ISBN 978-82-471-4597-5 (printed version)
ISBN 978-82-471-4598-2 (electronic version)
ISSN 1503-8181

NTNU – Trondheim
Norwegian University of
Science and Technology

Raquel Santos Jorge

Doctoral Thesis

Doctoral theses at NTNU, 2013:238

NTNU
Norwegian University of Science and Technology
Thesis for the degree of Philosophiae Doctor
Faculty of Engineering Science & Technology
Department of Energy and Process Engineering

NTNU

Doctoral theses at NTNU, 2013:238

Raquel Santos Jorge

Environmental consequences of electricity transmission and distribution - a life cycle perspective

NTNU – Trondheim
Norwegian University of
Science and Technology

Raquel Santos Jorge

Environmental consequences of electricity transmission and distribution - a life cycle perspective

Thesis for the degree of Philosophiae Doctor

Trondheim, September 2013

Norwegian University of Science and Technology
Faculty of Engineering Science & Technology
Department of Energy and Process Engineering

NTNU – Trondheim
Norwegian University of
Science and Technology

NTNU
Norwegian University of Science and Technology

Thesis for the degree of Philosophiae Doctor

Faculty of Engineering Science & Technology
Department of Energy and Process Engineering

ISBN 978-82-471-4597-5 (printed version)
ISBN 978-82-471-4598-2 (electronic version)
ISSN 1503-8181

Doctoral theses at NTNU, 2013:238

Printed by Skipnes Kommunikasjon as

"Climate change is an externality that is global in both its causes and consequences. The incremental impact of a tonne of GHG on climate change is independent of where in the world it is emitted (unlike other negative impacts such as air pollution and its costs to public health), because GHGs diffuse in the atmosphere and because local climate changes depend on the local climate system. While different countries produce different volumes, the marginal damage of an extra unit is independent of weather it comes from the UK or Australia".

N. Stern (2007). The Economics of Climate Change, The Stern Review.

To my grandfather Florindo

"The electrical grid goes practically everywhere. It reaches into your home, your bedroom, and climbs right up into the lamp next to your pillow. It's there while you sleep, and it's waiting for you in the morning. Taken in its entirety, the grid is a machine, the most complex machine ever made. The National Academy of Engineering called it the greatest engineering achievement of the 20th century. It represents the largest industrial investment in history".

Phillip F. Schewe (2007). The grid: a journey through the heart of our electrified world.

Preface

This thesis is the result of research work carried out at IndEcol, the Industrial Ecology Program of the Energy and Process Engineering Department (EPT), at the Norwegian University of Science and Technology (NTNU). The work was done under the supervision of Prof. Edgar Hertwich, who is affiliated with the same department.

The thesis has been submitted to NTNU for partial fulfillment of the requirements for the degree of philosophiae doctor, and it consists of four articles and a summary of the research work. Three of the articles are published in scientific journals, and the fourth article has been submitted to the journal Energy and is currently under review.

The PhD work was sponsored by NTNU and partly sponsored by EPT who provided funding for further two months of the research work.

Acknowledgements

My biggest acknowledgement goes to my supervisor, Prof. Edgar Hertwich, for having given me the opportunity to take the journey that culminated with this thesis. The PhD is with no doubt the most relevant work/study project I ever undertook, and the one that will have (or already has) the most implications for my future career. It was a golden opportunity to have spent 4 years at the Industrial Ecology group at NTNU, surrounded by very talented and interesting colleagues. I would like to thank Edgar for this opportunity and for his support throughout the PhD. Edgar was remarkably good at guiding this work, but at the same time giving me the freedom to do my own choices in terms of themes of research, projects, etc. That was very valuable.

I have much to thank to Prof. Anders Strømman at the Industrial Ecology Program at NTNU for having provided me with knowledge on fundamental methods and tools that Industrial Ecologists use, namely Life Cycle Assessment and Input-Output Analysis. Good theoretical foundations are always a good starting point for a PhD. I would also like to thank one of Anders's PhD students, Guillaume, for his help with computational tools, namely Matlab and ARDA, which were used in all of the articles from this thesis.

I would like to thank Troy Hawkins and Glen Peters for the long discussions at the beginning of my PhD about topics of interest and themes for the research. The discussions with Jan Weinzettel and Richard Wood were also very helpful.

I would like to thank the Norwegian government and the Norwegian University of Science and Technology for having provided funding for my doctoral research.

I would like to thank my parents for having believed that it was a good idea to move to a place 25 degrees north from Lisbon to study environmental stuff. They don’t realize it, but they are actually very energy-saving minded people. My mother often notices when I come for a visit that my water consumption per shower is too high. My father is reluctant about using a heater in the winter to raise the indoor temperature from 15 to 20 degrees and he rather goes around in a woolen sweater. And it's not because they can't afford the energy – it's just because they are used to using less. Compared to them, I feel that my generation takes the energy and other resources too much for granted.

Håvard, thank you for your support and care always and specially in the last months when I was finishing the PhD. Also, thank you for the help in proofreading the thesis.

Bhawna, you have been the best office mate one could wish for. I especially enjoyed the many Indian delicacies and snacks that I got to sample.

To all my friends, thank you for making my life in Trondheim so much more interesting.

Abstract

The transmission and distribution of electricity is increasingly important in the context of future energy systems and large investments are expected worldwide for this sector in the coming years. While knowledge and research about environmental consequences of systems for power generation is abundant, data and available studies on environmental impacts for power transmission and distribution systems are somehow limited.

This thesis consists of the investigation of environmental consequences for systems used in power transmission and distribution in a life cycle perspective. Three goals were set for the thesis: one was to investigate the impacts for transmission and distribution systems from a component level. Here the aim was to study the main component types in an electricity grid, e.g., a power line, a transformer, etc. to a level of detail that allowed for the investigation of important processes and causes of environmental impacts in each case. The second goal was to understand the impacts from an electricity grid system. To accomplish this, a real grid system was modeled and life cycle impacts were obtained per kWh transmitted. The third goal was to address a question that has recently been brought up to the attention of energy systems researchers: what are the environmental impacts associated with the scaling up of systems based on renewable energy sources? Here, that question is addressed in light of the transmission grid extensions that are necessary for upgrading the European system in order to integrate renewable energy sources.

The studies presented here cover the main components of an electrical grid. These components are: overhead lines, underground cables, subsea cables and equipment used in substations, e.g., transformers and switchgear. Different equipment ratings are considered, although most of the analyses cover the high-voltage range, or power transmission level. The analyses include both AC systems, which represent most of the transmission assets installed worldwide, and DC systems, which are used for specific applications such as the transmission of power over large distances, subsea transmission or interconnection of two regions operating at different frequencies.

The method used is Life Cycle Assessment. The impact assessment method used in all the studies undertaken is ReCiPe Midpoint, hierarchist version, with European normalisation.

The main conclusions from the thesis can be summarized as follows: at a component level, electrical losses in equipment used for transmission and distribution are the largest contributor to life cycle impacts in virtually all impact categories. After power losses, impacts arise mainly from these processes: for overhead lines, conductors and masts dominate; cable production is an important process in land and sea cables. For transformers and substation equipment, the production of raw materials is also important. Manufacturing of components, e.g., shaping the materials to a final product is important for some studied impact categories, e.g., water depletion. Processes such as maintenance and installation have a smaller contribution to life cycle impacts. Important direct emissions for transmission and distribution (T&D) systems are mineral oil, zinc and SF_6 that result from leakages in the equipment throughout the lifetime. For substation equipment using SF_6, the impacts due to gas leakages can be the main process for climate change scores. Recycling of metal parts brings benefits for overall performance of the

equipment studied. However, the impacts arising from other processes in the end-of-life may outweigh the benefits from avoided production.

At a system level, it was found that the transmission of electricity in the Norwegian grid causes an impact of 1.3 to 1.5 g CO_2 eq./kWh delivered to the distribution network. A sensitivity analysis of the results to the electricity mix considered for power losses shows that, for "cleaner" mixes, the share of impacts from infrastructure related processes is higher. For a Norwegian mix of power production, impacts due to losses contribute as much to climate change scores as impacts from infrastructure related processes.

Finally, the investigation of impacts for transmission grid upgrading projects in Europe indicates that over the lifecycle, total metal depletion impacts are of 11.2 Mton Fe eq. The projects also correspond to a total score for climate change of 10.7 Mton CO_2 eq. The grid upgrading corresponds to the construction of new grid equipment, such as new lines, subsea and underground cables, etc. and renovation of already installed equipment. For the construction of new equipment, inputs from several materials, e.g., sand, steel, limestone, aluminum, iron, copper, lead, transformer oil, zinc and gravel are significant. The new assets require approximately 2 Mton of iron and steel, 400,000 tons of aluminum and 150,000 tons of copper. A sensitivity analysis for recycling rates of metal parts indicates that the results are greatly affected by the assumptions made.

Table of contents

List of Figures

List of Tables

1 Introduction

1.1 Why Life Cycle Assessment for Transmission and Distribution?

For every kWh of electricity that is generated either by fossil or renewable technologies, a complex system made up of power lines, cables, transformers and other electrical devices has to be in place so that the energy produced by the power plants can be delivered to the final consumers. In Europe, the transmission grid has a length of roughly 300,000 km (ENTSO-E 2011), or more than 7 times the equatorial circumference of the Earth. In addition, a power distribution grid consisting of an even greater length, around 4.5 times as much (SETIS 2013), is required for further transporting the electricity to industries, households and service buildings.

The electrical grid is an important part of our built infrastructure. Moreover, the role of the grid for future energy systems will be even more important. As we shift away from fossil based power production and convert to renewable based technologies, more grid capacity will be required to harness the energy that these sources provide (IEA 2011a, IPCC 2012). In some regions, e.g., northern Germany, transmission constraints are already an issue as renewables are scaling up much quicker than the complementary technologies, which results in renewable energy being dumped. An increasing electrification of energy use, e.g., in transportation is also expected to drive up electricity use and hence demand for more grid and flexibility solutions (Kempton, Pimenta et al. 2010). As we reduce emissions from energy production, the grid gets even more important. Furthermore, by 2035 almost half of the installed grid infrastructure in Europe will have reached its operational lifetime and require renovation (IEA 2011b). All of these factors will drive intensive transmission and distribution (T&D) grid build-up in the region over the next years. The power grid and its elements are described in more detail in section 2.5.

The European Network of Transmission System Operators for Electricity (ENTSO-E) estimates that the integration of renewable energy sources alone - mainly solar and wind, will in a near future create the need for an extra 45,300 km of transmission assets in form of new or renovated aerial lines and land/sea cables (ENTSO-E 2012). These projects are part of an investment portfolio corresponding to more than €100 billion that is required to upgrade the European transmission grid over the next years, according to ENTSO-E. Given the dimension of T&D projects, it becomes crucial to have the right methods, tools and data to holistically evaluate the environmental consequences associated with these systems and which can assist in designing the optimal electricity supply system.

Environmental evaluations taking a holistic perspective in the assessment of impacts for several power production technologies, both fossil and renewable, are widely available in the literature (Lenzen and Munksgaard 2002, Lenzen 2008, Varun, Bhat et al. 2009, Weinzettel, Reenaas et al. 2009, Sherwani, Usmani et al. 2010, Singh 2011, Wiedmann, Suh et al. 2011, Arvesen and Hertwich 2012, Corsten, Ramirez et al. 2013, Hammond, Howard et al. 2013, Rashedi, Sridhar et al. 2013). Taking a holistic perspective means in this context that these studies consider both direct and indirect effects (e.g., direct and indirect greenhouse gas emissions), and a range of environmental impacts is investigated for the systems (e.g., climate change, acidification, etc.). However, even if transmission and distribution of electricity is part of any life cycle assessment (LCA) of electricity supply, the literature, research and data available on life cycle impacts of T&D systems is somehow limited. A consequence is that studies of environmental impacts of electricity supply systems often use either generic models to assess T&D impacts, e.g., based on an inventory for a specific country, or leave it out from the analysis altogether (Kleijn, Voet et al. 2011, Wiedmann, Suh et al. 2011).

The goal for this thesis was to contribute to building up data and knowledge about life cycle impacts of electricity grid systems. There are several types of environmental impacts caused by T&D systems. Figure 1 shows some relevant processes contributing to impacts for the different life cycle stages of a T&D project. During production, impacts occur for the fabrication of raw materials, transportation, manufacturing (shaping of raw materials to a final product) and installation activities such as excavation of land for installation of underground cables. During the use phase, important processes are electricity losses in the electrical wires which represent extra demand for generation and heat loss to the surrounding environment (Harrison, Maclean et al. 2010, Jones and McManus 2010, Itten, Frischknecht et al. 2012, Jorge, Hawkins et al. 2012a, Jorge, Hawkins et al. 2012b, Jorge and Hertwich 2012) and other processes such as maintenance, e.g., overhead line surveying inspections by helicopter.

Several pollutants are also emitted during the use phase of T&D systems: for overhead lines, a percentage of the zinc that is used for coating of the steel masts leaks to the surrounding soil (Itten, Frischknecht et al. 2012, Jorge, Hawkins et al. 2012a). For lines using wooden poles there is leakage of heavy metals (Itten, Frischknecht et al. 2012). In high voltage aerial lines, emissions of nitrous oxide (N_2O) and ozone formed at the corona can occur (Itten, Frischknecht et al. 2012). For gas insulated equipment, e.g., switchgear, there are leakages of sulfur hexafluoride (SF_6) which has an impact on climate change that is 23,900 as strong as the one of CO_2. In equipment containing mineral oil, losses can occur due to leakage/failure. Finally, electrical equipment used for T&D is also responsible for the emission of electromagnetic (EM) radiation, which has been associated with health damages. Impacts due to land use also occur. When the equipment has reached its operational lifetime, recycling of metal parts can bring benefits, but as will be shown, this can be outweighed by the negative environmental scores associated with other processes such as the disposal and incineration of waste.

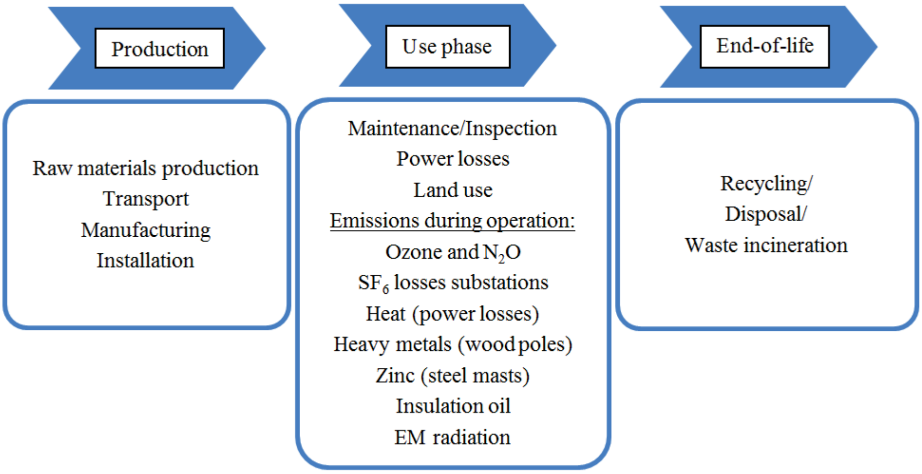


Figure 1: Important processes contributing to life cycle environmental impacts from T&D systems.

The literature on LCA for power grids has only a few references, each covering parts of the T&D system. For example, LCA for power distribution systems is addressed in (Bumby, Druzhinina et al. 2010, Jones and McManus 2010, Itten, Frischknecht et al. 2012, Jorge, Hawkins et al. 2012b). Power transmission is covered by (Jorge and Hertwich , Blackett, Savory et al. 2008, Harrison, Maclean et al. 2010, Jorge, Hawkins et al. 2012a, Jorge and Hertwich 2012). Power losses, although a large contributor to impacts in almost all impact categories, are only modeled in some studies. Losses using a static generation mix are addressed in (Harrison, Maclean et al. 2010, Jorge and Hertwich 2012). Losses as a function of system characteristics, e.g., line resistance are available in (Jones and McManus 2010, Jorge, Hawkins et al. 2012a), the first being the only reference which calculates LCA results as a function of load (Amps) in the system. SF_6 losses, although comprising up to 15% of total transmission system climate change impacts, are only included in these transmission system studies: (Jorge and Hertwich , Harrison, Maclean et al. 2010, Jorge, Hawkins et al. 2012b, Jorge and Hertwich 2012) and in the inventories provided by (Itten, Frischknecht et al. 2012). Ozone and N_2O emissions formed at the corona of high voltage transmission lines are only addressed in (Itten, Frischknecht et al. 2012).

The fact that T&D is increasingly important for future energy systems and that there is to date limited knowledge on the field of LCA for T&D were the two main factors motivating the topic of the thesis.

The work consisted in the compilation of life cycle inventories (LCIs) and life cycle assessment (LCA) results for different systems used in T&D. Both individual components, e.g., power lines, cables, etc., and grid systems are addressed. The thesis has a focus on T&D in Europe, but the method and data can be applied to grids in other contexts by making other assumptions, for example, for power losses, material production, etc. Since the life cycle inventories are provided at a component level, processes can easily be substituted.

The holistic perspective is an important characteristic of the method used here - LCA. By including both direct and indirect effects and covering a range of different types of impacts such as climate change, toxicity, eutrophication, etc., this method avoids problem shifting, i.e., that a certain environmental problem is overseen when trying to solve another. This is an important perspective when analyzing the potential environmental trade-offs from a transition towards low-carbon energy systems.

The main contribution of the thesis was the compilation of life cycle inventories for T&D. Some of the data compiled here, namely for high-voltage lines and cables and transformers, has been incorporated in the most recent version of the Ecoinvent database (v3) (Itten, Frischknecht et al. 2012). Further, the material collected here will hopefully be of interest for researchers working with assessment of energy systems and perhaps renewable energy/grid planners and policy makers. Suggestions for future work are provided in the Discussion section.

1.2 Research questions

The research questions for the thesis are:

1) What are the life cycle impacts for the main component types of an electrical grid such as overhead lines, land/sea cables, transformers, substations, etc.?

    a. What are the overall life cycle impacts for each component?
    b. How large are the impacts resulting from power losses for each impact category?
    c. How large are the impacts associated with the individual life cycle stages? What are the main materials and processes? What are the main sources of direct emissions for these systems?
    d. How do life cycle results change by assuming different electricity mixes?
    e. How do life cycle results change by assuming different scenarios for the end-of-life?

2) What are the life cycle consequences of an electrical grid system?

    a. What are the total impacts of T&D per kWh electricity delivered?
    b. What is the contribution of each component in the network for the total life cycle impacts per kWh?

3) What are the required transformations to the power grid as per today, in order to make it suitable for the accommodating future additions of renewable power capacity?

    a. In particular, what is the infrastructure required for transforming the European power transmission grid into a system suitable for the integration of renewable sources?
    b. What are the resulting environmental impacts associated with the investments in grid infrastructure?

1.3 Research structure

The structure for the research work is represented in Figure 2. The work consisted in three stages: first, an assessment of life cycle impacts for the most important components in a power grid, i.e., overhead lines, land/subsea cables, substations and transformers was performed. Stage number two consisted in the use of life cycle inventories for the individual components to model a real grid system. In this case the Norwegian transmission grid was used as a case study. The life cycle environmental impacts for this system were obtained per kWh of electricity delivered to the distribution grid. Finally, methods and data from the previous studies were extended to understand the role of the transmission grid extensions that are necessary in order to facilitate renewable energy integration in Europe and the resulting environmental impacts of the grid build-up. The scope goes from a component perspective to a national and regional perspective.

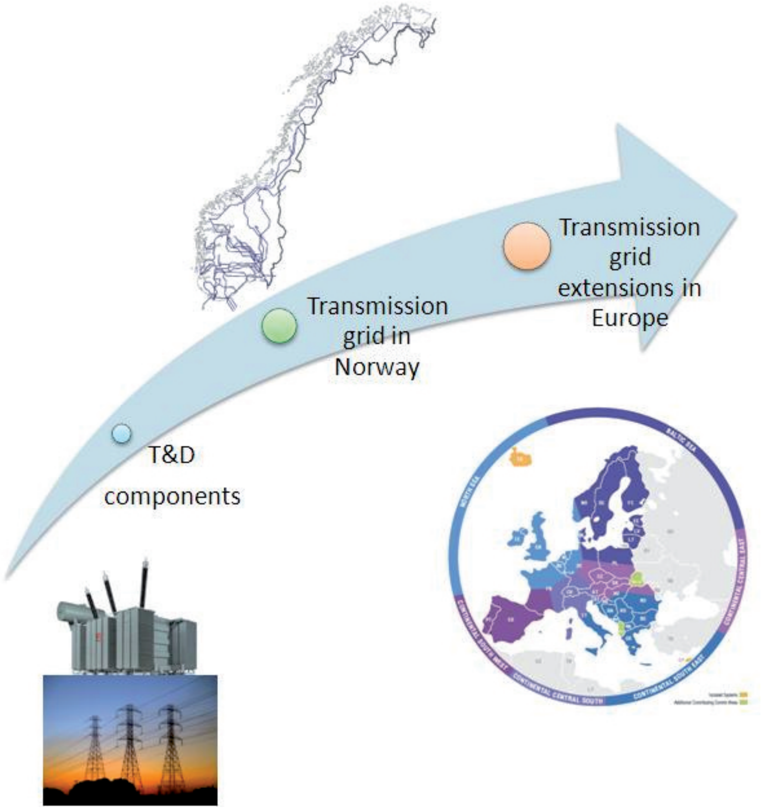


Figure 2: Structure of the research work for the thesis: from a component perspective to a system perspective (national and regional).

The thesis consists of four articles, each focusing on the following product systems:

1) Paper 1 – overhead lines, land and sea cables at different voltage levels used for electricity transmission, including HVDC systems.

2) Paper 2 – transformers and substation equipment, e.g., switchgear used for electricity T&D.

3) Paper 3 – the electricity transmission system in Norway (*Sentralnett*), including interconnectors, i.e., the cables between Norway and abroad.

4) Paper 4 – the product system comprising overhead lines, land/sea cables, transformers and substation equipment required to upgrade the European power transmission grid into a system able to integrate renewable sources.

1.4 Publication list with authorship information

The list of articles for the thesis with full references and abstract is provided in Table 1.

For paper 1 (Life cycle assessment of transmission and distribution – part 1: power lines and cables) the collection of data, analysis and paper writing was done by Jorge; Hawkins and Hertwich supervised the work.

For paper 2 (Life cycle assessment of transmission and distribution – part 2: transformers and substation equipment), Jorge collected the data, analyzed and wrote the study which was supervised by Hawkins and Hertwich.

For papers 3 and 4 (Environmental evaluation of power transmission in Norway; Grid infrastructure for renewable power in Europe – the environmental cost) the collection of data, analysis and writing was the responsibility of Jorge and the supervision was done by Hertwich.

Table 1: Publications

	Reference and abstract
1	Jorge, R.; Hawkins, T.; Hertwich, E. (2012). **Life cycle assessment of electricity transmission and distribution – part 1: power lines and cables**. *The International Journal of Life Cycle Assessment, 17*(1), pp9-15. **Purpose** The purpose of this study is to provide life cycle inventory data and results for components of electrical grids to the larger community of life cycle assessment practitioners. This article is the first in a series of two, each focusing on different components of power grids. In part 1, the objects under scope are power lines and cables. Systems for overhead, underground, and subsea transmission are modeled here, including HVDC systems used in long-distance transmission. **Methods** We use process-based life cycle assessment based on information provided by companies and in reports, Ecoinvent v2.2 as a background dataset and ReCiPe Midpoint Hierarchist perspective v1.0 as the impact assessment method. The average European power mix is used to model the electrical energy required to compensate power losses in the equipment. **Results and discussion** Under the assumption of European power mix, power losses are the dominant process for impacts of lines and cables in all impact categories, contributing with up to 99% to climate change impacts. An exception is the category of metal depletion, for which the production of metal parts is the most relevant process. **Conclusions** After power losses, processes generating the most impacts for overhead lines are the production of metals for masts and conductors; production of foundations comes third. Recycling of metal parts shows benefits in all impact categories. For cables, infrastructure impacts are dominated by cable production, and recycling of cable materials does not always compensate for the other impacts generated at the end-of-life.
2	Jorge, R.; Hawkins, T.; Hertwich, E. (2012). **Life cycle assessment of electricity transmission and distribution – part 2: transformers and substation equipment**. *The International Journal of Life Cycle Assessment*, *17*(2), pp184-191. **Purpose** The purpose of this paper is to characterize the environmental impacts of equipment used in power transmission and distribution. This study is divided in two parts, each addressing different main components of the electrical grid system. This part is concerned with the impacts of transformers and substation equipment while in part 1 a similar analysis is presented for power lines and cables. **Methods** The method used here is process-based life cycle assessment. Ecoinvent v 2.2 is used as a background dataset, and the results are obtained with the impact assessment method ReCiPe Midpoint Hierarchist perspective (v1.0). The average European power mix is used to model the electrical energy required to compensate power losses in the electrical equipment. **Results and discussion** Assuming a European power mix, results for transformers indicate that power losses are by far the most dominant process for almost all impact categories evaluated here, contributing at least 96% to climate change impacts. An exception is the category of metal depletion, for which production of raw materials is the most relevant process. Within infrastructure-related impacts, the production of raw materials is the most important process. Recycling shows benefits for most impact categories. For some substation equipment using sulfur hexafluoride (SF_6), climate change impacts due to SF_6 leakages surpass impacts due to losses. **Conclusions** The results suggest that improvements in component efficiency—reduction of power losses and reduction of SF_6 gas leakages in gas-insulated equipment—would significantly contribute to decreases in overall component impacts.

3

Jorge, R.; Hertwich, E. (2012). **Environmental evaluation of power transmission in Norway.** *Applied Energy, 11*(2), 201-207.

Electrical grid systems are required as a consequence of energy not being produced in the same place as it is consumed, and they are a key element of our energy systems. Transmission and distribution assets comprised of power lines, cables, transformers, substations and other electrical equipment generate a wide range of environmental impacts. Throughout the lifetime of the equipment, the impacts originate mainly from power losses during the use phase, but other life cycle stages such as installation, maintenance and dismantling also contribute significantly to some impact categories. In this paper, the environmental impacts of the Norwegian transmission grid are assessed. The methodology used here is Life Cycle Assessment (LCA) with ReCiPe as impact assessment method. In total, 11,097 km of lines and cables, 345 transformers and 121 substations were installed in the Norwegian transmission grid by the end of 2009; the network also included some hundreds of kilometers of sea cables between Norway and abroad. The results show that for each kWh of electricity transmitted in Norway, climate change impacts are of 1.3–1.5gCO_2eq., assuming a Norwegian electricity mix. Half of these emissions are associated with power losses, and the other half with infrastructure processes such as materials production, installation, maintenance, and end-of-life. The results also show that after the losses, the infrastructure processes for overhead lines and transformers, and the emissions of SF_6 from Gas Insulated equipment are the most relevant contributors for total climate impacts. A sensitivity analysis is done with respect to the electricity mix used to model power losses in the system. The results show that the contribution of power losses to the total climate change scores increases to 84% and 94%, by replacing the Norwegian mix by the Nordic mix and the European mix, respectively.

4

Jorge, R.; Hertwich, E. **Grid infrastructure for renewable power in Europe – the environmental cost.** (under review in *Energy*).

Climate mitigation policies in Europe call for an extensive build-up of renewable power, which will increase from 320 GW in 2012 to 536 GW by 2020. The renewable expansion will mainly consist of the installation of new wind and solar power plants, which require additional transmission lines. The European Network of Transmission System Operators for Electricity estimates that 45,300 km of new or upgraded lines are necessary in the region over the next decade to accommodate the renewable power sources. Building a grid for renewables will help Europe achieve its climate goals, but other resulting environmental impacts have not yet been quantified. In this article a Life Cycle Assessment for the transmission grid expansion is performed. The results show that the grid extension projects correspond to a total impact of 10.7 Mton CO_2 eq. and 11.2 Mton Fe eq. Electricity transmission in Europe in 2020 will be more material intensive, requiring about 10% more metal inputs per kWh than today. Manufacturing processes for the production of transmission equipment are important for some impacts categories, particularly water depletion. Finally, a sensitivity analysis regarding recycling rates indicates that the results in some impact categories present great variation depending on the rates assumed.

2 Background

2.1 Climate change

A few months before this thesis was finalized, the International Energy Agency (IEA) made a statement without precedents in its World Energy Outlook 2012:"No more than one-third of proven reserves of fossil fuels can be consumed prior to 2050 if the world is to achieve the 2°C goal, unless carbon capture and storage (CCS) technology is widely deployed" (IEA 2012). This much is required if we want to avoid climate change.

Man-made climate change is one of the most critical environmental problems we face today and for which urgent action is required. It is well established that the concentration of greenhouse gases (GHGs) in the earth's atmosphere is directly linked to the average global temperature on Earth. We also know that along with steady increases of GHG concentrations since the time of the Industrial Revolution, mean global temperatures are also rising. Finally, it is also unequivocal that the process of burning fossil fuels is the main one driving GHGs up and ultimately causing climate change (UNFCCC 2013).

Although the use of fossil fuels has been a driver for modernization, economic growth and societal development during several decades in the developed world and more recently in the developing world, we have now reached a point where the negative impacts from relying on these energy sources outweigh the benefits. Instead, our current levels of fossil fuel use are already causing societies economical costs (Stern 2007, Hanewinkel, Cullmann et al. 2013), and in most extreme cases, life costs. The Intergovernmental Panel on Climate Change (IPCC) has extensively documented the effects of climate change on ecosystems both evaluating vulnerability and adaptation (IPCC 2007a). Six main impacts are: sea-level rise and coastal impacts, ocean acidification, ecosystems and biodiversity, water resources and desertification, agriculture and food security and human health, for which data was recently updated by (Gossling, Warren et al. 2011).

In 2007, the IPCC concluded that warming of the climate system was evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice areas, and rising global average sea levels (IPCC 2007b). Although this thesis has by no means the ambition to describe why climate change happens, it is useful to go through a very short introduction on this theme because this will later be useful when trying to understand the role of the electricity supply system in the whole climate change picture. Also, this thesis would not have existed, hadn't it been because of the existence of climate change.

Climate models are quite complex and involve the analysis of several anthropogenic and natural factors. However, an easy way to understand how these factors affect the total climate energy balance is to relate to their radiative forcing, i.e., the measure of the influence that that factor has in altering the balancing of incoming effect and outgoing effect in the Earth-atmosphere system (IPCC 2007b). Some factors represent a positive forcing (i.e., tend to warm the surface of the Earth) and others a negative forcing (i.e., tend to cool the surface of the Earth). Figure 3 shows the global mean radiative forcing of the main factors affecting the climate. These values are for 2005, relative to pre-industrial conditions defined at 1750 (Solomon, Qin et al. 2007).

