cases where the studied product or system is widely adopted in the economy. Alas, the impacts are often more accurately related to the chosen reference units, rather than aggregated systems of larger scale. These weaknesses must be kept in mind when assessing the results of the impact calculations.

More specifically to the data acquisition, the different origins of the data used for the modelling inevitably reduce the validity of conclusions drawn. Especially when comparing the grid levels and assigning the degree of importance between them is the unequal data foundation an issue. However, the tendencies are occasionally so clear that minor discrepancies between the models do not alter the final conclusions. Henceforth this chapter will focus on the modelling limitations of the regional and distribution grid levels.

As in most studies, the data quality used for modelling the grids in Nord-Trøndelag is of varying quality and accuracy. The details of overhead lines, cables, masts, transformers and switchgear are very good, with precise accounting of components types and quantities present in NTE's grid. These were found in the power system plan from 2012 and acquired through NetBas, provided by NTE Nett. For the grid components, producer data was used to assess the material requirements in each conductor. The weakness with the implementation of this data material is the adaptation of a real-life system to the available Ecoinvent processes, but this will be the case when modelling any life cycle inventory.

Towards the final stages of the working process, it was discovered that an erroneous value has been used in processes involving softwood. Most notably the wood masts modelled are skewed by this mishap, however these processes are unlikely to significantly alter the final impact results discussed in this thesis.

Contrary to what is modelled in the regional grid, there are significant differences within transportation of components for the grid, especially for transformers. Total mass of around 40 tonnes is a rough theoretical estimation for separating transformers requiring standard (truck) transportation and transformer stations demanding specialised methods, with assembly on site. In this model, all mass used for transformers, regardless of transformer size, is assumed transported by truck, which increases the gap between the real life scenario and the theoretical inputs to the model.

Overall, transportation processes are based on generalisations and rough estimations regarding vehicles, distances and operation times. Even though this possibly obscures the results to a certain degree, the impacts would probably be more skewed without any form of transportation represented, which is the only realistic alternative.

The same reasoning is behind the assembly processes included in the models. However, more processes are omitted in this aspect of the grid model, meaning field construction and site assembly is not contributing to the impact categories. For cable manufacture and OHL manufacture however, wire drawing of the conductive metals is included, to imitate a part of the construction process.

Although touched upon in chapter 4.10, it is worth mentioning that power losses are incorporated in a manner that does not differentiate the contributions from the different components. The operating conditions will determine the specific losses in the grid components, however this study is a static year-long frame of a grid's lifetime, meaning dynamic conditions would not fit in with the rest of the data. Additionally, the inclusion of varying power losses would be too time-consuming to attempt in this study.

The only process modelled in the maintenance category is the routinely helicopter inspection, and this is only applied to the regional grid. Therefore it is possible that maintenance as a foreground process would have contributed with more impacts to the total midpoint, if more maintenance had been included. A challenge regarding maintenance outside scheduled operations, are the occasional faults and failure situations that may occur at any given time. These may happen at different places in different years, and vary in severity. The requirements for repair are highly dependent on the severity of the failure, the weather conditions and cost calculations, meaning an average maintenance scenario for 2011 is difficult to assemble. Additionally, a 2011 scenario will not automatically be relevant for other years, in case results from the LCA is to be extrapolated to future years or scenarios.

Furthermore, the extrapolation of results in relation to time frames is an important aspect to consider in terms of grid structures, technologies, and construction processes. Because a power grid is constructed continuously, the grid present in 2011 consists of elements originating from a wide spectre of eras. Technology, construction processes and health and safety regimes are determined by their respective era, meaning the correct modelling of the construction of the 2011 grid is hard to obtain. A possible solution could be to model all components as if they were constructed using present technology and methods. Alas, the present grid construction is the most similar to what will be the future technology of assembly. This will make the LCA results obtained more applicable, if results are to be used for future decision-making.

A methodological simplification is introduced through the application of only three electricity mix compositions. The supply situation in Norway will probably be somewhere between the NO and NORDEL compositions most of the time. As the real-life mixture of resource origin in the electricity mix constantly changes, the modelling with static mixes is a significant limitation.

Lastly, it is important to bear in mind how grid infrastructure and choice of construction solutions depend on geographic and climatic conditions. Consequently, results obtained from an LCA concerning a grid in Nord-Trøndelag will not necessarily serve for power grids situated in other geographic areas. However, some elements of the modelling are already generalised through the application of standardised Ecoinvent processes.

## 5.8 Comparison with Previous Studies

Climate change impact is the most commonly calculated impact category in studies of the environmental effects of T&D systems. In this thesis the impacts have been calculated in many different scenarios, resulting in divergent numbers of the climate change impacts. The total sum from the three grid levels with NO production mix fed into the system is 13.0 kg $CO_2$-equivalents per MWh of delivered energy. Of these, 9.2 kg stem from the distribution grid, 2.9 kg from the regional grid and 0.9 kg from the *sentralnett*.

**Table 7 Climate change impacts in the Norwegian grid [kg $CO_2$-eq]**

| Production mix | Distribution | Regional | Sentralnett | TOTAL |
|---|---|---|---|---|
| NO | 9.2 | 2.9 | 0.9 | 13.0 |
| NORDEL | 16.9 | 6.0 | 5.1 | 28.0 |
| RER | 33.1 | 12.5 | 13.8 | 59.3 |

Comparing these numbers directly to the previous studies presented in chapter 2.2 is somewhat complicated due to the difference in both functional units and scope limits and assumptions. Nevertheless, valuable insight can be gained from the comparisons, and it is therefore attempted for some of the studies.

(Jorge and Hertwich, 2013) found the transmission of 1 kWh of electricity brought on 1.3-1.5 g $CO_2$-eq. This corresponds to 1.3-1.5 kg per MWh, meaning it is fairly similar to the results from this study's *sentralnett* with NO-mix model. This is reasonable, considering the data are the exact same, modelled in very nearly the same manner, although with different versions of ReCiPe. Another difference in the modelling is the approach to recycling, which was included by (Jorge and Hertwich, 2013), unlike in this study, as explained in section 4.11.

The impacts from the Danish power system (Turconi et al., 2013) were also highly affected by energy losses, although metal depletion is noted to be mostly dependent on infrastructural processes, as was the case for the Norwegian grid. The total climate change impact from the system is 2 g $CO_2$-eq per kWh, which is comparable to the results from the Nord-Trøndelag regional grid, when using the NO mix. However, when modelling with the Nordic and European mixes, the impacts from all the Norwegian grid levels are much higher than that of the Danish system. This deviation may be explained by the differences of the scopes and grid systems, especially as the Norwegian grid is modelled with three distinct levels, two of which were at a higher voltage than the Danish model maximum of 50 kV. Additionally, the inclusion of grid components is different in the two studies.

The assessment by (Harrison et al., 2010) resulted in a global warming potential of 11 g $CO_2$-eq per kWh delivered. This is a size quite similar to the obtained climate change impact from the Norwegian grid, however the electricity mixes used should be very different in the two systems, to reflect the real-life production differences of Great Britain and Norway. Therefore, the similarity of climate change values should not be assigned too much importance, especially as the Norwegian grid's impacts are much larger when modelled with the NORDEL and RER production mixes. Another significant difference between the two studies is the modelling of power losses. In the British study they were modelled as load dependent, as opposed to the static percentage value applied in the Norwegian model.

With a slightly different scope, the environmental aspects of large-scale wind power integration was assessed by (Arvesen and Hertwich, 2012), and the climate change impact was 22.5 g $CO_2$-eq per kWh for the delivery of onshore wind and 21.2 g for offshore wind. These impacts are much larger than the transmission-induced impacts in general, which puts the abovementioned grid impacts in a relevant perspective. Alas, the impacts from transmission alone are small when set up against the impacts stemming from electricity generation, although this varies greatly. The production mixes applied in the assessment of the Norwegian grid are depicted in Figure 26.

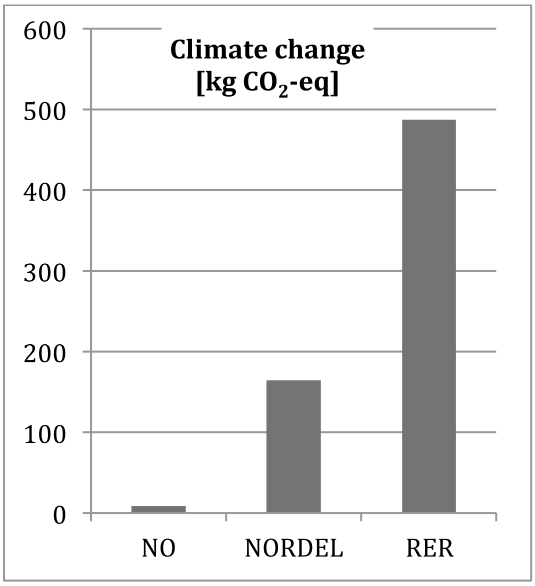

Figure 26 Climate change from electricity production

Compared to the production of 1 MWh of the RER electricity mix, the climate change impacts from T&D are negligible. This does not mean insignificant, however, as the European Union aims to increase the fraction of renewable energy in the production mix. The more renewable the energy mix, the less climate change impacts occur and the relative importance of the T&D impacts increases. Moreover, any reduction of impact is beneficial even if the cut is not from the main contributor, as every little bit helps.

## 5.9 The Road Ahead

The understanding of environmental implications of electricity transmission and distribution becomes increasingly relevant as more renewable power production is admitted to the grid system. Grid infrastructure is a prerequisite for the successful realisation of the ambitious plans for the future energy systems. Knowledge of the environmental strains associated with electricity transmission is therefore crucial if targets of combatting global warming are to be achieved.

A concept not fully covered in this thesis' models is the variability in the power losses. Although time-consuming, a method of incorporating the dynamic power losses should be attempted in future investigations. Not only because the resemblance to the real-life situation would improve, but more so because the power losses prove to be such a significant contributor to the overall impacts from the T&D system. Moreover, a thorough understanding of the occurrence of losses and ultimately the avoidance of these is probably the most efficient way of reducing impacts from the transmission system.

Power losses are inevitable however, and to be realistic, other tactics must be tried out alongside the potential power loss mitigations. Perhaps the most basic statement is that the less electricity transportation, the less impacts from said transportation. In other words, a long-term development in a direction of less travel distance for the electricity would be beneficial. In such a scenario, the production of electricity needs to be geographically close to the consumption. Of course a complete balance of local production and consumption within a small area is unrealistic, and a certain exchange across longer distances is unavoidable. Nevertheless, the amount of losses is directly proportional to the distance of transportation, and in addition to load situation of the conductors, determines the loss quantity. A closer integration between dynamic power electronic studies and LCA would therefore be very interesting, especially in terms of developing substantial strategies for impact mitigation.

Another aspect that should be explored further is the effect of reducing $SF_6$ losses in the grid system. In this thesis, rather surprisingly $SF_6$ was not found to be as significant as in the studies by (Harrison et al., 2010) and (Jorge et al., 2012b). The reasons for this were touched upon in section 5.6, and $SF_6$-impacts were concluded to be very likely underrepresented in this study. As climate change impacts are probably more significantly related to $SF_6$ use and leakages in the grid, it would be interesting to see if the reduction of $SF_6$ emissions over time will alter the climate change impacts from T&D systems.

Alas, comparisons of technical solutions for grid system operation could be interesting, even more so if it could become a general approach to environmental impact study. Comparative LCAs have already been performed in terms of cabling versus aerial lines, but holistic studies of benefits from changing operation practices of the power grid have not. Studying and comparing different use patterns of the TSOs in terms of environmental impacts is a complex, yet possible approach to future grid system LCAs.

Even if power grids do strain the environment simply by existing, it must be remembered that this infrastructure makes the exchange and trade of electricity possible. This means that given the right economic basis, such as relatively open markets and stock exchanges, cost-effective power production can be secured through the flow in the grids. With recent initiatives in Scandinavia of green certificates to ascertain more electricity of renewable origin, a strong and reliable grid is demanded to ensure the best possible allocation of this production. Although in this thesis the environmental consequences of power grids have been under scrutiny, it must not be forgotten that the most impacts still stem from electricity generation, most importantly non-renewable power production. The advantages of a reliable power grid may outweigh the detriment to the environment, as the infrastructure plays a crucial role in phasing in more renewable energy.

Realistically, the grid must therefore be seen as part of a bigger picture, allowing for mitigation of environmental impacts from other parts of the energy system.

# 6 Conclusion

When modelling the T&D grid with the Norwegian production mix, the distribution grid impacts dominate in most of the 18 Ecoinvent midpoint categories. The total amount from the three grid levels combined is 13.0 kg $CO_2$-equivalents per MWh of delivered energy. Of these, 9.2 kg stem from the distribution grid, 2.9 kg from the regional grid and 0.9 kg from the *sentralnett*.

Four impact categories were studied more thoroughly, and two were found to be more susceptible to power losses than the other two. Climate change and human toxicity impacts increased drastically when more carbon intensive electricity mixes were applied to the power losses in the model, whereas freshwater ecotoxicity and metal depletion remained more unchanged. The increase in impacts when varying the electricity mix indicates that an impact category is dependent on power losses. Following this statement is the conclusion that a power system cannot properly be evaluated unless seen in context with the electricity mix fed into the system.