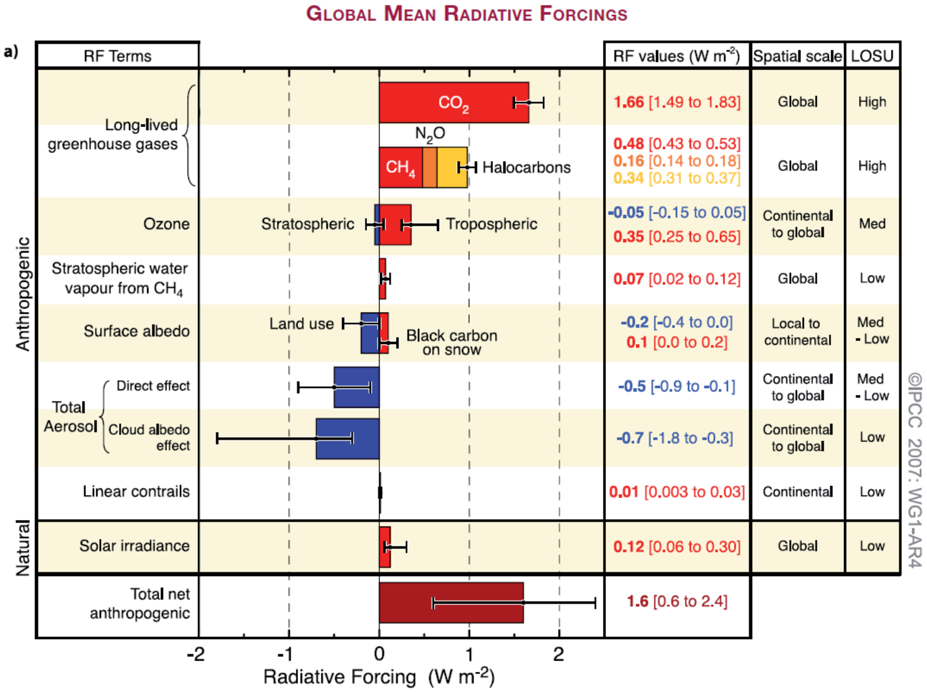


Figure 3: Global mean radiative forcings (Solomon, Qin et al. 2007).

The largest share from anthropogenic radiative forcing stems from CO_2 increases in the atmosphere since pre-industrial times, which prevails over all the other radiative forcing drivers. The level of confidence is also the highest for this factor. The drivers of increased atmospheric CO_2 are fossil fuel use and land use change. By the time the 4th Assessment Report (AR4) from the IPCC was published, data indicated that the global atmospheric concentration of CO_2 had increased from a pre-industrial value of 280 ppm to 379 ppm in 2005. Recent values indicate that this value is now of 392.6 ppm (Blasing 2013), which exceeds by far values dating back 650,000 years (IPCC, 2007), and the radiative forcing has also been updated to 1.85 (Blasing 2013). If the world is to stay below 2°C increase, then emissions should not exceed 450 ppm.

The radiative forcing (RF) of methane (CH_4) has also been updated since the AR4 and is now reported at 0.51 Wm^{-2}. The atmospheric concentration of this gas has gone up from 700 ppb in pre-industrial times to approximately 1800 ppb now (Blasing 2013). Methane emissions are mainly due to agriculture, with smaller contributions from industrial sources, including fossil-fuel emissions.

The concentration of nitrous oxide (N_2O) went up from 270 ppb in pre-industrial levels to about 324 ppb now (Blasing 2013), and the radiative forcing due to this gas is now estimated to be of 0.18 Wm^{-2}. N_2O emissions are mainly due to agriculture and land use change.

The direct radiative forcing due to halocarbons is 0.34 Wm^{-2} as opposed to 0 Wm^{-2} in pre-industrial times, since these emissions are purely anthropogenic. Tropospheric ozone is a short-lived GHG which corresponds to a radiative forcing of 0.35 Wm^{-2}. This value has not been updated since the AR4 (Blasing 2013). Both air quality and climate change are related to changes in tropospheric ozone.

From Figure 3 we can see that several factors exert a negative forcing: changes in surface albedo, i.e., changes in land use that lead to a higher reflectivity (e.g., harvesting crops in high latitude regions, exposing snow areas) and aerosols. However, land use can also cause increased CO_2 emissions due to deforestation and release of carbon from soil rotation.

The IPCC concluded in 2007 that there was a *very high* confidence that the global average net effect of human activities since 1750 has been one of warming, with a radiative effect of 1.6 Wm^{-2}. That was a step forward in relation to the previous assessment report in that the level of confidence had been raised from *high* to *very high*. The AR4 concluded that CO_2 is the most important anthropogenic GHG and that the primary source of increased concentration of CO_2 in the atmosphere is fossil fuel use (80%), although land use change also contributed, but to a smaller extent (land use change is responsible for around 20% of the increased atmospheric concentrations of CO_2). The way these two drivers lead to climate change is represented in Figure 4 (Stern 2007).

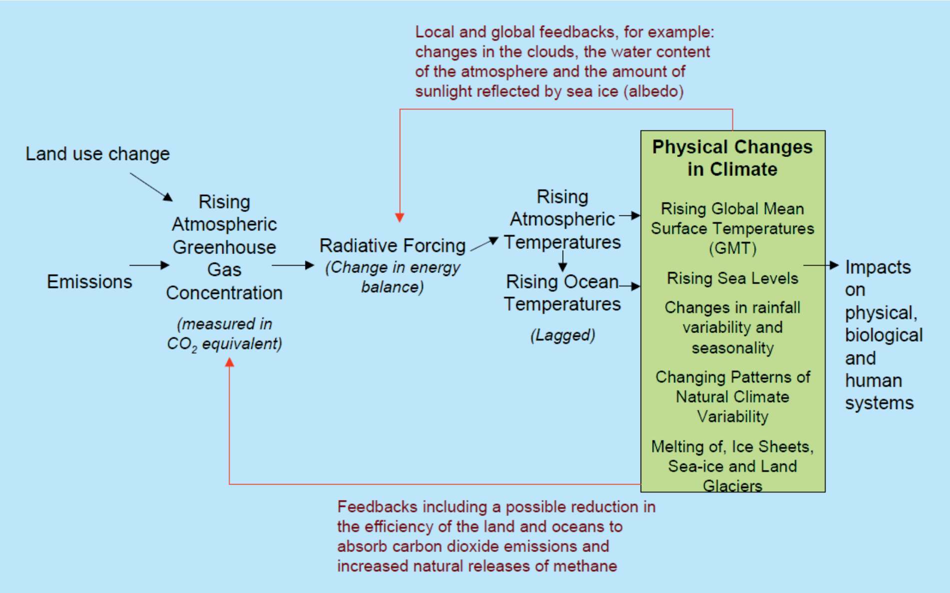
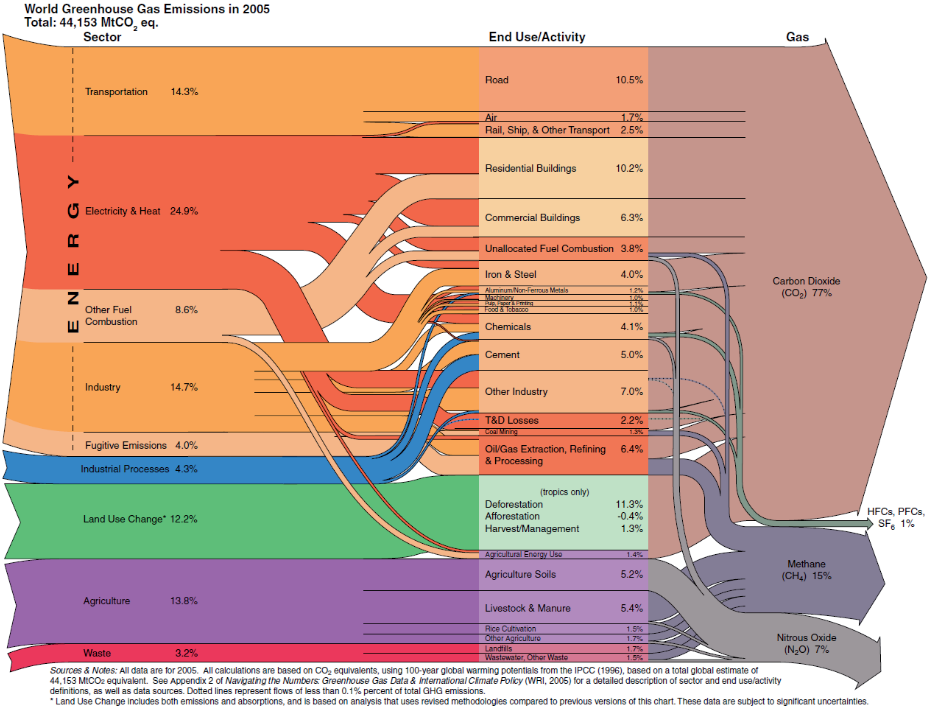


Figure 4: Mechanisms driving climate change (Stern 2007).

Some feedback mechanisms also take place that can either intensify or diminish the effects caused by the first order drivers, e.g., cloud feedback (Zhou, Zelinka et al. 2013) or albedo (Bright, Strømman et al. 2011, Rocha, Loranty et al. 2012).

2.2 The energy sector and the power sector in context

The latest data on emissions, based on 2010 data from bottom-up emission inventory studies, indicates that global GHG emissions stands at 50.1 $GtCO_2$ eq. (UNEP 2012). It is useful to relate total emissions to end-use drivers. Figure 5 provides a good overview of the breakdown of total GHG emissions by sector and end-use/activity (Herzog 2009). Although the numbers refer to data from 2005, global energy systems have not suffered dramatic changes since, so the figure provides a good picture of where emissions originate. As to sources, energy-related processes such as electricity and heat production, industry and transportation are responsible for the largest share of GHGs. The sector with highest contribution is electricity/heat production, representing one quarter of the total emissions. Land-use change and agriculture accounted for about 20% of the total GHGs. Regarding end-use activity, road, buildings and industry represent a large share, and the process of extracting and processing fossil fuels is also dominant. We will come back to it later, but we can already notice that losses in equipment for transmission and distribution of power stand for 2.2% of the world's GHG emissions. As for the GHG type, CO_2 represents more than ¾ of the total emissions, mainly driven by energy-related processes but also land-use changes. Methane represents 15% and nitrous oxide 7%. HFCs, PFCs and SF_6 are the other Kyoto greenhouse gases and together these represent 1% of total GHG emissions. As compared to CO_2, SF_6 has a global warming potential 23,900 times stronger (UNFCCC 2013), which is also something to keep in mind for later consideration.


World Greenhouse Gas Emissions in 2005

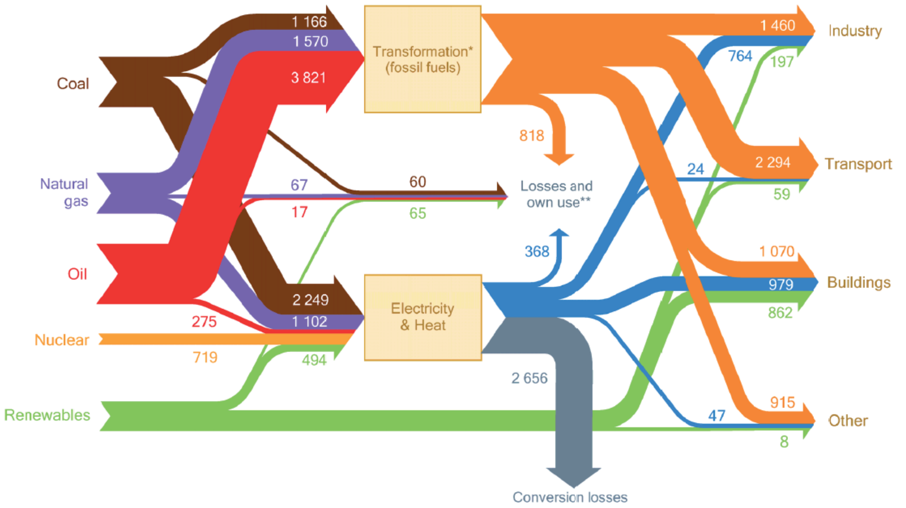
Total: 44,153 MtCO$_2$ eq.

Sources & Notes: All data are for 2005. All calculations are based on CO$_2$ equivalents, using 100-year global warming potentials from the IPCC (1996), based on a total global estimate of 44,153 MtCO$_2$ equivalent. See Appendix 2 of *Navigating the Numbers: Greenhouse Gas Data & International Climate Policy* (WRI, 2005) for a detailed description of sector and end use/activity definitions, as well as data sources. Dotted lines represent flows of less than 0.1% percent of total GHG emissions.

* Land Use Change includes both emissions and absorptions, and is based on analysis that uses revised methodologies compared to previous versions of this chart. These data are subject to significant uncertainties.

Figure 5: Breakdown of global GHG emissions by end-use activity in 2005 (Herzog 2009).

It does not come as a surprise that the IEA has acknowledged that if we are to succeed in limiting/reversing climate change, we have to burn much less fossil fuels than what is theoretically possible to extract. The question of reversibility of climate change is however questionable, as recent data shows that carbon change that takes place due to carbon dioxide emissions is largely irreversible for 1000 years after emissions stop (Solomon, Plattner et al. 2008). But we can try to limit it. A closer look on how we feed our energy systems today is elucidative about the challenge we are facing, as illustrated in Figure 6.



* Transformation of fossil fuels from primary energy into a form that can be used in the final consuming sectors. ** Includes losses and fuel consumed in oil and gas production, transformation losses and own use, generation lost or consumed in the process of electricity production, and transmission and distribution losses.

Figure 6: The global energy system 2010 in Mtoe (IEA 2012).

In the current global energy system, fossil fuels represent about 81% of the total global primary fuel mix (coal 27%, oil 32%, natural gas 21%) (IEA 2012). The input mix for electricity & heat is 46% coal, 23% natural gas, 6% oil, 15% nuclear and 10% renewables, so fossil fuels clearly dominate, with ¾ of the total inputs. When transporting power, this (fossil based) mix will also be reflected in the emissions intensities of the electricity that is lost in the network.

2.3 Energy revolution

Completely revolutionizing our energy system by phasing out fossil energy and introducing low-carbon technologies seems to be the key to solving the climate change issue. Options to achieve the mitigation goal for the electricity sector include either producing power from renewable or nuclear technologies, or using carbon capture and storage (CCS). The IEA expects that the share of renewables in world primary energy demand in 2035 reaches 18%, contra 13% in 2010. This implies significant investments since the energy demand is also expected to increase in the same period. Most of the renewable growth will happen in the power sector, where the renewables share in generation will grow from 20% to 31% (IEA 2012). In Europe, a “renewable boom” is expected to take place from now and up to 2020 (ENTSO-E 2012). Wind and solar power production capacity will go up from 320 GW in 2012 to 536 GW in 2020 and progress in the European energy revolution is being made (Renseen 2012).

Whatever technological choices are made regarding power generation, power will always have to be transported from the generation to the consumption site, and this will add to the total electrical grid supply chain environmental impacts, be it greenhouse gas emissions or resource use. Moreover, when substituting fossil based energy systems by renewable based ones, more grid is required either in form of new assets or renovated ones. The European Network of Transmission System Operators for electricity (ENTSO-E) estimates that €100 billion will be invested to renovate the European transmission grid system over the next decade. Overall, 45,300 km of new or upgraded transmission assets will be built in order to facilitate renewable power integration in the region. How will this help Europe achieve its climate goals as set by the 2020 targets? What other environmental issues can arise? The climate change issue is one of urgency. At current levels of CO_2 concentrations exceeding 390 ppm, we don't have much room until we use up the climate budget that could guarantee we don't go above 2ºC temperature increases. The energy infrastructure we will build today is going to influence greenhouse gas emissions in the future, so we want to make sure we avoid any lock-in effects. We want to have tools and models that can assist us in understanding the mitigation potential of future energy systems and any such tools must include the possibility to analyze aspect related to systems for energy supply, i.e., transmission and distribution systems.

2.4 Beyond CO_2

Apart from climate change, a number of other environmental concerns have been highlighted for current and future energy systems. Impacts arise from emissions into the environment, consumption of resources and other interventions, such as land use.

For the first time, the IEA has in 2012 included a section on the water-energy nexus in the World Energy Outlook, which explores the link between energy production and water use, as water resources are becoming increasingly stressed (IEA 2012). The report concluded that global water withdrawals for energy production in 2010 were of 583 billion cubic meters, from which 66 were not returned to their original source. Fossil-fuel and nuclear based power plants are the largest users of water in the energy sector and several low-carbon energy technologies, e.g., carbon capture and storage (CCS) and concentrating solar power can be highly water-intensive. A shift towards higher efficiency power plants does not necessarily lead to higher water withdrawals, but water consumption/kWh increases. Water use for renewable energy is also addressed for example by (Strzepek, Baker et al. 2012) and by (Dawkins, Chadwick et al. 2012). The former has found benefits not only for CO_2 but also for water, for most types of renewable energy (except for biomass). The major part of water that is used in electricity production is for the purpose of cooling, and renewables have the benefit of not requiring steam for turbines or cooling of steam. The latter study has however found that water requirements for solar thermal could be a problem since this technology is best suited for areas that already might have some water constraints.

For CCS, a recent literature review study found that CCS results in a net reduction of global warming potential (GWP) between 47% for pulverized coal (PC) and 97% for Oxyfuel. However, deploying CCS in PC, integrated gasification combined cycle (IGCC) and natural gas combined cycle (NGCC) results in relative increases in eutrophication and acidification compared to power plants without the capture (Corsten, Ramirez et al. 2013).

Some of the issues with low-carbon systems may not be straightforward to grasp unless we consider the scaling-up of the technologies. One thing is to build a 1.5 MW wind turbine, which corresponds to certain requirements in terms of materials and other inputs. Another thing is to build a project corresponding to 245 times that capacity, such as for example the Walney offshore windfarms project, with a total of 367 MW (Walney offshore windfarms 2011). There are plenty of recent studies which have focused on environmental impacts related to up-scaling of low-carbon technologies (Kleijn, Voet et al. 2011, Alonso, Sherman et al. 2012, Dawkins, Chadwick et al. 2012, Pihl, Kushnir et al. 2012, Sathre, Chester et al. 2012), while other references explored the technical feasibility of the scale-up (Delucchi and Jacobson 2010, Jacobson and Delucchi 2011).

The available literature shows that even though renewable generation and also carbon capture and storage (CCS) are effective options for satisfying increasing future power demands while safeguarding the world from undesired climate change, this transition is not free from concerns. The main identified issues with the up-scaling of low-carbon power systems have been resource constraints in form of materials and water, and also trade-offs between climate benefits and non-climate impacts. The studies have however had a focus on the power generation side, and did not include the effects of the necessary extensions in the power grid. The present thesis can therefore provide a contribution for this part of the electricity supply chain.

In (Kleijn, Voet et al. 2011), the authors estimated the material requirements for scaling up low-carbon power generation technologies, and explored to what extent the availability of some metals may constrain the desired levels of penetration for renewable and CCS technologies. The authors analyzed the requirements for iron, aluminum, copper, zinc, nickel, tin, molybdenum, silver and uranium. The study concluded that although very effective in reducing CO_2 emissions, both CCS and especially non-fossil technologies are substantially more metal intensive than the existing power generation. Applying CCS would result in 10-30% more metal requirements than the current generation mix. The transition to renewable based power generation with solar photovoltaic (PV), non-waste biomass and wind technologies represents an increase of between a few percent to a factor of thousand in metal use. A study has evaluated rare earth element availability demand from clean technologies and it concluded that future needs in the wind and electric vehicle applications could translate into an increase of at least 700% and 2600% of neodymium (Nd) and dysprosium (Dy) respectively (Alonso, Sherman et al. 2012). In (Pihl, Kushnir et al. 2012), an assessment of material constraints for concentrating solar thermal power (CSP) showed that despite the fact that material scarcity in absolute terms is not an issue of particular concern, some components required for large scale CSP will be challenging as to current levels of production capacity. The study further concluded that nitrate salts and silver could face supply shortage, which could be remediated through substitution for silver. Metal availability for cobalt, neodymium, indium and tellurium were analyzed in light of the scenarios from the IEA's World Energy Outlook 2010, and the Mining and Mineral Scenarios 2010 from the World Economic Forum (Dawkins, Chadwick et al. 2012). The study concluded that there were severe risks of cumulative supply deficits (CSD) of indium and tellurium, moderate risks of medium term and severe risks of long term of CSD of neodymium and limited risk of long term CSD of lithium.

Understanding the effects from scaling-up a technology is complex. Size effects are one thing, but there are other factors, e.g., learning and experience, which will also have an influence in the resulting impacts from technology scale-up. Caduff and colleagues quantified whether the trend towards larger wind turbines affected the environmental performance of the produced electricity (Caduff et al. 2012). The study found that due to size effects, as well as learning and experience, the larger the turbine, the greener the electricity. The study emphasized that scaling and progress rates are seldom taken into account in LCAs of wind energy. Such effects should be taken into consideration when assessing technology scale-up.

From the literature review we conclude that there is a substantial body of references addressing the impacts of renewable energy scale-up. Nevertheless, impacts from the additional T&D requirements of the renewable systems have not been taken into account in the previous assessments, and this thesis can hence bring a contribution in this aspect. As recommended by Sathre et al. (Sathre, Chester et al. 2012), LCAs for assisting decision making should aim at describing system-wide environmental impacts resulting from technology up-scaling, rather than narrowing down the analysis to the performance of individual technologies.

In summary, although we expect that the transition to renewable energy systems will help us become less dependent on fossil energy and achieve climate goals, it is important to understand that there is a broader dimension to sustainability, and that we want to avoid solving the climate change problem while contributing to creating another type of problem. As we saw, issues such as water and material availability could eventually become relevant when scaling up renewable energy production and could ultimately hinder the development of renewables to expected levels of penetration. A recent thesis by Arvesen about wind power has concluded that there is a poor understanding of toxicity impacts and resource depletion impacts in studies for the development of this technology (Arvesen 2013). It is therefore fundamental that a broad range of impacts is taken into account when assessing the sustainability performance of future energy systems.

It is however unconvincing that progress towards sustainability can be made by focusing only on the "supply side". The energy system is ultimately driven by our demand of energy services like heat and electricity for heating and lighting our homes, but energy is also required directly and/or indirectly as an input to goods and services that we purchase. GHG mitigation has historically focused on emission sources and given relatively little attention to emission drivers (Peters 2010). Should we succeed in environmentally sound policies, then both production and consumption should be addressed. Sustainable consumption although not addressed here is a research subject of its own (Hertwich 2005a, Hertwich 2005b, Hertwich and Peters 2009).

2.5 The power grid

2.5.1 Transmission and distribution

The power grid is the infrastructure system which allows electricity to be transferred from the power plants to the final consumers (industry, households, service buildings, etc.). Transmission and distribution networks are an important part of our built infrastructure and account for 54% of the global capital assets of electric power (IEA 2008). The T&D grid is part of the electricity supply system, which is represented in Figure 7.

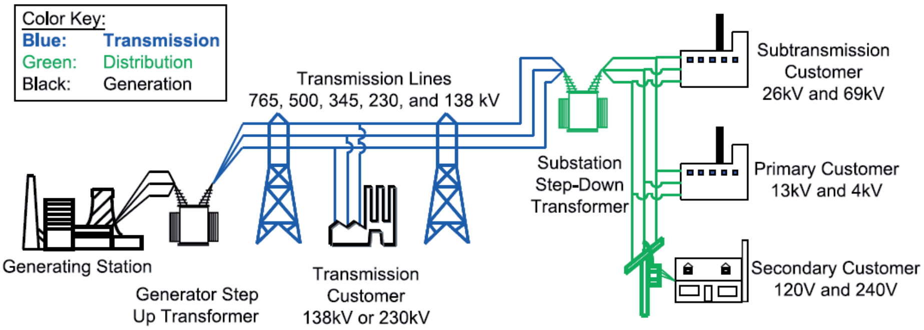


Figure 7: Schematic representation of an electricity supply system, including generation and T&D network (US-Canada Power System Outage Task Force 2004).

The main components of an electrical supply system are (L'Abbate, Fulli et al. 2008):

1) Generators, i.e., the power plants: they produce and feed the electrical power to the grid system.
2) Transmission and distribution lines/cables (overhead, land or sea): these are the physical structures used for transporting the power from the generators to the loads.
3) Towers or poles: structures supporting the overhead lines.
4) Substations: they have transformers and autotransformers and are used to switch voltage levels between the different subsystems in the grid.
5) Induction motors.
6) Loads: households, industry or buildings that draw power from the grid.
7) Switchgears and circuits breakers: provide protection to overhead lines.
8) Mechanical and electronic controllers: used to control voltage, frequency and power flow (active and reactive).

The power grid itself consist of two 2 subsystems: 1) transmission, which designates the high and extra-high voltage parts of the system connecting generators to electrical substations and 2) distribution, which is the part of the grid operating at low to medium voltages and further delivering power to the end-consumers.

Most of the installed T&D systems worldwide today operate using an alternating current (AC) mode. The first ever demonstration of a 3-phase AC line in the world dates back to 1891, when a 15 kV line with 175 km was built to transfer 200 kW between Lauffen and Frankfurt. The AC mode became the preferred one after the introduction of AC electrical machines, e.g., power transformers that allowed smooth changes in voltage levels – this made it possible to transmit power at higher voltages, therefore reducing power losses in the system (Ohm's law: $V=RI$ and $P=IV=I^2R$). However, direct current (DC) transmission systems are also found in today's grid in situations that require absence of reactive power, e.g., long distance transmission lines (above 400 km), sea cables longer than 30 km, or interconnection of two systems at different frequency or with stability problems.

There are different components contributing for total costs of AC and DC projects, such as terminal costs, line costs (e.g., land acquisition, installation, operation and maintenance), and losses. A HVDC transmission line costs less than an AC line for the same capacity, but on the other hand HVDC requires the conversion of power from AC and vice-versa, which makes DC terminal costs higher in the DC case. Land acquisition, operation and maintenance are more expensive for AC systems; losses are initially higher in HVDC systems, but contrary to HVAC, they do not increase with distance (Larruskain et al. 2011). The distance above which it is economical to use DC instead of AC transmission is called the break-even distance and is represented in Figure 8, which provides the values for both overhead lines (OHLs) and cable solutions for two regions (Europe and Asia).

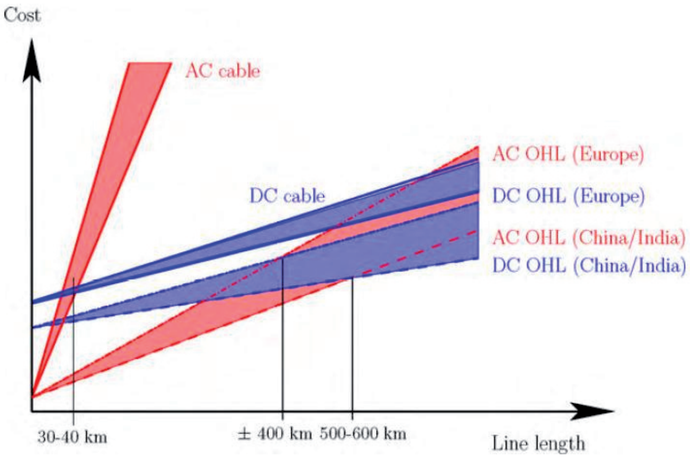


Figure 8: Break-even distances for AC and DC cables and OHLs (Hertem and Ghandhari 2010).

In Europe, the break-even distance for DC overhead lines (OHLs) is 400 km, and for cables is 30 km. Similarly to economic break-even points, it would be interesting to identify the environmental break-even points for these systems. That would require knowledge on life cycle inventory data for conversion stations, which this thesis did not address, but could be interesting to include in future studies of AC versus DC systems. Some suggestions are provided in section 6.3.

The physical difference between AC and DC modes is that in DC mode the current and voltage are constant while in AC both current and voltage vary sinusoidally in time with a certain frequency; this frequency is 50 Hz for European networks or 60 Hz for USA. The AC mode uses mainly a three-phase system, which uses three separate wires to transmit the power. There is also a fourth wire normally at neutral (zero) voltage.

Although the prevailing infrastructures for power systems used today are based on AC technology, some studies propose the use of a DC distribution system in the future as a way of avoiding losses from converting between DC and AC, the argument being that two of the most promising green technologies, fuel cells and photovoltaic produce direct current (Starke, Tolbert et al. 2008).

2.5.2 Global context and drivers for development

In 2009, transmission and distribution (T&D) assets installed globally summed up to about 70 million kilometers, and they are expected to be expanded to around 93 million kilometers within 2035 (IEA 2011b). Around 90% of the total infrastructure corresponds to distribution assets, while the remainder is transmission. Today's electricity grids use mostly the same technology features as when they were first introduced over a century ago - power is still transported over "copper and iron" wires. However, the grid is undergoing a number of changes in order to adapt to the current energy context**.** According to the IEA, the three key factors that will drive the development and expansion of today's grids are: additional capacity to meet an increase in electricity demand, integration of renewable energy sources and refurbishment of assets as they reach their technical lifetime (IEA 2011). According to the IEA, expected cumulative investments in T&D over the next years almost equal the ones in generation capacity, as shown in Figure 9.

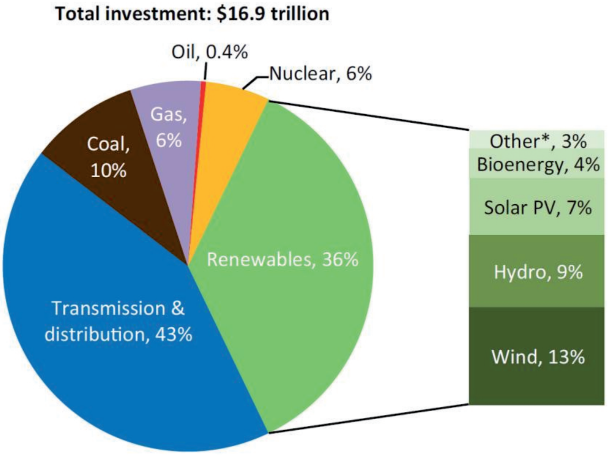
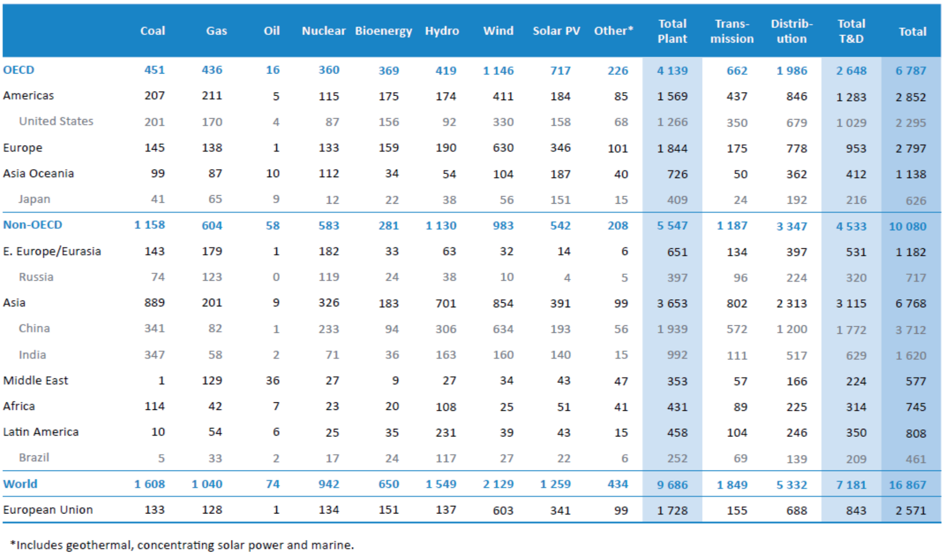


Figure 9: Power sector cumulative investment by type in the New Policies Scenario from the IEA, 2012-2035 (IEA 2012).

The geography plays a role in the drivers for grid expansion. In OECD countries, the main driver is refurbishment and replacement of assets. A great part of the infrastructure was installed in the 1960s and 1970s, and by 2035 about half of the infrastructure will have reached 40 years of age (IEA 2012). In non-OECD countries, refurbishment is also a driver for grid expansion, but the most important factor is the growth in demand for electricity, as more households, industry and other users connect to the grid.

Globally, the demand for electricity is projected to continue growing faster than any other form of energy (IEA 2012). The increase in demand is mainly driven by growth in non-OECD countries, which will create large investments in T&D in these regions. In total, investments in T&D in non-OECD countries reach 63% of the global T&D investments, with China alone corresponding to 40% of the non-OECD total, as shown in Table 2. Investments in India are the second largest and are also significant.

Table 2: Investment in electricity supply infrastructure by region and source in the New Policies Scenario, put forward by the IEA ($2011 billion) (IEA 2012).



	Coal	Gas	Oil	Nuclear	Bioenergy	Hydro	Wind	Solar PV	Other*	Total Plant	Trans-mission	Distrib-ution	Total T&D	Total
OECD	451	436	16	360	369	419	1 146	717	226	4 139	662	1 986	2 648	6 787
Americas	207	211	5	115	175	174	411	184	85	1 569	437	846	1 283	2 852
United States	201	170	4	87	156	92	330	158	68	1 266	350	679	1 029	2 295
Europe	145	138	1	133	159	190	630	346	101	1 844	175	778	953	2 797
Asia Oceania	99	87	10	112	34	54	104	187	40	726	50	362	412	1 138
Japan	41	65	9	12	22	38	56	151	15	409	24	192	216	626
Non-OECD	1 158	604	58	583	281	1 130	983	542	208	5 547	1 187	3 347	4 533	10 080
E. Europe/Eurasia	143	179	1	182	33	63	32	14	6	651	134	397	531	1 182
Russia	74	123	0	119	24	38	10	4	5	397	96	224	320	717
Asia	889	201	9	326	183	701	854	391	99	3 653	802	2 313	3 115	6 768
China	341	82	1	233	94	306	634	193	56	1 939	572	1 200	1 772	3 712
India	347	58	2	71	36	163	160	140	15	992	111	517	629	1 620
Middle East	1	129	36	27	9	27	34	43	47	353	57	166	224	577
Africa	114	42	7	23	20	108	25	51	41	431	89	225	314	745
Latin America	10	54	6	25	35	231	39	43	15	458	104	246	350	808
Brazil	5	33	2	17	24	117	27	22	6	252	69	139	209	461
World	1 608	1 040	74	942	650	1 549	2 129	1 259	434	9 686	1 849	5 332	7 181	16 867
European Union	133	128	1	134	151	137	603	341	99	1 728	155	688	843	2 571

*Includes geothermal, concentrating solar power and marine.

After demand growth and refurbishment of assets, the factor that contributes the most to grid expansion is the integration of renewable energy sources (RES) (IEA 2011b). There is often a spatial mismatch between renewable energy supply and demand, which requires additional long transmission infrastructure (Hu and Cheng 2013). Along with spatial mismatches between supply and demand, temporal mismatches are also a challenge. The question is whether renewable sources such as wind or solar can follow up on the variation of demand that occurs over seconds, minutes, hours, seasons and years, and if they can handle unanticipated changes in generation availability (Delucchi and Jacobson 2010). In order to accommodate renewable power sources, the following solutions have been put forward: 1) interconnection of geographically dispersed generators; 2) use of complementary and non-variable sources to help supply match demand; 3) use of "smart" demand-response management to shift flexible loads to better match available renewable generation; 4) storage of electrical power at generation; 5) oversize renewable generation capacity to match demand better and produce hydrogen; 6) store electric power at points of end use in electric vehicle batteries (Delucchi and Jacobson 2010). The first option, interconnection, can contribute to significantly smooth electricity supply and demand (Kempton, Pimenta et al. 2010); this options calls for a significant build-up of the transmission system. Power grid interconnections between different regions in the same country (Zhu, Zheng et al. 2005) or connecting different countries (Fernandes, Frías et al. 2013) have been suggested as a way to harness RES. Some plans even include the vision for a global grid that would facilitate harnessing energy produced by sources located far away from each other; the argument is to maximize the use of each resource where it is most abundant (Chatzivasileiadis, Ernst et al. 2013).

The IEA has investigated how much RES represent in terms of T&D investments in a near future (IEA 2012). The data shows that in OECD countries, RES integration represents a larger share of the total T&D investments than in non-OECD countries because demand growth dominates in the latter. The IEA estimates that in Europe, around \$915 billion (~€700 billion) in T&D investments are expected from 2012 to 2035, from which \$179 billion are expected in transmission and \$737 billion in distribution. Within transmission, \$87 billion would correspond to refurbishment, \$49 billion to demand growth and \$42 billion to renewable integration; within distribution, \$431 billion, \$297 billion and \$8 billion would correspond to the previous mentioned categories respectively. It is interesting to compare the investment numbers that have been put forward by IEA and by the European Network of Transmission Operators (ENTSO-E 2012). According to ENTSO-E, a total of €134 billion (~\$134 billion) are required for upgrading the transmission grid in the period from 2012 to 2022, which is not very different from the IEA values. However, the share of investment corresponding to RES integration would correspond to €89.4 billion, if one takes into account the volume of RES projects as compared to projects related to market integration and security of supply.

2.5.3 Transmission and distribution in Europe

Figure 10 shows a schematic representation of the T&D system for countries within continental Europe. Generators usually operate at voltage levels between 10 and 30 kV. Only generators with a net capacity up to 20-30 MW may connect directly to the distribution grid, else the connection is through the transmission grid level. In this case, the electricity is fed to the step-up transformers that increase the voltage of the electricity to levels of 110 kV or above. Power is then transmitted in high voltage AC or DC transmission circuits. The AC and DC transmission levels found in European networks are, respectively 110, 130-132, 150, 220-230, 275, 300-330, 380, 500, 750 kV and 150, 200, 250, 270, 285, 350, 400 and 450 kV (L'Abbate, Fulli et al. 2008). Power is then further fed to a step-down transformer that decreases the voltage, usually in the range 10÷70 kV up to 110 kV. The electricity is then conveyed to the distribution grid and further transformed to 220/380 V, which is suitable for end-consumers, e.g., households, service buildings, etc. Some consumers, e.g., energy intensive industry can however draw power directly from the transmission or subtransmission grid.

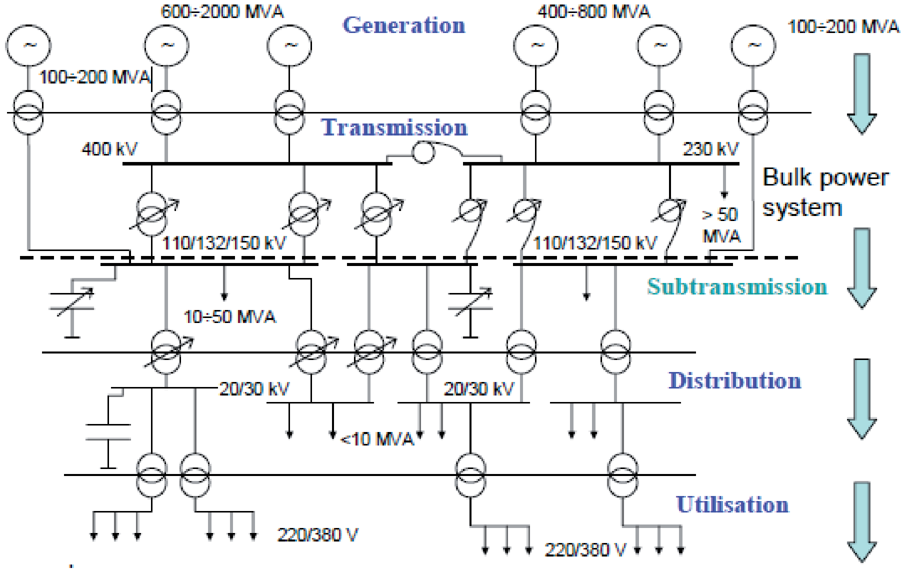
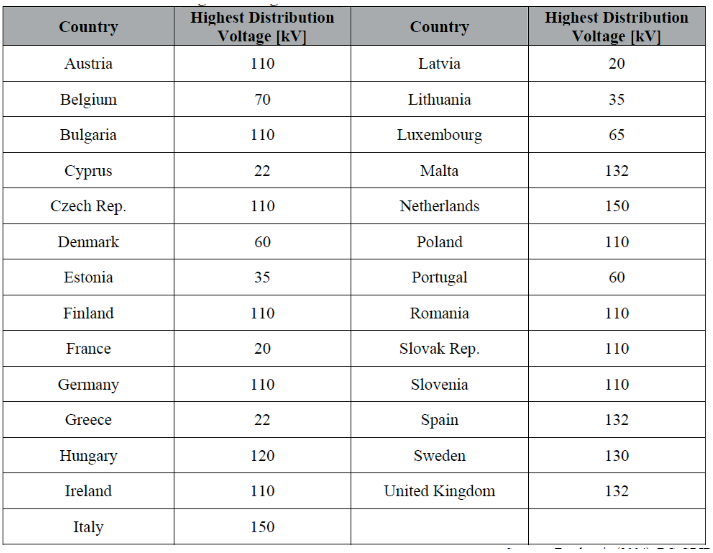


Figure 10: Representation of the T&D grid system in Europe (L'Abbate, Fulli et al. 2008).

The voltage levels of power distribution vary across Europe. Table 3 provides values for the highest allowed distribution voltages per country.

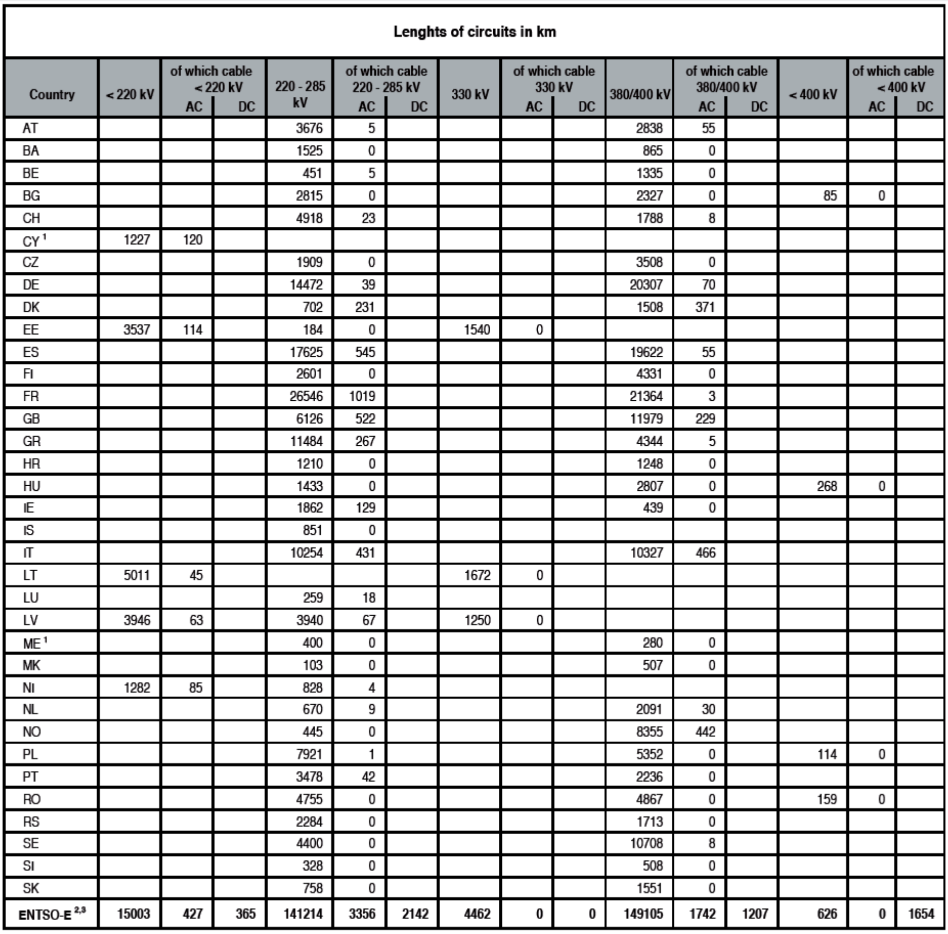
Table 3: Highest voltage levels in distributions grids in Europe (L'Abbate, Fulli et al. 2008).



Country	Highest Distribution Voltage [kV]	Country	Highest Distribution Voltage [kV]
Austria	110	Latvia	20
Belgium	70	Lithuania	35
Bulgaria	110	Luxembourg	65
Cyprus	22	Malta	132
Czech Rep.	110	Netherlands	150
Denmark	60	Poland	110
Estonia	35	Portugal	60
Finland	110	Romania	110
France	20	Slovak Rep.	110
Germany	110	Slovenia	110
Greece	22	Spain	132
Hungary	120	Sweden	130
Ireland	110	United Kingdom	132
Italy	150		

The transmission assets in Europe sum up to over 312,000 km of lines and cables. An overview of transmission assets per country (total km per voltage level) is provided in Table 4.

Table 4: Inventory for grid infrastructure in Europe by December 2011 (ENTSO-E 2011)[1].



Lenghts of circuits in km

Country	< 220 kV	of which cable < 220 kV		220 - 285 kV	of which cable 220 - 285 kV		330 kV	of which cable 330 kV		380/400 kV	of which cable 380/400 kV		< 400 kV	of which cable < 400 kV	
		AC	DC		AC	DC		AC	DC		AC	DC		AC	DC
AT				3676	5					2838	55				
BA				1525	0					865	0				
BE				451	5					1335	0				
BG				2815	0					2327	0		85	0	
CH				4918	23					1788	8				
CY [1]	1227	120													
CZ				1909	0					3508	0				
DE				14472	39					20307	70				
DK				702	231					1508	371				
EE	3537	114		184	0		1540	0							
ES				17625	545					19622	55				
FI				2601	0					4331	0				
FR				26546	1019					21364	3				
GB				6126	522					11979	229				
GR				11484	267					4344	5				
HR				1210	0					1248	0				
HU				1433	0					2807	0		268	0	
IE				1862	129					439	0				
IS				851	0										
IT				10254	431					10327	466				
LT	5011	45					1672	0							
LU				259	18										
LV	3946	63		3940	67		1250	0							
ME [1]				400	0					280	0				
MK				103	0					507	0				
NI	1282	85		828	4										
NL				670	9					2091	30				
NO				445	0					8355	442				
PL				7921	1					5352	0		114	0	
PT				3478	42					2236	0				
RO				4755	0					4867	0		159	0	
RS				2284	0					1713	0				
SE				4400	0					10708	8				
SI				328	0					508	0				
SK				758	0					1551	0				
ENTSO-E [2,3]	**15003**	**427**	**365**	**141214**	**3356**	**2142**	**4462**	**0**	**0**	**149105**	**1742**	**1207**	**626**	**0**	**1654**

As for the distribution grid, an estimate indicates that the assets shall correspond to 1,500,000 km (SETIS 2013).

As mentioned in 1.5.2., The European Network for Transmission System Operators for Electricity has evaluated the investment needs for Europe over the next years and estimated that €104 billion will be required to upgrade the transmission grid (ENTSO-E 2012). The investments target three objectives: integration of renewable power in the region, market integration of different regions and security of supply. The projects referring to RES integration correspond to 45,300 km of assets, or 80% of the total planned renovations. The projects consist mainly in the construction of new high-voltage overhead lines, but cable connections are also

---

[1] The last three columns of the table state voltage level of < 400kV. This is assumed to be > 400 kV.

envisioned. The increase in HVDC interconnections is significant. A comparison of length and circuit voltage for the current grid and for the grid after renovations as proposed by ENTSO-E is provided in Figure 11. Paper 4 in this thesis has the goal of characterizing the life cycle impacts associated with this grid build-up.

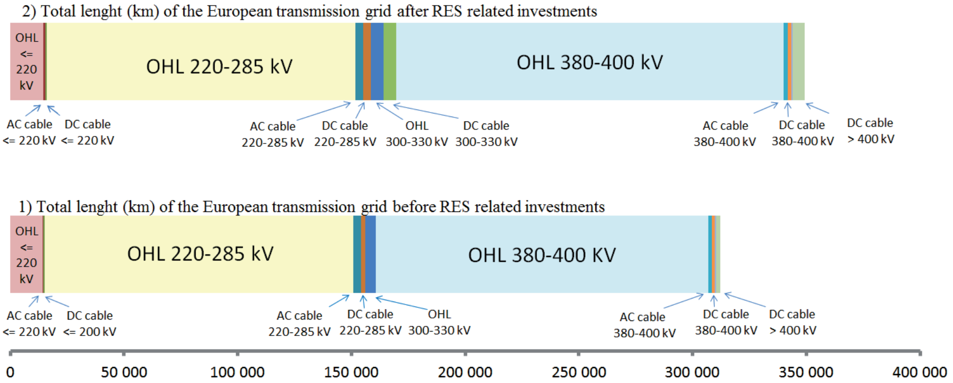


Figure 11: Transmission circuit length (km) by voltage level in Europe before 1) and after 2) RES related investments.

2.5.4 Transmission and distribution system efficiency

The transmission and distribution of power is subject to losses which have an influence on the system efficiency. Losses decrease with the increase in voltage level as mentioned in Section 2.5.1. However, increasing transmission voltages will also increase costs and hence material demand. The life cycle trade-off between losses and materials for grid has been discussed by (Aten and Ferris 2009).

T&D losses as a percentage of total power delivered for different countries/regions are provided in Figure 12 (Graus and Worrell 2011). The values refer to data from 2006.

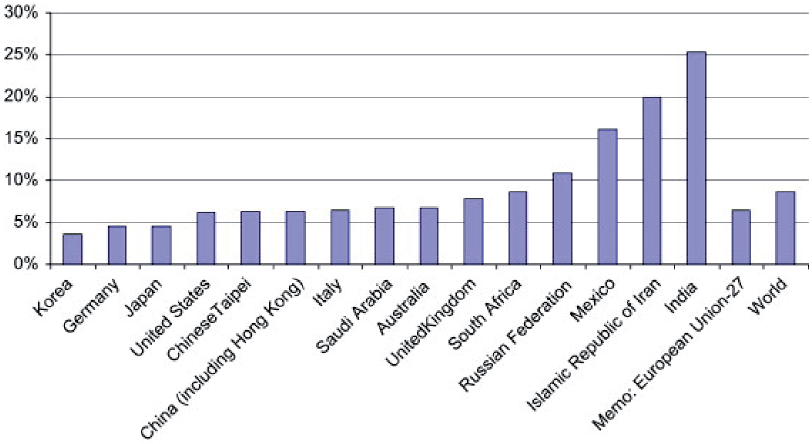


Figure 12: Transmission and distribution losses in several countries/regions in 2006 (Graus and Worrell 2011).

The values show that few countries have losses under 5%. In most cases, T&D losses are between 5 and 10%, while some countries can have losses above 10%. For some countries, though, losses could reach 25% of the total power in the network, as for example, in India. The extreme values may be a result of higher technical losses, e.g., from lack of investment, but also higher losses of commercial nature, e.g., due to errors in metering, meter reading, theft, etc.

Regarding losses per component type in a transmission system, an example can be provided by analyzing the results obtained by a recent assessment of an ultra-high-voltage (UHV) system. The study refers to an LCA for a 765 kV transmission system in Venezuela. A comparison is provided for the environmental impacts during the use phase. Three processes are analyzed: power losses in lines, power losses in substations and leakages of SF_6 in circuit breakers. The results summarized in Figure 13 show that power losses in transmission lines clearly dominate over the ones in substations (Wang, Beroual et al. 2012).

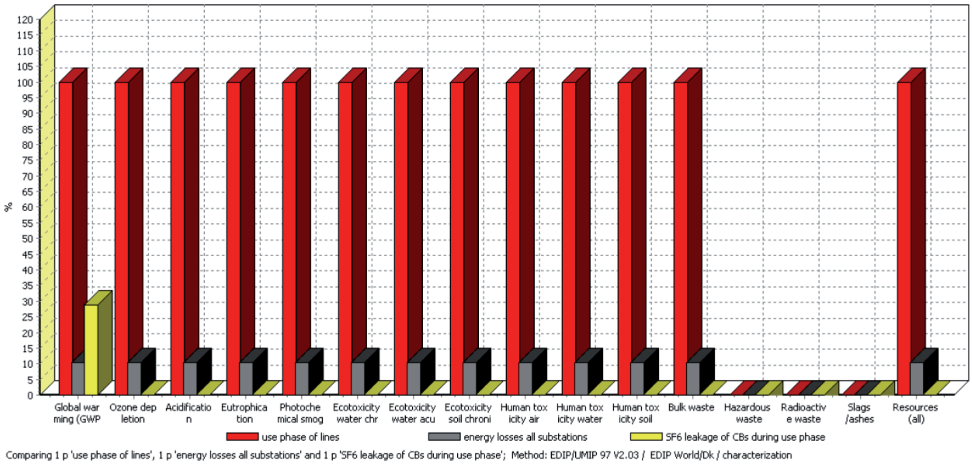


Figure 13: Comparison of the contribution of losses in transmission lines vs. losses in substations (and SF_6 leakages in circuit breakers) for total LCA scores (Wang, Beroual et al. 2012).

The study also provides the breakdown of power losses in the substations by component type, as presented in Figure 14. Most losses occur in the transformers followed by the shunt reactors (Wang, Beroual et al. 2012). Total power losses in conductors in substations are relatively small.

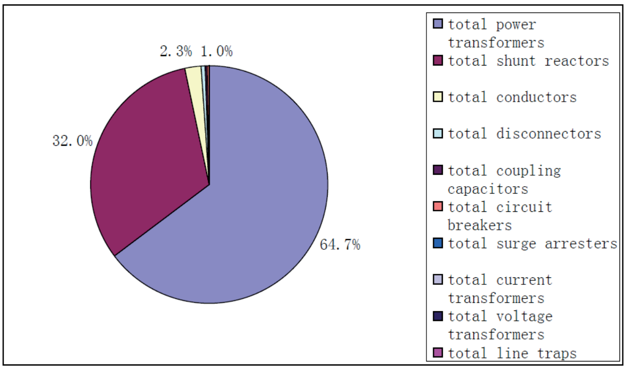


Figure 14: Breakdown of energy losses in substations for a 765 kV AC transmission system (Wang, Beroual et al. 2012).

For transformers, it is usual to distinguish between load losses and no-load losses, although two more types of losses exist: losses created by harmonics and auxiliary losses (IEE 2008). No-load losses are constant core losses and happen whenever the transformer is energized; they comprise hysteresis losses and eddy current losses. Load losses are also known as copper losses or short-circuit losses and vary with the transformer loading. They comprise ohmic heat losses and conductor eddy current losses. Figure 15 shows values of total, load and no-load losses for distribution transformers in electricity distribution companies in the EU-27 and Norway (IEE 2008).

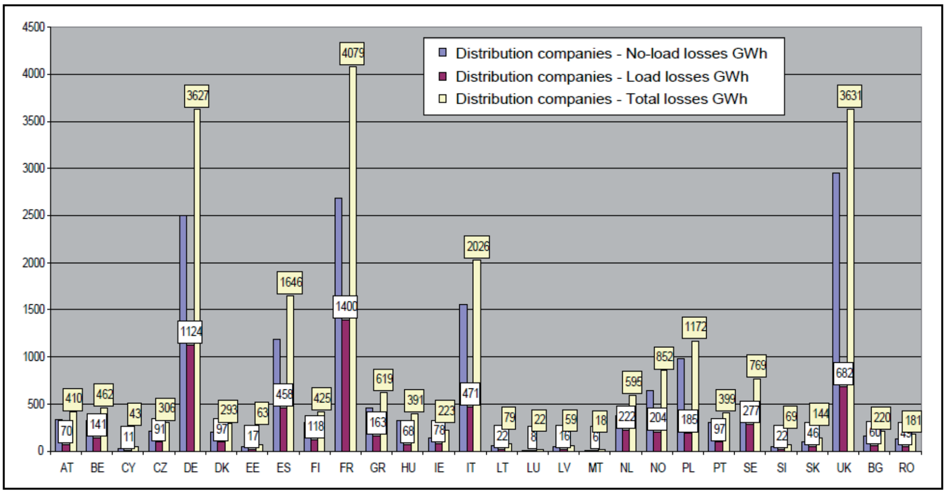


Figure 15: Breakdown for distribution sector distribution transformer losses for EU 27 + Norway (IEE 2008).

The data shows that the ratio no-load/load losses is close to 3. The reduction of no-load losses in distribution transformers has been pointed out as an important measure regarding improvement of system efficiency. Overall there were around 4 million distribution transformers installed in Europe by 2009 corresponding to a total loss of 38 TWh/yr from which 70% are no-load losses (Borghetto, Barberis et al. 2009). Paper 2 provides data on no-load and load losses for transformers at different ratings and these have been included in the calculation of life cycle impacts. The values provided by the equipment producer are summarized in the Supplemental Information for this paper.

3 Method

We need initiatives that protect the environment as an overall system. The choice between either clean air or mitigating climate change is a false dichotomy - Europe needs both.

Jacqueline McGlade, EEA Executive Director

3.1 Life Cycle Assessment (LCA)

The method used for the environmental assessment presented in this thesis is Life Cycle Assessment (LCA) which is a tool for the assessment of "cradle-to-grave" environmental impacts of products and services. Two essential features of this method are that 1) it allows for the investigation of a wide range of environmental impacts for the system in study, e.g., climate change, acidification, eutrophication, etc. therefore avoiding problem shifting from one media to another and 2) it considers all stages in the life cycle of the system under study, therefore avoiding problem shifting from one life cycle stage to another, or between systems or other parts of the system.

A short historical account on LCA and how it derived from previous methods, e.g., ecobalances, is provided here (Bauman and Tillmann 2004). Three important foci related to the development of the LCA methodology were the Society for Environmental Toxicology and Chemistry (SETAC), the International Organization for Standardization (ISO), and various EU funded projects (Blackett, Savory et al. 2008). Early references on LCA include (Hunt, Seller et al. 1992, White, Hindle et al. 1992, Clift 1993, Perriman 1993, Ayres 1995). By 1997, the first International Standard on LCA was issued by the ISO, which has been updated since (Finkbeiner, Inaba et al. 2006, ISO 2006a, ISO 2006b). A good description on the method is found in (Rebitzer et al. 2004), and impact assessment practices are covered in (Pennington, Potting et al. 2004). Recent methodological developments are provided in (Finnveden, Hauschild et al. 2009).

LCA models may use physical data, economic data or a combination of the two as input. In the first case, the model is referred to as a process-LCA model, which is described in the references provided above. Models using economic data as input are referred to as input-output LCA models. These models are based on the use of an input-output table complemented with environmental extensions, which are compiled by statistical offices. Input-output models are described, e.g., in the documentation for the project EXIOPOL (EXIOPOL 2012). It is also possible to combine the two types of datasets, physical and economical, to produce a so called hybrid model, see for example (Wiedmann, Suh et al. 2011). The studies presented in this thesis use process-based LCA.

4 Literature review

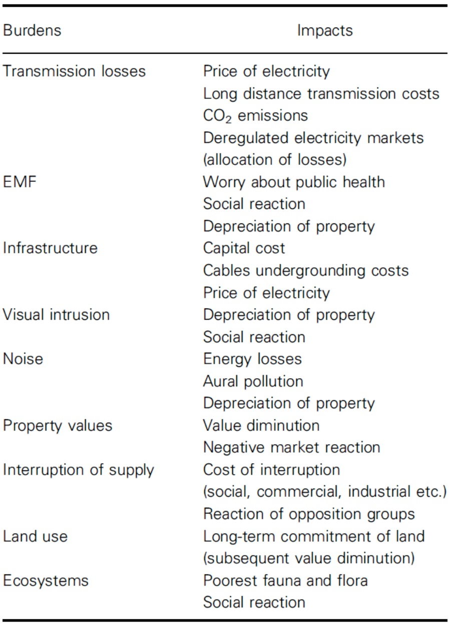
Do people really need to be reminded that a massively engineered quilt of energy-filled wires is on duty inside their walls? Yes. So great is the prevalence of electrical infrastructure that at times our powered devices might seem part of the environment.

Schewe, Phillip F. The grid: a journey through the heart of our electrified world.

4.1 Environmental impacts of power transmission and distribution systems

T&D systems provide us with access to energy, yet they are responsible for several types of environmental pressures. Table 5 summarizes some relevant burdens and associated impacts from T&D (Doukas, Karakosta et al. 2011). In this section, an overview of environmental consequences that can result from electrical grids is provided. Sections 4.2 and 4.3 provide a summary about the state-of-art for LCA literature on T&D.

Table 5: Overview of burdens and impacts due to T&D systems (Doukas, Karakosta et al. 2011).



Burdens	Impacts
Transmission losses	Price of electricity Long distance transmission costs CO_2 emissions Deregulated electricity markets (allocation of losses)
EMF	Worry about public health Social reaction Depreciation of property
Infrastructure	Capital cost Cables undergrounding costs Price of electricity
Visual intrusion	Depreciation of property Social reaction
Noise	Energy losses Aural pollution Depreciation of property
Property values	Value diminution Negative market reaction
Interruption of supply	Cost of interruption (social, commercial, industrial etc.) Reaction of opposition groups
Land use	Long-term commitment of land (subsequent value diminution)
Ecosystems	Poorest fauna and flora Social reaction

Regarding environmental impacts, ecosystem burdens such as wildlife interactions with utility structures are often documented. A topic that has deserved special attention is bird collisions with T&D structures (Bevanger 1998, Barrientos, Ponce et al. 2011). The influence of T&D infrastructure in migration patterns of species, in this case reindeer, has also been documented (Vistnes, Nellemann et al. 2004). Other types of environmental impacts reported are land-use (Furby, Slovic et al. 1988) and visual and noise impacts (Ackermann, Andersson et al. 2001). Table 5 refers transmission losses as a main burden, and CO_2 emissions as a consequence. As we will see, this is supported by the literature in LCA for T&D. Losses represent a big share of overall system life cycle impacts in that they correspond to extra demand for generation. In addition to CO_2 emissions, other burdens result from transmission losses, e.g., increased prices of electricity and long distance transmission costs. Another issue pointed out by (Doukas, Karakosta et al. 2011) is the potential health effects due to the proximity of electromagnetic fields. This issue has long been debated in the literature (Feychting and Ahlbom 1993, Draper, Vincent et al. 2005). Power lines and electrical wiring are a source of extremely low frequency (50 or 60 Hz) non-ionising radiation. For 50 Hz, the International Commission on Non-Ionizing Radiation Protection (ICNIRP) recommends that general public exposure does not exceed 200 μT and 5 kVm^{-1}, which should be higher than the maximum magnetic and electric fields intensities measured for power lines (National Grid UK 2013). In the context of LCA, damage factors have been developed for ionising radiation by (Solberg-Johansen 1998, Frischknecht, Braunschweig et al. 2000), (Solberg-Johansen 1998) and (Goedkoop and Spriensma 1999), the latter including the damage level based on (Frischknecht, Braunschweig et al. 2000) in terms of DALY’s. For non-ionising radiation, such factors have not yet been derived.

T&D can also result in economic depreciation of properties, due to visual intrusion or noise originated from high-voltage lines. Figure 16 shows an example of the construction of a substation in a family property (the field was originally used for agriculture). In such cases, the transmission system operator (TSO) and the property owner would reach an agreement for a monetary compensation of lost value.

Figure 16: Substation in terrain previously used for agriculture, Algarve, Portugal (source: F. Jorge, 2013).

Due to the potential environmental burdens that can result from T&D projects, it is required by practically all countries in the world to carry out environmental impact studies for constructing a new overhead line. Such assessments should cover a project justification, electromagnetic fields (EMF) effects, visual impact of the lines, interests of communities and effect on land use and property value (Kiessling, Nefzger et al. 2003).

4.2 Life Cycle Assessment for Electricity Transmission and Distribution – Review of peer-reviewed literature

The literature on life cycle impacts of power generation systems is abundant and has been produced over a period of several years (Yasukawa, Tadokoro et al. 1992, Hynes 1994, Waku, Tamura et al. 1995, Dones and Frischknecht 1998, Rafaschieri, Rapaccini et al. 2000, Schleisner 2000, Hondo 2005, Weisser 2007, Corsten, Ramirez et al. 2013). In contrast, literature on LCA for T&D is somehow limited and most of the references are more recent.