Comparing the impacts from electricity transmission to the power production showed that in the energy system as a whole, the significance of T&D is relatively small. When compared to the production of 1 MWh of the European electricity mix, the climate change impacts from T&D are negligible. However, the less fossil fuel based the electricity production is, the more significant are the infrastructure impacts. Therefore, in case of a future transition towards a more renewable electricity production, the environmental strains of the grid will become more important. Political action should in the first instance prioritise the improvement of the environmental performance of the electricity production. When the electricity mix is freed from carbon intensive technologies however, more can be gained in terms of environmental benefits from grid infrastructure improvement.

$SF_6$ leakages contributed surprisingly little to the climate change impacts. It was deemed likely that the model contains underestimation for this aspect of grid operation. However, rapid development of $SF_6$ leakage quenching has been reported in the power sector, which in turn may promise a lower impact contribution of $SF_6$ in the future.

A closer integration between dynamic power electronic studies and LCA methodology is suggested for future investigations of environmental impacts from T&D system. This would be particularly interesting as a foundation for developing impact mitigation strategies.

Even if power grids in themselves strain the environment, this infrastructure makes the exchange of electricity possible. The advantages of a reliable power grid may outweigh the detriment to the environment, as the infrastructure plays a crucial role in phasing in more renewable energy.

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# APPENDIX

## Numerical impacts values

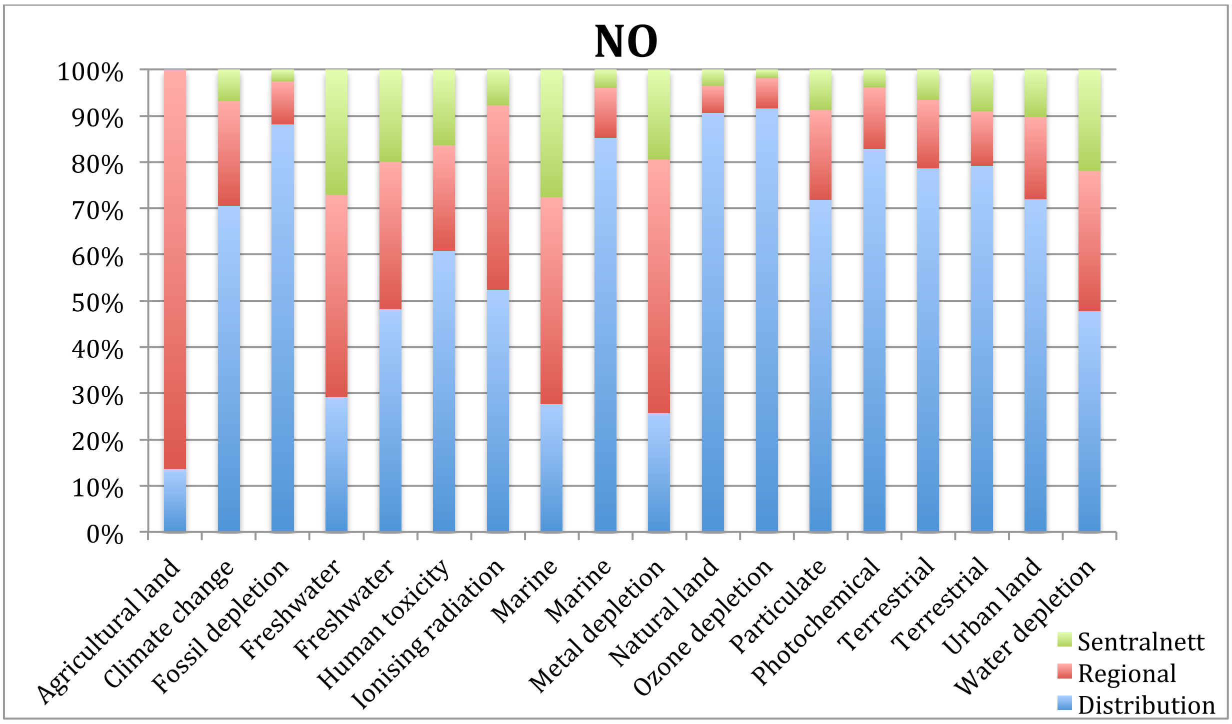
| | | d_NO | | |
|---|---|---|---|---|
| **Name** | **Unit** | **Distribution** | **Regional** | **Sentralnett** |
| Agricultural land occupation | m2a | 1753.707 | 11084.484 | 0.038 |
| Climate change | kg CO2 eq | 9.151 | 2.940 | 0.878 |
| Fossil depletion | kg oil eq | 7.753 | 0.812 | 0.223 |
| Freshwater ecotoxicity | kg 1,4-DB eq | 0.697 | 1.044 | 0.644 |
| Freshwater eutrophication | kg P eq | 0.003 | 0.002 | 0.001 |
| Human toxicity | kg 1,4-DB eq | 9.001 | 3.370 | 2.412 |
| Ionising radiation | kg U235 eq | 1.108 | 0.844 | 0.163 |
| Marine ecotoxicity | kg 1,4-DB eq | 0.565 | 0.912 | 0.563 |
| Marine eutrophication | kg N eq | 0.005 | 0.001 | 0.000 |
| Metal depletion | kg Fe eq | 0.900 | 1.920 | 0.679 |
| Natural land transformation | m2 | 0.011 | 0.001 | 0.000 |
| Ozone depletion | kg CFC-11 eq | 0.000 | 0.000 | 0.000 |
| Particulate matter formation | kg PM10 eq | 0.023 | 0.006 | 0.003 |
| Photochemical oxidant formation | kg NMVOC | 0.069 | 0.011 | 0.003 |
| Terrestrial acidification | kg SO2 eq | 0.062 | 0.012 | 0.005 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 0.004 | 0.001 | 0.000 |
| Urban land occupation | m2a | 0.099 | 0.025 | 0.014 |
| Water depletion | m3 | 70.941 | 45.182 | 32.474 |

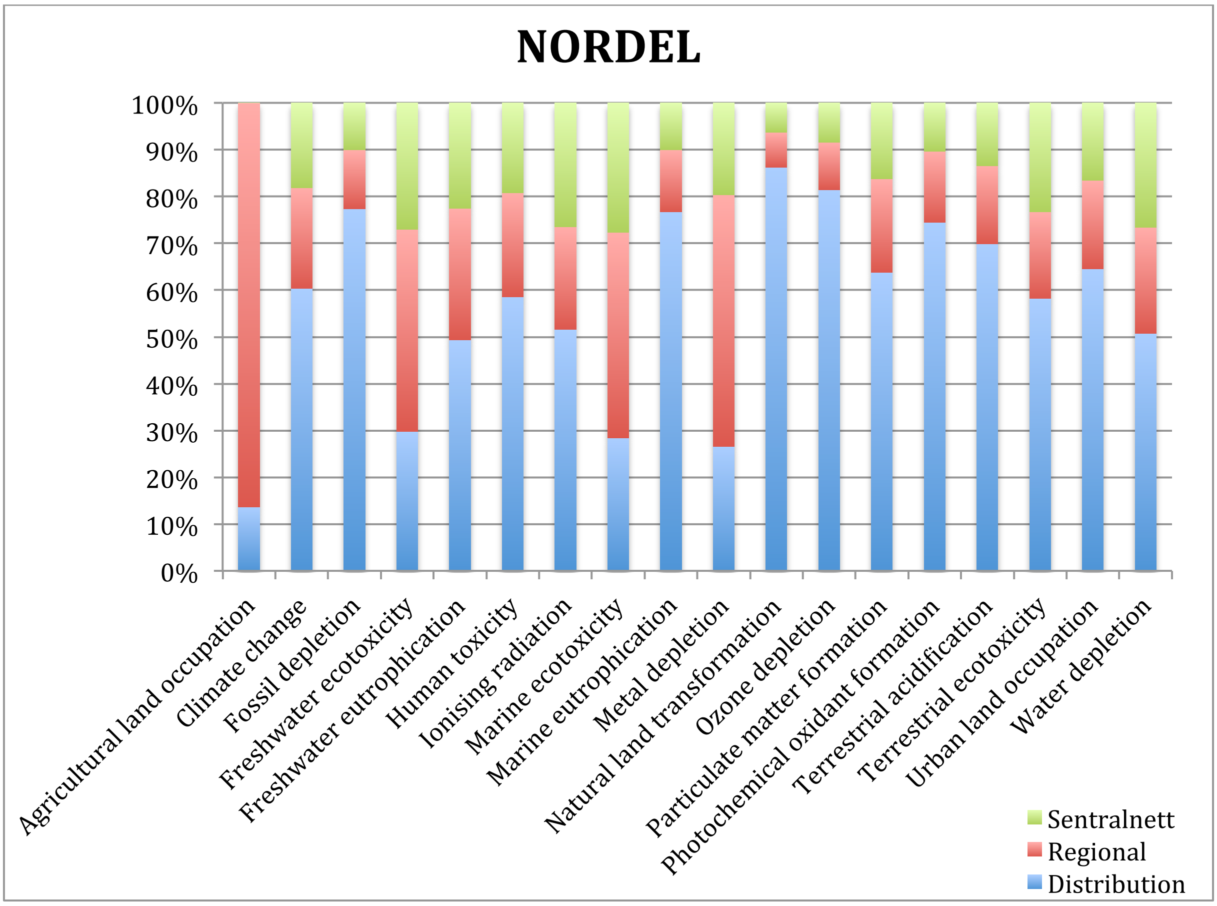
| | | d_NORDEL | | |
|---|---|---|---|---|
| **Name** | **Unit** | **Distribution** | **Regional** | **Sentralnett** |
| Agricultural land occupation | m2a | 1754.503 | 11084.802 | 0.468 |
| Climate change | kg CO2 eq | 16.898 | 6.038 | 5.061 |
| Fossil depletion | kg oil eq | 9.657 | 1.574 | 1.251 |
| Freshwater ecotoxicity | kg 1,4-DB eq | 0.728 | 1.057 | 0.661 |
| Freshwater eutrophication | kg P eq | 0.004 | 0.002 | 0.002 |
| Human toxicity | kg 1,4-DB eq | 11.491 | 4.365 | 3.757 |
| Ionising radiation | kg U235 eq | 16.709 | 7.084 | 8.588 |
| Marine ecotoxicity | kg 1,4-DB eq | 0.598 | 0.925 | 0.581 |
| Marine eutrophication | kg N eq | 0.005 | 0.001 | 0.001 |
| Metal depletion | kg Fe eq | 0.962 | 1.945 | 0.712 |
| Natural land transformation | m2 | 0.012 | 0.001 | 0.001 |
| Ozone depletion | kg CFC-11 eq | 0.000 | 0.000 | 0.000 |
| Particulate matter formation | kg PM10 eq | 0.034 | 0.011 | 0.009 |
| Photochemical oxidant formation | kg NMVOC | 0.085 | 0.017 | 0.012 |
| Terrestrial acidification | kg SO2 eq | 0.082 | 0.019 | 0.016 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 0.011 | 0.004 | 0.005 |
| Urban land occupation | m2a | 0.139 | 0.041 | 0.036 |
| Water depletion | m3 | 372.511 | 165.810 | 195.321 |

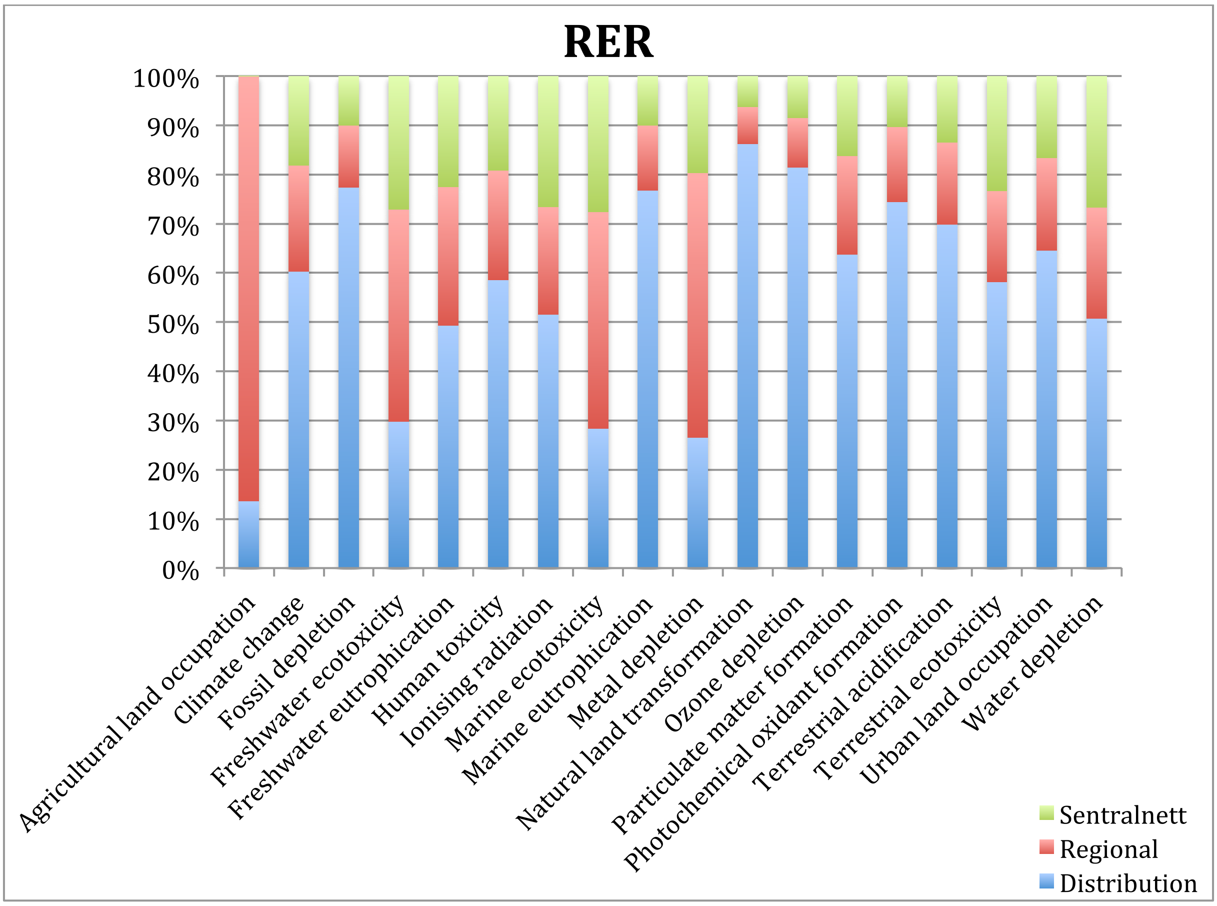
|  |  | d_RER |  |  |
|---|---|---|---|---|
| **Name** | **Unit** | **Distribution** | **Regional** | **Sentralnett** |
| Agricultural land occupation | m2a | 1754.074 | 11084.631 | 0.237 |
| Climate change | kg CO2 eq | 33.068 | 12.506 | 13.793 |
| Fossil depletion | kg oil eq | 14.349 | 3.451 | 3.785 |
| Freshwater ecotoxicity | kg 1,4-DB eq | 1.016 | 1.172 | 0.817 |
| Freshwater eutrophication | kg P eq | 0.023 | 0.010 | 0.012 |
| Human toxicity | kg 1,4-DB eq | 22.468 | 8.756 | 9.684 |
| Ionising radiation | kg U235 eq | 19.896 | 8.359 | 10.309 |
| Marine ecotoxicity | kg 1,4-DB eq | 0.877 | 1.037 | 0.732 |
| Marine eutrophication | kg N eq | 0.011 | 0.003 | 0.004 |
| Metal depletion | kg Fe eq | 0.970 | 1.948 | 0.716 |
| Natural land transformation | m2 | 0.013 | 0.002 | 0.002 |
| Ozone depletion | kg CFC-11 eq | 0.000 | 0.000 | 0.000 |
| Particulate matter formation | kg PM10 eq | 0.053 | 0.018 | 0.019 |
| Photochemical oxidant formation | kg NMVOC | 0.118 | 0.031 | 0.030 |
| Terrestrial acidification | kg SO2 eq | 0.158 | 0.050 | 0.057 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 0.006 | 0.001 | 0.002 |
| Urban land occupation | m2a | 0.176 | 0.055 | 0.056 |
| Water depletion | m3 | 216.764 | 103.511 | 111.218 |

|  |  | d_production |  |  |
|---|---|---|---|---|
| **Name** | **Unit** | **NO** | **NORDEL** | **RER** |
| Agricultural land occupation | m2a | 0.853 | 16.780 | 8.210 |
| Climate change | kg CO2 eq | 8.982 | 163.927 | 487.324 |
| Fossil depletion | kg oil eq | 1.947 | 40.022 | 133.853 |
| Freshwater ecotoxicity | kg 1,4-DB eq | 0.068 | 0.693 | 6.451 |
| Freshwater eutrophication | kg P eq | 0.002 | 0.029 | 0.413 |
| Human toxicity | kg 1,4-DB eq | 2.838 | 52.631 | 272.168 |
| Ionising radiation | kg U235 eq | 1.444 | 313.476 | 377.213 |
| Marine ecotoxicity | kg 1,4-DB eq | 0.070 | 0.732 | 6.326 |
| Marine eutrophication | kg N eq | 0.001 | 0.020 | 0.124 |
| Metal depletion | kg Fe eq | 2.140 | 3.377 | 3.540 |
| Natural land transformation | m2 | 0.009 | 0.025 | 0.060 |
| Ozone depletion | kg CFC-11 eq | 0.000 | 0.000 | 0.000 |
| Particulate matter formation | kg PM10 eq | 0.025 | 0.244 | 0.622 |
| Photochemical oxidant formation | kg NMVOC | 0.031 | 0.345 | 1.016 |
| Terrestrial acidification | kg SO2 eq | 0.024 | 0.415 | 1.934 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 0.009 | 0.162 | 0.051 |
| Urban land occupation | m2a | 0.088 | 0.887 | 1.637 |
| Water depletion | m3 | 874.554 | 6905.944 | 3791.010 |

## Impact Shares: Varying the Electricity Mix

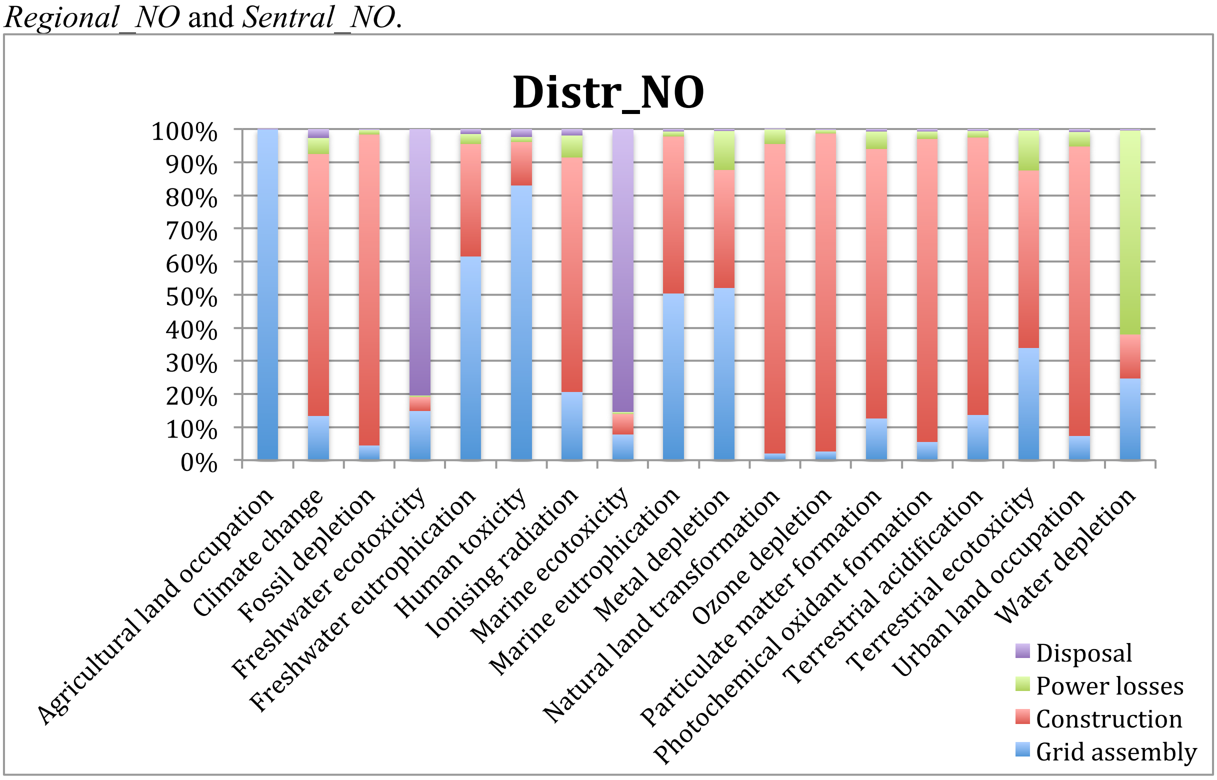


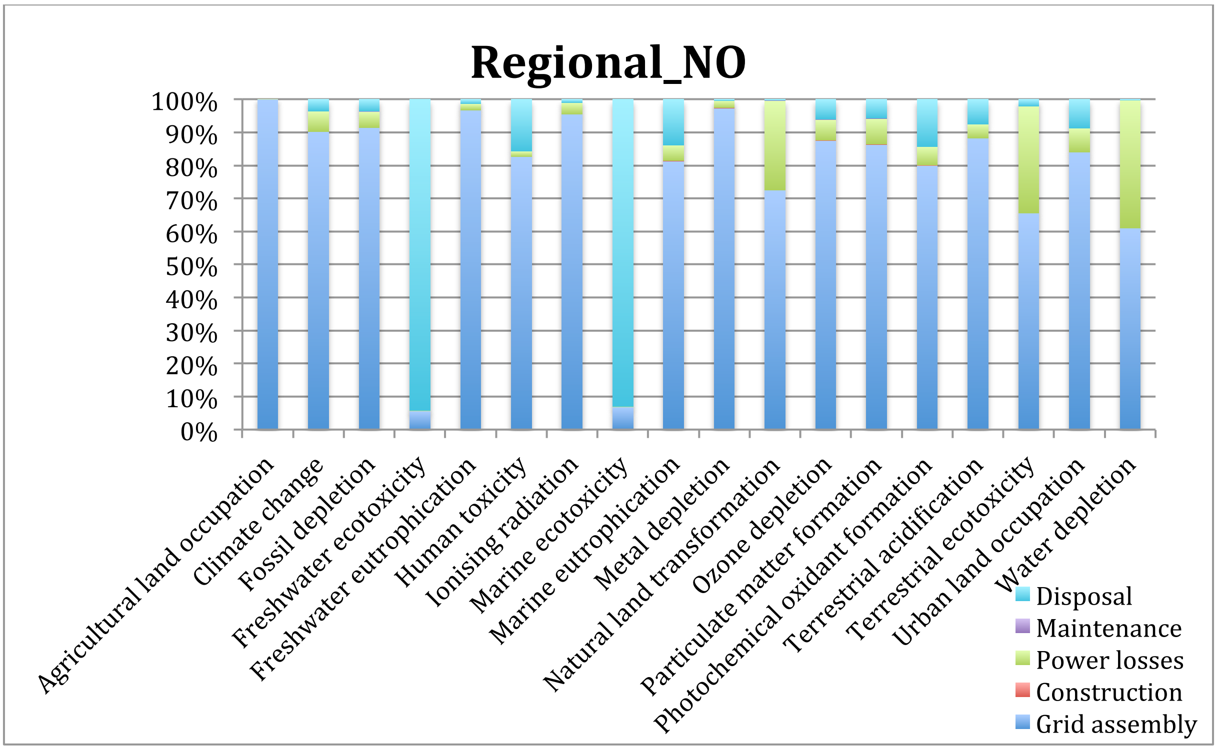


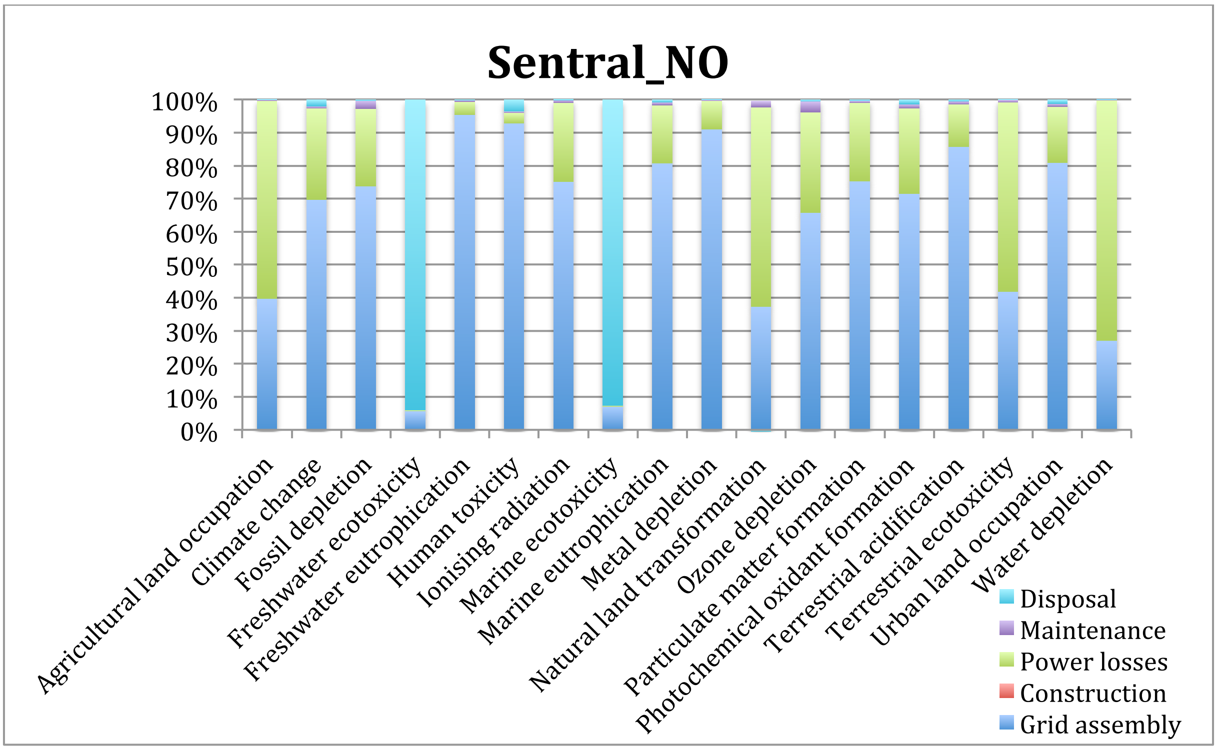

RER
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Agricultural land occupation
Climate change
Fossil depletion
Freshwater ecotoxicity
Freshwater eutrophication
Human toxicity
Ionising radiation
Marine ecotoxicity
Marine eutrophication
Metal depletion
Natural land transformation
Ozone depletion
Particulate matter formation
Photochemical oxidant formation
Terrestrial acidification
Terrestrial ecotoxicity
Urban land occupation
Water depletion
Sentralnett
Regional
Distribution