For power generation systems, both renewable and fossil based, literature sources are found using process-based LCA methods (Varun, Bhat et al. 2009, Weinzettel, Reenaas et al. 2009, Sherwani, Usmani et al. 2010, Prempreeda 2012), hybrid-LCA methods (Singh 2011, Wiedmann, Suh et al. 2011, Arvesen 2013) and pure economic Input-Output methods (Proops, Gay et al. 1996, EXIOPOL 2012, Lindner, Legault et al. 2013). Some studies have also considered the effects of transfers of electricity between regions with different mixes and have explored the question of average generation mix assumption made in many environmental assessments (Marriott 2007).

Literature and datasets for LCA of T&D are not abundant in the literature, but the interest on the theme is picking up. Very few references have addressed life cycle impacts for T&D using economic Input-Output based methods (EXIOPOL 2012, Lindner, Legault et al. 2013) and most of the existing literature consists of studies based on the application of process-based LCA. This section provides an overview of the literature on LCA for T&D and its evolution with time.

In (Knoepfel 1996) the author describes a framework for LCA for the comparison of long-distance energy transport systems including high-voltage alternating and direct current transmission lines. The study develops quantitative indicators for fossil-energy consumption, air-emission impacts, land use, audible noise impacts, and visual impacts. The Ecoinvent database has modeled grid in their processes for electricity supply since 1996 (Bollens, Bosshart et al. 1996). The latest version of the data for T&D from Ecoinvent which is described in (Itten, Frischknecht et al. 2012) has now incorporated results from (Bumby, Druzhinina et al. 2010, Jones and McManus 2010, Jorge, Hawkins et al. 2012a, Jorge, Hawkins et al. 2012b).

In a study from 2005 (Bergerson and Lave 2005), the authors examine the life cycle costs, environmental discharges and the social costs (life losses) of moving coal via rail, gas via pipeline, and electricity via wire. The inclusion of social aspects, such as social costs, into the environmental life cycle assessment of products and systems has gained interest in recent years.

In (Blackett, Savory et al. 2008), the authors determined the environmental impacts associated with typical constructions utilized in high voltage electricity transmission in the UK, and compared it with alternative materials. The following alternatives were investigated: for towers, typical constructions based on galvanized mild steel were compared with aluminum towers. For conductors, the following configurations were analyzed: aluminum alloy for Rubus configuration (6101 grade aluminum with magnesium-silicon alloy) versus aluminum conductor steel reinforced (ACSR) consisting of pure (90%) aluminum over galvanized steel wires. For insulators, the alternatives investigated were glass and porcelain. A summary of the assumptions is given in Table 6. The study also included the investigation of the role of different locations, i.e., coastal, rural and industrial, to address the effects of different corrosive environments to which tower materials are exposed. The system boundary encompassed the stages from extraction of raw materials through installation in the field. The study considers the processing of raw materials, i.e., the inputs required to shaping the materials to a final product, which is not always taken into account in other references (Itten, Frischknecht et al. 2012, Jorge, Hawkins et al. 2012a). For steel, "hot rolled steel" is chosen, which reflects not only raw materials but also the energy for further material processing. According to the authors, there is a significant energy utilization relating to the galvanizing process, and that is also included for steel towers. For the aluminum towers, extrusion (for which energy inputs are much larger than the required for equivalent steel) and anodizing processes are also modeled. The study does not include impacts from the following processes: installation, maintenance/inspection (except subsequent paint application to towers), power losses, land use, emissions during operation (see Figure 1) and end-of-life. The study concluded that the environmental burdens of steel and aluminum towers are very similar and that the same was the case for the two conductor options that were analyzed. Painted steel towers have lower associated impacts; glass creates fewer burdens than porcelain but the difference is small.

In (Jones and McManus 2010), the life-cycle impacts of five different 11 kV electrical distribution systems used for high voltage distribution (three overhead lines with copper conductors and three underground cables using aluminum conductors) were analyzed. These stages were included: production, installation, maintenance, power losses and end-of-life. For end-of-life, overhead lines were assumed recoverable and land cables assumed to be left buried underground. The characteristics of the product systems analyzed are summarized in Table 6. One interesting aspect of this study is that it has a model for power losses as a function of line/cable loading conditions. Conductor electrical losses are calculated as a function of load factors, current and resistance. Results are provided separately for cradle to pre-disposal, power losses and end-of-life; the cradle-to-pre-disposal phase adopted a recycled content (cut-off) approach and the justification is that this approach better reflects the impacts to produce the product system and thus emissions that are released in the present rather than incorporating future benefits into a single result. The results of full life cycle assessment are provided using ReCiPe Midpoint and Endpoint (Goedkoop, Heijungs et al. 2009). From the 18 impact categories, significant environmental issues are selected with help of Endpoint indicators and further analyzed (the selection did not include water depletion and marine ecotoxicity). The key identified issues were climate change, particulate matter formation and fossil depletion, which were studied further at Midpoint level. For fossil depletion, results were analyzed using the Cumulative Energy Demand method, and showed that for all cables the life cycle fossil consumption increases at higher operating currents as a consequence of increased cable resistance. For climate change, conclusions were that underground cables were determined to have the lower life cycle impact. Overall, the study concluded that the majority of embodied impacts were considered insignificant when compared to power losses. The exception was for underground cables at low operating loads, for which particular matter formation (PMF) was more significant as a result of the high embodied impacts of the cables. Further analysis revealed that these impacts could be mitigated with an end-of-life material recovery program. At present the underground cables are not recovered, but if they were the recycling benefits would give rise to a notable improvement in PMF. For the other impact categories, operational conductor losses were the dominant cause of impacts. In summary it was concluded that to minimize the life-cycle impacts of 11 kV cables, the system with the lowest conductor resistance should be selected.

In (Bumby, Druzhinina et al. 2010) the environmental impacts from overhead and underground medium voltage power distribution systems operating in Southern California are compared using process-based LCA. Potential environmental impacts were calculated using midpoint indicators with the CML 2001 method. A sensitivity analysis of the most uncertain and potentially significant parameters, i.e., line/cable lifetime, underground infrastructure lifetime, rates of pentachlorophenol (PCP) leakage from the poles for lines, recycling rates, failure frequency and planning horizon was undertaken. The study includes materials, processing (e.g., wire drawing and cable extrusion), installation, maintenance, repair and decommissioning. The results from this study were that the underground system had higher environmental impacts in all indicators and for all parameter values due mostly to its higher material intensity. Cable production was found to cause the majority of impacts for both systems in all indicators. The following were identified as strategies leading to reduced life cycle impacts: cable failure rate reduction for overhead lines and cable lifetime extension for underground systems.

The life cycle environmental impacts in terms of embodied energy and CO_2 per kWh transmitted from the UK transmission network were obtained by Harrison and colleagues (Harrison, Maclean et al. 2010). As the study reports, it is not a full LCA but rather a life cycle inventory (LCI), since other impact categories, e.g., acidification, toxicity, etc. are not included. The following life cycle stages are taken into account: materials and manufacturing, installation and assembly, operations and maintenance (including power losses and SF_6 losses) as well as decommissioning and disposal. Transmission components included were: overhead lines, underground cables, substations and transformers. Power losses are modeled assuming a static generation mix. SF_6 losses in gas insulated substations are included and based on values provided by UK's TSO - National Grid, for a specific year. The study again confirms that power losses are the main contributor to embodied CO_2 and energy and discusses the possibility of using regulatory incentive mechanisms that could contribute to carbon savings from losses. The article further finds that operational emissions account for 96% of total CO_2 eq. scores with transmission losses alone totaling 85%, and that sulfur hexafluoride (SF_6) emissions feature an important share.

The Ecoinvent database models electricity supply for selected countries in Europe, Asia, Americas and Africa (Itten, Frischknecht et al. 2012). The model includes inventories for electricity mixes and the transmission and distribution grid. The latest version of the Ecoinvent data has incorporated some of the results obtained by (Bumby, Druzhinina et al. 2010, Jones and McManus 2010, Jorge, Hawkins et al. 2012a, Jorge, Hawkins et al. 2012b). The inventories for the grid infrastructure for the different countries are based on the Swiss network, and some country specific data, e.g., total electricity supply and total transmission losses is used. The share of losses attributed to the high, medium and low voltages are based on Swiss shares of electricity demand and losses at each level. The SF_6 losses are based on regional values, i.e., not country-specific. The inventories comprise the processes listed in Figure 1 except from EM radiation.

Recently, a reference has addressed the environmental impacts from the Danish distribution network in a life cycle perspective (Turconi et al. 2013). The study concluded that electricity transmission and distribution provided non-negligible impacts, related mainly to power losses. As expected, impacts from distribution were larger than those of transmission due to higher losses and material consumption. The study also compared underground versus overhead lines and aluminum versus copper lines.

Overall, the available literature seems to have reached a consensus about the following conclusions:

- Electric losses in T&D equipment represent an important share of life cycle impacts in almost all impact categories (Harrison, Maclean et al. 2010, Jones and McManus 2010, Jorge, Hawkins et al. 2012a, Jorge, Hawkins et al. 2012b, Jorge and Hertwich 2012).
- Production and shaping of materials have significant impacts, but installation and maintenance seem to have a considerably smaller contribution to life cycle scores (Harrison, Maclean et al. 2010, Jones and McManus 2010, Jorge, Hawkins et al. 2012a, Jorge, Hawkins et al. 2012b).
- The climate change impacts due to SF_6 used in substation equipment can outweigh those of electrical losses in this equipment and should therefore not be trivialized (Harrison, Maclean et al. 2010, Jorge, Hawkins et al. 2012b, Jorge and Hertwich 2012).
- Impacts can be mitigated by material recovery at the end-of-life (Jones and McManus 2010, Jorge, Hawkins et al. 2012a).

The references regarding publications from this thesis are described in Section 5.

Table 6: Summary of peer-reviewed references on Life Cycle Assessment for Transmission and Distribution, by publication date.

Ref.	Scope	Functional unit	Lifetime (years)	Product system(s)	LCIA method	Impact categories	Assumptions power losses	Assumptions SF_6 losses	Excluded processes	End-of-life scenario
(Blackett, Savory et al. 2008)	Transmission grid network in England and Wales.	1 tower operating during lifetime; 1 conductor (10 km length) and 1 insulator operating during lifetime.	Towers = 85 yrs; Conductors and insulators = 40 yrs.	Steel tower type L2, Aluminum tower , Conductor type aluminum alloy for Rubus configuration (6101 grade aluminum magnesium-silicon alloy), Conductor type ACSR (pure aluminum over galvanized steel wires), Insulators (glass vs. porcelain).	Different methods available from the TEAM software (JRC 2013).	Electricity usage, Air acidification, Aquatic eco tox., Depletion non-ren., Greenhouse effect, Ozone layer depl., Eutrophication, Eutroph. (water), Human toxicity.	Not included.	N.a.	Installation, maintenance /inspection (except paint for towers), power losses, land use, emissions during operation; end-of-life.	N.a.
(Bumby, Druzhinina et al. 2010)	Overhead and underground primary power distribution.	Distribution of MV power in one circuit over 1 mile and for 1 year.	Overhead = 40±10; Land = 30± 10.	Overhead system: cables, reels, poles, crossarms, steel brackets, insulators. Underground system: cables, reels, cable duct, vaults, cable conduits; (transformers excluded in both systems).	CML 2001.	Abiotic depletion, Acid. potential, Eutroph. potential, Fresh water a.e.pot., Global warm. pot., Human tox. potential, Phot. ozone c. pot., Terrestrial ecotoxicity.	Not included.	N.a.	Power losses, heat losses, land use, EM fields.	Avoided burden approach.
(Jones and McManus 2010)	High-voltage distribution network at11 kV.	1 kWh dist. through 1 km of an 11 kV OHL or land cable (as a function of current).	OHL = 80 yrs; Land cable = 70 yrs.	25 mm^2 OHL (Cu), 38 mm^2 OHL (Cu), 100 mm^2 OHL (Cu), 95 mm^2 land (Al), 185 mm^2 land (Al).	ReCiPe 2008 (Midpoint + Endpoint); Cumulative Energy Demand (for fossil fuel depletion).	All ReCiPe suite of impact categories (18).	Included as function of loading.	N.a.	EM fields, heat losses, (power losses are included).	Recycled content (cut-off) approach.
(Harrison, Maclean et al. 2010)	Transmission network in Great Britain.	1 kWh transmitted in Great Britain.	40 yrs.	132 kV OHL, 275/400 kV OHL, 400 kV OHL, AIS substations, GIS substations, 132 kV land cable (Cu), 275/400 kV cable (Cu), 400 kV cable (Cu).	The study is an LCI.	Embodied energy, Embodied CO_2.	Based on total system losses for year 2007.	Based on total system losses for year 2009.	Land use, EM fields, N_2O, ozone, heat losses (power losses are included); zinc and insulating oil leakages.	Savings in energy and carbon ‘credited’ to the system.

(Jorge, Hawkins et al. 2012a)	Power lines and cables.	1 km OHL, land/sea cable operating during the lifetime.	40 yrs.	150 kV OHL (ACSR),
				400 kV OHL (ACSR),
				150 kV oil land cable (Cu),
				150 kV oil sea cable (Cu),
				HVDC OHL (ACSR),
				HVDC land cable (Cu),
				HVDC sea cable (Cu).
					ReCiPe 2008 (Midpoint).	Climate change,
						Fossil depletion,
						Human toxicity,
						Metal depletion,
						Ozone depletion,
						Part. mat. form.,
						Terrestrial ac.,
						Terr. ecotoxicity,
						Freshw. eutroph.
							AC: $I^2R*a*t*l$
							I=phase current
							R = resistance
							a= #phases
							t = lifetime
							l = load (=50%).
							
							HVDC losses = $2*R*10^{-}3*I^2$.
								N.a.	Manufact.
									land use
									EM fields
									N_2O, ozone
									heat losses (power losses are included).
										Recycled content (cut-off) approach.

(Jorge, Hawkins et al. 2012b)	Transformers and substation equipment.	1 device operating during lifetime.	30 yrs for trafos ≤ 20 MVA; 35 yrs for trafos 20 -500 MVA; 20 yrs for D.B.D and C.B.D.; 40 yrs for gas ins. switchgear and other equipment.	315 kVA distribution trafo, 9,6 MVA large dist. trafo, 16 MVA large dist. trafo, 20 MVA large dist. trafo, 40 MVA power trafo, 50MVA power trafo, 63 MVA power trafo, 250 MVA power trafo, 500 MVA power trafo, Gas Ins. Switchg. 300 kV, Gas Ins. Switchg. 420 kV, Plug and Switch System, Double Breaker Disc., Center Breaker Disc., Power Generator Circuit B., Uniswitch, Surge arrester.	ReCiPe 2008 (Midpoint).	Climate change, Fossil depletion, Human toxicity, Metal depletion, Ozone depletion, Part. mat. form., Terrestrial ac., Terr. ecotoxicity, Freshw. eutroph.	Total losses over the lifetime and for transformers load losses vs. no-load losses are distinguished.	Losses during lifetime for gas insulated equipment.	Land use, EM fields, N_2O, ozone, heat losses (power losses are included).	Recycled content (cut-off) approach.
(Jorge and Hertwich 2012)	Transmission network in Norway.	1 kWh transmitted in Norway.	40 yrs.	OHLs (132, 220, 300, 420 kV), Land (132, 300, 420 kV), Sea cables (132, 300, 420 kV), HVDC (220 kV, 420 kV), Transformers (132, 220, 300, 420 kV) by loading rate, Air insulated substations and gas insulated substations (132, 220, 300 and 420 kV).	ReCiPe 2008 (Midpoint).	Agricultural land oc., Climate change, Fossil depletion, Freshwater eutr., Human toxicity, Marine eutrof., Metal depletion, Ozone depletion, Part. mat. form., Phot. oxidant form., Terrestrial ac., Water depletion.	Based on total system losses for year 2007.	Based on total system losses for year 2009.	EM fields, N_2O, ozone, heat losses (power losses are included).	Recycled content (cut-off) approach.
(Itten, Frischknecht et al. 2012)	Life cycle inventories for grid network from the Ecoinvent database (covers 55 countries).	1 kWh HV (>24 kV); 1 km MV (1-24 kV); 1 km LV (<1 kV).	40 yrs. (except HV masts = 60 yrs).	Land cable LV, Land cable MV, MV OHL, 150 kV OHL, 150 kV land, 400 kV OHL, 0.3MVA trafo, 16/20 MVA trafo, 63 MVA trafo.	LCI data.	N.a.	Total power losses are country-specific; % losses assigned to LV, MV and HV based on shares for the Swiss grid.	Country specific SF_6 losses provided for 5 countries.	EM fields.	N.a.
(Turconi et al. 2013)	Distribution of electricity in Denmark.	1 kWh of electricity in Denmark.	30-40 yrs.	0.4, 10 and 50 kV power lines Trafos 50/10 and 10/0.4 kV Auxiliary equipment.	ReCiPe 2008 (Midpoint).	Climate change, Human toxicity, Freshwater eutr., Phot. oxidant form, Terrestrial ac., Terr. ecotoxicity, Fossil depletion, Metal depletion.	Based on total system losses for year 2010.	Based on total system losses for year 2009.	EM fields, N_2O, ozone, heat losses (power losses are included).	Recycled content (cut-off) approach.
(Jorge and Hertwich) (Under review)	Transmission infrastructure for grid integration of renewable sources in Europe.	Transmission equipment for RES integration, as described in the TYNDP.	40 yrs.	OHLs, land cables, sea cables, transformers, substations and switchgear.	ReCiPe 2008 (Midpoint).	All ReCiPe suite of impact categories (18).	Not included.	Based on estimated losses for lifetime.	Power losses, EM field, N_2O, ozone.	Recycled content (cut-off) approach.

4.3 Life Cycle Assessment for Electricity Transmission and Distribution – Summary of non peer-reviewed references

The literature on LCA for T&D also includes references from the industry, e.g., ABB or from electric engineering councils such as the International Council on Large Electric Systems (CIGRE) or forums, e.g., the International Conference on Electricity Distribution (CIRED).

CIGRE has published some reports on LCA for overhead lines, high voltage cables and transmission using SF_6 technology (CIGRÉ 1996, ABB 2003, CIGRÉ 2004b, CIGRÉ 2004a, ABB 2013).

In (Aten and Ferris 2009), calculations of distribution network losses at different voltage levels for a UK operator are presented. The paper investigates what are the life cycle effects of reducing losses in conductors by using a larger conductor size and to which extent the gains are outweighed by increases in material demand. The results show that there is an effect of diminishing returns when the cable utilization becomes extremely low (peak load current over rated current).

The LCA of a 745 kV transmission system is presented in (Wang, Beroual et al. 2012), including both power lines and substations. In the study, materials, losses and end-of-life are included and the method used is EDIP/UMIP 97 v2.3. The study concluded that for the different components of OHLs, towers represent large impacts in most categories. Zinc coatings of steel masts show large contributions in eco-toxicity and human toxicity. Insulators were found to be a small part of total impacts and it was found that the benefits from the recycling not always compensate for the increase in impacts at end-of-life.

A comparative LCA for medium-voltage switchgears for high-voltage/medium-voltage distribution substations concluded that the air insulated compact switchgear was the most environmentally friendly of three options: an SF_6 switchgear, an air-insulated double level panel switchgear and an air insulated compact switchgear (Petroni, Sartore et al. 2003). The double level panel switchgear was found to be the most polluting, although the use phase caused less impacts due to lower electrical losses. The functional unit for the analysis was the distribution of energy supplied by two 25 MV transformers of a HV/MV distribution substation, to 20 MV line feeders across 25 years, according to a typical load loss curve. Raw material acquisition, production, use (including power losses) and end-of-life were included.

A comparative LCA of two technologies of MV/LV transformers, amorphous metal core and grain-oriented magnetic silicon steel core (Borghetto, Barberis et al. 2009), concluded that the first variant had smaller losses and therefore 20% less impacts.

Some studies have looked at technical aspects of T&D management and their influence on the environment. In (Le Poidevin 2003), approaches to the end-of-life of oil filled cables were discussed. The study considered the three current approaches for decommissioning: 1) maintain and monitor the oil pressure in the system; 2) cut and cap sections of the cable and 3) purge the cable with nitrogen. Current practices were compared with alternative methods, e.g., immobilization (gelation of the oil), bio-remediation, solvent/water washing, water washing and detergent washing. The study concluded that current decommissioning practice does not remove nearly all of the oil from cables and the solution that seemed to perform best in terms of environmental performance was cleaning with a detergent solution, for which a high degree of oil removal could be achieved.

Asset management impacts on the environment are discussed by (Polimac 2005), covering measures for preventing or reducing the negative environmental impacts when installing, repairing or maintaining assets. Environmental considerations in product design are addressed by (Lauraire, Barbetta et al. 2003) and the recycling concept as part of life cycle management for medium voltage gas insulated switchgear is explained in (Meyer, Müller et al. 2003).

Component producers have produced Environmental Product Declarations for some equipment (ABB 2013) and electricity companies have also produced some LCA reports related to T&D. The report (Lindgren, Strafström et al. 2002) summarizes LCA studies on overhead lines done before 2002 in Scandinavia, including references from Vattenfall, Syndkraft and Eltra. The latter has provided inventories for all overhead and sea/land cables modeled in the thesis.

5 Articles

5.1 Method details and assumptions

Sections 5.2 to 5.5 summarize each paper individually. This section provides an overview of method choices and assumptions which are common to the fours papers. For all the LCA case studies, the background system consists of the matrix of unit processes from the Ecoinvent v2.2 database (Frischknecht, Jungbluth et al. 2005). The impact assessment method is ReCiPe in all case studies (Goedkoop, Heijungs et al. 2009). This method was chosen because it is the most complete, covering a range of 18 impact categories, and most up-to-date method for impact assessment. The impact categories included in each study are summarized in Table 6.

To the extent that was possible, material unit processes that were chosen from the Ecoinvent database reflect an average European technology of production. Aluminum (primary and aluminum scrap), copper (primary and secondary), copper wire drawing, steel (primary and iron scrap), glass, glass fiber, cast iron, kraft paper, rubber, epoxy, secondary lead, wood and zinc are modeled as average European processes. Brass, bronze, cement, concrete, gravel, paper and sand correspond to Swiss production processes. For some materials however, e.g., lead, limestone or nickel, only global production is available. The closest match possible between materials and processes available from the database was used. In cases for which the specific material is not available from the database, a related material was chosen. This was for example the case of asphalt which was modeled as petroleum coke, porcelain which was modeled as ceramic tiles, transformer oil which was modeled as lubricating oil and tungsten which was modeled as molybdenum.

The recycling was modeled according to the cut-off approach (Frischknecht 2010). Whenever the inventories called for recycling of metal parts (i.e., steel, aluminum, copper, lead) at the end-of-life, it was assumed a recycling rate of 90%. Following the cut-off approach, recycling of steel was modeled so that the benefits (avoiding the production of pig iron) and burdens (production of scrap iron) were taken into account. Therefore, the production of pig iron was modeled as a negative contribution to total impacts (i.e., negative sign) and scrap iron was modeled as a positive contribution to total impacts (i.e., plus sign). Recycling of aluminum was modeled as avoided production of primary aluminum and old aluminum scrap was used as input. Following this logic, recycling of copper/lead was modeled as avoided production of primary copper/lead and input of secondary copper/lead. The remaining 10% of the metals that are not recycled are assumed to go to landfill. To see details on the assumptions for the end-of-life treatment of other materials, e.g., glass, asphalt, etc. please consult the Supplemental Information for papers 1 and 2.

The LCA software used was ARDA, which is a tool developed by researchers at the Industrial Ecology Programme at NTNU. This tool provides the flexibility of working with an inventory in Excel format, which is convenient if one needs to make changes and adjustments in the system. Matlab is then used for linking the inventory to the Ecoinvent database. Furthermore, ARDA provides for robust analytical possibilities, e.g., in contribution analysis and structural path analysis, which could be relevant for further uses of the data compiled in this thesis.

5.2 Paper 1

Ref: Jorge, R., Hawkins, T., Hertwich, E. (2012). Life cycle assessment of electricity transmission and distribution: Part 1 - power lines and cables. *International Journal of Life Cycle Assessment, 17* (1), 9-15.

The first paper focused on the life cycle impacts for different types of line and cable assets used in transmission, including aerial lines, land cables and sea cables. The characteristics for the product systems are summarized in Table 6. In total, 3 types of overhead lines were considered: 150 kV aluminum conductor steel reinforced (ACSR), 400 kV ACSR and HVDC; in addition, 2 land cables (150 kV and HVDC) and 2 sea cables (150 kV oil sea cable and HVDC sea) were included.

System boundaries: the following processes were included for each component: production of raw materials, installation activities, i.e., transportation, power losses during use phase, maintenance and associated activities, and end-of-life. Excluded processes were: manufacturing (i.e., shaping the raw materials to a final product) land use, N_2O and ozone emissions from high-voltage lines and heat losses. The power losses were estimated using an assumption of 50% load in the lines. For HVDC, losses were estimated according to information from a producer (ABB).

With the assumption of European power mix for power losses and the assumptions described above, the results indicate that power losses represent up to more than 95% of the total life cycle scores for all impact categories; an exception is metal depletion for which the production of metal parts dominates. As for the breakdown of process contribution, once losses are disregarded (i.e., only considering infrastructure processes – Figures 1a and 1b in the article), the results for overhead lines show that masts and conductors represent the largest contribution due to large amounts of energy intensive materials, e.g., steel and aluminum. Installation is found to have little influence in the results, in accordance to what had previously been demonstrated by (Jones and McManus 2010) and (Harrison, Maclean et al. 2010). For land and sea cables, and again once losses are disregarded, the materials for the cable itself represent most of the impacts and other relevant processes are the materials for cable traces in land cables. Installation activities represent a larger share of impacts than for aerial lines, but still the overall contribution taking into account the remaining processes is small. The impacts for the end-of-life are shown separately from the impacts for other life cycle stages in the results graphs for both aerial lines and land/sea cables. With the assumptions used to model the end-of-life, the recycling of metal parts can bring some benefits (negative impacts) for aerial lines in all impact categories considered, but since there are also other processes causing positive impacts during the phase, e.g., incineration, landfill, etc., in some cases the benefits due to recycling are relatively small (for example, in the case of terrestrial ecotoxicity impacts). Nevertheless, with the assumptions used there is a reduction of overall impacts due to recycling in all aerial lines modeled. For land/sea cables, the benefits of recycling are mainly noticed for the metal depletion, human toxicity and particulate matter formation categories. In the other categories, the recycling benefits are outweighed by other processes causing (positive) impacts in the end-of-life. Maintenance is not found to cause significant impacts neither in aerial lines nor land/sea cables.

5.3 Paper 2

Ref: Jorge, R., Hawkins, T., Hertwich, E. (2012). Life cycle assessment of electricity transmission and distribution: Part 2 – transformers and substation equipment. *International Journal of Life Cycle Assessment, 17* (2), 184-191.

The second paper had a similar goal as that of paper 1, but in this case the scope was the analysis of life cycle impacts for transformers and substation equipment. The characteristics of the equipment are listed in Table 1 in paper 2. One difference from the first paper is that now some components using SF_6 are included, e.g., gas insulated switchgear. Also, in this paper there is one set of components, i.e., transformers, for which manufacturing is included. When modeling LCA for lines and cables this process was excluded and only the production of raw materials and installation activities, e.g., excavation for land cables was included. Yet, for transformers, data on manufacturing was obtained directly from the manufacturer (ABB), which helped us estimate the impacts related to the energy use in this life cycle stage. For transformers, power losses were modeled as the sum of load and no-load losses, which were provided by the manufacturer. For load losses, a load of 50% was assumed.

System boundaries: for transformers, included processes were raw materials production, manufacturing, transportation (of raw materials to the factory and of the finished product to the installation site), maintenance, power losses and end-of-life. For substation equipment, raw materials production, transportation, use phase, SF_6 losses, power losses and end-of-life were included.

As for the previous paper, results show that power losses are a dominant process at least for the transformers. Power losses in transformers (load + no-load) represent over 96% of contribution to climate change impacts. Load losses were found to be larger than no-load losses during the lifetime of the equipment. Data from (IEE 2008) had indicated that no-load losses are greater than load losses. The difference may be due to the average load assumed here for the transformers, 50%. Yet, for some gas insulated equipment, e.g., gas insulated switchgear, leakages of SF_6 may represent an impact for climate change quite higher than that of power losses. In some components, SF_6 leakages cause 78% of global warming potential scores. This does not go against the results obtained by other studies which found that SF_6 can feature significantly for total impacts (Harrison, Maclean et al. 2010). After power losses, in transformers the most important process is raw materials production which has a high share in all impact categories. Transportation is also important in some impact categories. Manufacturing was found not to be a process causing very large scores, however the impacts of this process for climate change, fossil depletion and ozone depletion are not negligible, especially for the largest transformers. Maintenance has insignificant contributions, as found also in paper 1. The benefits of recycling are in some categories outweighed by the impacts of other processes in the end-of-life, e.g., disposal (incineration) of mineral oil. In substation equipment, raw material production is also an important process once losses are disregarded and transportation also accounts for an important share in some impact categories.

5.4 Paper 3

Ref: Jorge, R., Hertwich, E. (2013). Environmental evaluation of power transmission in Norway. *Applied Energy, 101*, 513-520.

The third paper was an application of the datasets compiled in the first two papers to a specific grid system, the Norwegian transmission grid, or *Sentralnett*. The inventories obtained in papers 1 and 2 were in this paper customized in order to reflect the characteristics of the *Sentralnett*, which by 2009 comprised 11,097 km of lines and cables, 345 transformers and 121 substations, plus some hundreds of kilometers in interconnectors connecting Norway to the Netherlands and Denmark. The functional unit was 1 kWh of electricity delivered to the distribution grid during the lifetime of the system. For the two previous studies the chosen functional unit was 1 device (component) operating during the lifetime, but here the goal was to investigate impacts for the actual delivery of power from a transmission system and therefore 1 kWh unit was more suited as functional unit. For power losses, it was assumed that they were constant during the lifetime and a static generation mix was also assumed. A sensitivity analysis for different power losses was performed using a Norwegian power mix, a Nordic mix and a European mix.

The same system boundaries for each component type as described in papers 1 and 2 were used.

Information on material of the conductor for each type of line, conductor configuration, i.e., how many conductors per phase exist, and cross-section were used to estimate more accurately conductor weight per km of grid for OHLs. To do this, the densities for steel and aluminum were used.

The paper concludes that the transmission of 1 kWh of electricity in Norway generates 1.32 g CO_2 eq. (ReCiPe method with the egalitarian perspective), 1.34 g CO2 eq. (same method with hierarchical perspective) and 1.45 g CO_2 eq. (ReCiPe, individualistic perspective). A large part of the impacts per kWh transmitted are due to power losses. This is in accordance with results obtained by (Wang, Beroual et al. 2012) and (Harrison, Maclean et al. 2010). A sensitivity analysis for the electricity mix used to model power losses showed that, as expected, there is a great difference in the results by substituting the electricity mix from a European mix with the Nordic and the Norwegian mixes. In short, the cleaner the electricity mix, the larger share of impacts is due to infrastructure and the smaller the contribution of power losses.

5.5 Paper 4

Ref: Jorge, R., Hertwich, E. Grid infrastructure for renewable power in Europe: the environmental cost. (submitted to *Energy*).

The forth paper investigates how the power grids will have to adapt in order to accommodate additions of renewable power capacity and what will the resulting environmental impacts be. As described in 2.5.2, massive investments are expected for refurbishing electricity grids worldwide with one of the drivers being the additions of renewable energy sources (RES). In

Europe, the European Network of Transmission System Operators for Electricity estimates that the transmission grid in the region will need to be upgraded by constructing and renovating assets corresponding to a total length of 52,300 km. From these, 45,300 are required for connecting renewable sources to the grid. These projects are described in the Ten Year Development Plan for the European transmission grid put forward by ENTSO-E (ENTSO-E 2012). Overall, upgrading the European transmission grid so that it can accommodate renewables will require the build-up of 25,800 km of new overhead lines, 8,277 km of new sea cables and 3,227 of new land cables. Also, about 8,000 km of already existing transmission assets will have to be upgraded for increasing the transmission capacity in the region.