### Breakdown to Life Cycle Phases – All Categories

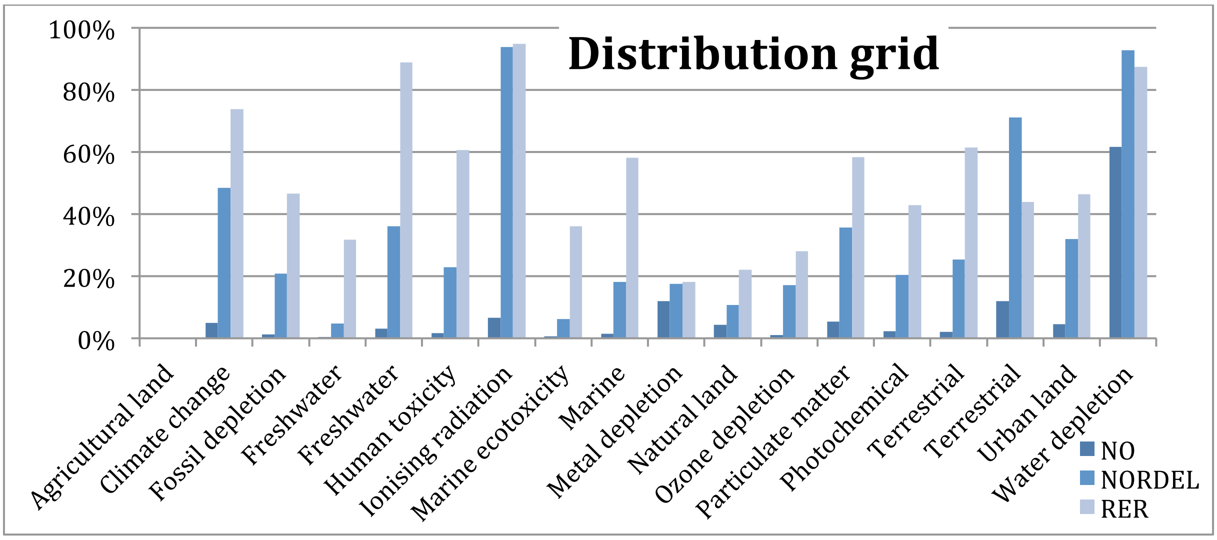
For a closer inspection of the impact origins in the different grid levels, the impacts are initially grouped together according to component group. However, an even more comprehensible representation is achieved when sorting the components into their respective life cycle stages. This latter presentation is depicted below for the models *Distr_NO*, *Regional_NO* and *Sentral_NO*.

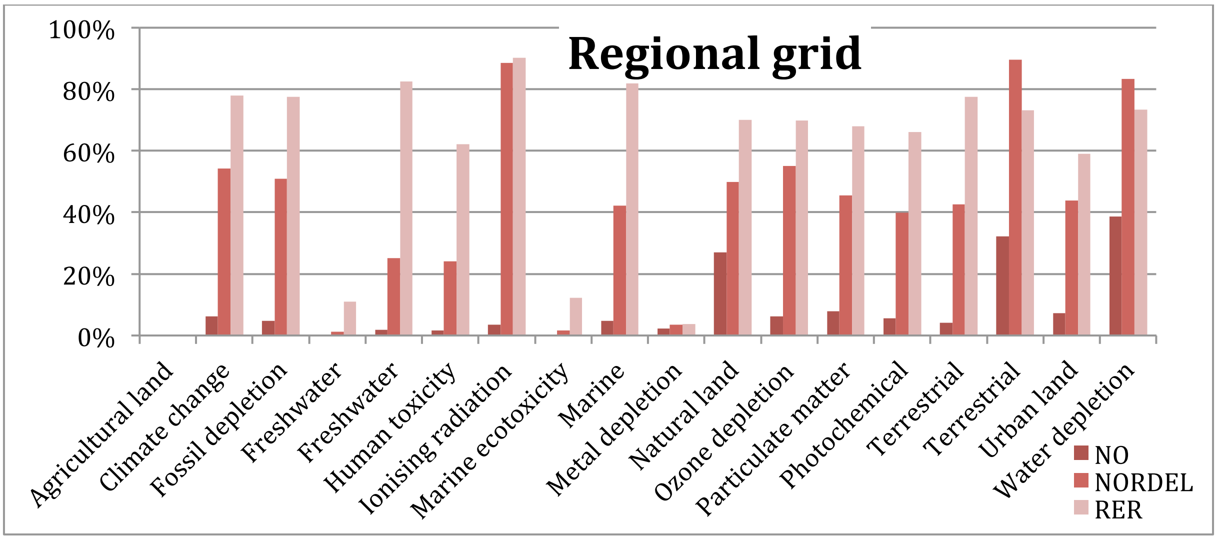


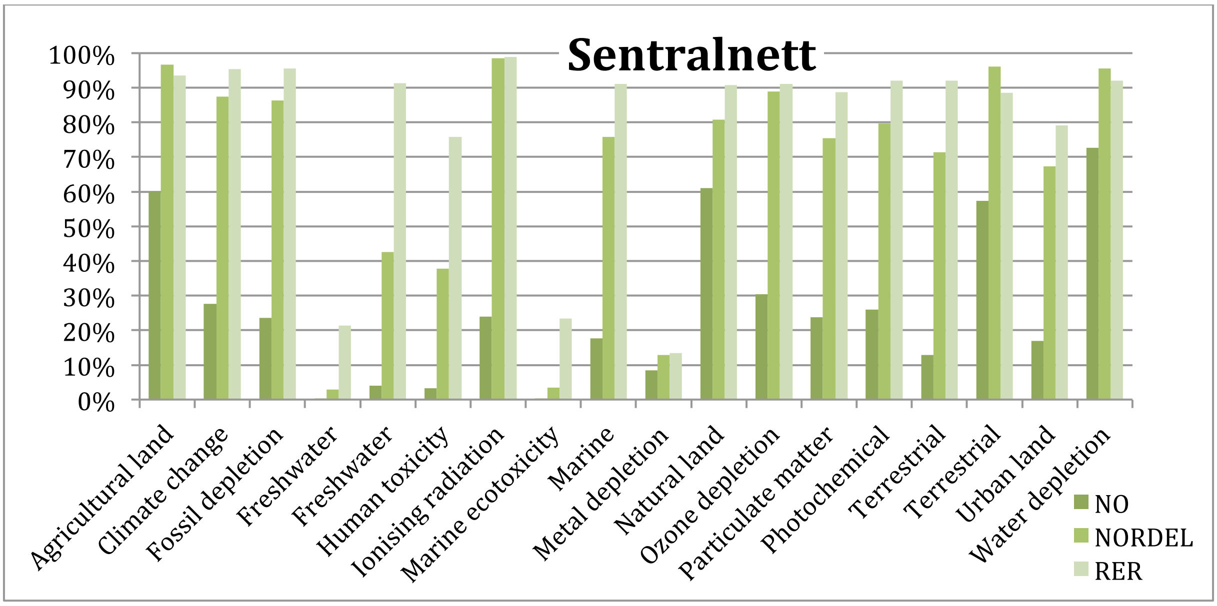



Sentral_NO
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Agricultural land occupation
Climate change
Fossil depletion
Freshwater ecotoxicity
Freshwater eutrophication
Human toxicity
Ionising radiation
Marine ecotoxicity
Marine eutrophication
Metal depletion
Natural land transformation
Ozone depletion
Particulate matter formation
Photochemical oxidant formation
Terrestrial acidification
Terrestrial ecotoxicity
Urban land occupation
Water depletion
Disposal
Maintenance
Power losses
Construction
Grid assembly

## Relative Impacts from Power Losses







## Distribution grid

| Foreground process | Amount | → | Delivered to |
|---|---|---|---|
| *FU: Delivery of 1 MWh electricity* | *1* | *MWh* | *Output* |
| Overhead lines 230 V (95 mm2) | 6.32E-04 | km | Grid assembly |
| Overhead lines 230 V (50 mm2) | 3.16E-04 | km | Grid assembly |
| Overhead lines 22 kV (25 mm2) | 8.92E-04 | km | Grid assembly |
| Overhead lines 22 kV (50 mm2) | 4.46E-04 | km | Grid assembly |
| Cables 230 V (PVC) | 5.89E-04 | km | Grid assembly |
| Cables 230 V (PEX) | 5.89E-04 | km | Grid assembly |
| Cables 22 kV (95 mm2) | 1.49E-04 | km | Grid assembly |
| Cables 22 kV (150 mm2) | 1.49E-04 | km | Grid assembly |
| Wood masts 230 V | 1.57E-02 | pc | Grid assembly |
| Wood masts 1 kV | 3.04E-04 | pc | Grid assembly |
| Wood masts 22 kV | 1.97E-02 | pc | Grid assembly |
| Circuit breakers 230 V | 5.62E-06 | pc | Grid assembly |
| Circuit breakers 3.3 - 11 kV | 1.25E-05 | pc | Grid assembly |
| Circuit breakers 22 kV | 1.20E-04 | pc | Grid assembly |
| Disconnectors | 1.74E-03 | pc | Grid assembly |
| Load breakers | 1.97E-03 | pc | Grid assembly |
| Transformers | 3.00E-03 | pc | Grid assembly |
| Grid assembly | 1 |  | Functional Unit |
| Construction | 1 |  | Grid assembly |
| Use phase | 1 |  | Functional Unit |
| Power losses | 1 |  | Use phase |
| Disposal | 1 |  | Functional Unit |
| OHL disposal | 1 |  | Disposal |
| OHL disposal 230 V (95 mm2) | 6.32E-04 | pc | OHL disposal |
| OHL disposal 230 V (50 mm2) | 3.16E-04 | pc | OHL disposal |
| OHL disposal 22 kV (25 mm2) | 8.92E-04 | pc | OHL disposal |
| OHL disposal 22 kV (50 mm2) | 4.46E-04 | pc | OHL disposal |
| Cable disposal | 1 |  | Disposal |
| Cable disposal 230 V (PVC) | 5.89E-04 | pc | Cable disposal |
| Cable disposal 230 V (PEX) | 5.89E-04 | pc | Cable disposal |
| Cable disposal 22 kV (95 mm2) | 1.49E-04 | pc | Cable disposal |
| Cable disposal 22 kV (150 mm2) | 1.49E-04 | pc | Cable disposal |
| Mast disposal | 1 |  | Disposal |
| Mast disposal 230 V | 1.57E-02 |  | Mast disposal |
| Mast disposal 1 kV | 3.04E-04 |  | Mast disposal |
| Mast disposal 22 kV | 1.97E-02 |  | Mast disposal |
| Switchgear disposal | 1 |  | Disposal |
| Circuit breaker disposal 230 V | 5.62E-06 |  | Switchgear disposal |
| Circuit breaker disposal 3.3 - 11 kV | 1.25E-05 |  | Switchgear disposal |
| Circuit breaker disposal 22 kV | 1.20E-04 |  | Switchgear disposal |
| Disconnector disposal | 1.74E-03 |  | Switchgear disposal |
| Load breaker disposal | 1.97E-03 |  | Switchgear disposal |
| Transformer disposal | 1 |  | Disposal |

## Background processes

All values are per year

(Erroneous values for softwood processes.)

## Overhead lines

### 230 V (95 mm$^2$)

| Background process | ID | Amount | Unit |
|---|---|---|---|
| aluminium, primary, at plant/ RER/ kg | 1755 | 2.00E+01 | kg/km |
| wire drawing, steel/ RER/ kg | 1962 | 2.00E+01 | kg/km |
| polyethylene terephthalate, granulate, amorphous, at plant/ RER/ kg | 2653 | 3.71E+00 | kg/km |
| transport, lorry >32t, EURO5/ RER/ tkm | 2811 | 1.83E+01 | tkm/km$_{wire}$ |

| Values for the other OHL | **230 V (50 mm$^2$)** | **22 kV (25 mm$^2$)** | **22 kV (50 mm$^2$)** |
|---|---|---|---|
| aluminium, primary, at plant/ RER/ kg | 1.02E+01 | 5.56E+00 | 1.02E+01 |
| wire drawing, steel/ RER/ kg | 1.02E+01 | 5.56E+00 | 1.02E+01 |
| polyethylene terephthalate, granulate, amorphous, at plant/ RER/ kg | 2.33E+00 | 5.53E+00 | 6.49E+00 |
| transport, lorry >32t, EURO5/ RER/ tkm | 9.66E+00 | 8.54E+00 | 1.29E+01 |

## Cables

### 230 V (PVC)

| Background process | ID | Amount | Unit |
|---|---|---|---|
| aluminium, primary, at plant/ RER/ kg | 1755 | 5.58E+00 | kg/km |
| wire drawing, steel/ RER/ kg | 1962 | 5.58E+00 | kg/km |
| polyvinylchloride, at regional storage/ RER/ kg | 2669 | 9.92E+00 | kg/km |
| transport, lorry >32t, EURO5/ RER/ tkm | 2811 | 1.19E+01 | tkm/km$_{wire}$ |

| Values for the other cables | **230 V (PEX)** | **22 kV (95 mm$^2$)** | **22 kV (150 mm$^2$)** |
|---|---|---|---|
| aluminium, primary, at plant/ RER/ kg | 3.51E+00 | 6.94E+00 | 1.06E+01 |
| wire drawing, steel/ RER/ kg | 3.51E+00 | 6.94E+00 | 1.06E+01 |
| polyvinylchloride, at regional storage/ RER/ kg | 1.97E+01 | 6.96E+01 | 8.26E+01 |
| transport, lorry >32t, EURO5/ RER/ tkm | 1.79E+01 | 5.89E+01 | 7.18E+01 |

## Masts

### Wood masts 230 V

| Background process | ID | **230 V** | **1 kV** | **22 kV** |
|---|---|---|---|---|
| softwood, Scandinavian, standing, under bark, in forest/ NORDEL/ m3 | 3583 | 1.05E+01 | 1.18E+01 | 1.28E+01 |
| transport, lorry >32t, EURO5/ RER/ tkm | 2811 | 5.24E+00 | 5.90E+00 | 6.42E+00 |

## Switchgear

### Circuit breakers 230 V

| Background process | ID | Amount | Unit |
|---|---|---|---|
| acrylonitrile-butadiene-styrene copolymer, ABS, at plant/ RER/ kg | 2642 | 1.43E-04 | kg/pc |
| copper, primary, at refinery/ GLO/ kg | 1796 | 3.35E-03 | kg/pc |
| glass fibre reinforced plastic, polyester resin, hand lay-up, at plant/ RER/ kg | 2639 | 1.12E-02 | kg/pc |
| glass fibre reinforced plastic, polyamide, injection moulding, at plant/ RER/ kg | 2638 | 4.43E-04 | kg/pc |
| polycarbonate, at plant/ RER/ kg | 2652 | 1.04E-03 | kg/pc |
| steel, low-alloyed, at plant/ RER/ kg | 1914 | 7.65E-03 | kg/pc |
| sheet rolling, steel/ RER/ kg | 1956 | 5.95E-03 | kg/pc |
| silver, at regional storage/ RER/ kg | 1893 | 7.00E-05 | kg/pc |
| disposal, municipal solid waste, 22.9% water, to sanitary landfill/ CH/ kg | 3326 | 2.45E-02 | kg/pc |
| disposal, hazardous waste, 25% water, to hazardous waste incineration/ CH/ kg | 3067 | 3.00E-04 | kg/pc |
| electricity, high voltage, at grid/ DE/ kWh | 1075 | 2.42E-01 | kWh/pc |
| transport, lorry >32t, EURO5/ RER/ tkm | 2811 | 4.29E-02 | tkm/pc |

### Circuit breakers 3.3 – 11 kV

| Background process | ID | Amount | Unit |
|---|---|---|---|
| steel, low-alloyed, at plant/ RER/ kg | 1914 | 2.39E+00 | kg/pc |
| copper, primary, at refinery/ GLO/ kg | 1796 | 1.90E-01 | kg/pc |
| brass, at plant/ CH/ kg | 1766 | 1.00E-02 | kg/pc |
| polycarbonate, at plant/ RER/ kg | 2652 | 2.25E-02 | kg/pc |
| synthetic rubber, at plant/ RER/ kg | 2676 | 1.75E-02 | kg/pc |
| polypropylene, granulate, at plant/ RER/ kg | 2662 | 2.50E-03 | kg/pc |
| glass fibre reinforced plastic, polyester resin, hand lay-up, at plant/ RER/ kg | 2639 | 2.50E-03 | kg/pc |
| glass fibre, at plant/ RER/ kg | 1358 | 2.50E-03 | kg/pc |
| epoxy resin insulator (Al2O3), at plant/ RER/ kg | 2616 | 5.65E-01 | kg/pc |
| sulphur hexafluoride, liquid, at plant/ RER/ kg | 600 | 5.00E-03 | kg/pc |
| zinc, primary, at regional storage/ RER/ kg | 1923 | 1.25E-02 | kg/pc |
| aluminium, primary, at plant/ RER/ kg | 1755 | 2.75E-02 | kg/pc |
| coating powder, at plant/ RER/ kg | 1943 | 2.00E-02 | kg/pc |
| transport, lorry >32t, EURO5/ RER/ tkm | 2811 | 5.89E+00 | tkm/pc |

### Circuit breakers 22 kV

| Background process | ID | Amount | Unit |
|---|---|---|---|
| steel, low-alloyed, at plant/ RER/ kg | 1914 | 1.41E+00 | kg/pc |
| aluminium, primary, at plant/ RER/ kg | 1755 | 2.25E-02 | kg/pc |
| aluminium oxide, at plant/ RER/ kg | 442 | 9.45E-03 | kg/pc |
| copper, primary, at refinery/ GLO/ kg | 1796 | 4.26E-01 | kg/pc |
| glass fibre reinforced plastic, polyamide, injection moulding, at plant/ RER/ kg | 2638 | 4.95E-03 | kg/pc |
| polycarbonate, at plant/ RER/ kg | 2652 | 5.03E-03 | kg/pc |
| polyvinylchloride, at regional storage/ RER/ kg | 2669 | 2.00E-04 | kg/pc |
| bronze, at plant/ CH/ kg | 1768 | 2.25E-04 | kg/pc |

|  |  |  |  |
|---|---|---|---|
| polyethylene, HDPE, granulate, at plant/ RER/ kg | 2655 | 5.68E-03 | kg/pc |
| epoxy resin insulator (Al2O3), at plant/ RER/ kg | 2616 | 6.15E-01 | kg/pc |
| sulphur hexafluoride, liquid, at plant/ RER/ kg | 600 | 7.05E-03 | kg/pc |
| brass, at plant/ CH/ kg | 1766 | 4.95E-03 | kg/pc |
| disposal, municipal solid waste, 22.9% water, to sanitary landfill/ CH/ kg | 3326 | 3.15E+00 | kg/pc |
| disposal, hazardous waste, 25% water, to hazardous waste incineration/ CH/ kg | 3067 | 2.15E-02 | kg/pc |
| transport, lorry >32t, EURO5/ RER/ tkm | 2811 | 4.73E+00 | tkm/pc |

**Disconnectors**

| Background process | ID | Amount | Unit |
|---|---|---|---|
| acrylonitrile-butadiene-styrene copolymer, ABS, at plant/ RER/ kg | 2642 | 2.67E-02 | kg/pc |
| copper, primary, at refinery/ GLO/ kg | 1796 | 6.28E-01 | kg/pc |
| glass fibre reinforced plastic, polyester resin, hand lay-up, at plant/ RER/ kg | 2639 | 2.09E+00 | kg/pc |
| glass fibre reinforced plastic, polyamide, injection moulding, at plant/ RER/ kg | 2638 | 8.29E-02 | kg/pc |
| polycarbonate, at plant/ RER/ kg | 2652 | 1.95E-01 | kg/pc |
| steel, low-alloyed, at plant/ RER/ kg | 1914 | 1.43E+00 | kg/pc |
| sheet rolling, steel/ RER/ kg | 1956 | 1.12E+00 | kg/pc |
| silver, at regional storage/ RER/ kg | 1893 | 1.31E-02 | kg/pc |
| disposal, municipal solid waste, 22.9% water, to sanitary landfill/ CH/ kg | 3326 | 4.61E+00 | kg/pc |
| disposal, hazardous waste, 25% water, to hazardous waste incineration/ CH/ kg | 3067 | 5.66E-02 | kg/pc |
| electricity, high voltage, at grid/ DE/ kWh | 1075 | 4.56E+01 | kWh/pc |
| transport, lorry >32t, EURO5/ RER/ tkm | 2811 | 1.21E+01 | tkm/pc |

**Load breakers**

| Background process | ID | Amount | Unit |
|---|---|---|---|
| steel, low-alloyed, at plant/ RER/ kg | 1914 | 3.76E+00 | kg/pc |
| aluminium, primary, at plant/ RER/ kg | 1755 | 5.99E-02 | kg/pc |
| aluminium oxide, at plant/ RER/ kg | 442 | 2.52E-02 | kg/pc |
| copper, primary, at refinery/ GLO/ kg | 1796 | 1.14E+00 | kg/pc |
| glass fibre reinforced plastic, polyamide, injection moulding, at plant/ RER/ kg | 2638 | 1.32E-02 | kg/pc |
| polycarbonate, at plant/ RER/ kg | 2652 | 1.34E-02 | kg/pc |
| polyvinylchloride, at regional storage/ RER/ kg | 2669 | 5.33E-04 | kg/pc |
| bronze, at plant/ CH/ kg | 1768 | 6.00E-04 | kg/pc |
| polyethylene, HDPE, granulate, at plant/ RER/ kg | 2655 | 1.51E-02 | kg/pc |
| epoxy resin insulator (Al2O3), at plant/ RER/ kg | 2616 | 1.64E+00 | kg/pc |
| sulphur hexafluoride, liquid, at plant/ RER/ kg | 600 | 1.88E-02 | kg/pc |
| brass, at plant/ CH/ kg | 1766 | 1.32E-02 | kg/pc |
| disposal, municipal solid waste, 22.9% water, to sanitary landfill/ CH/ kg | 3326 | 8.78E+00 | kg/pc |
| disposal, hazardous waste, 25% water, to hazardous waste incineration/ CH/ kg | 3067 | 5.99E-02 | kg/pc |
| transport, lorry >32t, EURO5/ RER/ tkm | 2811 | 8.04E+00 | tkm/pc |

## Transformers

| Background process | ID | Amount | Unit |
|---|---|---|---|
| aluminium, primary, at plant/ RER/ kg | 1755 | 5.00E+00 | kg/pc |
| sheet rolling, aluminium/ RER/ kg | 1953 | 2.16E+00 | kg/pc |
| wire drawing, steel/ RER/ kg | 1962 | 2.84E+00 | kg/pc |
| polystyrene foam slab, at plant/ RER/ kg | 1563 | 1.50E+00 | kg/pc |
| ceramic tiles, at regional storage/ CH/ kg | 864 | 2.75E-01 | kg/pc |
| steel, low-alloyed, at plant/ RER/ kg | 1914 | 2.14E+01 | kg/pc |
| lubricating oil, at plant/ RER/ kg | 740 | 8.50E+00 | kg/pc |
| electricity, high voltage, at grid/ IT/ kWh | 1081 | 3.68E+00 | kWh/pc |
| heat, natural gas, at industrial furnace >100kW/ RER/ MJ | 2118 | 5.63E+01 | MJ/pc |
| disposal, municipal solid waste, 22.9% water, to sanitary landfill/ CH/ kg | 3326 | 7.29E-02 | kg/pc |
| disposal, hazardous waste, 25% water, to hazardous waste incineration/ CH/ kg | 3067 | 3.89E-01 | kg/pc |
| transport, lorry >32t, EURO5/ RER/ tkm | 2811 | 1.01E+02 | tkm/pc |

## Construction

| Background process | ID | Amount | Unit |
|---|---|---|---|
| transport, lorry >16t, fleet average/ RER/ tkm | 2807 | 3.56E+01 | tkm |
| transport, passenger car/ RER/ pkm | 2812 | 9.55E-01 | pkm |
| diesel, at regional storage/ RER/ kg | 2343 | 4.55E+00 | kg |

## Power losses

Three different scenarios

| Background process | ID | Amount | Unit |
|---|---|---|---|
| electricity, production mix NO/ NO/ kWh | 1028 | 5.00E+01 | kWh |
| electricity, production mix NORDEL/ NORDEL/ kWh | 1029 | 5.00E+01 | kWh |
| electricity, production mix RER/ RER/ kWh | 1032 | 5.00E+01 | kWh |

## Disposal

For practical reasons all disposal processes are kept out of this appendix. They are found in the electronic attachment.