Potential environmental consequences resulting from converting to renewable energy systems have been previously described by other studies, such as the ones presented in 2.4. This paper however looks at the grid extension issues, which are often left out from the previous analyses.

A modification with regard to the previous papers from the thesis is that paper 4 models manufacturing of components. Manufacturing had been included for substation equipment in previous papers, but not for lines and cables. For HVAC and HVDC OHLs, manufacturing is estimated by including the energy use in hot steel rolling for shaping the masts and galvanization of masts, which is the process by which zinc is applied to the masts to prevent corrosion. Finally, the energy to produce the conductor strands was also included. For cables, manufacturing was included by estimating the energy used in copper wire drawing.

The paper identifies important materials that are required to the grid upgrade. Metals, in particular steel, aluminum, iron, copper, lead and zinc are relevant inputs over the lifecycle of the projects. Other important materials are sand for cable traces and limestone for substations. The largest emissions arise from zinc, mineral oil and SF_6 leakages. Overall, the whole project portfolio as described in the TYNDP 2012, comprising construction of new assets and renovation of old ones (ENTSO-E 2012), corresponds to a total metal depletion of 11.2 Mton Fe eq. The total life cycle emissions of greenhouse gases are of about 10.7 Mton CO_2 eq.

By using an assumption that half of the new substations will be of type gas insulated, the results showed that SF_6 leakages from this equipment corresponded to 6% of total GWP scores for new equipment. Manufacturing was found to have a relatively small contribution in some impact categories, but a quite important share of total scores for categories such as water depletion, climate change, fossil depletion, freshwater eutrophication, ionizing radiation, natural land transformation, ozone depletion and in particular water depletion. For OHLs, manufacturing accounted for about 30% of the total life cycle scores in this category.

A sensitivity analysis for the assumptions relative to recycling rates showed that results are greatly affected by the recycling rates of metal parts due to avoided production. This is true for all categories, but to a lesser extent for the categories of terrestrial ecotoxicity, freshwater ecotoxicity and marine ecotoxicity.

6 Discussion

This section discusses contributions from the thesis, limitations and suggestions for further research.

6.1 Contributions

The main contribution from the thesis is the compilation of life cycle inventories for transmission and distribution systems. Some of the inventories compiled here have been incorporated in the most recent version of the Ecoinvent database (v3) (Itten, Frischknecht et al. 2012), which is an extensive life cycle database with a special focus on energy systems. The following life cycle inventories from Ecoinvent v3 are based on data from papers 1 and 2: 150 kV aerial lines and cables, 400 kV aerial lines and transformers at 0.3, 16/20 and 63 MVA (Itten, Frischknecht et al. 2012).

The structure of the thesis is such that the analysis is first done at a component level (papers 1 and 2) and then at a system level (papers 3 and 4). This allows for the identification of important processes per component but also to understand what are the life cycle impacts for the transmission of power in a real grid system. One contribution regarding previous studies is that power losses are included in papers 1, 2 and 3. Losses had been included in a couple of previous studies, but they either had a different scope (Jones and McManus 2010) or focused on a reduced number of impact categories (Harrison, Maclean et al. 2010). Another contribution is the presentation of data and inventories for the Norwegian transmission system with details on line configuration types, which could be useful for studying other grid systems if their characteristics are also known.

Finally, the thesis contributes to understanding what are the trade-offs associated with grid build-up that is necessary for the integration of renewable sources. Life cycle resource use and emissions are quantified for projects corresponding to upgrading the European transmission grid so that renewable capacity is increased. Several authors have previously addressed the life cycle impacts from up-scaling renewable energy production but the studies did not include the effects of extending the power grid. The 4th paper from the thesis contributes to a better understanding of the environmental consequences of converting to renewable energy systems by focusing on the grid effects.

An advantage of the data collected here is that the inventories are provided separately for each component, e.g., power line, transformer, etc. so that it is possible to model a customized grid project, e.g., a wind farm grid connection or a transmission power system.

6.2 Limitations

A critical look is required while reading the results from the papers in the thesis, namely regarding limitations, representativeness, uncertainty and assumptions, which all have an influence on the significance of the results. First, regarding technological representativeness it is worth mentioning that the thesis addresses environmental impacts for the main components in a T&D system, but not all types of systems are covered. The main assets of an HVAC system are overhead lines, cables, transformers, substations, reactive compensators, phase shifting transformers (PST), flexible alternating current transmission systems (FACTS), smart lines (RTTR), smart cables (RTTR), high temperature low sag (HTLS) lines/high temperature conductors (HTC), gas insulated lines (GILs) and high temperature superconducting (HTS) cables (L'Abbate and Migliavacca 2011). This thesis covers overhead lines, cables transformers and substations, therefore leaving out many transmission components. As for HVDC assets, the main components are overhead lines, cables and converter stations - current source converters and voltage source converters (CSC/VSC). This thesis has covered both HVDC lines and cables, but not converter stations, which are required for transforming power from DC sources to AC power that can further be transported in the grid. According to (L'Abbate and Migliavacca 2011), for a typical DC 1000 MW project, typical costs per km of line/cable are 300-700 k€/km and 700-2000k€/km respectively for an HVDC OHL and HVDC land cable (XLPE), and the costs for the converter range between 70,000k€ and 125,000k€. This shows that any analysis of DC transmission should include converters.

In the first paper it is assumed that there is recovery of land and sea cables, allowing recycling of the metal parts, for which benefits are accounted. However, cables are not always recovered at the end-of-life (Le Poidevin 2003, Worzyk 2009) and therefore it is questionable if this assumption is the most correct in each case. For cables, it would make sense to model the end-of-life in a case to case basis when information is available, or include different scenarios for modeling this life cycle stage.

The assumptions for power losses in conductors in papers 1 and 2 are somehow simplistic and although providing some reference values, they don’t reflect the real losses in the systems. At first, losses depend on the load, which was assumed constant in the calculations (see Supplemental Information of paper 1). In (Jones and McManus 2010) losses are provided as a function of the load in the circuits, which provides a more realistic view about the range of impacts caused by losses. Further, the load factor assumed for transformers was of 50%, in accordance with the data from the manufacturer, ABB. With this assumption, load losses are higher than no-load losses during the lifetime. As we saw in Figure 15, the ratio no-load to load losses in Europe is 3, which again suggests making different scenarios as a function of the load in the system. Another limitation is that losses depend on other characteristics of the T&D system such as total distance, mode of transmission – AC or DC, etc. which were not evaluated here.

Regarding technological representativeness, the aerial lines that are modeled correspond to aluminum conductor steel reinforced lines (ACSR), which are the type of aerial line most used worldwide. As for cables, both oil cables and cross-linked polyethylene (XLPE) cables are included. It is worth noticing that oil cables are increasingly replaced by XLPE cables. These have the advantage of avoiding the leakages of oil which are a cause of environmental concern for oil-paper insulated devices.

Although the thesis considers both AC and DC systems, it does not have the goal of comparing these two modes in terms of overall environmental performance. This would require a much more detailed evaluation of system characteristics.

The references presented here cover most of the processes described in Table 1. Exceptions are ozone and N_2O emissions, which are not considered in any of the papers and electromagnetic radiation which is not included due to lack of data and method for impact assessment. Heavy metal leakages from wooden poles are also excluded since all OHLs considered are of type steel mast.

Although the thesis addresses environmental impacts for some systems used in power distribution, papers 3 and 4 focuses only on the transmission system. This was mainly due to data availability issues. For paper 3, which studies the Norwegian system, distribution was not included because the information that was available from the data provider was at a much more aggregated level, e.g., a breakdown of components by voltage levels was not available. The distribution grid in Norway is almost 30 times as long (in km) than the transmission grid, and while the transmission grid is 90% owned by a single state owned company, there are many more companies managing the distribution grid, which may make it more complex to collect data at a detailed level for this grid. For paper 4, focusing on grid expansion in Europe for the next decade, a detailed plan was available for the transmission grid, but again equivalent data for the distribution data was not found.

Finally, assumptions are made with regard to recycling rates, technology of production and electricity for power losses, which should be taken into account when interpreting the results in each case.

6.3 Further work

There are several suggestions for future work related to LCA for T&D. The components traditionally included in LCAs for electrical grids are power lines, cables, transformers and substation equipment, but many more component types exist and are being developed, as shown in the previous section. One suggestion is to compile inventories for the component types which are not yet covered by previous LCA studies with the aim of complementing the existing data. The availability of physical data might be a barrier, but one idea is to use investment costs and a monetary input-output model for carrying out the analysis. A review of costs for transmission infrastructures is described at (L'Abbate and Migliavacca 2011) which can provide useful data. The data covers costs for systems such as FACTS and PSTs for HVAC systems, or converter stations for HVDC systems. Converter stations, for example, are an important part of DC transmission and it would be important that the LCA data on T&D includes these systems.

Furthermore, (L'Abbate and Migliavacca 2011) provide costs of transmission assets per country, including cross-border connections. Such data could be used as a complement to the physical data compiled in paper 4 for setting up a hybrid model for impacts of grid extensions. Hybrid models for LCA have the advantage of avoiding the system boundary issue of process-based LCAs, and hence account for impacts which could otherwise be relevant and left out.

Finally, since losses are an important part of T&D impacts, it would be interesting that LCA case studies for T&D in the future consider more robust models than the ones available in previous references. These models could consider the effect of variation of load in the systems for different hours of the day, days of the week, months of the year, etc. This would provide more realistic models for overall environmental system impacts.

7 Conclusions

The main conclusions from the thesis can be summed up as follows:

1) Power losses in T&D equipment are the most important contributor to life cycle impacts for most impact categories, both for AC and DC equipment. This is valid for overhead, underground and subsea systems.

2) An exception to 1) was found regarding some substation equipment for which SF_6 losses can represent most of the life cycle impacts in the category of climate change, which is the only relevant category in this case.

3) Another exception to 1) was found for the category of metal depletion, for which the production of metal parts dominates the total scores.

4) After losses, important processes in OHLs are the production of metals for masts and conductors followed by production of foundations. For cables, the production of the cables dominates the infrastructure related impacts. For transformers and substation equipment, the production of raw materials is an important infrastructure process.

5) The results obtained for transformers in paper 2 showed that manufacturing was relevant for climate change, fossil depletion, ozone depletion, and terrestrial ecotoxicity. The last paper confirms the importance of manufacturing processes for life cycle scores of T&D equipment, in particular for water depletion, which had not been included in the previous results.

6) Maintenance and installation were found to cause relatively small impacts, as compared to other phases. An exception would be the installation of land cables, for which installation accounts for high results in some impacts categories.

7) When 1 kWh of electricity is transmitted in Norway, total climate change impacts are estimated between 1.3 to 1.5 g CO_2 eq. These values correspond to power delivered from the transmission to the distribution grid, so the total power supply impacts will be larger.

8) For the Norwegian transmission system, most impacts in climate change arise from power losses, but after power losses important contributions arise mainly from infrastructure processes for overhead lines and transformers and from SF_6 emissions in substations.

9) A sensitivity analysis of the results for transmission of power in Norway was made with regard to the electricity mix for electricity losses. As we move from an electricity mix that is "cleaner" to one that is "dirtier", the share of impacts from power losses increases and the share of impacts from infrastructure decreases, and vice-versa. Assuming a

Norwegian mix for power losses, half of the climate change results are due to infrastructure processes and the other half is due to power losses in the system.

10) Important sources of direct emissions for T&D systems are leakages of mineral oil from oil insulated equipment, emissions of zinc from OHLs masts and leakages of SF_6 from gas insulated equipment. The latter accounts for 15% of total climate change scores arising from infrastructure processes, i.e., after losses, for transmission of electricity in Norway.

11) The integration of renewable energy sources is an important factor for grid development in Europe over the next years. The grid extension projects are expected to contribute to a depletion of metal resources corresponding to about 11.2 Mton Fe eq. Over the lifecycle, these projects will also generate 10.7 Mton CO_2 eq.

12) Impacts can be mitigated by recovery, i.e., recycling of metal parts at the end-of-life, but this not always compensates for impacts arising from other end-of-life processes, e.g., incineration and disposal of other waste.

13) The results are tested for sensitivity by assuming 3 scenarios for the recycling rate of metal parts – no recycling, 50% recycling and 90% recycling. This greatly influences the final results in all impact categories.

8 Bibliography

ABB (2003). LCA technical report for oil filled Large Distribution Transformer (LTD), ABB PTTR-Monselice.

ABB (2013). "Environmental Product Declarations." Retrieved March, 2013, from http://www.abb.com/cawp/abbzh258/3d76091aeb235c70c12569ee002b47f4.aspx.

Ackermann, T., et al. (2001). "Distributed generation: a definition." Electric Power Systems Research **57**(3): 195-204.

Alonso, E., et al. (2012). "Evaluating rare element availability: A case with revolutionary demand from clean technologies." Environmental Science & Technology **46**(6): 3406-3414.

Arvesen, A. (2013). Understanding the environmental implications of energy transitions. Department of Energy and Process Engineering Trondheim, Norwegian University of Science & Technology. **PhD**.

Arvesen, A. and E. Hertwich (2012). "Assessing the life cycle environmental impacts of wind power: A review of present knowledge and research needs." Renewable and Sustainable Energy Reviews **16**(8): 5994-6006.

Aten, M. and R. Ferris (2009). Analysis of distribution losses and life cycle CO_2 emissions. 20th International Conference on Electricity Distribution, CIRED. Prague, Czech Republic.

Ayres, R. (1995). "Life cycle analysis: a critique." Resources Conservation & Recycling **14**(3-4): 199-223.

Barrientos, R., et al. (2011). "Meta-analysis of the effectiveness of marked wires in reducing avian collisions with power lines." Conservation Biology **25**(5): 893-903.

Bauman, H. and A.-M. Tillmann (2004). The hitch hiker's guide to LCA: an orientation in life cycle assessment methodology and application. Lund, Sweden, Studentlitteratur AB.

Bergerson, J. and L. Lave (2005). "Should we transport coal, gas, or electricity: cost, efficiency and environmental implications." Environmental Science & Technology **39**(16): 5905-5910.

Bevanger, K. (1998). "Biological and conservation aspects of bird mortality caused by electrical power lines: A review." Biological Conservation **86**(1): 67-76.

Blackett, G., et al. (2008). "An evaluation of the environmental burdens of present and alternative materials used for electricity transmission." Building and Environment **43**: 1326-1338.

Blasing, T. J. (2013) Recent greenhouse gas concentrations. DOI: 10.3334/CDIAC/atg.032

Bollens, U., et al. (1996). Ökoinventare von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz, ETH Zürich, Paul Scherrer Institute.

Borghetto, J., et al. (2009). Comparative life cycle assessment of a MV/LV transformer with an amorphous metal core and a MV/LV transformer with a grain-oriented magnetic silicon steel core. 20th International Conference on Electricity Distribution, CIRED. Prague, Czech Republic**:** 745.

Bright, R., et al. (2011). "Radiative forcing impacts of boreal forest biofuels: A scenario study for Norway in light of albedo." Environmental Science & Technology **45**(17): 7570-7580.

Bumby, S., et al. (2010). "Life cycle assessment of overhead and underground primary power distribution." Environmental Science & Technology **44**: 5587-5593.

Caduff et al. (2012). "Wind power electricity: The Bigger the Turbine, The Greener the Electricity?" Environmental Science & Technology **46**: 4725-4733.

Chatzivasileiadis, S., et al. (2013). "The global grid." Renewable Energy **57**(372-383).

CIGRÉ (1996). Life cycle assessment on high voltage power cables. Paris, France, International Council on Large Electric Systems (Cigré).

CIGRÉ (2004a). Electrical power supply using SF6 technology. Paris, France, International Council on Large Electric Systems (Cigré).

CIGRÉ (2004b). Life Cycle Assessment (LCA) for Overhead Lines. Paris, France, International Council on Large Electric Systems (Cigré).

Clift, R. (1993). "Life cycle assessment and ecolabelling." Journal of Cleaner Production **1**(3-4): 155-159.

Corsten, M., et al. (2013). "Environmental impact assessment of CCS chains - Lessons learned and limitations from LCA literature." International Journal of Greenhouse Gas Control **13**: 59-71.

Dawkins, E., et al. (2012). Metals in a low-carbon economy: resource scarcity, climate change and business in a finite world, Swedish Environmental Institute (SEI).

Delucchi, M. A. and M. Z. Jacobson (2010). "Providing all global energy with wind, water and solar power, Part II: Reliability, system and transmission costs, and policies." Energy Policy **39**: 1170-1190.

Dones, R. and R. Frischknecht (1998). "Life-cycle assessment of photovoltaic systems: Results of Swiss studies on energy chains." Progress on Photovoltaics **6**(2): 117-125.

Doukas, H., et al. (2011). "Electric power transmission: An overview of associated burdens." International Journal of Energy Research **35**(11): 979-988.

Draper, G., et al. (2005). "Childhood cancer in relation to distance from high voltage power lines in England and Wales: A case control study." BMJ **330**: 1290.

ENTSO-E (2011). Statistical Yearbook 2011, European Network of Transmission System Operators for Electricity.

ENTSO-E (2012). Ten year network development plan 2012, European Network of Transmission System Operators for Electricity.

EXIOPOL (2012). EXIOPOL, European Commission, 6th Framework.

Fernandes, C., et al. (2013). "Expanding interconnection capacity to integrate intermittent generation in the Iberian Peninsula." IET Renewable Power Generation **7**(1): 45-54.

Feychting, M. and M. Ahlbom (1993). "Magnetic fields and cancer in children residing near Swedish high-voltage power lines." American Journal of Epidemiology **138**(7): 467-481.

Finkbeiner, M., et al. (2006). "The new international standards for life cycle assessment: ISO 14040 and ISO 14044." The International Journal of Life Cycle Assessment **11**(2): 80-85.

Finnveden, G., et al. (2009). "Recent developments in life cycle assessment." Journal of Environmental Management **91**(1): 1-21.

Frischknecht, R. (2010). "LCI modelling approaches applied on recycling of materials in view of environmental sustainability, risk perception and eco-efficiency." The International Journal of Life Cycle Assessment.

Frischknecht, R., et al. (2000). "Human health damages due to ionising radiation in life cycle impact assessment." Environmental Impact Assessment Review **20**: 159-189.

Frischknecht, R., et al. (2005). "The Ecoinvent Database: Overview and methodological framework." The International Journal of Life Cycle Assessment **10**(1): 3-9.

Furby, L., et al. (1988). "Public perceptions of electric power lines." Journal of Environmental Psychology **8**(1): 19-43.

Goedkoop, M., et al. (2009). A life cycle impact assessment method which comprises harmonized category indicators at the midpoint and the endpoint level.

Goedkoop, M. and R. Spriensma (1999). The Eco-indicator 99. A damage oriented method for life cycle assessment. Amersfoort, Netherlands, PRé Consultants.

Gossling, S. N., et al. (2011). "A review of recent developments in climate change science. Part II: The global-scale impacts of climate change." Progress in Physical Geography **35**(4): 443-464.

Graus, W. and E. Worrell (2011). "Methods for calculating CO_2 intensity of power generation and consumption: A global perspective." Energy Policy **39**(2): 613-627.

Hammond, G. P., et al. (2013). "The energy and environmental implications of UK more electric transition pathways: A whole systems perspective." Energy Policy **52**: 103-116.

Hanewinkel, M., et al. (2013). "Climate change may cause severe loss in the economic value of European forest." Nature Climate Change **3**: 203-207.

Harrison, G., et al. (2010). "Life cycle assessment of the transmission network in Great Britain." Energy Policy **38**(7): 3622-3631.

Hertem, D. and M. Ghandhari (2010). "Multi-terminal VSC HVDC for the European supergrid: Obstacles." Renewable and Sustainable Energy Reviews **14**(9): 3156-3163.

Hertwich, E. (2005a). "Consumption and the rebound effect: An industrial ecology perspective." Journal of Industrial Ecology **9**(1-2): 85-98.

Hertwich, E. (2005b). "Life cycle approaches to sustainable consumption: A critical review." Environmental Science & Technology **39**(13): 4673-4684.

Hertwich, E. and G. Peters (2009). "Carbon footprint of nations: A global, trade-linked analysis." Environmental Science & Technology **43**(16): 6414-6420.

Herzog, T. (2009). World greenhouse gas emissions in 2005, World Resources Institute (WRI).

Hondo, H. (2005). "Life cycle GHG emission analysis of power generation systems: Japanese case." Energy **30**: 2040-2056.

Hu, Y. and H. Cheng (2013). "Development and bottlenecks of renewable electricity generation in China: A critical review." Environmental Science & Technology **47**(7): 3044-3056.

Hunt, R., et al. (1992). "Resource and environmental profile analysis: A life cycle environmental assessment for products and procedures." Environmental Impact Assessment Review **12**(3): 245-269.

Hynes, K. M. (1994). An assessment of the environmental impacts of thin film cadmium telluride modules based on life cycle analysis. IEEE Photovoltaic Specialists Conference 1994. **1:** 958-961.

IEA (2008). World Energy Outlook 2008. Paris, France, International Energy Agency of the Organisation for Economic Cooperation and Development.

IEA (2011a). Harnessing variable renewables. Paris, France, International Energy Agency of the Organisation for Economic Cooperation and Development.

IEA (2011b). World Energy Outlook 2011. Paris, France, International Energy Agency of the Organisation for Economic Cooperation and Development.

IEA (2012). World Energy Outlook 2012. Paris, France, International Energy Agency of the Organisation for Economic Cooperation and Development.

IEE (2008). Selecting Energy Efficiency Distribution Transformers - A Guide to Achieving Least-Cost Solutions, International Energy Europe.

IPCC (2007a). Climate change 2007: Impacts adaptation and vulnerability. Contribution of Working Group III to the fourth assessment report of the Intergovernmental Panel on Climate Change, Cambridge University Press.

IPCC (2007b). Climate change 2007: The physical science basis. Contribution of Working Group I to the fourth assessment report of the Intergovernmental Panel on Climate Change, Cambridge University Press.

IPCC (2012). Renewable energy sources and climate change mitigation, International Panel on Climate Change.

ISO (2006a). Environmental management - Life cycle assessment - Principles and framework (ISO 14040:2006), International Organization for Standardization.

ISO (2006b). Environmental management - Life cycle assessment - Requirements and guidelines (ISO 14044:2006), International Organization for Standardization.

Itten, R., et al. (2012). Life cycle inventories of electricity mixes and grid, ESU-services Ltd.

Jacobson, M. and M. Delucchi (2011). "Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure." Energy Policy **39**: 1154-1169.

Jones, C. and M. McManus (2010). "Life-cycle assessment of 11 kV electrical overhead lines and underground cables." Journal of Cleaner Production **18**: 1464-1477.

Jorge, R., et al. (2012a). "Life cycle assessment of electricity transmission and distribution - Part 1: power lines and cables." The International Journal of Life Cycle Assessment **17**(1): 9-15.

Jorge, R., et al. (2012b). "Life cycle assessment of electricity transmission and distribution - Part 2: transformers and substation equipment." The International Journal of Life Cycle Assessment **17**(2): 184-191.

Jorge, R. and E. Hertwich. "Grid infrastructure for renewable power in Europe - The environmental cost." Submitted to Energy, 2013.

Jorge, R. and E. Hertwich (2012). "Environmental evaluation of power transmission in Norway." Applied Energy **101**: 513-520.

Kempton, W., et al. (2010). "Electric power from offshore wind via synoptic-scale interconnection." Proceedings of the National Academy of Sciences **107**(16).

Kiessling, F., et al. (2003). Overhead power lines: planning, design, construction, Springer-Verlag Berlin Heidelberg.

Kleijn, R., et al. (2011). "Metal requirements of low-carbon power generation." Energy **36**: 5640-5648.

Knoepfel, H. (1996). "A framework for environmental impact assessment of long-distance energy transport systems." Energy **21**(7-8): 693-702.

L'Abbate, A., et al. (2008). Distributed power generation in Europe: Technical issues for further integration, European Commission Joint Research Centre.

L'Abbate, A. and G. Migliavacca (2011). Review of costs of transmission infrastructures, including cross border connections, Ricerca sul Sistema Energetico SpA (RSE).

Larruskain, D., et al. (2011). "Conversion of AC distribution lines into DC lines to upgrade transmission capacity." Electric Power Systems Research **81**(7): 1341-1348.

Lauraire, M., et al. (2003). Environmental considerations in product design: a reality for French manufacturers. 17th International Conference on Electricity Distribution, CIRED. Barcelona, Spain.

Le Poidevin, G. (2003). Approaches to the decommissioning of end-of-life oil filled cables. 17th International Conference on Electricity Distribution, CIRED. Barcelona, Spain.

Lenzen, M. (2008). "Life cycle energy and greenhouse gas emissions of nuclear energy: A review." Energy Conversion and Management **49**(8).

Lenzen, M. and J. Munksgaard (2002). "Energy and CO_2 life cycle analyses of wind turbines - Review and applications." Renewable Energy **26**(3): 339-362.

Lindgren, R., et al. (2002). LCA of overhead lines in Scandinavia, Cigré.

Lindner, S., et al. (2013). "Disaggregating the electricity sector of China's Input-Output Table for Improved Life-Cycle Assessment." Economic Systems Research.

Marriott, J. (2007). An Electricity-focused Economic Input-output Model: Life-cycle Assessment and Policy Implications of Future Electricity Generation Scenarios. Civil & Environmental Engineering, Carnegie Mellon University. **Submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy**.

Meyer, B., et al. (2003). Recycling concept as integral part of life cycle management for gas-insulated medium-voltage switchgear. 17th International Conference on Electricity Distribution, CIRED. Barcelona, Spain.

National Grid UK (2013). "Electric and Magnetic Fields." from http://www.emfs.info/.

Pennington, D., et al. (2004). "Life cycle assessment Part 2: Current impact assessment practice." Environment International **30**(5): 721-739.

Perriman, R. (1993). "A summary of SETAC guidelines for life cycle assessment." Journal of Cleaner Production **1**(3-4): 209-212.

Peters, G. (2010). "Carbon footprints and embodied carbon at multiple scales." Current Opinion on Environmental Sustainability **2**(4): 245-250.

Petroni, F., et al. (2003). Comparative life cycle assessment among MV metal-enclosed switchgears for HV/MV distribution substations. 17th International Conference on Electricity Distribution, CIRED. Barcelona, Spain.

Pihl, E., et al. (2012). "Material constraints for concentrating solar thermal power." Energy **44**(1): 944-954.

Polimac, J. (2005). Environmental requirements for power system projects. 18th International Conference on Electricity Distribution, CIRED. Turin, Italy.

Prempreeda, P. (2012). Investigation of the environmental impacts of wind energy and supplemental energy systems using a life cycle approach, Oregon State University. **MSc in Industrial Engineering**.

Proops, J., et al. (1996). "The lifetime pollution implications of various types of electricity generation. An input-output analysis." Energy Policy **24**(3): 229-237.

Rafaschieri, A., et al. (2000). "Life cycle assessment of electricity production from poplar energy crops compared with conventional fossil fuels." Energy Conversion and Management **40**(14): 1477-1493.

Rashedi, A., et al. (2013). "Life cycle assessment of 50 MW wind farms and strategies for impact reduction." Renewable and Sustainable Energy Reviews **21**: 89-101.

Renseen, S. (2012). "An energy revolution." Nature Climate Change **2**: 19-20.

Rocha, A., et al. (2012). "The footprint of Alaskan tundra fires during the past half-century: Implications for surface properties and radiative forcing." Environmental Research Letters **7**(4).

Sathre, R., et al. (2012). "A framework for environmental assessment of CO_2 capture and storage systems." Energy **37**(1): 540-548.

Schleisner, L. (2000). "Life cycle assessment of a wind turbine and related externalities." Renewable Energy **20**(3): 279-288.

SETIS (2013). "Strategic Energy Technologies Information System." Retrieved March, 2013, from http://setis.ec.europa.eu/technologies/Smart-grids/info.

Sherwani, A. F., et al. (2010). "Life cycle assessment of solar PV based electricity generation systems: A review." Renewable and Sustainable Energy Reviews **14**(1): 540-544.

Singh, B. (2011). Environmental evaluation of carbon capture and storage technology and large scale deployment scenarios. Department of Energy and Process Engineering. Trondheim, Norway, Norwegian University of Science and Technology. **Ph.D.**

Solberg-Johansen, B. (1998). Environmental life cycle assessment of the nuclear fuel cycle

Centre for Environmental Strategy. Guildford, University of Surrey. **PhD**.

Solomon, S., et al. (2008). "Irreversible climate change due to carbon dioxide emissions." Proceedings of the National Academy of Sciences **106**(6): 1704-1709.

Solomon, S., et al. (2007). Technical summary. In: Climate Change 2007: The physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change. S. Solomon, D. Qin, M. Manning et al., IPCC.

Starke, M., et al. (2008). AC vs. DC distribution: A loss comparison. Transmission and Distribution Conference and Exposition, 2008.

Stern, N. (2007). The economics of climate change.

Strzepek, K., et al. (2012). Modeling water withdrawal and consumption for electricity generation in the United States, MIT Joint Program on the Science and Policy of Global Change.

Turconi, R., et al. (2013). "Life cycle assessment of the Danish electricity distribution network." The International Journal of Life Cycle Assessment **published online 30 July 2013**.

UNEP (2012). The emissions gap report 2012, United Nations Environment Programme.

UNFCCC (2013). "Feeling the heat: Climate Science and the basis of the convention."
Retrieved February, 2013, from
http://unfccc.int/essential_background/the_science/items/6064.php.

US-Canada Power System Outage Task Force (2004). Final report on the August 14, 2003 blackout in the United States and Canada: Causes and recommendations.

Varun, et al. (2009). "LCA of renewable energy for electricity generations systems - A review." Renewable and Sustainable Energy Reviews **11**(5): 1067-1073.

Vistnes, I., et al. (2004). "Effects of infrastructure on migration and range of wild reindeer." Journal of Wildlife Management **68**(1): 101-108.

Waku, H., et al. (1995). "Life cycle analysis of fossil power plant with CO_2 recovery and sequestration system." Energy Conversion and Management **36**(6-9): 877-880.

Walney offshore windfarms (2011). Project brochure.

Wang, W., et al. (2012). Life cycle assessment of a 745 kV AC transmission system, Cigre.

Weinzettel, J., et al. (2009). "Life cycle assessment of a floating offshore wind turbine." Renewable Energy **34**(3): 742-747.

Weisser, D. (2007). "A guide to life cycle greenhouse gas (GHG) emissions from electric supply technologies." Energy **32**(9): 1543-1559.

White, P., et al. (1992). "Life cycle assessment of packaging." Packaging in the environment: 118-146.

Wiedmann, T., et al. (2011). "Application of hybrid life cycle approaches to emerging energy technologies - The case of wind power in the UK." Environmental Science & Technology **45**(13): 5900-5907.

Worzyk, T. (2009). Submarine Power Cables: design, installation, repair, environmental aspects. Berlin, Germany, Springer Verlag Berlin Heidelberg.

Yasukawa, S., et al. (1992). Life cycle CO_2 emissions from nuclear power reactor and fuel cycle system. Expert Workshop on Life-Cycle Analysis of Energy Systems, Methods and Experience.

Zhou, C., et al. (2013). "An analysis of short-term cloud feedback using MODIS data." Journal of Climate.

Zhu, F., et al. (2005). "Environmental impacts and benefits of regional power grid interconnections in China." Energy Policy **33**: 1797-1805.

Appendix 1.

Paper 1:

Jorge, R., et al. (2012). "Life cycle assessment for transmission and distribution – part 1: power lines and cables." The International Journal of Life Cycle Assessment, 17(1): 9-15.