## Stressors

| Stressor name | Foreground process | ID | Amount | Unit |
|---|---|---|---|---|
| Carbon dioxide, fossil/ air/ unspecified | Transformers | 114 | 4.79E-02 | kg |
| COD, Chemical Oxygen Demand/ water/ unspecified | Transformers | 1235 | 3.40E+01 | kg |
| BOD5, Biological Oxygen Demand/ water/ unspecified | Transformers | 1192 | 1.99E+01 | kg |
| Suspended solids, unspecified/ water/ unspecified | Transformers | 1543 | 3.78E+01 | kg |
| Hydrocarbons, aliphatic, alkanes, unspecified/ air/ unspecified | Transformers | 252 | 5.95E-01 | kg |
| Ammonia/ air/ unspecified | Transformers | 40 | 3.97E-01 | kg |
| Nitrate/ water/ ground- | Transformers | 1430 | 2.59E+00 | kg |
| Nitrite/ water/ ground-, long-term | Transformers | 1434 | 9.77E-02 | kg |
| Phosphorus/ water/ unspecified | Transformers | 1461 | 1.98E-01 | kg |
| sulphur hexafluoride, air, unspecified, kg | Circuit | 509 | 8.14E-04 | kg |

| | | | | |
|---|---|---|---|---|
| | breakers 3.3 - 11 kV | | | |
| sulphur hexafluoride, air, unspecified, kg | Circuit breakers 22 kV | 509 | 1.15E-03 | kg |
| sulphur hexafluoride, air, unspecified, kg | Load breakers | 509 | 3.06E-03 | kg |

## Regional grid

| Foreground process | Amount | → | Delivered to |
|---|---|---|---|
| *FU: Delivery of 1 MWh electricity* | *1* | *MWh* | *Output* |
| Wood mast 66kV manufacture | 3.45E-03 | pc | Grid assembly |
| Wood mast 132kV manufacture | 3.84E-04 | pc | Grid assembly |
| Steel mast manufacture | 9.37E-06 | pc | Grid assembly |
| FeAL 50 line manufacture | 4.68E-05 | km | Grid assembly |
| FeAL 70 line manufacture | 2.29E-05 | km | Grid assembly |
| FeAL 95 line manufacture | 8.71E-05 | km | Grid assembly |
| FeAL 120 line manufacture | 2.63E-04 | km | Grid assembly |
| FeAL 185 line manufacture | 2.80E-04 | km | Grid assembly |
| FeAL 240 line manufacture | 8.27E-05 | km | Grid assembly |
| FeAL 300 line manufacture | 4.35E-05 | km | Grid assembly |
| AL 59-225 line manufacture | 3.77E-05 | km | Grid assembly |
| AL 59-444 line manufacture | 7.74E-05 | km | Grid assembly |
| SUPER A-444 line manufacture | 1.59E-06 | km | Grid assembly |
| AL 59-454 line manufacture | 1.94E-05 | km | Grid assembly |
| AL 59-594 line manufacture | 2.24E-05 | km | Grid assembly |
| PEX cable, low conductivity | 2.25E-06 | km | Grid assembly |
| PEX cable, medium conductivity | 3.06E-06 | km | Grid assembly |
| PEX cable, high conductivity | 2.42E-06 | km | Grid assembly |
| Oil cable, lead | 1.95E-06 | km | Grid assembly |
| Oil cable, aluminium | 2.57E-07 | km | Grid assembly |
| 10 MVA Transformer manufacture | 3.44E-06 | pc | Grid assembly |
| 16 MVA Transformer manufacture | 4.37E-06 | pc | Grid assembly |
| 20 MVA Transformer manufacture | 2.19E-06 | pc | Grid assembly |
| 40 MVA Transformer manufacture | 1.25E-06 | pc | Grid assembly |
| 50 MVA Transformer manufacture | 2.50E-06 | pc | Grid assembly |
| 63 MVA Transformer manufacture | 1.25E-06 | pc | Grid assembly |
| 250 MVA Transformer manufacture | 6.25E-07 | pc | Grid assembly |
| 500 MVA Transformer manufacture | 3.12E-07 | pc | Grid assembly |
| Grid assembly | 1 | | Functional Unit |
| Energy losses | 1 | | Functional Unit |
| Maintenance | 3.61E-04 | h | Functional Unit |
| Switch: 66 kV w/SF6 | 3.72E-05 | pc | Grid assembly |
| Switch: 66 kV w/o SF6 | 2.25E-05 | pc | Grid assembly |
| Switch: 132 kV w/SF6 | 2.19E-06 | pc | Grid assembly |
| Construction | 1 | | Grid assembly |
| Disposal | 1 | | Functional Unit |
| OHL disposal | 3.28E-04 | km | Disposal |
| Cable disposal | 9.93E-06 | km | Disposal |
| Mast disposal | 3.45E-03 | pc | Disposal |
| Transformer disposal | 1.59E-05 | pc | Disposal |
| Switchgear disposal | 6.19E-05 | pc | Disposal |

## Background processes

All values are per year

(Erroneous values for softwood processes.)

## Masts

**Wood masts**

| Background process | ID | **66 kV** | **132 kV** |
|---|---|---|---|
| softwood, Scandinavian, standing, under bark, in forest/ NORDEL/ m3 | 3583 | 6.49E+02 | 1.10E+03 |
| transport, lorry >32t, EURO5/ RER/ tkm | 2811 | 3.33E+02 | 5.62E+02 |
| wood preservative, creosote, at plant/ RER/ kg | 2496 | 1.63E+01 | 2.41E+01 |
| preservative treatment, logs, pressure vessel/ RER/ m3 | 3605 | 1.48E-02 | 2.20E-02 |
| foam glass, at plant/ RER/ kg | 1557 | 1.06E+02 | 1.06E+02 |
| steel, low-alloyed, at plant/ RER/ kg | 1914 | 5.83E+01 | 5.83E+01 |
| zinc, primary, at regional storage/ RER/ kg | 1923 | 2.24E+00 | 2.24E+00 |

**Steel masts**

| Background process | ID | Amount | Unit |
|---|---|---|---|
| foam glass, at plant/ RER/ kg | 1557 | 1.06E+02 | kg |
| zinc, primary, at regional storage/ RER/ kg | 1923 | 2.24E+00 | kg |
| steel, low-alloyed, at plant/ RER/ kg | 1914 | 7.12E+03 | kg |

## Overhead lines

**FeAl 50**

| Background process | ID | Amount | Unit |
|---|---|---|---|
| aluminium, primary, at plant/ RER/ kg | 1755 | 2.02E+01 | kg/km |
| steel, low-alloyed, at plant/ RER/ kg | 1914 | 9.53E+00 | kg/km |
| wire drawing, steel/ RER/ kg | 1962 | 2.97E+01 | kg/km |
| transport, lorry >32t, EURO5/ RER/ tkm | 2811 | 2.29E+01 | tkm/km$_{wire}$ |

**Other FeAl lines (values are “amount”)**

| **FeAl 70** | **FeAl 95** | **FeAl 120** | **FeAl 185** | **FeAl 240** | **FeAl 300** |
|---|---|---|---|---|---|
| 2.84E+01 | 3.86E+01 | 4.88E+01 | 7.49E+01 | 9.73E+01 | 1.22E+02 |
| 1.33E+01 | 2.17E+01 | 2.75E+01 | 4.22E+01 | 4.79E+01 | 5.38E+01 |
| 4.17E+01 | 6.03E+01 | 7.63E+01 | 1.17E+02 | 1.45E+02 | 1.75E+02 |
| 3.21E+01 | 4.64E+01 | 5.87E+01 | 9.01E+01 | 1.12E+02 | 1.35E+02 |

**Al 59-225**

| Background process | ID | Amount | Unit |
|---|---|---|---|
| aluminium, primary, at plant/ RER/ kg | 1755 | 5.71E+01 | kg/km |
| wire drawing, steel/ RER/ kg | 1962 | 5.71E+01 | kg/km |
| transport, lorry >32t, EURO5/ RER/ tkm | 2811 | 4.39E+01 | tkm/km$_{wire}$ |

**Other types of Al lines (values are “amount”)**

| **Al 59-444** | **Super A-444** | **Al 59-454** | **Al 59-594** |
|---|---|---|---|
| 4.59E+01 | 1.13E+02 | 1.16E+02 | 1.52E+02 |
| 4.59E+01 | 1.13E+02 | 1.16E+02 | 1.52E+02 |
| 8.72E+01 | 8.72E+01 | 8.93E+01 | 1.17E+02 |

## Cables

### PEX cable – low conductivity

| Background process | ID | Amount | Unit |
|---|---|---|---|
| polyvinylchloride, suspension polymerised, at plant/ RER/ kg | 2672 | 3.28E+01 | kg/km |
| extrusion, plastic pipes/ RER/ kg | 2680 | 3.28E+01 | kg/km |
| aluminium, primary, at plant/ RER/ kg | 1755 | 1.38E+01 | kg/km |
| wire drawing, steel/ RER/ kg | 1962 | 1.38E+01 | kg/km |
| transport, lorry >32t, EURO5/ RER/ tkm | 2811 | 3.60E+01 | tkm/km$_{wire}$ |

### Other cables (values are “amount”)

| PEX - med. | PEX - high | Oil cable - lead | Oil cable – al. |
|---|---|---|---|
| 4.68E+01 | 6.23E+01 | 3.20E+01 | 3.73E+01 |
| 4.68E+01 | 6.23E+01 | 3.20E+01 | 3.73E+01 |
| 4.63E+01 | 9.80E+01 | 6.89E+00 | 2.32E+01 |
| 4.63E+01 | 9.80E+01 | 6.89E+00 | 2.32E+01 |
| 7.18E+01 | 1.24E+02 | 2.98E+01 | 4.65E+01 |

## Transformers

### 10 MVA

| Background process | ID | Amount | Unit |
|---|---|---|---|
| aluminium, primary, at plant/ RER/ kg | 1755 | 1.63E+00 | kg |
| brass, at plant/ CH/ kg | 1766 | 1.00E+00 | kg |
| copper, primary, at refinery/ GLO/ kg | 1796 | 8.82E+01 | kg |
| kraft paper, unbleached, at plant/ RER/ kg | 2544 | 1.03E+00 | kg |
| alkyd paint, white, 60% in H2O, at plant/ RER/ kg | 2485 | 4.50E+00 | kg |
| cellulose fibre, inclusive blowing in, at plant/ CH/ kg | 1554 | 7.40E+00 | kg |
| ceramic tiles, at regional storage/ CH/ kg | 864 | 1.33E+00 | kg |
| resin size, at plant/ RER/ kg | 2493 | 1.10E+00 | kg |
| silver, at regional storage/ RER/ kg | 1893 | 1.50E-03 | kg |
| steel, low-alloyed, at plant/ RER/ kg | 1914 | 3.97E+02 | kg |
| sheet rolling, steel/ RER/ kg | 1956 | 1.45E+02 | kg |
| lubricating oil, at plant/ RER/ kg | 740 | 1.70E+02 | kg |
| softwood, stand establishment / tending / site development, under bark/ RER/ m3 | 3587 | 9.15E+00 | kg |
| disposal, municipal solid waste, 22.9% water, to sanitary landfill/ CH/ kg | 3326 | 1.23E+01 | kg |
| disposal, hazardous waste, 25% water, to hazardous waste incineration/ CH/ kg | 3067 | 2.32E+00 | kg |
| electricity, high voltage, at grid/ IT/ kWh | 1081 | 1.12E+02 | kWh |
| heat, natural gas, at industrial furnace >100kW/ RER/ MJ | 2118 | 1.72E+03 | MJ |
| transport, lorry >32t, EURO5/ RER/ tkm | 2811 | 1.87E+03 | tkm |

### 16 MVA

| Background process | ID | Amount | Unit |
|---|---|---|---|
| aluminium, primary, at plant/ RER/ kg | 1755 | 2.35E+00 | kg |
| brass, at plant/ CH/ kg | 1766 | 6.25E-01 | kg |
| copper, primary, at refinery/ GLO/ kg | 1796 | 2.17E+02 | kg |
| kraft paper, unbleached, at plant/ RER/ kg | 2544 | 2.25E+00 | kg |

|  |  |  |  |
|---|---|---|---|
| alkyd paint, white, 60% in H2O, at plant/ RER/ kg | 2485 | 5.25E+00 | kg |
| cellulose fibre, inclusive blowing in, at plant/ CH/ kg | 1554 | 1.42E+01 | kg |
| ceramic tiles, at regional storage/ CH/ kg | 864 | 3.13E+00 | kg |
| resin size, at plant/ RER/ kg | 2493 | 1.45E+00 | kg |
| silver, at regional storage/ RER/ kg | 1893 | 2.00E-03 | kg |
| steel, low-alloyed, at plant/ RER/ kg | 1914 | 5.10E+02 | kg |
| sheet rolling, steel/ RER/ kg | 1956 | 1.39E+02 | kg |
| lubricating oil, at plant/ RER/ kg | 740 | 2.55E+02 | kg |
| softwood, stand establishment / tending / site development, under bark/ RER/ m3 | 3587 | 1.29E+01 | kg |
| disposal, municipal solid waste, 22.9% water, to sanitary landfill/ CH/ kg | 3326 | 1.98E+01 | kg |
| disposal, hazardous waste, 25% water, to hazardous waste incineration/ CH/ kg | 3067 | 3.70E+00 | kg |
| electricity, high voltage, at grid/ IT/ kWh | 1081 | 1.87E+02 | kWh |
| heat, natural gas, at industrial furnace >100kW/ RER/ MJ | 2118 | 2.86E+03 | MJ |
| transport, lorry >32t, EURO5/ RER/ tkm | 2811 | 2.80E+03 | tkm |

**20 MVA**

| Background process | ID | Amount | Unit |
|---|---|---|---|
| aluminium, primary, at plant/ RER/ kg | 1755 | 2.35E+00 | kg |
| brass, at plant/ CH/ kg | 1766 | 6.25E-01 | kg |
| copper, primary, at refinery/ GLO/ kg | 1796 | 2.17E+02 | kg |
| kraft paper, unbleached, at plant/ RER/ kg | 2544 | 2.25E+00 | kg |
| alkyd paint, white, 60% in H2O, at plant/ RER/ kg | 2485 | 5.25E+00 | kg |
| cellulose fibre, inclusive blowing in, at plant/ CH/ kg | 1554 | 1.42E+01 | kg |
| ceramic tiles, at regional storage/ CH/ kg | 864 | 3.13E+00 | kg |
| resin size, at plant/ RER/ kg | 2493 | 1.45E+00 | kg |
| silver, at regional storage/ RER/ kg | 1893 | 2.00E-03 | kg |
| steel, low-alloyed, at plant/ RER/ kg | 1914 | 5.10E+02 | kg |
| sheet rolling, steel/ RER/ kg | 1956 | 1.39E+02 | kg |
| softwood, stand establishment / tending / site development, under bark/ RER/ m3 | 3587 | 1.29E+01 | kg |
| disposal, municipal solid waste, 22.9% water, to sanitary landfill/ CH/ kg | 3326 | 2.47E+01 | kg |
| disposal, hazardous waste, 25% water, to hazardous waste incineration/ CH/ kg | 3067 | 4.63E+00 | kg |
| electricity, high voltage, at grid/ IT/ kWh | 1081 | 2.34E+02 | kWh |
| heat, natural gas, at industrial furnace >100kW/ RER/ MJ | 2118 | 3.58E+03 | MJ |
| transport, lorry >32t, EURO5/ RER/ tkm | 2811 | 2.80E+03 | tkm |

**40 MVA**

| Background process | ID | Amount | Unit |
|---|---|---|---|
| aluminium, primary, at plant/ RER/ kg | 1755 | 2.33E+00 | kg |
| copper, primary, at refinery/ GLO/ kg | 1796 | 2.26E+02 | kg |
| glass fibre, at plant/ RER/ kg | 1358 | 1.16E+01 | kg |
| polystyrene foam slab, at plant/ RER/ kg | 1563 | 0.00E+00 | kg |
| kraft paper, unbleached, at plant/ RER/ kg | 2544 | 1.05E+01 | kg |
| alkyd paint, white, 60% in H2O, at plant/ RER/ kg | 2485 | 9.50E-01 | kg |
| cellulose fibre, inclusive blowing in, at plant/ CH/ kg | 1554 | 2.80E+01 | kg |

| | | | |
|---|---|---|---|
| ceramic tiles, at regional storage/ CH/ kg | 864 | 3.95E+00 | kg |
| bronze, at plant/ CH/ kg | 1768 | 1.03E+00 | kg |
| resin size, at plant/ RER/ kg | 2493 | 1.50E-01 | kg |
| steel, low-alloyed, at plant/ RER/ kg | 1914 | 8.98E+02 | kg |
| sheet rolling, steel/ RER/ kg | 1956 | 2.06E+02 | kg |
| lubricating oil, at plant/ RER/ kg | 740 | 3.88E+02 | kg |
| disposal, municipal solid waste, 22.9% water, to sanitary landfill/ CH/ kg | 3326 | 4.94E+01 | kg |
| disposal, hazardous waste, 25% water, to hazardous waste incineration/ CH/ kg | 3067 | 9.26E+00 | kg |
| electricity, high voltage, at grid/ IT/ kWh | 1081 | 4.67E+02 | kWh |
| heat, natural gas, at industrial furnace >100kW/ RER/ MJ | 2118 | 7.16E+03 | MJ |
| transport, lorry >32t, EURO5/ RER/ tkm | 2811 | 4.30E+03 | tkm |

**50 MVA**

| Background process | ID | Amount | Unit |
|---|---|---|---|
| aluminium, primary, at plant/ RER/ kg | 1755 | 2.33E+00 | kg |
| copper, primary, at refinery/ GLO/ kg | 1796 | 2.26E+02 | kg |
| glass fibre, at plant/ RER/ kg | 1358 | 1.16E+01 | kg |
| polystyrene foam slab, at plant/ RER/ kg | 1563 | 0.00E+00 | kg |
| kraft paper, unbleached, at plant/ RER/ kg | 2544 | 1.05E+01 | kg |
| alkyd paint, white, 60% in H2O, at plant/ RER/ kg | 2485 | 9.50E-01 | kg |
| cellulose fibre, inclusive blowing in, at plant/ CH/ kg | 1554 | 2.80E+01 | kg |
| ceramic tiles, at regional storage/ CH/ kg | 864 | 3.95E+00 | kg |
| bronze, at plant/ CH/ kg | 1768 | 1.03E+00 | kg |
| resin size, at plant/ RER/ kg | 2493 | 1.50E-01 | kg |
| steel, low-alloyed, at plant/ RER/ kg | 1914 | 8.98E+02 | kg |
| sheet rolling, steel/ RER/ kg | 1956 | 2.06E+02 | kg |
| lubricating oil, at plant/ RER/ kg | 740 | 3.88E+02 | kg |
| disposal, municipal solid waste, 22.9% water, to sanitary landfill/ CH/ kg | 3326 | 6.17E+01 | kg |
| disposal, hazardous waste, 25% water, to hazardous waste incineration/ CH/ kg | 3067 | 1.16E+01 | kg |
| electricity, high voltage, at grid/ IT/ kWh | 1081 | 5.84E+02 | kWh |
| heat, natural gas, at industrial furnace >100kW/ RER/ MJ | 2118 | 8.94E+03 | MJ |
| transport, lorry >32t, EURO5/ RER/ tkm | 2811 | 4.30E+03 | tkm |

**63 MVA**

| Background process | ID | Amount | Unit |
|---|---|---|---|
| aluminium, primary, at plant/ RER/ kg | 1755 | 0.00E+00 | kg |
| copper, primary, at refinery/ GLO/ kg | 1796 | 4.59E+02 | kg |
| glass fibre, at plant/ RER/ kg | 1358 | 0.00E+00 | kg |
| polystyrene foam slab, at plant/ RER/ kg | 1563 | 4.75E+01 | kg |
| kraft paper, unbleached, at plant/ RER/ kg | 2544 | 0.00E+00 | kg |
| alkyd paint, white, 60% in H2O, at plant/ RER/ kg | 2485 | 6.93E+00 | kg |
| cellulose fibre, inclusive blowing in, at plant/ CH/ kg | 1554 | 0.00E+00 | kg |
| ceramic tiles, at regional storage/ CH/ kg | 864 | 8.35E+00 | kg |
| bronze, at plant/ CH/ kg | 1768 | 0.00E+00 | kg |
| resin size, at plant/ RER/ kg | 2493 | 0.00E+00 | kg |
| steel, low-alloyed, at plant/ RER/ kg | 1914 | 8.92E+02 | kg |

| | | | |
|---|---|---|---|
| sheet rolling, steel/ RER/ kg | 1956 | 0.00E+00 | kg |
| lubricating oil, at plant/ RER/ kg | 740 | 5.00E+02 | kg |
| softwood, stand establishment / tending / site development, under bark/ RER/ m3 | 3587 | 4.73E+01 | kg |
| disposal, municipal solid waste, 22.9% water, to sanitary landfill/ CH/ kg | 3326 | 7.78E+01 | kg |
| disposal, hazardous waste, 25% water, to hazardous waste incineration/ CH/ kg | 3067 | 1.46E+01 | kg |
| electricity, high voltage, at grid/ IT/ kWh | 1081 | 7.36E+02 | kWh |
| heat, natural gas, at industrial furnace >100kW/ RER/ MJ | 2118 | 1.13E+04 | MJ |
| transport, lorry >32t, EURO5/ RER/ tkm | 2811 | 5.58E+03 | tkm |

**250 MVA**

| Background process | ID | Amount | Unit |
|---|---|---|---|
| aluminium, primary, at plant/ RER/ kg | 1755 | 4.97E+01 | kg |
| copper, primary, at refinery/ GLO/ kg | 1796 | 6.06E+02 | kg |
| glass fibre, at plant/ RER/ kg | 1358 | 2.77E+01 | kg |
| polystyrene foam slab, at plant/ RER/ kg | 1563 | 0.00E+00 | kg |
| kraft paper, unbleached, at plant/ RER/ kg | 2544 | 3.70E+01 | kg |
| alkyd paint, white, 60% in H2O, at plant/ RER/ kg | 2485 | 2.38E+00 | kg |
| cellulose fibre, inclusive blowing in, at plant/ CH/ kg | 1554 | 1.32E+02 | kg |
| ceramic tiles, at regional storage/ CH/ kg | 864 | 5.02E+01 | kg |
| bronze, at plant/ CH/ kg | 1768 | 0.00E+00 | kg |
| resin size, at plant/ RER/ kg | 2493 | 4.70E+00 | kg |
| steel, low-alloyed, at plant/ RER/ kg | 1914 | 2.82E+03 | kg |
| sheet rolling, steel/ RER/ kg | 1956 | 9.52E+02 | kg |
| lubricating oil, at plant/ RER/ kg | 740 | 1.20E+03 | kg |
| disposal, municipal solid waste, 22.9% water, to sanitary landfill/ CH/ kg | 3326 | 3.09E+02 | kg |
| disposal, hazardous waste, 25% water, to hazardous waste incineration/ CH/ kg | 3067 | 5.79E+01 | kg |
| electricity, high voltage, at grid/ IT/ kWh | 1081 | 2.92E+03 | kWh |
| heat, natural gas, at industrial furnace >100kW/ RER/ MJ | 2118 | 4.47E+04 | MJ |
| transport, lorry >32t, EURO5/ RER/ tkm | 2811 | 1.35E+04 | tkm |

**500 MVA**

| Background process | ID | Amount | Unit |
|---|---|---|---|
| aluminium, primary, at plant/ RER/ kg | 1755 | 0.00E+00 | kg |
| copper, primary, at refinery/ GLO/ kg | 1796 | 9.99E+02 | kg |
| glass fibre, at plant/ RER/ kg | 1358 | 0.00E+00 | kg |
| polystyrene foam slab, at plant/ RER/ kg | 1563 | 1.63E+02 | kg |
| kraft paper, unbleached, at plant/ RER/ kg | 2544 | 0.00E+00 | kg |
| alkyd paint, white, 60% in H2O, at plant/ RER/ kg | 2485 | 5.50E+01 | kg |
| cellulose fibre, inclusive blowing in, at plant/ CH/ kg | 1554 | 0.00E+00 | kg |
| ceramic tiles, at regional storage/ CH/ kg | 864 | 6.63E+01 | kg |
| bronze, at plant/ CH/ kg | 1768 | 0.00E+00 | kg |
| resin size, at plant/ RER/ kg | 2493 | 0.00E+00 | kg |
| steel, low-alloyed, at plant/ RER/ kg | 1914 | 3.83E+03 | kg |
| sheet rolling, steel/ RER/ kg | 1956 | 0.00E+00 | kg |
| lubricating oil, at plant/ RER/ kg | 740 | 1.58E+03 | kg |

|  |  |  |  |
|---|---|---|---|
| softwood, stand establishment / tending / site development, under bark/ RER/ m3 | 3587 | 3.75E+02 | kg |
| disposal, municipal solid waste, 22.9% water, to sanitary landfill/ CH/ kg | 3326 | 6.17E+02 | kg |
| disposal, hazardous waste, 25% water, to hazardous waste incineration/ CH/ kg | 3067 | 1.16E+02 | kg |
| electricity, high voltage, at grid/ IT/ kWh | 1081 | 5.84E+03 | kWh |
| heat, natural gas, at industrial furnace >100kW/ RER/ MJ | 2118 | 8.94E+04 | MJ |
| transport, lorry >32t, EURO5/ RER/ tkm | 2811 | 1.99E+04 | tkm |

## Maintenance

| Background process | ID | Amount | Unit |
|---|---|---|---|
| transport, helicopter/ GLO/ h | 2722 | 8.00E-02 | h |