Is not included due to copyright

ELECTRONIC SUPPLEMENTARY MATERIAL – PART 1

LCA FOR ENERGY SYSTEMS

Life cycle assessment of electricity transmission and distribution - Part 1: Power lines and cables

Raquel S. Jorge • Troy R. Hawkins • Edgar G. Hertwich

Received: 11 February 2011 / Accepted: 26 August 2011

Responsible editor: Wulf-Peter Schmidt

R. S. Jorge (✉) • R. R. Hawkins • E. G. Hertwich

Industrial Ecology Programme, Department of Energy and Process Engineering, Norwegian University of Science and Technology (NTNU), Trondheim-7491, Norway

e-mail: raquel.s.jorge@ntnu.no

(✉) **Corresponding author:**

Tel. +47 73598957

e-mail: raquel.s.jorge@ntnu.no

Appendix 2.

Paper 2:

Jorge, R., et al. (2012). "Life cycle assessment for transmission and distribution – Part 2: transformers and substation equipment." The International Journal of Life Cycle Assessment, 17(2): 184-191.

Is not included due to copyright

ELECTRONIC SUPPLEMENTARY MATERIAL – PART 2

LCA FOR ENERGY SYSTEMS

Life cycle assessment of electricity transmission and distribution - Part 2: Transformers and substation equipment

Raquel S. Jorge • Troy R. Hawkins • Edgar G. Hertwich

Received: 11 February 2011 / Accepted: 26 August 2011

Responsible editor: Wulf-Peter Schmidt

R. S. Jorge (🖂) • R. R. Hawkins • E. G. Hertwich
Industrial Ecology Programme, Department of Energy and Process Engineering, Norwegian University of Science and Technology (NTNU), Trondheim-7491, Norway
e-mail: raquel.s.jorge@ntnu.no

(🖂) **Corresponding author:**
Tel. +47 73598957
e-mail: raquel.s.jorge@ntnu.no

Appendix 3.

Paper 3

Jorge, R., Hertwich, E. (2012). "Environmental evaluation of power transmission in Norway." Applied Energy, 101: 513-520.

Applied Energy 101 (2013) 513–520

Contents lists available at SciVerse ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Environmental evaluation of power transmission in Norway

Raquel S. Jorge *, Edgar G. Hertwich

Industrial Ecology Programme, Department of Energy and Process Engineering, Norwegian University of Science and Technology (NTNU), Trondheim 7491, Norway

HIGHLIGHTS

- ▶ A life cycle assessment for the transmission of power in Norway is undertaken.
- ▶ Study includes: power lines, cables, transformers and substations installed by 2009.
- ▶ The transmission of 1 kW h of electricity in Norway generates 1.3–1.5 g CO_2 eq.
- ▶ Overhead lines, transformers and SF_6 losses cause most infrastructure impacts.
- ▶ A sensitivity analysis for different power mixes when modelling losses is performed.

ARTICLE INFO

Article history:
Received 24 February 2012
Received in revised form 16 May 2012
Accepted 6 June 2012
Available online 23 July 2012

Keywords:
Life cycle assessment
Power transmission
Renewable power
Electrical grid infrastructure
Grid expansion

ABSTRACT

Electrical grid systems are required as a consequence of energy not being produced in the same place as it is consumed, and they are a key element of our energy systems. Transmission and distribution assets comprised of power lines, cables, transformers, substations and other electrical equipment generate a wide range of environmental impacts. Throughout the lifetime of the equipment, the impacts originate mainly from power losses during the use phase, but other life cycle stages such as installation, maintenance and dismantling also contribute significantly to some impact categories. In this paper, the environmental impacts of the Norwegian transmission grid are assessed. The methodology used here is Life Cycle Assessment (LCA) with ReCiPe as impact assessment method. In total, 11,097 km of lines and cables, 345 transformers and 121 substations were installed in the Norwegian transmission grid by the end of 2009; the network also included some hundreds of kilometers of sea cables between Norway and abroad. The results show that for each kW h of electricity transmitted in Norway, climate change impacts are of 1.3–1.5 g CO_2 eq., assuming a Norwegian electricity mix. Half of these emissions are associated with power losses, and the other half with infrastructure processes such as materials production, installation, maintenance, and end-of-life. The results also show that after the losses, the infrastructure processes for overhead lines and transformers, and the emissions of SF_6 from Gas Insulated equipment are the most relevant contributors for total climate impacts. A sensitivity analysis is done with respect to the electricity mix used to model power losses in the system. The results show that the contribution of power losses to the total climate change scores increases to 84% and 94%, by replacing the Norwegian mix by the Nordic mix and the European mix, respectively.

1. Introduction

The electricity grid is a key component of our energy systems, allowing power to be transferred from the power plant to the consumer. There is a growing body of scientific literature on environmental impacts for power generation processes, including several Life Cycle Assessment (LCA) studies [1–11] and hybrid life cycle approaches [12,13], to cite a few. However, not many studies on power systems include or provide detailed life cycle data for transmission and distribution (T&D) impacts. T&D is important for every LCA of electricity and understanding its environmental impacts is increasingly relevant in the context of planning future energy systems. The power grid is expected to play a key role in the phasing in of renewable power supply [14], as well as in the electrification of transportation [15]. Many studies throughout the world have demonstrated that increasing network investments towards additional kilometers and capacity to the transmission network are required in order to achieve successful rates of renewable energy integration [16]. Some projects suggest that linking different regions through expansion of the connecting power grid will help meet emissions targets [17] and achieve other environmental benefits [18]. Additionally, other interventions, such as adding communication and control capabilities to optimize network

---

* Corresponding author. Tel.: +47 73598957.
E-mail address: raquel.s.jorge@ntnu.no (R.S. Jorge).

0306-2619/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apenergy.2012.06.004

operation, are expected to enable the grid system to reduce the overall environmental impacts of the electricity supply system [19]. Although there will be changes in the way they operate, the power grids of the future will still transport power over ‘‘copper and iron’’, i.e. future grids will still be made of power lines, cables, transformers and substations amongst other components. Therefore, knowing the impacts for future grid systems and understanding their potential role for a greener electricity sector requires a good comprehension of today’s grids impacts.

The research questions for this article are the following: what are the life cycle impacts of a grid system used for the transmission of power? Which processes and components cause the most emissions? If power losses in the network are modeled with different electricity mixes, how does that change the overall life cycle impacts?

The goal of this paper is to estimate and characterize the environmental impacts of the Norwegian transmission system, also called *Sentralnett*. The methodology used here is Life Cycle Assessment (LCA), with the impact assessment method ReCiPe. Detailed data on the infrastructure installed at the *Sentralnett* was provided by the electricity regulator in Norway – NVE [20] and the Norwegian transmission system operator (TSO) – Statnett [21]. Physical and electrical parameters for the installed power lines and cables were obtained from Sintef Energy AS [22]. This study builds on a previous life cycle analysis on the environmental impacts of different components of electrical grid systems – such as power lines, cables, transformers and other equipment [23,24]. This paper takes a step further on the analysis presented in [23,24] by modeling a real grid system and going from a component’s perspective to a system perspective. Also, instead of using hypothetical values for power losses, real system data is used in this study. The aim is to understand the relative importance of the different components and life cycle stages for the total grid system impacts. Previous LCAs of T&D systems exist in the literature, but they either have a different scope [25,26], do not include some of the impact categories included here [27] or as previously mentioned, include only components of the system but not the system as a whole [23,24,28–30]. This study can therefore bring a contribution to the field of LCA for T&D. The Norwegian electrical grid is an interesting case study. Norway’s electricity production relies almost exclusively on hydro power. In 2009, 96% of the country’s total 132.8 TWh of electricity production was generated by hydro power plants [31]. There is an idea of utilizing Norwegian pumped storage power as one of the solutions for balancing North European intermittent renewable power production [32]. This requires an upgrade of the Norwegian and the trading countries electrical grid system along with the construction of several thousand of kilometers of cables from Norway to other countries in the North of Europe, e.g. Germany, Netherlands, UK [33]. The study of the life cycle impacts of the currently installed transmission system in Norway can therefore prove useful for actors working with grid extension planning issues; in fact, the decision makers have already identified the need for LCA studies in helping choosing different transmission solutions [34]. Previous studies indicate that the largest environmental impacts for T&D systems originate from power losses [23,24,27]. According to NVE [31], total losses in the T&D system in Norway are of 7% of the total power production, corresponding to 9296 GW h of losses in 2009. Of these, 2215 GW h, or approximately 24% of the total T&D system losses, occur in the *Sentralnett* [20]. The goal for this article is to estimate and characterize the environmental burdens of transmitting power in the *Sentralnett* system and to understand how the different processes in the life cycle of the network contribute to the overall impacts. Apart from losses, the study aims at identifying which other important processes have a relevant contribution to the total impacts.

2. Material and methods

2.1. Method details

Life Cycle Assessment (LCA) is used to evaluate the environmental performance of the Norwegian transmission system. LCA is a well-established method applied in the calculation of ‘‘cradle-to-grave’’ impacts of products or services. The procedure of the LCA method is defined in the ISO 14,040 and 14,044 standards [35,36]. The results are obtained using the ReCiPe 2008 midpoint-oriented impact assessment method [37]. There is a degree of uncertainty in the knowledge of the mechanisms which lead to climate change and other environmental impacts. As a way of addressing this uncertainty, the ReCiPe method proposes the use of three perspectives – egalitarian, individualistic and hierarchical, which make different scenarios with regard to the environmental consequences of a certain process. By considering different time frames, rates of adaptation, etc., the three perspectives reflect different degrees of optimism for the causality process-effect [37]. In this paper, results are obtained for the three perspectives. From the 18 impact categories addressed by the method, the following are included in this analysis: agricultural land occupation, climate change, freshwater eutrophication, human toxicity, marine eutrophication, metal depletion, ozone depletion, particulate matter formation, photochemical oxidant formation, terrestrial acidification and water depletion. In order to understand how different electricity mixes affect the final results, a sensitivity analysis is done with respect to the mix used for modeling electricity losses in the network. In addition to the Norwegian supply mix, results are also obtained for the Nordic mix (corresponding to the Nordel mix in Ecoinvent) and for the average European mix. The end-of-life scenarios include processes such as disposal, landfill and recycling, and these have been included. To account for the benefits of recycling, the approach indicated by Ecoinvent is followed here, i.e., recycling of steel is modeled by using pig iron as avoided product and scrap iron as an input. The LCA calculations were performed by linking the foreground system to a background system – the Ecoinvent v2.2 database. The computations were done by using ARDA, an LCA software tool developed by researchers at the Industrial Ecology Programme at NTNU [38].

2.2. Scope and functional unit

Power in the Norwegian grid is transported from generators via the transmission grid (132–420 kV), main distribution grid (47–132 kV), and high-voltage (11–22 kV) and low-voltage (230–400 V) distribution grids to the final consumers [22]. The scope of this LCA study is the Norwegian transmission grid (132–420 kV), also called *Sentralnett*. Overall, by the end of 2009, approximately 300,000 km of lines and cables, 32,500 transformers, and 125,500 substations were installed in Norway [20]. From these, a total of 10,971 km overhead lines, 52 km of underground cables, 1037 km of sea cables, 345 transformers and 121 transformer stations are part of the transmission network, which is evaluated here. The functional unit is 1 kW h of electricity delivered from the *Sentralnett* to the main distribution grid.

2.3. System boundary

This section addresses time and geographical coverage of the study, included components and processes as well as data sources, quality and representativeness. This LCA study refers to the infrastructure installed in the Norwegian transmission grid by the year 2009. The *Sentralnett* infrastructure includes overhead lines, underwater cables, underground cables, transformers and substations, which are included in the analysis. Interconnector cables, which make the connection between the Norwegian power grid and the power grids in the Netherlands and Denmark, are also included. The emissions resulting from half interconnector length are allocated to Norway. However, due to lack of LCI data for HVDC converter stations, these are not included. Direct emissions resulting from SF_6 leakages in Gas Insulated Substations (GISs) are included. It is assumed that during the lifetime of the components, the total power transmitted in a year is constant, and that the power losses in the grid and the electricity mixes are also constant with time. Power losses for the *Sentralnett* system as a whole in the year 2009 are included.

Regarding data sources, data on the total km of power lines and total number of transformers and substations installed at the Norwegian transmission grid was obtained through the Norwegian Water Resources and Energy Directorate, NVE [20]. Life cycle inventories (LCIs) for overhead lines, underground cables and sea cables are based on data compiled by Jorge et al. [23] and obtained from Energinet.dk. The data refers to the year 1999.

For overhead lines, the inventories draw on resource use reports for aluminum conductor steel reinforced (ACSR) lines, which are also the same type of lines used in the *Sentralnett*. Included processes are: production of materials for the different components of the lines (foundations, masts, conductors and insulators), installation, operation/maintenance and end-of-life treatment for each material type. The inventories include materials, fuels and transportation activities required for each stage. For land cables, processes included in the model are cable manufacturing, cable trace, installation, maintenance and end-of-life treatment. Materials, fuels and transportation activities required for each stage are included. For sea cables, included processes are the same as for land cables, with addition of the inputs required for the cable armoring. LCI data for transformers are based on technical reports for transformers and on environmental product declarations (EPDs) for different transformer sizes compiled by Jorge et al. [24] and obtained from ABB. Infrastructure processes modeled include production and transportation of raw materials, manufacturing, transportation of final product, operation/maintenance and end-of-life. LCI data for air insulated substations (AISs) and gas insulated substations (GISs) were obtained from Harrison et al. [27]. Production of materials and construction work are included. Assumptions were made for the end-of-life treatment (recycling, landfill, etc.) of each material type (copper, steel, porcelain, etc.) according to what is described in the inventories for lines and cables [23].

To model material production for the lines, cables, transformers and substations, average European production processes from Ecoinvent v2.2 were selected, whenever possible. Power losses are modeled for three power mixes, which are also part of the Ecoinvent database: Norwegian supply mix, Nordic mix and average European mix. The results obtained here hence reflect a European technological context. However, since detailed inventories for the different components are available [23,24], it is possible to generalize the method presented here to analyze other countries' electrical grids, provided that the assumptions for material production and power losses mixes are adjusted accordingly.

2.4. Transmission grid inventories

The next sections provide detailed data on the inventories for each component type on the transmission grid.

2.4.1. Overhead lines

Table 1
Total length (km) of lines and cables installed at *Sentralnett* for different voltage levels, by 2009. *Source*: NVE, 2011 [20].

Type	Voltage level (kV)			
	132(145)	220	300	420
Overhead	2892	197	5009	2873
Underground	7	0	43	2
Sea	22	0	31	21

Table 1 contains data on the total km of overhead lines installed at the Norwegian transmission grid, by voltage level. For voltages of 220 kV and above, the following information was also provided by NVE for each line: material of the conductor, conductor configuration, i.e., how many conductors per phase exist, and conductor cross section (mm^2 Cu eq.). Overhead lines installed at the *Sentralnett* are almost exclusively of the type ACSR, with one (simplex), two (duplex) or three (triplex) conductors per phase. In addition to the phase conductors, there are two smaller earth conductors per line [22]. Fig. A1 in the Appendix A shows the mast configurations for simplex, duplex and triplex 420 kV overhead lines in Norway [22]. The inventory for infrastructure related processes of the 132 (145) kV lines is based on the inventory for the 150 kV lines compiled in Jorge et al. [23]. For overhead lines at 220 and 300 kV, the processes for foundations, masts, insulators and transportation activities were adjusted from the LCI for 150 kV lines, but for the conductors, a more accurate estimate of their weight was possible to obtain by using the data for the cross section (mm^2 Cu eq.) available from NVE for each km of line installed. The cross sections (expressed in Cu eq.) were used to identify the aluminum and steel cross sections of the lines, using data provided by Sintef Energy AS [22]. With the average densities for aluminum (2734 kg/m^3) and steel (7905 kg/m^3) [39], it is then possible to calculate the total weight of these metals in the conductors. Table 2 shows the calculations for the 220 kV overhead lines. Since the systems are three-phase, the weight of aluminum and steel in one conductor is multiplied by 3 for the simplex lines, by 6 for the duplex lines and by 9 for the triplex lines, to get the total weight of these metals in the lines (see Fig. A1). In addition, there are two earth conductors for each line, which weight was added. Table A1 in the appendix contains similar calculations for the 300 kV lines. For the lines at 420 kV, the inventory for infrastructure processes is based on data for the 400 kV line [23]. However, since NVE provided the cross sections for each line installed at the *Sentralnett*, it was possible to do a more accurate estimate of the weight of aluminum and steel in the conductors, using the same method as for the 220 and 300 kV lines. These values are presented in Table A2, in the appendix.

2.4.2. Land cables

Total km of underground (land) cables for each voltage level installed in the Norwegian *Sentralnett* is provided in Table 1. The infrastructure related processes for the 132(145) kV cables are modeled based on a resource use report for a 132/150 kV oil-filled land cable [23]. For the 300 kV cables, the inventory was adjusted from the data for the 132/150 kV oil-filled cable. For the 420 kV cables inventory, the inventory for a 400 kV cable from Energinet.dk [40] was used.

2.4.3. Sea cables

Sea cables comprise cables installed in Norway and connections between Norway and abroad. The total km of sea cables installed in the Norwegian territory is given in Table 1. LCI data for sea cables at 132(145) kV installed in Norway are based on a resource use report for an oil sea cable at 132/150 kV compiled in [23]. For 300 and 400 kV, data has been adjusted from the inventory for the

Table 2
Weight of aluminum (Al) and steel (Fe) per km of ACSR overhead line at 220 kV, and total line length for each configuration type.

Type	Cross-section (mm^2 Cu eq.)	Al cross-section (mm^2)	Fe cross-section (mm^2)	Weight Al/km line (kg/km)	Weight Fe/km line (kg/km)	Total line length (km)
Simplex	329	525.5	68.1	4310.2	1615.0	75
Duplex	150	239.0	39.0	3920.6	1849.8	38
Duplex	430	705.6	89.4	11574.7	4237.9	84
Earth conductors		79.6	13.3	435.3	210.3	197
Total						197

Table 3
Total length of DC interconnectors between Norway and abroad (km) by 2009. Source: NVE, 2011 [20].

Cable	km	Voltage (kV)
Skagerrak 1	127.5	220
Skagerrak 2	127.5	220
Skagerrak 3	127.5	220
Norned	580	420

132/150 kV cable. Table 3 has data on the length of submarine inter-country connections. The Skagerrak cables make the connection between the Norwegian and the Danish power grid, while Norned is a connection between Norway and the Netherlands. The Skagerrak cables are mass-impregnated (MI) cables with a copper conductor and a lead metallic sheath type; the cross section is 800 mm^2 for cables 1 and 2 and 1400 mm^2 for cable 3 [41]. The Norned cable consists of 270 km of a two core MI cable (2×790 mm^2) and 300 km (2×150 km) of a single core MI cable (1×700 mm^2) [42]; Norned also uses copper as the conductor material. LCIs for the interconnectors are based on a resource use report for an HVDC oil-filled sea cable, compiled in [23]. According to the same data source, a mass cable contains approximately the same materials as an oil-filled cable with exception of the insulation oil, which was taken into account. The report refers to a cable with two 800 mm^2 copper conductors. The inventory was used to estimate the amount of copper in each of the cables modeled, using the density for copper (9014 kg/m^3) [39] and the cross-sections for each cable.

2.4.4. Transformers and substations

Table 4 contains data on the number of transformers installed at the Norwegian transmission grid, for different transformer load ratings and voltage levels of the grid. LCI data for a 9.6 MVA transformer compiled in [24] is used to model transformers in the range 5–12 MVA. LCI data for transformers at 16, 40, 63 and 250 MVA compiled in [24] is used for modeling transformers in the ranges 12–20 MVA, 20–50 MVA, 50–100 MVA and >100 MVA, respectively. Data on the substation equipment installed at the *Sentralnett*, both air insulated substations (AISs) and gas insulated substations (GISs), are presented on Table 5. Emissions of SF_6 from GIS equipment installed at the *Sentralnett* are included in the model. According to Statnett [43] its assets retained a total of 106,703 kg of SF_6 in 2009 and total emissions of the gas in the same year were of 405 kg. Since Statnett owns 90% of the *Sentralnett* [21], it is estimated that the total emissions of SF_6 for the network in 2009 were of 450 kg.

Table 4
Number of transformers installed at *Sentralnett* by 2009, for different voltage levels and transformer load ratings. Source: NVE, 2011 [20].

	Transformer load rating (MVA)					
kV	5–12	12–20	20–50	50–100	>100	Total
132	4	3	42	16	6	71
220					2	2
300			22	39	147	208
420					64	64
Total	4	3	64	55	219	345

Table 5
Number of AIS and GIS substations installed at *Sentralnett* by 2009. Source: NVE 2011 [20].

kV	AIS	GIS	Total
132	20	20	41
220	1	0	1
300	41	22	63
420	0	16	16
Total			121

2.4.5. Land use

The total km of lines installed at the *Sentralnett* in 2009 is 10,971. With an average right-of-way of 38 m [21], the estimated land occupation is 417 km^2. According to [44], approximately 38% of the land in Norway is forest and woodland, and 3.3% arable land. Estimated forest (158.5 km^2) and arable land use (14 km^2) are included.

2.4.6. Power losses

Power losses in the *Sentralnett* for the year 2009 were of 22,14,864 MW h [20].

Table 6
Life cycle environmental impacts for the transmission of 1 kW h in the *Sentralnett* Impact assessment method: ReCiPe 2008 Midpoint, for three perspectives: Equalitarian (*E*), Hierarchical (*H*) and Individualistic (*I*).

Impact category	Unit	Norwegian supply mix		
		E	*H*	*I*
Agric. land occupation	cm^2	17.15	17.15	17.15
Climate change	g CO_2 eq.	1.32	1.34	1.45
Fossil depletion	g oil eq.	0.35	0.35	0.35
Freshwater eutrophication	mg P eq.	0.37	0.37	0.37
Human toxicity	g 1,4DCBeq.	16.96	0.73	0.25
Marine eutrophication	mg N eq.	0.74	0.74	0.74
Metal depletion	g Fe eq.	0.76	0.76	0.76
Ozone depletion	µg CFC11 eq.	0.11	0.11	0.11
Part. matter formation	µg PM10 eq.	3.36	3.36	3.36
Pho. oxidant formation	mg NMVOC	3.81	3.81	3.81
Terrestrial acidification	mg SO_2-eq.	5.25	4.77	4.54
Water depletion	dm^3	11.19	11.19	11.19

Table 7
Sensitivity analysis – life cycle environmental impacts for transmission of 1 kW h in the *Sentralnett*, for different power loss mixes.

Impact category	Unit	Nordic supply mix			European mix		
		E	*H*	*I*	*E*	*H*	*I*
Agric. land occupation	cm^2	20.09	20.09	20.09	18.29	18.29	18.29
Climate change	g CO_2 eq.	3.91	4.11	4.65	10.57	10.90	11.77
Fossil depletion	g oil eq.	1.07	1.07	1.07	3.17	3.17	3.17
Freshwater eutrophication	mg P eq.	53.34	52.98	52.98	8.88	8.88	8.88
Human toxicity	g 1,4DCBeq.	41.63	1.52	0.58	247.54	6.25	0.45
Marine eutrophication	mg N eq.	1.85	1.85	1.85	10.81	10.81	10.81
Metal depletion	g Fe eq.	0.78	0.78	0.78	0.78	0.78	0.78
Ozone depletion	μg CFC11 eq.	0.31	0.31	0.31	0.54	0.54	0.54
Part. matter formation	mg PM10 eq.	7.33	7.33	7.33	0.02	0.02	0.02
Pho. oxidant formation	mg NMVOC	9.45	9.45	9.45	23.55	23.55	23.55
Terrestrial acidification	mg SO_2-eq.	12.84	11.62	11.03	46.41	43.51	42.12
Water depletion	dm^3	51.64	51.64	51.64	81.40	81.40	81.40

3. Results and discussion

Life cycle environmental impacts for the transmission of electricity in the *Sentralnett* are summarized in Table 6. The results are obtained with the ReCiPe 2008 Midpoint-oriented method, for three perspectives: egalitarian (*E*), hierarchical (*H*) and individualistic (*I*). The results show that the transmission of 1 kW h in the *Sentralnett* contributes between 1.3 and 1.5 g CO_2 eq. to climate change impacts. Table 7 shows the results for a sensitivity analysis of the results regarding the power mix used to model losses in the network. For the Nordic power mix, climate change impacts range between 3.9 and 4.7 g CO_2 eq./kW h of electricity transmitted. Using the average European power mix for modeling losses, total climate change impacts are of 10.6–11.8 g CO_2 eq./kW h transmitted. This result is within the range of a previous LCA study of transmission for the UK [27]. An increase of the climate change score with the power mix emissions intensities is expected since power losses – demand for extra power production – represent a large share of the total impact. Impacts for all categories are always higher for the European mix and lower for the Norwegian mix, an exception being the category of agricultural land occupation, for which the results are higher with the Nordic mix. Climate change scores are higher for the individualistic approach and lower for the equalitarian. This is because for the midpoint level, climate change time-frames for the individualistic, hierarchical and egalitarian perspectives are of respectively 20, 100 and 500 years and the characterization factors for methane and nitrous oxide are both higher, the shorter the time-frame used. The opposite is true for sulfur hexafluoride, which also contributes to climate change, but as will later be shown, these emissions only represent around 7% of the total scores for transmission in this impact category. For the category of human toxicity, the results are significantly higher for the egalitarian perspective. This is expected since more chemicals are considered toxic in this perspective. For agricultural land occupation, fossil fuel depletion, freshwater eutrophication, marine eutrophication, metal depletion, ozone depletion, particulate matter formation, photochemical oxidant formation and water depletion, the results do not change across different perspectives. This is because there are currently no differences in the characterization factors derived for the three perspectives for these impact categories.

The life cycle environmental impacts from a transmission system are a result of the construction, operation and dismantling of the network infrastructure, and of power losses in the system – which represent extra demand for power generation. Fig. 1 shows the contribution of the different life cycle stages to the global warming potential (GWP 100) score for the *Sentralnett*. The results refer to the hierarchical perspective. The production of raw materials is the process contributing the most to GWP 100, but around half of this contribution is offset by gains from recycling at the end-of-life. The end-of-life scenarios for lines and cables are described in detail in [23] and for transformers and substations in [24]; the scenarios also include processes with positive contribution to GWP, such as landfill, incineration e.g. for transformer oil, and transportation activities associated with dismantling of the components. However, the total balance for the end-of-life is negative since the benefits of recycling outweigh the impacts generated by the other processes. According to Fig. 1, maintenance and operations for the overall grid system represent 0.11 g CO_2 eq./kW h transmitted in the *Sentralnett*. From these, 92% result from SF_6 losses in GIS equipment. Harrison et al. [27] have also concluded that for the transmission grid, losses of SF_6 are the key component for climate change scores related to maintenance and operations. Manufacturing of the components and activities related to assembly and installation represent the smallest share to GWP 100. The balance for GWP 100 for the different life cycle stages, including the gains at the end-of-life, shows that power losses in the *Sentralnett* make up half of the total scores. The percentage contribution of power losses to the total environmental scores for climate change and other impact categories is presented in Table 8. The results are obtained using the ReCiPe 2008 Midpoint-oriented method, with the hierarchical perspective. Table 8 also contains a sensitivity analysis of the results using other power mixes to model losses in the system. The results confirm that when changing to

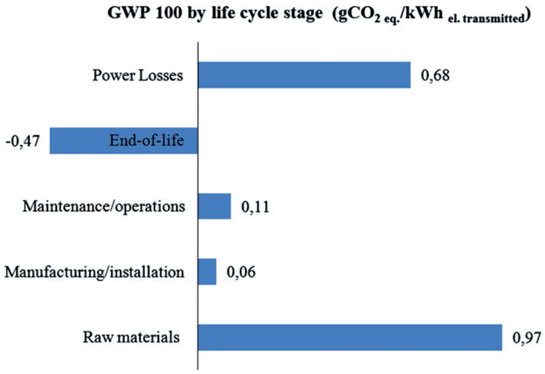


Fig. 1. Breakdown of GWP 100 for the *Sentralnett* by life cycle stage.

Table 8
Percentage contribution of power losses for the total life cycle impacts, for different power loss mixes. Impact assessment method: ReCiPe 2008 Midpoint, *H* perspective.

Impact category	Norwegian supply mix (%)	Nordic supply mix (%)	European prod. mix (%)
Agric. land occupation	3.4	17.5	9.4
Climate change	50.6	83.9	93.9
Fossil depletion	53.3	84.7	94.8
Freshwater eutrop.	42.6	73.7	97.6
Human toxicity	28.7	65.5	91.6
Marine eutrophication	45.0	77.9	96.2
Metal depletion	4.8	7.4	8.1
Ozone depletion	50.9	83.2	90.4
Particulate mat. format	34.6	70.0	85.6
Photochemical ox. form	42.1	76.6	90.6
Terrestrial acidification	39.1	75.0	93.3
Water depletion	79.0	95.5	97.1

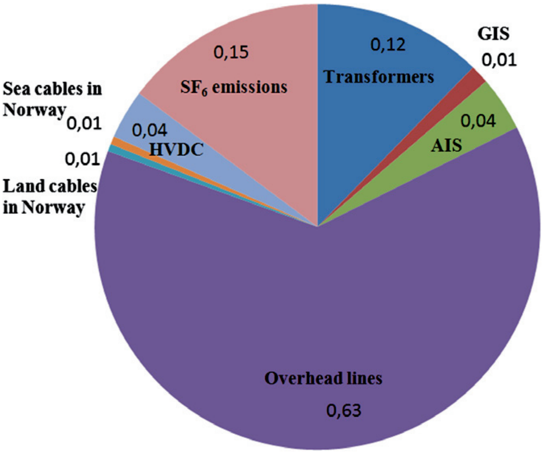


Fig. 2. Breakdown of infrastructure related scores (excluding power losses) for climate change. GIS: gas insulated substations; AIS: air insulated substations; HVDC: High-voltage DC cables between Norway and abroad.

power mixes that are more emissions intensive, the contribution of power losses for climate change and other impact categories is higher. For the Nordic electricity mix, losses represent 84% of the total climate change impacts, while for the European mix the contribution is of 94%. The calculations done here refer to the *Sentralnett* system i.e. it is assumed that the percentage power losses are 2.1% per kW h transmitted. The efficiency of the transmission system for different countries can vary substantially. For Norway, the sum of losses for transmission and distribution in 2009 was of 7% of the total power output, while, e.g. in India total T&D losses for the same year were above 20% [45]. For all power mix cases, losses represent a modest part of impacts for the category of metal depletion. This is because the production of metals (mainly copper, steel and aluminum) contributes the most for the results in this category.

Another interesting result is the contribution of each component type – transformers, power lines, cables, etc., to the total system environmental scores. Fig. 2 shows the relative contribution of each component type to the total climate change score related to infrastructure (excluding losses). Overhead lines, totaling 10,971 km, represent 63% of the total impact. The second largest contributor is the emission of SF_6 in the GIS substations, with a share of 15% (while the infrastructure of the GIS substations themselves represents only 1%). Transformers come third, representing 12% of the climate change score related to infrastructure, or 6% of the total (infrastructure + losses) climate change score. Using the assumption described in 2.2 of allocating half of the emissions from the interconnectors (HVDC cables from Norway to Denmark and the Netherlands) to Norway, they represent around 4% of climate change scores for infrastructure. The AIS substations represent around 4% of the total climate change score. The 74 km of sea cables and the 52 km of land cables installed in Norwegian territory are each responsible for 1% of the total climate change impact for infrastructure.

Overall, the results obtained here compare well with previous LCA studies for electricity networks [27,46]. The Ecoinvent database provides the value of 2.3 gCO_2 eq. per kW h transmitted in Norway, which is higher than obtained here, but there are also differences in the inventories and assumptions used here and by Ecoinvent. For example, in Ecoinvent SF_6 losses are assumed to be of 1% per year of the stock in the Nordic countries [47], which would correspond to approximately 2000 kg being emitted by the *Sentralnett* annually, a value considerably higher than our estimate of 450 kg emitted annually.