## Construction

| Background process | ID | Amount | Unit |
|---|---|---|---|
| transport, lorry >16t, fleet average/ RER/ tkm | 2807 | 1.06E-02 | tkm |
| transport, passenger car/ RER/ pkm | 2812 | 2.84E-04 | pkm |

## Power losses

Three different scenarios

| Background process | ID | Amount | Unit |
|---|---|---|---|
| electricity, production mix NO/ NO/ kWh | 1028 | 2.00E+01 | kWh |
| electricity, production mix NORDEL/ NORDEL/ kWh | 1029 | 2.00E+01 | kWh |
| electricity, production mix RER/ RER/ kWh | 1032 | 2.00E+01 | kWh |

## Switchgear

**66 kV w/$SF_6$**

| Background process | ID | Amount | Unit |
|---|---|---|---|
| steel, low-alloyed, at plant/ RER/ kg | 1914 | 6.15E+00 | kg |
| aluminium, primary, at plant/ RER/ kg | 1755 | 2.24E+00 | kg |
| copper, primary, at refinery/ GLO/ kg | 1796 | 7.45E-01 | kg |
| silver, at regional storage/ RER/ kg | 1893 | 1.12E-03 | kg |
| zinc, primary, at regional storage/ RER/ kg | 1923 | 9.31E-02 | kg |
| polyethylene, HDPE, granulate, at plant/ RER/ kg | 2655 | 1.49E-01 | kg |
| epoxy resin insulator (Al2O3), at plant/ RER/ kg | 2616 | 5.59E-02 | kg |
| ceramic tiles, at regional storage/ CH/ kg | 864 | 9.13E+00 | kg |
| sulphur hexafluoride, liquid, at plant/ RER/ kg | 600 | 1.13E-01 | kg |
| electricity, production mix DE/ DE/ kWh | 1013 | 8.11E+00 | kWh |
| heat, natural gas, at industrial furnace >100kW/ RER/ MJ | 2118 | 1.54E+01 | MJ |
| disposal, municipal solid waste, 22.9% water, to sanitary landfill/ CH/ kg | 3326 | 1.56E+00 | kg |
| disposal, hazardous waste, 25% water, to hazardous waste incineration/ CH/ kg | 3067 | 3.75E-01 | kg |
| transport, lorry >32t, EURO5/ RER/ tkm | 2811 | 3.35E+01 | tkm |

**66 kV w/o $SF_6$**

| Background process | ID | Amount | Unit |
|---|---|---|---|
| steel, low-alloyed, at plant/ RER/ kg | 1914 | 8.25E+00 | kg |
| aluminium, primary, at plant/ RER/ kg | 1755 | 3.00E+00 | kg |
| copper, primary, at refinery/ GLO/ kg | 1796 | 1.00E+00 | kg |
| silver, at regional storage/ RER/ kg | 1893 | 1.50E-03 | kg |
| zinc, primary, at regional storage/ RER/ kg | 1923 | 1.25E-01 | kg |
| polyethylene, HDPE, granulate, at plant/ RER/ kg | 2655 | 2.00E-01 | kg |
| epoxy resin insulator (Al2O3), at plant/ RER/ kg | 2616 | 7.50E-02 | kg |
| ceramic tiles, at regional storage/ CH/ kg | 864 | 1.25E+01 | kg |
| sulphur hexafluoride, liquid, at plant/ RER/ kg | 600 | 0.00E+00 | kg |
| electricity, production mix DE/ DE/ kWh | 1013 | 1.09E+01 | kWh |
| heat, natural gas, at industrial furnace >100kW/ RER/ MJ | 2118 | 2.07E+01 | MJ |
| disposal, municipal solid waste, 22.9% water, to sanitary landfill/ CH/ kg | 3326 | 2.09E+00 | kg |
| disposal, hazardous waste, 25% water, to hazardous waste incineration/ CH/ kg | 3067 | 5.04E-01 | kg |
| transport, lorry >32t, EURO5/ RER/ tkm | 2811 | 4.50E+01 | tkm |

**132 kV w/$SF_6$**

| Background process | ID | Amount | Unit |
|---|---|---|---|
| steel, low-alloyed, at plant/ RER/ kg | 1914 | 1.60E+01 | kg |
| aluminium, primary, at plant/ RER/ kg | 1755 | 5.81E+00 | kg |
| copper, primary, at refinery/ GLO/ kg | 1796 | 1.94E+00 | kg |
| silver, at regional storage/ RER/ kg | 1893 | 2.90E-03 | kg |
| zinc, primary, at regional storage/ RER/ kg | 1923 | 2.42E-01 | kg |
| polyethylene, HDPE, granulate, at plant/ RER/ kg | 2655 | 3.87E-01 | kg |
| epoxy resin insulator (Al2O3), at plant/ RER/ kg | 2616 | 1.45E-01 | kg |
| ceramic tiles, at regional storage/ CH/ kg | 864 | 2.37E+01 | kg |
| sulphur hexafluoride, liquid, at plant/ RER/ kg | 600 | 1.45E-01 | kg |
| electricity, production mix DE/ DE/ kWh | 1013 | 2.11E+01 | kWh |
| heat, natural gas, at industrial furnace >100kW/ RER/ MJ | 2118 | 4.01E+01 | MJ |
| disposal, municipal solid waste, 22.9% water, to sanitary landfill/ CH/ kg | 3326 | 4.04E+00 | kg |
| disposal, hazardous waste, 25% water, to hazardous waste incineration/ CH/ kg | 3067 | 9.75E-01 | kg |
| transport, lorry >32t, EURO5/ RER/ tkm | 2811 | 8.71E+01 | tkm |

## Disposal

For practical reasons all disposal processes are kept out of this appendix. They are found in the electronic attachment.

## Stressors

For practical reasons all stressor details are kept out of this appendix. They are found in the electronic attachment.

**Transformer stressors**

| Stressor name | ID |
|---|---|
| Carbon dioxide, fossil/ air/ unspecified | 114 |
| COD, Chemical Oxygen Demand/ water/ unspecified | 1235 |
| BOD5, Biological Oxygen Demand/ water/ unspecified | 1192 |
| Suspended solids, unspecified/ water/ unspecified | 1543 |
| Hydrocarbons, aliphatic, alkanes, unspecified/ air/ unspecified | 252 |
| Ammonia/ air/ unspecified | 40 |
| Nitrate/ water/ ground- | 1430 |
| Nitrite/ water/ ground-, long-term | 1434 |
| Phosphorus/ water/ unspecified | 1461 |

**Switchgear stressors**

| Stressor name | ID |
|---|---|
| carbon dioxide, air, unspecified, kg | 15521 |
| chlorofluoromethane, air, high population density, kg | 23264 |
| acetylene, air, high population density, kg | 219 |
| sulphur hexafluoride, air, unspecified, kg | 509 |

## Sentralnett

(All background and stressor data are from the doctoral thesis of Raquel Jorge, and not displayed here. They are found in the electronic attachment.)

| Foreground process | Amount | → | Delivered to |
|---|---|---|---|
| *FU: Delivery of 1 MWh electricity* | *1* | *MWh* | *Output* |
| Trafo 9.6 MVA | 6.32E-04 | pc | Grid assembly |
| Trafo 16 MVA | 3.16E-04 | pc | Grid assembly |
| Trafo 40 MVA | 8.92E-04 | pc | Grid assembly |
| Trafo 63 MVA | 4.46E-04 | pc | Grid assembly |
| Trafo 250 MVA | 5.89E-04 | pc | Grid assembly |
| Trafo 500 MVA | 5.89E-04 | pc | Grid assembly |
| Gas Insulated Switchgear 300 kV | 1.49E-04 | pc | Grid assembly |
| Gas Insulated Switchgear 420 kV | 1.49E-04 | pc | Grid assembly |
| Plug and switch system, PASS MO | 1.57E-02 | pc | Grid assembly |
| Double break disconnector SDB 245p | 3.04E-04 | pc | Grid assembly |
| 150 kV aerial line | 1.97E-02 | km | Grid assembly |
| 220 kV aerial line | 5.62E-06 | km | Grid assembly |
| 300 kV aerial line | 1.25E-05 | km | Grid assembly |
| 400 kV aerial line | 1.20E-04 | km | Grid assembly |
| 150 kV Masts | 1.74E-03 | pc | Grid assembly |
| 220 kV Masts | 1.97E-03 | pc | Grid assembly |
| 300 kV Masts | 3.00E-03 | pc | Grid assembly |
| 400 kV Masts | 1 | pc | Functional Unit |
| HVDC sea cable | 1 | km | Grid assembly |
| Grid assembly | 1 |  | Functional Unit |
| Construction | 1 |  | Use phase |
| Use phase | 1 |  | Functional Unit |
| Maintenance | 1 |  | Disposal |
| 150 kV OHL maintenance | 6.32E-04 | pc | OHL disposal |
| 220 kV OHL maintenance | 3.16E-04 | pc | OHL disposal |
| 300 kV OHL maintenance | 8.92E-04 | pc | OHL disposal |
| 400 kV OHL maintenance | 4.46E-04 | pc | OHL disposal |
| Power losses | 1 |  | Disposal |
| Disposal | 5.89E-04 | pc | Cable disposal |
| Disposal of Trafo 9.6 MVA | 5.89E-04 | pc | Cable disposal |
| Disposal of Trafo 16 MVA | 1.49E-04 | pc | Cable disposal |
| Disposal of Trafo 40 MVA | 1.49E-04 | pc | Cable disposal |
| Disposal of Trafo 63 MVA | 1 |  | Disposal |
| Disposal of Trafo 250 MVA | 1.57E-02 |  | Mast disposal |
| Disposal of Trafo 500 MVA | 3.04E-04 |  | Mast disposal |
| Disposal of Gas Insulated Switchgear 300 kV | 1.97E-02 |  | Mast disposal |
| Disposal of Gas Insulated Switchgear 420 kV | 1 |  | Disposal |
| Disposal of Plug and switch system, PASS MO | 5.62E-06 |  | Switchgear disposal |
| Disposal of Double break disconnector SDB 245p | 1.25E-05 |  | Switchgear disposal |
| Disposal of 150 kV aerial line | 1.20E-04 |  | Switchgear disposal |
| Disposal of 220 kV aerial line | 1.74E-03 |  | Switchgear disposal |
| Disposal of 300 kV aerial line | 1.97E-03 |  | Switchgear disposal |
| Disposal of 400 kV aerial line | 1 |  | Disposal |
| Disposal of HVDC sea cable |  |  |  |

## Switchgear Modelling Details

In the regional grid the switchgear can be found on voltage levels of both 66 kV and 132 kV. Of the former, 116 are registered as $SF_6$-insulated switches, whereas 75 are either using pressurized air, oil or other technologies. As the number of switches without $SF_6$ at this voltage level is significant, these are modelled with the same material requirements as the $SF_6$ switches, excluding the $SF_6$ gas. Although this simplification is slightly inaccurate, the guessing of excessive material use due to lack of $SF_6$ is considered even more inaccurate.

At 132 kV there are fewer switches, but of the 17 found in this part of the grid, seven operate with $SF_6$ as insulation and are included in the model. The 10 132 kV switches without $SF_6$ lack insulation technology data and are thus excluded, unlike the 66 kV switches. This cut off is also applied due to the fact that only the $SF_6$ containing switches are owned by NTE Nett, whereas Statnett SF own a significant part of the remaining 132 kV switchgear. These are therefore most likely already accounted for in the LCA study of the *sentralnett*.

Data for the switchgear stems from an ABB product sheet, and although Siemens manufactures most of the switches in the Nord-Trøndelag grid, the material requirements should be reasonably similar.

Thus, the switches are modelled as three types, namely 66 kV with $SF_6$ insulation, 66 kV without $SF_6$ insulation, and 132 kV with $SF_6$ insulation. All are modelled according to the data sheet for the Live tank Circuit Breaker type LTB 145D produced by ABB. The total mass of the LTB 145D is 1,389 kg, whereas the 132 kV switch by Siemens is 1,935 kg. The material requirements for the switches are assumed to increase linearly with the total mass of the switch, leaving the relative shares of the different components equal. The same assumption is used for the 66 kV switches, where the total mass is listed as either 680 kg or 810 kg, modelling these switches with the average of 745 kg.

The 66 kV switches with non-$SF_6$ insulating technologies are assumed to be slightly heavier, due to the fact that their physical dimensions will be larger. Applying $SF_6$ technology enables a substantial reduction of electric power component size, as mentioned in section 2.3.2. Therefore, according to personal communication with NTE Nett, the switchgear without $SF_6$ is assumed to have a total mass of 1,000 kg, of which 500 kg is insulation.

The energy consumption of electricity and heat in the production phase of the switches are also assumed linear to the total mass, as are the waste products, emissions and stressors related to production. As for transportation, the production facility of Siemens and not ABB is assumed to be the place of origin for all the switches. The Schaltwerk factory is the world's largest of its kind, and is located in Berlin The transportation from Berlin to Nord-Trøndelag is assumed to be 1,800 km by truck.