Finally, some limitations and sources of uncertainty for this study shall be highlighted. First, the method used is process-based life cycle assessment, which requires the delineation of a finite system boundary, and therefore suffers from truncations errors [48]. Also, the inventories for lines and cables were obtained from the Danish company Energinet.dk. Although the inventories for lines in Norway are expected to be quite similar for raw materials used in construction and maintenance and for end-of-life options for each material type, the line/cable installation in Norway or in Denmark (or within different regions in Norway) might require different inputs. Also, for modeling sea cables, according to the data sources used it is assumed that the metals are recycled at the end-of-life, but as per today it is not uncommon that cables are left at the seabed when no longer in use. Making different assumptions for recycling would affect the results.

4. Conclusions

This paper makes a contribution for understanding the life cycle environmental impacts caused by systems for power transmission and distribution. All the electricity that is generated either by conventional or renewable power needs to be transported from the power plants over to the end-costumers, and this process contributes to the overall power sector emissions. Renewable power production is often located far from consumption centers, and if clean power technologies are to be adapted on a large-scale basis, this will require the construction of longer networks, and networks with increased capacities [16,49]. This study found that the currently installed transmission grid in Norway has an environmental impact of 1.3–1.5 g CO_2 eq./per kW h of electricity transmitted. The balance between how much the infrastructure and the power losses in the network contribute to the total impacts depends on the electricity mix flowing in the network: for the *Sentralnett*, power losses and infrastructure contribute equally to the impacts. If one considers that the average European electricity mix is flowing in the network, then power losses represent as much as 94% of the total impacts. A suggestion for future work is to look at what the impacts would be if more kilometers are added to the Norwegian grid in order to concretize the grid expansion plans of connecting Norway with other countries. There is a trade-off between the gains in loss reductions in the network and the increase of impacts from the extra infrastructure required, which would be interesting to investigate.

Acknowledgements

The authors would like to thank Astri Gillund, Vegard Willumsen and Ole-Petter Kordahl from the Norwegian Water Resources and Energy Directorate (NVE) for providing data on the *Sentralnett*. We would like to thank Thomas Worzyk from ABB, for providing references on the submarine cables. Finally, thanks to PhD student Guillaume Majeau-Bettez, who provided guidance in the use of ARDA, an LCA software tool developed at the Industrial Ecology Programme at NTNU.

Appendix A. Appendix

See Fig. A1 and Tables A1 and A2.

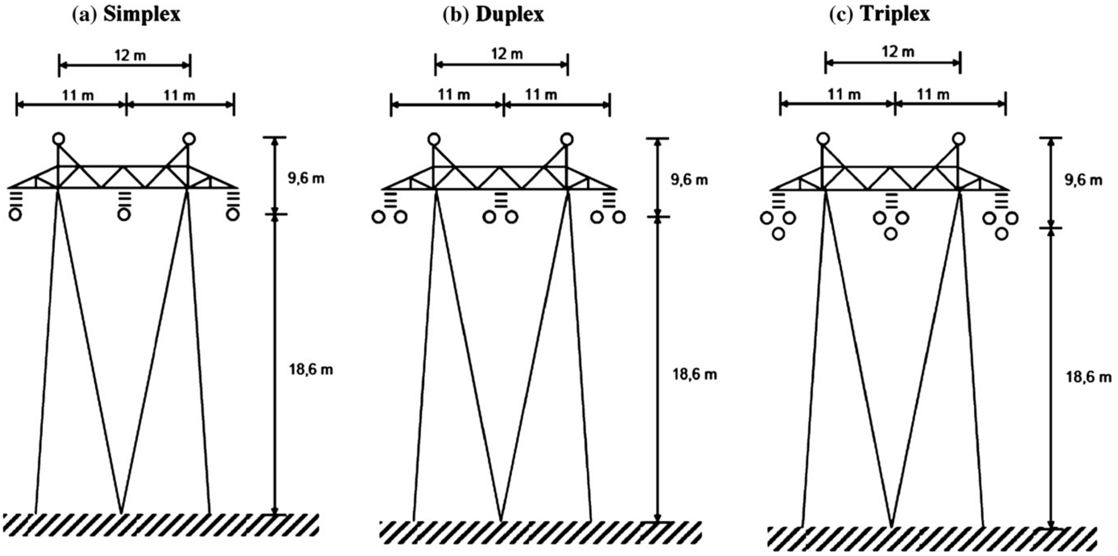


Fig. A1. Mast configurations for 420 kV simplex, duplex and triplex overhead lines installed in Norway [1].

Table A1
Weight of aluminium (Al) and steel (Fe) per km of overhead line at 300 kV and total line length for each configuration type.

Type	Cross-section (mm^2 Cu eq.)	Al cross-section (mm^2)	Fe cross-section (mm^2)	Weight Al/ km line (kg/km)	Weight Fe/km line (kg/km)	Total line length (km)
Simplex	253	402.3	52.2	3299.7	1237.9	0.1
Simplex	329	525.5	68.1	4310.2	1615.0	207.2
Simplex	380	606	77	4970.4	1826.1	65.9
Simplex	405	645.1	82	5291.1	1944.6	386.3
Simplex	456	705.5	89.5	5786.5	2122.5	252.3
Simplex	474	767	–	6290.9	–	87.8
Simplex	480	766.1	97	6283.6	2300.4	140.6
Simplex	481	766.1	97	6283.6	2300.4	2334.2
Simplex	552	850	150	6971.7	3557.3	25.2
Simplex	770	1223	307	10031.0	7280.5	23.9
Simplex	1022	1623	216	13311.8	5122.4	23.5
Duplex	300	476.4	77.7	7814.9	3685.3	10.6
Duplex	329	525.5	68.1	8620.3	3230.0	359.9
Duplex	380	606	77	9940.8	3652.1	951
Duplex	405	645	82	10580.6	3889.3	15.0
Duplex	481	766	97	12565.5	4600.7	80.5
Duplex	683	766	97	12565.5	4600.7	6.2
Duplex (4*2)	329	525	68	34448.4	3225.2	22.0
Triplex	380	606	77	14911.2	5478.2	16.8
Earth conductors		79.6	13.3	435.3	210.3	5008.9
Total						5008.9

Table A2
Weight of aluminium (Al) and steel (Fe) per km of overhead line at 420 kV and total line length for each configuration type.

Type	Cross-section (mm^2 Cu eq.)	Al cross-section (mm^2)	Fe cross-section (mm^2)	Weight Al/ km line (kg/km)	Weight Fe/km line (kg/km)	Total line length (km)
Simplex	456	705.6	89.5	5786.5	2122.5	32.9
Simplex	770	1223	307	10031.0	7280.5	19.0
Simplex	1022	1623	216	13311.8	5122.4	21.0
Duplex	329	525.5	68.1	8620.3	3230.0	164.2
Duplex	380	606	77	9940.8	3652.1	890.8
Duplex	405	645	82	10580.6	3889.3	310.3
Duplex	440	705.5				84.7
Duplex	481	766	97	12565.5	4600.7	883.4
Triplex	329	525.5				108.4
Triplex	330	525.5				28.1
Triplex	380	606	77	14911.2	5478.2	329.8
Earth conductors		79.6	13.3	429.8	209.3	2872.6
Total						2872.6

References

[1] Weisser D. A guide to life cycle greenhouse gas (GHG) emissions from electric supply technologies. Energy 2007;32(9):1543–59.
[2] Ou X, Xiaoyu Y, Zhang X. Life-cycle energy consumption and greenhouse gas emissions for electricity generation and supply in China. Appl Energy 2011;88(1):289–97.
[3] Lenzen M. Life cycle energy and greenhouse gas emissions of nuclear energy: a review. Energy Convers Manage 2008;49(8):2178–99.
[4] Lenzen M, Munksgaard J. Energy and CO_2 life cycle analyses of wind turbines – review and applications. Renew Energy 2002;26(3):339–62.
[5] Góralczyk M. Life-cycle assessment in the renewable energy sector. Appl Energy 2003;75(3–4):205–11.
[6] Ardente F, Beccali G, et al. Life cycle assessment of a solar thermal collector. Renew Energy 2005;30(7):1031–54.
[7] Coltro L, Garcia E, et al. Life cycle inventory for electric energy systems in Brazil. Int J Life Cycle Assess 2003;8(5):290–6.
[8] Pehnt M. Dynamic life cycle assessment (LCA) of renewable energy technologies. Renewable 2006;31(1):55–71.
[9] Varun, Bhat K, Ravi P. LCA of renewable energy for electricity generation systems-a review. Renew Sust Energy Rev 2009;13(5):1067–73.
[10] Lerche R, Luc G, Saur M, et al. Life cycle greenhouse gas (GHG) emissions from the generation of wind and hydro power. Renew Sust Energy Rev 2001;15(7):3417–22.
[11] Rene K, van der Voet E, Gert Jan K, et al. Metal requirements of low-carbon power generation. Energy 2001;36(9):5640–8.
[12] Singh B. Environmental evaluation of carbon capture and storage technology and large scale deployment scenarios. PhD thesis NTNU; 2011.
[13] Wiedmann T, Suh S, Feng K, Lenzen M, Acquaye A, Scott K, et al. Applications of hybrid life cycle approaches to emerging energy technologies – the case of wind power in the UK. Environ Sci Technol 2011;45(13):5900–7.
[14] Denny E, Tuohy A, Meibom P, Keane A, Flynn D, Mullane A, et al. The impact of increased interconnection on electricity systems with large penetrations of wind generation: a case study of Ireland and Great Britain. Energy Policy 2010;38(11):6946–54.
[15] Kempton W, Tomic J. Vehicle-to-grid power implementation: from stabilizing the grid to supporting large-scale renewable energy. J Power Sources 2005;144(1):280–94.
[16] Sims R, Mercado P, Krewitt W, Bhuyan G, Flynn D, Holttinen H, et al. Integration of renewable energy into present and future energy systems. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Seyboth K, Matschoss P, Kadner S, et al. editors. IPCC Special report on renewable energy sources and climate change mitigation, Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2001.
[17] Macilwain C. Supergrid. Nature 2010;624(468).
[18] Zhu F, Zheng Y, Guo X, Wang S. Environmental impacts and benefits of regional power grid interconnections in China. Energy Policy 2005;33:1797–805.
[19] The green grid – energy savings and carbon emissions reductions enabled by a smart grid. Electr Pow Res I, CA: Palo Alto; 2008. p.1016905.
[20] Norges vassdrags- og energidirektorat (NVE). Personal, communication; 2011.
[21] Statnett. <http://www.statnett.no/> [accessed January 2012].
[22] SINTEF Energi AS. Planlegginsbok for kraftnett, teknisk data; 2010.
[23] Jorge R, Hawkins T, Hertwich E. Life cycle assessment of electricity transmission and distribution – Part 1: Power lines and cables. Int J Life Cycle Assess 2011;17(1):9–15.
[24] Jorge R, Hawkins T, Hertwich E. Life cycle assessment of electricity transmission and distribution – Part 2: Transformers and substation equipment. Int J Life Cycle Assess 2011;17(2):184–91.
[25] Jones C, McManus M. Life-cycle assessment of 11 kV electrical overhead lines and underground cables. J Cleaner Prod 2010;18(14):1464–77.
[26] Bumby S, Druzhinina E, Feraldi R, Werthmann D, Geyer R, Sahl J. Life cycle assessment of overhead and underground primary power distribution. Environ Sci Technol 2009;44:5587–93.
[27] Harrison G, Maclean E, Kalamanlis S, Ochoa L. Life cycle assessment of the transmission network in Great Britain. Energy Policy 2010;38(7):3622–31.
[28] Cigré. Life Cycle Assessment (LCA) for Overhead Lines. Paris: International Council on Large Electric Systems (Cigré); 2004.
[29] Cigré. Electrical power supply using SF_6 technology. Paris: International Council on Large Electric Systems (Cigré); 2004.
[30] Cigré. Life cycle assessment on high voltage power cables. Paris: International Council on Large Electric Systems (Cigré); 1996.
[31] Energistatus 2010. Oslo: NVE, December 2010.
[32] Midttun A, Ruohonen T. Norway and the north sea grid – key positions and players, from a Norwegian perspective. Smart energy for europe platform; 2012.
[33] Trötscher T, Korpås M. A framework to determine optimal offshore grid structures for wind power integration and power exchange. Wind Energy 2011;14(8):977–92.
[34] Teknologi, økonomi og andre forhold knyttet til en sjøkabelløsning, Rapport fra sjøkabelutredning, Utvalg I, Febuary. 2011. <http://www.regjeringen.no/pages/15604222/Utvalg_I.pdf>.
[35] ISO. ISO 14040:2006 Environmental management-life cycle assessment-principles and framework. Geneva: International Organization for Standardization; 2006.
[36] ISO. ISO 14044:2006 Environmental management – life cycle assessment – requirements and guidelines. Geneva: International Organization for Standardization; 2006.
[37] Goedkoop MJ, Heijungs R, Huijbregts M, De Schryver A, Struijs J, Van Zelm R, ReCiPe 2008, A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. 1st ed. Report I: Characterization, 6 January 2009.
[38] Industrial Ecology Programme. Trondheim (Norway): NTNU.
[39] Perry's chemical engineer's handbook. 8th ed. McGraw-Hill; 2008.
[40] Eltra. LCA analyse av 400 kV Pex kabelanlæg, landbaseret; 1999.
[41] Gilbertson O. Electrical cables for power and signal transmission. John Wiley & Sons; 2000.
[42] Skog J, Asten H, Worzyk T, Andersrød T. NorNed – world's longest power cable, B1_106_201. Cigre; 2010.
[43] Statnett. Årsrapport 2010. 20:10 Vi binder Norge sammen. <http://www.statnett.no/Documents/Om_Statnett/Finans/%C3%85rsrapporter/Statnett%20%C3%85rsrapport%202010%20NORSK%20-%20ENDELIG%20OG%20OFFENTLIGGORT%2020110406.pdf> [accessed Jan 2012].
[44] Moen A. Nasjonalatlas for Norge: Vegetasjon; 1998.
[45] ABB Energy efficiency performance in power generation <http://www.abb.com/product/ap/db0003db004052/df6806e02bb3959ec1257863004202f6.aspx> [accessed January 2012].
[46] Ecoinvent Centre. Ecoinvent data v2.2. Switzerland: Swiss Centre for Life Cycle Inventories; 2007.
[47] Ecoinvent Centre. Life cycle inventories of energy systems: results for current systems in Switzerland and other UCTE countries. Data v2.0. Ecoinvent report no. 5. Switzerland: Ecoinvent Centre; 2007.
[48] Lenzen M, Wachsmann U. Wind turbines in Brazil and Germany: an example of geographical variability in life-cycle assessment. Appl Energy 2004;77(2):119–30.
[49] Arvesen A, Hertwich E. Environmental implications of large scale adoption of wind power: a scenario based life cycle assessment. Environ Res Lett 2001;6(4).

Appendix 4.

Paper 4:

Jorge, R., Hertwich, E. "Grid infrastructure for renewable power in Europe: the environmental cost." (under review in Energy).

Grid infrastructure for renewable power in Europe: the environmental cost

Raquel S. Jorge[a*], *Edgar G. Hertwich*[b]

[a, b] Industrial Ecology Programme, Department of Energy and Process Engineering, Norwegian University of Science and Technology (NTNU), 7491, Trondheim, Norway.

[*] Corresponding author contacts: e-mail: raquel.santos.jorge@enova.no; phone number: 0047 73190430.

Abstract

Climate mitigation policies in Europe call for an extensive build-up of renewable power, which will increase from 320 GW in 2012 to 536 GW by 2020. The renewable expansion will mainly consist of the installation of new wind and solar power plants, which require additional transmission lines. The European Network of Transmission System Operators for Electricity estimates that 45,300 km of new or upgraded lines are necessary in the region over the next decade to accommodate the renewable power sources. Building a grid for renewables will help Europe achieve its climate goals, but other resulting environmental impacts have not yet been quantified. In this article a Life Cycle Assessment for the transmission grid expansion is performed. The results show that the grid extension projects correspond to a total impact of 10.7 MtonCO_2 eq. and 11.2 Mton Fe eq. Electricity transmission in Europe in 2020 will be more material intensive, requiring about 10% more metal inputs per kWh than today. Manufacturing processes for the production of transmission equipment are important for some impacts categories, particularly water depletion. Finally, a sensitivity analysis regarding recycling rates indicates that the results in some impact categories present great variation depending on the rates assumed.

Keywords: life cycle assessment, EU 20-20-20 targets, renewable power, European transmission grid, ENTSO-E.

1. INTRODUCTION

With planned investments in the order of €100 billion, the European power transmission grid is about to be extensively developed and refurbished over the coming decade mainly due to the integration of a higher percentage of intermittent renewable power. According to the European Network for Transmission System Operators for Electricity (ENTSO-E)[1] a total of 52,300 km of new or refurbished Extra High voltage routes are envisioned for the region until 2022 [1]. For comparison, the current European transmission grid has a length of about 312,000 km [2], see Table A.1. According to ENTSO-E, the number one driver for this expansion is the integration of renewable energy sources (RES), which alone is said to create a demand for 45,300 km of new or refurbished electrical transmission lines in the region. Other drivers for grid development include security of supply and internal market integration. In this article the authors are concerned about understanding the role RES integration in the overall electric grid developments planned for Europe, and its subsequent environmental impacts. The goal is to understand the life-cycle environmental impacts which will arise from the transmission grid expansion in Europe.

The analysis in this article is based on the Ten Year Network Development Plan 2012 (TYNDP 2012) [1] in which ENTSO-E provides a thorough overview of future major investment needs for the European transmission grid. A summary of the grid extension projects evaluated in this study is provided in the Appendix (Tables A.2-A.9). The tables summarize data on planned lines, cables, transformers and substations by voltage level. For geographical details about the location of the grid projects, consult the maps provided at [1]. The transmission grid investments presented in the TYNDP 2012 are derived from the expected development in the generation profile, load and demand in the region for the coming years [3]. Three scenarios are put forward, but the reference scenario is the EU 2020 scenario, which derives from the National Renewable Action Plans, in compliance with the European 20-20-20 targets. The expected evolution in generation and consumption according to this scenario is summarized in Table 1. According to ENTSO-E, Europe is currently facing a "renewable energy boom". From 2012 to 2020, it is expected that RES, mainly solar and wind power, will increase from 320 GW to 536 GW, making this the most noticeable change in the overall generating capacity in the region [1]. Of the total 250 GW net generating increase in capacity forecasted for Europe up to 2020, RES corresponds to a share of 216 GW. This extensive development of renewable energy is in turn the main driver

---

[1] **ENTSO-E member states by 2012 include all European countries except Russia, Belarus, Moldavia, Albania and Ukraine.**

for larger and more volatile power flows across larger distances in Europe, which will require the transmission grid to adapt.

The European transmission system installed today is mainly based on HVAC assets at 220/275/300/330 kV and 380/400 kV. Table A.1 in the Appendix provides an inventory of the transmission equipment installed in Europe by 2011, with circuit length by voltage level and country. Overhead lines sum up to about 301,000 km, in addition to approximately 10,900 km of land/sea cables from which 5,300 km use direct current (DC) technology. DC is used for long submarine connections or for linking asynchronous systems. The integration of RES creates a demand for additional transmission infrastructure. In total 25,800 km of overhead lines (OHLs), 8,277 km of subsea cables and 3,227 km of land cables are planned up to 2020. In addition, more than 160 substations will be built, and some existing substations will require new transformers. Some already existing transmission equipment, corresponding to a length of 8,000 km will also have to be renovated, according to ENTSO-E. The planned infrastructure is described in more detail in 2.3.4. Figure 1 shows the total length of transmission circuits by type before and after the expected RES related extensions. As indicated in Table 1, the European transmission grid length will increase by 12% up to 2020, while the electricity delivered increases by 6%. As expected, for a system with a higher share of renewables, more grid length is required per kWh delivered. This brings us to the question: are renewable energy systems more material intensive per kWh than fossil based ones? How will a transition from fossil to renewable sources contribute to the overall sustainability of the power sector?

Building an extensive grid for renewable power integration in Europe will contribute to CO_2 savings in the region, but will also result in a number of other environmental pressures which have not yet been quantified. In this article the authors aim to understand the environmental costs of RES integration by analyzing the life cycle consequences of the grid build-up in Europe. The article provides a life cycle inventory (LCI) of the main materials, fuels and other requirements for the transmission grid upgrade. The analysis will also characterize how the different electrical components and life cycle processes contribute to the overall impacts. Previous studies have addressed environmental aspects from up-scaling of low-carbon power systems: [4], [5], [6], [7], [8], [9], [10]. The available literature shows that the transition to low-carbon technologies such as renewable generation and carbon capture and storage (CCS) is not free of concerns, even though these technologies are effective at mitigating damage due to climate change. The central identified issues with the up-scaling of low-carbon power systems have been resource constraints in form of materials and water, and also potential trade-offs between different types of environmental impacts. Most studies, however, have focused on power generation and have not addressed the effects of the necessary extensions in the power grid. Power grid extensions in form of new or refurbished assets are a requirement if the current fossil fuel based generation system is to be replaced by a system based on RES. The present study provides a contribution to the literature by focusing on the transmission aspects, which are a part of the whole system of power supply. As recommended by Sathre and colleagues [8], LCAs for assisting decision making should aim at describing system-wide environmental impacts resulting from technology up-scaling, rather than narrowing down the analysis to the performance of individual technologies. Transmission grid upgrading is required for about 125 GW or about half of the expected capacity increase in Europe, and should hence be included in any system-wide study of renewable energy deployment.

2. METHOD AND DATA

2.1. Method

The method used is Life Cycle Assessment (LCA), which is a tool for assessment of a broad range of environmental impacts resulting from product systems throughout their life cycle. By including several impact categories and by looking at life cycle impacts rather than just direct impacts, LCA provides a holistic approach for environmental evaluations. The LCA method is standardized by the International Organization for Standardization in ISO 14040 [11] and 14044 [12]. The inventory results in this study are assessed using the ReCiPe 2008 midpoint-oriented impact assessment method, Hierarchist version [13]. Results are generated with the LCA software tool ARDA which was developed by researchers at the Norwegian University of Science and Technology. Background processes are modeled according to unit processes found in Ecoinvent v2.2 [14].

2.2. Goal

The goal of this study is to characterize the life cycle environmental consequences of upgrading the current European power grid as required for the integration of intermittent renewable power.

2.3. Scope

2.3.1. Product system and functional unit

The scope is the product system consisting of overhead lines, land/subsea cables and substation equipment, which is also the functional unit for this study. The equipment included is summarized in Tables A.2-A.9 in the Appendix. All transmission grid extension projects modeled in this article are described in the TYNDP 2012 [1].

This study covers projects aiming at facilitating RES integration. Of the 506 specific investment plans listed in the TYNDP 2012 [1], 427 projects are identified to contribute to RES integration. The remaining 79 investment plans target exclusively market integration and/or security of supply. These projects are outside the scope for this study. It is assumed that all equipment types have a lifetime of 40 years [15], [16].

2.3.2. System boundary

An electrical transmission system reaches from the power plants to the distribution system that further transmits the power at lower voltage levels suited for the end-consumers (industry, service and public buildings and households). The system modeled here includes the components that are most relevant in a transmission grid: power lines, cables, substations, switchgear and transformers. Some specific electrical equipment for which there is no LCA data available such as converter stations, series compensators or reactive power devices, are not included. For substations, new substation build-up is included but not substation extensions as there is no information in the TYNDP 2012 about the degree of renovation and required operations.

Electrical transmission causes negative impacts on the environment due to resource use in terms of materials, energy, etc. that are required for construction, maintenance and end-of-life, and due to the emission of different metals/pollutants associated with the different components. Figure 2 shows the generic life cycle stages of an electrical grid project. The production phase consists in the production of raw materials, manufacturing of the components, i.e., processing of raw materials/assembling of components, transport and activities related to installation, e.g., excavation for installing land cables. The above mentioned processes are included in this study. During the use phase, impacts are caused by different processes: maintenance and inspection, land use, electrical power losses in the equipment, SF_6 losses in gas insulated substations (GIS), zinc emissions from galvanized masts, ozone and N_2O emissions from high voltage conductors and electromagnetic (EM) radiation in the proximity of the OHLs. This study includes maintenance/inspection, land use, SF_6 losses and zinc emissions. Power losses are not included since data is not available. EM radiation is also not included due to the lack of impact assessment methods to model it in LCA [16]. EM radiation from power lines falls in the category of non-ionizing radiation from which suitable impact assessment methods are yet not developed. Ozone and N_2O emissions are not included but they are expected to represent only a small share of total impacts for a transmission system [16].

2.3.3. Land use

Land use for new and renovated transmission equipment is estimated with base on the land use values reported by the Ecoinvent report on electricity grids [16]. The values in Ecoinvent refer to the land use for the Swiss high voltage grid. Land transformation processes are not included.

2.3.4. Data

Table A.2 in the Appendix summarizes data on new HVAC and HVDC OHL grid projects by voltage level and type of line. An HVAC OHL is of type simplex when it has one conductor by phase and of duplex type when it has two conductors per phase. When no information was provided in the TYNDP 2012 [1] regarding the type of OHL that is planned to be built, it was assumed that the OHL is duplex. The TYNDP 2012[1] has data on the total km and circuit voltage level for most projects. In cases for which total length or circuit voltage was not available, the authors used specific information obtained from project websites or other internet resources containing information about the project, for example: application for project concession, environmental assessments of the projects, etc. When no details were found about circuit length either in the TYNDP 2012 [1] or through other resources, this was estimated by using the online tool DistanceFromTo, a distance calculator tool by Google Maps [17]. The distance was estimated by using the names of the two end-substations and it corresponds to bird-fly distance, i.e., the shortest distance between two places. Overall, the total estimated circuit length for new OHLs, cables (land and sea) and line upgrading projects was measured at 45,293 km. The TYNDP 2012 [1] indicates that the total length for projects facilitating RES integration is of 45,300 km, so there is a good match between the estimates and the length indicated by ENTSO-E. In order for the life cycle assessment to represent the data from the TYNDP 2012 [1] as accurately as possible, the remaining 7 km were modeled as an OHL at 400 kV, which is the OHL category with most km of circuit. Table A.2 shows that around 3/4 of the planned OHLs correspond to lines at 400 kV, and approximately 2/3 of these are duplex circuits. These projects are quite spread out between the different geographical regions covered in the TYNDP 2012 [1], but central Europe and the Iberian Peninsula are the regions with the largest investments.

To model the life cycle processes for HVAC OHLs, inventories for the construction of the different parts, i.e., foundations, masts, conductors and insulators as well as installation, operation/maintenance and end-of-life are based on life cycle inventories for T&D systems previously compiled in a previous study [15]. The inventories for lines at 200 and 330 kV were scaled from an inventory for an OHL at 150 kV. For duplex lines it was taken into account that the conductor weight is double that of simplex lines since they have two conductors per phase. The OHLs at 380 and 400 kV were modeled by using the life cycle inventory for a duplex OHL at 400 kV [15].

An estimation of the energy required for manufacturing the OHLS was obtained using the data from [18]. According to this source, the process of manufacturing the masts for overhead lines is modeled by using hot rolled steel as input. Here the Ecoinvent unit process 'hot rolling steel' [14] was used to estimate the required energy for working the steel. The authors in [18] also refer that a fair amount of energy goes to galvanizing the OHLs masts. Galvanization is a process by which a zinc coating is applied to the masts, in order to avoid corrosion. The energy inputs are of 1480 MJ of natural gas per ton zinc utilized [18]. Manufacturing of conductor strands is another process requiring energy inputs: for an aluminum conductor steel reinforced (ACSR) conductor, per kg aluminum, 7.6 MJ of electricity and 0.37 MJ of natural gas are used [18]. The amount of natural gas to galvanize the steel strands in the conductor is 0.14 MJ/kg of steel [18]. The same ratios were applied here. For HVDC OHLs, the inventories are based on life data from [15]. The energy required in manufacturing is estimated as described for the HVAC OHLs.

Data relative to additions of new land and sea cables, both AC and DC, is presented in Tables A.3 and A.4, respectively. In total, more than 8,000 km of sea cables and 3,000 km of land cables are planned to facilitate RES integration in Europe. Relevant projects concerning the construction of subsea links include the NORD.LINK project connecting Norway to Germany, a 1,000 MW bipolar installation connecting Western Norway and Great Britain, a similar interconnector between Italy and Montenegro, a cable connecting the Baltic region and Sweden, several projects to connect wind farms in the UK and Germany, and reinforcements of the Norway-Denmark and Denmark-Germany connections. France will also reinforce its connection to neighboring countries through the construction of sea cables to Spain, UK and Ireland [1]. As expected, the vast majority of subsea projects correspond to HVDC links, with only 2% corresponding to 155 kV AC links. Previous references indicate that the break-even distance for HVDC subsea cables in Europe is 30-40 km. Above that distance it becomes cheaper to build a subsea cable using DC rather than AC technology [19]. For comparison, the same break-even distance in Europe for OHLs is of approximately 400 km.

Included life cycle processes for HVAC and HVDC land cables are: materials for cable and cable trace, manufacturing, installation, maintenance and end-of-life treatment. For all processes excluding manufacturing, the inventories are scaled based on data for land cables from [15]. LCIs for AC land cables at 200 and 300 kV are based on data for a 132/150 kV oil land cable with adjustments. For the cables at 400 kV, an inventory for a cross-linked polyethylene (XLPE) cable was used [20]. Since the sources did not include data on cable manufacturing, the energy used in shaping the copper conductors was estimated here by using the unit process 'copper wire drawing' from Ecoinvent [14].

For sea cables, included processes are the same as for land cables except that there is no cable trace in this case. Another difference is that sea cables require material for armoring, which is taken into account. For the 155 kV AC cables, the LCI for a 150 kV cable is used, and for the HVDC sea links, the LCI for a 400 kV HVDC cable is used, with adjustments. All inventories are based on data compiled at [15].

As for new planned transformers, data from Table A.5 indicates that 44 new units will be built in Europe. Most of these will be used in Germany to transform power from 380 kV to lower voltage levels. For transformers, the following processes are included: production and transportation of materials, manufacturing, transportation of finished product, maintenance and end-of-life [21]. In total, 163 substations will be built to facilitate RES transfers in Europe, as shown in Table A.6. The majority will be used to convert power from 400 kV to lower voltage levels, which are suitable for further distribution. Here it is assumed that half of the new substations will use air and half will use SF_6 as mean of insulating. Both technologies are possible in the context of current transmission planning, and the choice of which type is used depends on project costs, which in turn if affected by the location of installation and other factors. Gas Insulated Substations (GIS) are more compact and therefore can be advantageous in urban areas where sites which are large enough for air insulated substations are costly or rarely available. For substations and switchgear, processes included are production of materials, energy used in manufacturing and end-of-life. LCIs for substations are based on data for substations provided by [22]. For switchgear, the inventory is based on data compiled by [20]. For GIS and switchgear, the calculations include an estimate of the SF_6 gas leakages in manufacturing, use and end-of-life by using data for lifetime SF_6 leakages for this type of equipment [20].

While Tables A.2-A.6 provided data corresponding to the construction of new equipment, the upgrading of already existing equipment is summarized in Tables A.7 to A.9. Table A.7 shows data relative to projects consisting of reconductoring or reinsulating of OHLs which were modeled by taking into account the material and energy inputs required for the production of new conductors and insulators. Life cycle data for these components is found at [15]. Table A.8 summarizes the length corresponding to projects for decommissioning of old lines. This was modeled by considering the required operations for the end-of-life of OHLs, as described in inventories from [15]. Both consumption of fuels and processes such as disposal of waste are included, however recycling is not included since material production is also not included for line upgrading. Table A.9 has data on projects consisting of OHL voltage upgrades. The calculations for these processes were based on the cost of

OHL upgrades relative to costs for building a new line [23]. According to the data source, upgrading an OHL can cost between 40 to 60% of the total cost for building a new line. The calculations in this article are based on the assumption that upgrading an OHL is 50% the cost of building a new one, and the requirements are modeled accordingly. Due to the uncertainty in these values, the results for new equipment and renovations will be presented separately (see section 3).

2.3.5. Time/geographical coverage and data quality

The list of countries included in the TYNDP 2012 [1] sets the geographical boundary for this study. Countries covered are all ENTSO-E member states, which by 2012 correspond to all European countries except Russia, Belarus, Moldavia, Albania and Ukraine. As for time coverage, this analysis concerns projects with expected commissioning dates from now and up to 2020 (or > 2020, for projects for which current status is "under consideration"). Data for the European transmission investment projects was published by ENTSO-E in July 2012 and this data is updated every second year. The LCIs that were used to model the transmission equipment modeled here are available from the literature and correspond to data that was compiled by electrical companies in the period between 1999 and 2005 [15], [21].

3. RESULTS

Table A.10 shows the life cycle inventory for new transmission equipment aiming at facilitating RES integration in Europe. This includes results for the set of equipment described in Tables A.2-A.6 corresponding to the installation of new equipment: overhead lines, land and sea cables, substations, transformers and switchgear. Important materials are metals, from which steel, aluminum, iron, copper, lead and zinc represent a large share. Sand for the cable trace in land cables and limestone chipping for substations are also considerable inputs. Mineral oil, which is an input to all equipment types, except for AC land cables at 400 kV which are modeled as type XPLE, is also an important contributor. For OHLs, it is worth noticing the emissions to soil of zinc and mineral oil which are washed away with rain water to the ground around the masts [15]. The emissions to air of SF_6 from substation equipment correspond to a global warming potential of 508 kton CO_2 eq. or 6% of the total GWP 100 during the lifetime of the projects, using the assumption described in 2.3.4. SF_6 only affects results for climate change.

Table 2 shows the results from the life cycle impact assessment for grid renovation projects consisting of new assets, while results for renovation of existing assets will be shown in Table 4. The results in Table 2 are divided into the categories materials, manufacturing, installation, use, SF_6 losses and end-of-life (EOL). The use phase includes impacts for maintenance and land use. For land use, the values are taken directly from the life cycle inventory and no emissions are calculated for this process. The scores for SF_6 losses correspond to total losses in manufacturing, use and EOL. SF_6 losses in the use phase are 71% of the total lifetime losses [21]. The column end-of-life in Table 2 corresponds to the sum of contributions from different processes, some of which, e.g., incineration of paper or mineral oil will have a positive contribution (or negative effect on the environment), while others such as recycling of metal parts will have a negative contribution, reflecting the avoided use of materials and energy. For all impact categories, the EOL is a negative number, which indicates that the benefits of recycling are larger than the impacts caused by the other processes. A recycling rate of 90% for metal parts is assumed in this study. The remaining 10% are assumed to go to be deposited in a landfill. A sensitivity analysis with regard to recycling rates is presented later. The total results indicate that over the life cycle, the new assets contribute 8.7 Mton CO_2 eq. to Global Warming Potential, using the assumptions described in 2.3.

In order to investigate how the different processes, and in particular manufacturing, contribute to the total life cycle scores, a breakdown of results per life cycle stage is provided in Table 3. Here, we focus on the results for OHLs, which correspond to 70% of the total of new transmission lines. Results in Table 3 are divided into the categories: materials, manufacturing, installation, maintenance/use, and EOL. Manufacturing is then divided into the following processes: hot steel rolling, galvanization of masts and manufacturing of conductors. The final column has data on the contribution of manufacturing processes to the total scores in each impact category. Manufacturing constitutes a considerable share of scores in some impacts categories, particularly for water depletion, confirming that this process should be taken into account when doing LCAs for T&D systems.

Table 4 shows the LCA results for upgrading of already existing OHLs, as described in Tables A.7 to A.9. The results show that projects for voltage upgrading represent the largest share of impacts followed, by projects for line reconductoring. Line decommissioning or reinsulating represent a smaller share of impacts for refurbishing of existing lines.

Table 5 shows the total results for the whole project portfolio, i.e., considering both the construction of new equipment and the renovation of existing lines. In total, the grid upgrading projects in Europe with the purpose of facilitating RES integration will contribute with 10.7 Mton CO_2eq. to GWP100 over the lifetime of the equipment. The projects correspond to a total metal depletion of 11.2 Mton Fe eq.

Finally, a sensitivity analysis of the results to recycling assumptions is provided in Figure 3. This analysis is performed for results corresponding to new AC OHLs at 380 kV or above, which represent most of the length for new projects, or over 65%. The results were obtained for three scenarios. In the first scenario, it is assumed that there is no recycling of metal parts, e.g., aluminum and steel, at the EOL. Instead, these are assumed to be deposited in a landfill. For the second scenario, it was assumed a recycling rate of 50% for the metal parts. The remaining 50% are assumed to be deposited in a landfill. In the third scenario, the assumption is that 90% of metal parts are recycled at the EOL and 10% are assumed to be non-recoverable and be deposited in a landfill. The EOL for all other materials apart from metal parts are assumed to be treated as described in [15] for all scenarios. The results for selected impacts categories show a great variation of the total scores depending on the recycling rate assumed, in particular for climate change, fossil depletion, metal depletion and human toxicity. For freshwater ecotoxicity the different assumptions do not greatly affect the results.

4. DISCUSSION

4.1. Contributions

This paper analysis what modifications are required to upgrade the European transmission grid so that renewable energy capacity can be developed in the region and estimates the life cycle consequences associated with grid investments. The results show that over the life cycle of the projects, approximately 10.7 Mton CO_2 eq. will be generated, 8.7 Mton CO_2 eq. from new lines and 2 Mton CO_2 eq. from the renovation or upgrading of already existing lines. ENTSO-E indicates that 150 $MtCO_2$ will be saved through the connection of renewable energy technologies [1], but no time frame is provided nor an explanation about the method to calculate this number. If we assume that ENTSO-E refers to the time frame from now to 2022, when all projects will be completed, then our results represent around 3.5% of this budget. As for metal resource use, this study found that the projects correspond to a metal depletion of 11.2 Mton Fe eq.

The contribution of SF_6 is found to be considerable for total LCA results of new assets, using the assumption that half of the introduced substations will be gas insulated. Manufacturing processes are shown to have a large contribution to some impact categories, e.g., water depletion, and hence should be taken into account for these types of assessments. Different recycling rates will markedly reduce impacts in several categories, e.g., metal depletion and climate change. This can be of importance when designing end-of-life best practices for transmission equipment. For example, for oil-filled cables current practice for decommissioning often consists in abandoning circuits which are left in the ground [24]. This has of course important implications for pollution from potential oil leakages but also influences recovery of metals parts, which was shown in this paper to greatly affects the overall performance from T&D equipment. As a final note of interest, there is a study which describes local power grids as "hibernating copper stocks" [25]. As the authors mention, parts of power grids are taken out of use without the infrastructure being removed from its original location. The conclusion was that at present prices of copper, recovery of cables was not economically justified but that this could be beneficial if integrated with other maintenance work on the grid.

4.2. Relation to previous studies

This study aims to understand possible environmental consequences from a transition to a renewable power system. The environmental impacts for electricity supply arise from the generation, transmission and distribution of power. This article analyses the transmission part of the electricity value chain, but all parts must be evaluated if one wants to compare the environmental impacts for current systems versus future renewable based systems. For generation, previous studies indicate that the transition to a renewable system increases metal use per kWh, despite lowering CO_2 emissions [4]. Wind power requires 20% more iron than coal + CCS and solar is in the same range as natural gas plants [4]. Also, the intensity for other metals, e.g., Cu, Al, Ni or Zn was found to be high for all non-fossil technologies, in particular PV solar and wind [4].

Regarding the transmission part of the value chain, previous LCA results indicate that for today's systems, power transmission causes a climate change impact of between 10.57 and 11.77 g CO_2 eq./kWh, assuming a European power mix [26]. As for metal resource use, previous results indicate that power transmission corresponds to around 0.78 g Fe eq./kWh [26]. Calculating the CO_2/kWh and material use/kWh for the transmission grid in 2020 is a complex exercise which would require additional system data, e.g., power losses, which are not available. However, with the results obtained here for the construction, maintenance and demolition of the transmission equipment used for the grid extensions (Table 5), it is possible to get an estimate of the contribution of these processes for the grid impacts in 2020. By assuming a static attributional perspective, i.e., disregarding the dynamics of the transition to the power mix in 2020, the results indicate that per kWh delivered in 2020 (Table 1), the transmission grid extension projects contribute 0.074 g CO_2 eq./kWh. However, the generation mix will be less CO_2 intensive in 2020 than now since the share of fossil fuel power is reduced from 48% to 38% in 2020 (Table 1). How much CO_2 will be emitted per kWh in 2020 will also depend on how widespread the use of CO_2 capture technologies will be at that time. Regarding material use for the transmission of electricity, the results indicate that the grid investment plans contribute with 0.08 g Fe eq./kWh. Data for current transmission systems indicates a result of 0.78 g Fe eq./kWh [26], so the transition to a renewable based power system in Europe could represent a 10% increase in metal use for transmission, in a life cycle perspective. This comes in addition to the increase in material use for generation [4] and distribution.

4.3. Limitations

The results obtained here are subject to limitations arising from availability of data, methodological choices and assumptions. First, the effect of power losses in the transmission system before and after the grid extensions is not included. While data on the current power losses for the European transmission system is available through ENTSO-E, transmission losses after the upgrading were not found in publicly available data sources. An analysis of system losses before and after the investment plans is only provided for the Baltic Sea region, which is one out of 6 regions [27]. The available data shows that the sum of losses for Sweden, Norway, Denmark and Finland will increase until 2020 relative to the present, despite the increase in interconnectors and lower impedance. This could be due to longer distances over which power is transmitted, or higher loads. For Estonia, Latvia and Lithuania the summed losses will go down as a result of investments, according to the analysis presented in [27]. If data on losses becomes available for the other regions, it would be interesting to account for that in future assessments.

For modeling land cables at 400 kV, an inventory of a XLPE cable is used, but for land cables at lower voltages only data for oil based technology was available. Oil cables are increasingly being replaced by XLPE, and ideally the calculations should reflect this. Nevertheless, the total sum of km for 200 and 330 kV land cables is only 134 km, or 0.3% of the whole project portfolio length and hence the results will not be strongly affected by this choice.

Processes from the Ecoinvent database [14] were chosen such that there is a best possible match between what is available from the database and what is modeled here. However, there are some limitations, e.g., the process for recycling of asphalt is not available from the Ecoinvent so it was modeled as landfill. Most processes chosen reflect a context of European technology of production. However, in some cases global production is considered, e.g., for production of lead or limestone, since global processes are the only ones available from Ecoinvent.

4.4. Further work

Grid investments are a challenge for renewables and this article tries to find how important investment is in terms of the total impacts. The limitations of the present study open room for possible investigations in subsequent studies. One suggestion is to look at the development plans for the distribution part of the power grid, i.e., the grid that further connects power at high voltages to power suitable to be delivered to final consumers, which is not part of this analysis. Another suggestion to include the effect of losses in the future grid in the life cycle assessment of the transmission projects evaluated here. Also, it would be interesting to estimate the life cycle impacts for components which are not included here, e.g., converter stations for HVDC or reactive compensators and phase-shifting transformers (PSTs) for HVAC. Those components are described in the TYNDP 2012 [1] but there is no LCA data available, and hence they are not included in this analysis. One option would be to use cost data available from the Realise Grid project [28] and an input-output LCA model to estimate these.

BIBLIOGRAPHY

[1] ENTSO-E. Ten Year Network Development Plan 2012. European Network of Transmission System Operators for Electricity 2012.

[2] ENTSO-E. Statistical Yearbook 2011. European Network of Transmission System Operators for Electricity 2011.

[3] ENTSO-E. SOAF 2020 - Scenario Outlook and Adequacy Forecast 2012-2030. European Network of Transmission System Operators for Electricity 2012.

[4] Kleijn R, van der Voet E, Kramer G, van Oers L, van der Giesen C. Metal requirements of low carbon power generation. Energy 2011; 36:5640-5648.

[5] Arvesen A. Understanding the environmental implications of energy transitions. PhD Thesis, Energy and Process Engineering Department, NTNU 2013.

[6] Alonso E, Sherman A, Wallington T, Everson M, Field F, Roth R, Kirchain R. Evaluating Rare Element Availability: A Case with Revolutionary Demand from Clean Technologies. Environmental Science and Technology 2012; 46 (6):3406-3414.

[7] Pihl E, Kushnir D, Sandén B, Johnsson F. Material constraints for concentrating solar thermal power. Energy 2012; 44 (1):944-954.

[8] Sathre R, Chester M, Cain J, Masanet E. A framework for environmental assessment of CO_2 capture and storage systems. Energy 2012; 37(1):540-548.

[9] Dawkins E, Chadwick M, Falk R, Roelich K. Metals in a low-carbon economy: resource scarcity, climate change and business in a finite world, Stockholm Environment Institute 2012.

[10] Fencl A, Clark V, Metha V, Purkey D, Davis M, Yates D. Water for Electricity: Resource Scarcity and Business in a Finite World. Stockholm Environment Institute 2012.

[11] ISO. Environmental management - Life cycle assessment - Principles and framework (ISO 14040:2006): International Organization for Standardization 2006.

[12] ISO. Environmental management - Life cycle assessment - Requirements and guidelines (ISO 14044:2006): International Organization for Standardization 2006.

[13] Goedkoop MJ, Heijungs R, Huijbregts M, De Schryver A, Struijs J, Van Zelm R. ReCiPe 2008, A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level; First edition Report I: Characterization; 6 January 2009.

[14] Frischknecht R, Rebitzer G. The Ecoinvent database system: a comprehensive web-based LCA database. Journal of Cleaner Production 2004; 13(13-14):1337-1343.

[15] Jorge R, Hawkins T, Hertwich E. Life cycle assessment of electricity transmission and distribution - part 1: power lines and cables. International Journal of Life Cycle Assessment 2012; 17 (1):9-15.

[16] Itten R, Frischknecht R, Stucki M. Life Cycle Inventories of Electricity Mixes and Grid. ESU-services Ltd., Uster, Switzerland 2012.

[17] Google Maps Api (2009-2013). Retrieved from www.distancefromto.net (last accessed February 2012).

[18] Blackett G, Savory E, Toy N, Parke GAR, Clarck M, Rabjohns B. An evaluation of the environmental burdens of present and alternative materials used for electricity transmission. Building and Environment 2008; 43:1326-1338.

[19] Hertem D, Ghandhari M. Multi-terminal VSC HVDC for the European supergrid: Obstacles. Renewable and Sustainable Energy Reviews 2010; 14 (9):3156-3163.

[20] Eltra. LCA analyse 400 kV Pex kabelanlæg, landbaseret (personnal communication).

[21] Jorge R, Hawkins T, Hertwich E. Life cycle assessment of electricity transmission and distribution - part 2: transformers and substation equipment. International Journal of Life Cycle Assessment 2012; 17(2):184-191.

[22] Harrison G, Maclean E, Kalamanlis S, Ochoa L. Life cycle assessment of the transmission network in Great Britain. Energy Policy 2010; 38 (7):3622-3631.

[23] Hanson J. Upgrading transmission lines. Transmission and Distribution Conference 1991; Proceeding of the 1991 IEEE Power Engineering Society.

[24] Le Poidevin G. Approaches to the decommissioning of end-of-life oil filled cables. 17th International Conference on Electricity Distribution, CIRED. Barcelona, Spain 2003.

[25] Krook J, Carlsson A, Eklund M, Frändegård P, Svensson N. Urban mining: hibernating copper stocks in local power grids. Journal of Cleaner Production 2011; 19:1052-1056.

[26] Jorge R, Hertwich E. Environmental Evaluation of Power Transmission in Norway. Applied Energy 2012; 101:513-520.

[27] ENTSO-E. Regional Investment Plan Baltic Sea. European Network of Transmission System Operators for Electricity 2012.

[28] L'Abbate. Draft Deliverable D3.3.2 Review of costs of transmission infrastructures, including cross-border connections. Realisegrid, 7th Framework Programme 2011.

Tables

Table 1: Generating capacity (GW), electricity consumption (TWh) and transmission grid length (km) in Europe in 2012 and 2020, according to ENTSO-E.

Generation and transmission data for ENTSO-E countries	2012	2020	% increase
Generating capacity (GW)			
RES	320	536	67,5
Nuclear	126	132	4,8
Fossil	458	456	-0,4
Non-RES hydro	53	82	54,7
Others	6	8	33,3
TOTAL	963	1214	26,1
Electricity consumption (TWh)	3400	3615	6,3
Transmission grid length (km)	312064	349372	12

Table 2: LCA results for new transmission grid equipment in Europe concerning projects facilitating renewable power penetration in the region (Impact assessment method: ReCiPe; H perspective). EOL = end-of-life. Power losses are not included in the use phase, only maintenance.

	Unit	Materials	Manuf.	Install.	Use	SF_6 losses	EOL	Total
Agric. land occup.	m^2	4,70E+08	1,34E+07	3,13E+07	2,73E+07		-1,02E+08	4,40E+08
Climate Change	kg CO_2eq.	1,32E+10	8,83E+08	4,07E+08	1,16E+08	5,08E+08	-6,33E+09	8,74E+09
Fossil depletion	kg oil-eq.	3,62E+09	3,03E+08	2,19E+08	9,72E+07		-1,73E+09	2,51E+09
Freshwater ecotoxicity	kg 1,4-DCB-eq.	6,83E+08	1,90E+07	1,83E+06	2,20E+06		-1,35E+08	5,71E+08
Freshwater eutrophication	kg P-Eq	8,76E+06	8,83E+05	7,08E+04	1,06E+05		-6,20E+06	3,62E+06
Human Toxicity	kg 1,4-DCB-eq.	1,60E+10	1,07E+09	8,86E+07	2,36E+08		-9,51E+09	7,88E+09
Ionising radiation	kg U_{235}-eq.	3,12E+09	4,47E+08	6,00E+07	2,40E+07		-1,22E+09	2,43E+09
Marine ecotoxicity	kg 1,4-DCB-eq.	7,19E+08	2,01E+07	2,01E+06	3,23E+06		-1,39E+08	6,05E+08
Marine eutrophication	kg N-eq.	9,91E+06	2,03E+05	4,08E+05	1,16E+05		-5,05E+06	5,59E+06
Metal depletion	kg Fe-eq.	1,71E+10	2,92E+08	4,11E+07	4,85E+07		-7,92E+09	9,59E+09
Natural land transf.	m^2	2,01E+06	1,63E+05	2,48E+05	1,64E+05		-1,27E+06	1,32E+06
Ozone depletion	kg CFC_{-11}-eq.	7,83E+02	6,64E+01	8,35E+01	1,94E+04		-2,56E+02	2,00E+04
PMF	kg PM_{10}-Eq	4,93E+07	1,53E+06	1,13E+06	3,20E+05		-2,14E+07	3,09E+07
Photoc. oxidant form.	kg NMVOC	4,33E+07	2,59E+06	3,47E+06	7,27E+05		-1,99E+07	3,02E+07
Terrestrial acidification	kg SO_2-eq	6,82E+07	3,61E+06	2,37E+06	1,06E+06		-3,21E+07	4,31E+07
Terrestrial ecotoxicity	kg 1,4-DCB-eq.	2,56E+06	1,10E+05	7,49E+04	7,23E+04		-5,76E+05	2,25E+06
Urban land occupation	m^2	1,57E+08	4,30E+06	1,03E+07	2,78E+07		-3,52E+07	1,64E+08
Water depletion	m^3	5,31E+07	1,31E+07	7,39E+05	1,34E+06		-2,30E+07	4,53E+07

Table 3: LCA results per life cycle stage for new OHLs facilitating RES penetration, as described in the TYNDP2012. (Impact assessment method: ReCiPe; H perspective). EOL = end of life. The last column shows the % contribution of manufacturing processes to the total LCA results. Power losses are not included in the use phase, only maintenance.

	Unit	Materials	Hot steel rolling	Galvanization	Manuf. conductors	Installation	Use phase	EOL	% Man.
Agric. land occup.	m^2	2,22E+08	4,43E+06	1,98E+03	7,00E+06	7,34E+05	2,36E+07	-9,18E+07	8 %
Climate Change	kg CO_2eq.	1,20E+10	3,60E+08	5,67E+06	4,22E+08	1,72E+08	9,94E+07	-6,11E+09	11 %
Fossil depletion	kg oil-eq.	3,24E+09	1,32E+08	2,35E+06	1,24E+08	1,05E+08	6,50E+07	-1,70E+09	13 %
Freshwater ecotoxicity	kg 1,4-DCB-eq.	5,79E+08	6,65E+06	1,49E+03	4,95E+06	5,41E+05	2,09E+06	-8,07E+07	2 %
Freshwater eutrophication	kg P-Eq	5,36E+06	1,74E+05	8,49E+01	3,48E+05	1,87E+04	1,02E+05	-3,73E+06	23 %
Human toxicity	kg 1,4-DCB-eq.	8,75E+09	1,31E+08	8,07E+04	2,34E+08	2,37E+07	2,30E+08	-4,21E+09	7 %
Ionising radiation	kg U_{235}-eq.	2,87E+09	9,10E+07	5,71E+04	3,14E+08	1,86E+07	2,13E+07	-1,20E+09	19 %
Marine ecotoxicity	kg 1,4-DCB-eq.	6,08E+08	6,60E+06	2,81E+03	4,93E+06	6,20E+05	3,10E+06	-8,43E+07	2 %
Marine eutrophication	kg N-eq.	8,06E+06	5,49E+04	1,55E+02	1,04E+05	1,68E+05	1,04E+05	-4,08E+06	4 %
Metal depletion	kg Fe-eq.	1,12E+10	8,78E+07	2,04E+04	5,07E+06	8,34E+06	4,65E+07	-3,63E+09	1 %
Natural land transf.	m^2	1,63E+06	6,59E+04	1,25E+03	5,26E+04	1,24E+05	7,61E+04	-1,23E+06	17 %
Ozone depletion	kg CFC_{-11}-eq.	6,89E+02	3,16E+01	8,14E-01	2,10E+01	4,18E+01	2,09E+01	-2,63E+02	10 %
PMF	kg PM_{10}-Eq	4,21E+07	6,35E+05	1,33E+03	5,26E+05	4,10E+05	2,77E+05	-1,76E+07	4 %
Photoc. oxidant form.	kg NMVOC	3,64E+07	1,21E+06	5,50E+03	8,63E+05	1,49E+06	6,19E+05	-1,70E+07	9 %
Terrestrial acidification	kg SO_2-eq	5,45E+07	9,47E+05	4,06E+03	1,63E+06	9,93E+05	9,19E+05	-2,53E+07	8 %
Terrestrial ecotoxicity	kg 1,4-DCB-eq.	2,18E+06	2,13E+04	9,89E+01	4,51E+04	3,33E+04	6,46E+04	-4,98E+05	4 %
Urban land occupation	m^2	1,30E+08	1,66E+06	2,20E+03	1,40E+06	2,26E+06	2,39E+07	-2,73E+07	3 %
Water depletion	m^3	4,40E+07	9,03E+06	1,32E+03	3,24E+06	2,60E+05	1,28E+06	-1,81E+07	31 %

Table 4: LCA results for renovation of existing transmission equipment in Europe in order to facilitate renewable power penetration in the region. (Impact assessment method: ReCiPe; H perspective).

	Unit	Decommissioning	Reconductoring	Reinsulating	Upgrading lines/cables	Total
Agric. land occup.	m^2	1,33E+04	1,94E+06	2,76E+04	3,18E+07	3,37E+07
Climate change	kg CO_2eq.	8,69E+05	1,64E+08	1,54E+06	1,78E+09	1,95E+09
Fossil depletion	kg oil-eq.	5,42E+05	4,24E+07	4,77E+05	4,86E+08	5,29E+08
Freshwater ecotoxicity	kg 1,4-DCB-eq.	2,05E+03	3,22E+06	7,64E+04	8,12E+07	8,45E+07
Freshwater eutroph.	kg P-Eq	8,15E+01	7,20E+04	6,53E+02	7,87E+05	8,59E+05
Human toxicity	kg 1,4-DCB-eq.	8,08E+04	7,74E+07	1,39E+06	1,25E+09	1,33E+09
Ionising radiation	kg U_{235}-eq.	6,76E+04	4,21E+07	4,09E+05	4,24E+08	4,67E+08
Marine ecotoxicity	kg 1,4-DCB-eq.	2,18E+03	3,36E+06	8,00E+04	8,52E+07	8,87E+07
Marine eutrophication	kg N-eq.	6,35E+02	9,74E+04	1,21E+03	1,19E+06	1,29E+06
Metal depletion	kg Fe-eq.	2,37E+04	4,00E+07	1,53E+06	1,55E+09	1,59E+09
Natural land transf.	m^2	-1,55E+03	2,86E+04	2,03E+02	2,60E+05	2,87E+05
Ozone depletion	kg CFC_{-11}-eq.	2,24E-01	1,02E+01	1,10E-01	1,07E+02	1,17E+02
PMF	kg PM_{10}-Eq	1,68E+03	3,87E+05	5,47E+03	6,07E+06	6,46E+06
Photoc. oxidant form.	kg NMVOC	5,93E+03	4,32E+05	5,47E+03	5,47E+06	5,91E+06
Terrestrial acidif.	kg SO_2-eq	4,06E+03	6,92E+05	8,07E+03	8,07E+06	8,78E+06
Terrestrial ecotoxicity	kg 1,4-DCB-eq.	1,21E+02	1,84E+04	2,87E+02	3,16E+05	3,34E+05
Urban land occupation	m^2	5,33E+04	9,88E+05	1,67E+04	1,87E+07	1,98E+07
Water depletion	m^3	1,41E+03	5,17E+05	8,16E+03	6,42E+06	6,94E+06

Table 5: LCA results for entire grid renovation portfolio (new equipment + upgrading of existing OHLs).

	Unit	Total
Agric. land occupation	m^2	4,96E+08
Climate change	kg CO$_2$eq.	1,07E+10
Fossil depletion	kg oil-eq.	3,04E+09
Freshwater ecotoxicity	kg 1,4-DCB-eq.	6,56E+08
Freshwater eutrophication	kg P-Eq	4,48E+06
Human toxicity	kg 1,4-DCB-eq.	9,21E+09
Ionising radiation	kg U$_{235}$-eq.	2,90E+09
Marine ecotoxicity	kg 1,4-DCB-eq.	6,94E+08
Marine eutrophication	kg N-eq.	6,88E+06
Metal depletion	kg Fe-eq.	1,12E+10
Natural land transf.	m^2	1,61E+06
Ozone depletion	kg CFC$_{-11}$-eq.	2,01E+04
PMF	kg PM$_{10}$-Eq	3,74E+07
Photoc. oxidant form.	kg NMVOC	3,61E+07
Terrestrial acidification	kg SO$_2$-eq	5,19E+07
Terrestrial ecotoxicity	kg 1,4-DCB-eq.	2,58E+06
Urban land occupation	m^2	2,06E+08
Water depletion	m^3	5,22E+07

Figures

Figure 1: Total length (km) of transmission grid in Europe before 1) and after 2) grid renovation projects related to RES integration.

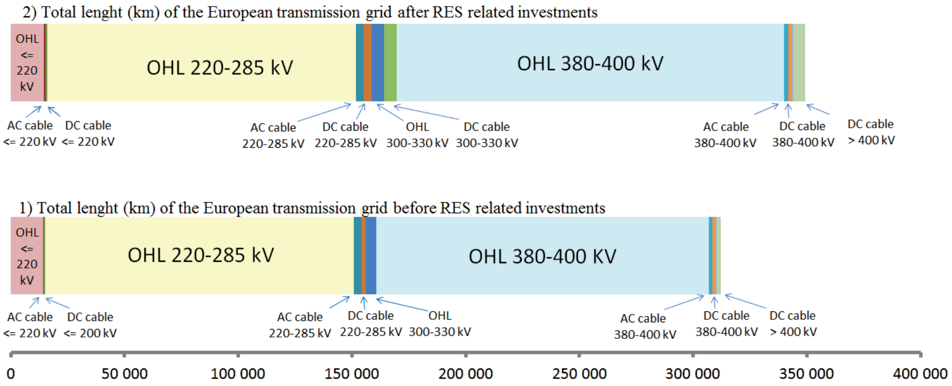


Figure 2: Life cycle impacts from electricity transmission systems.

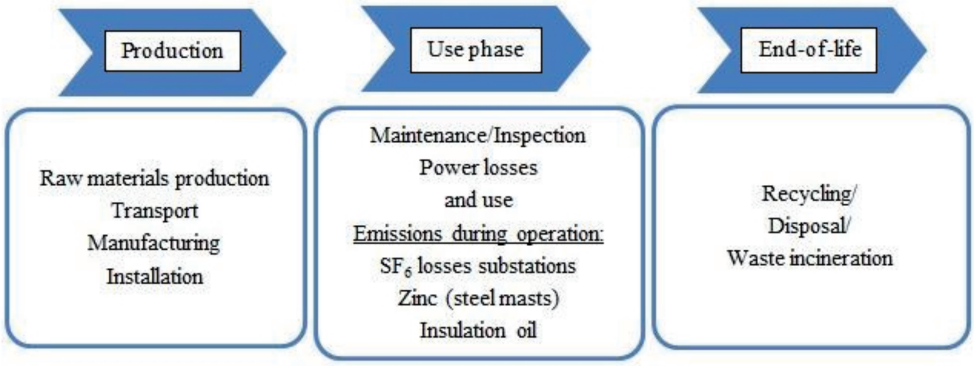
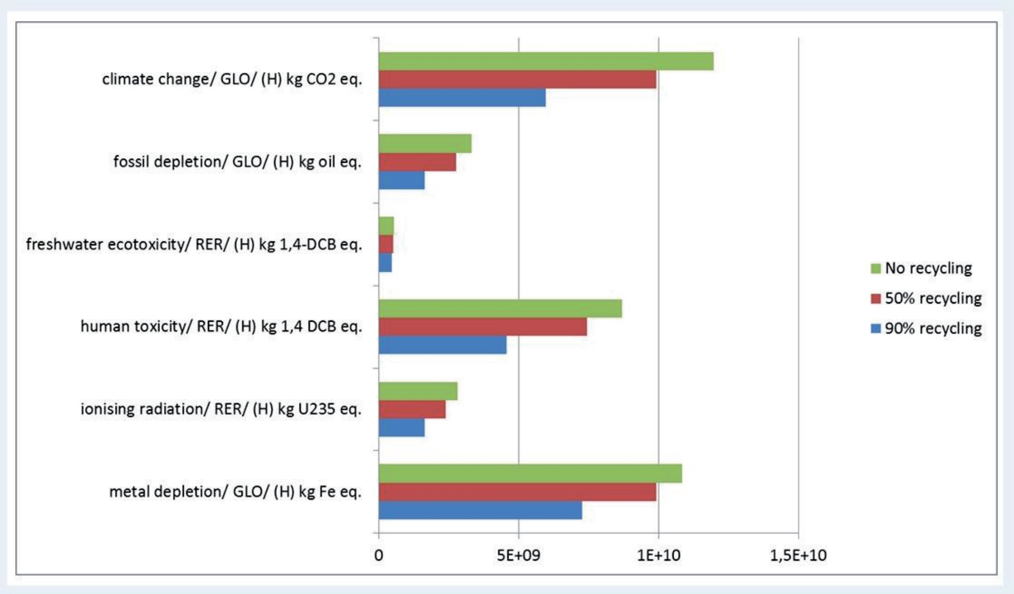
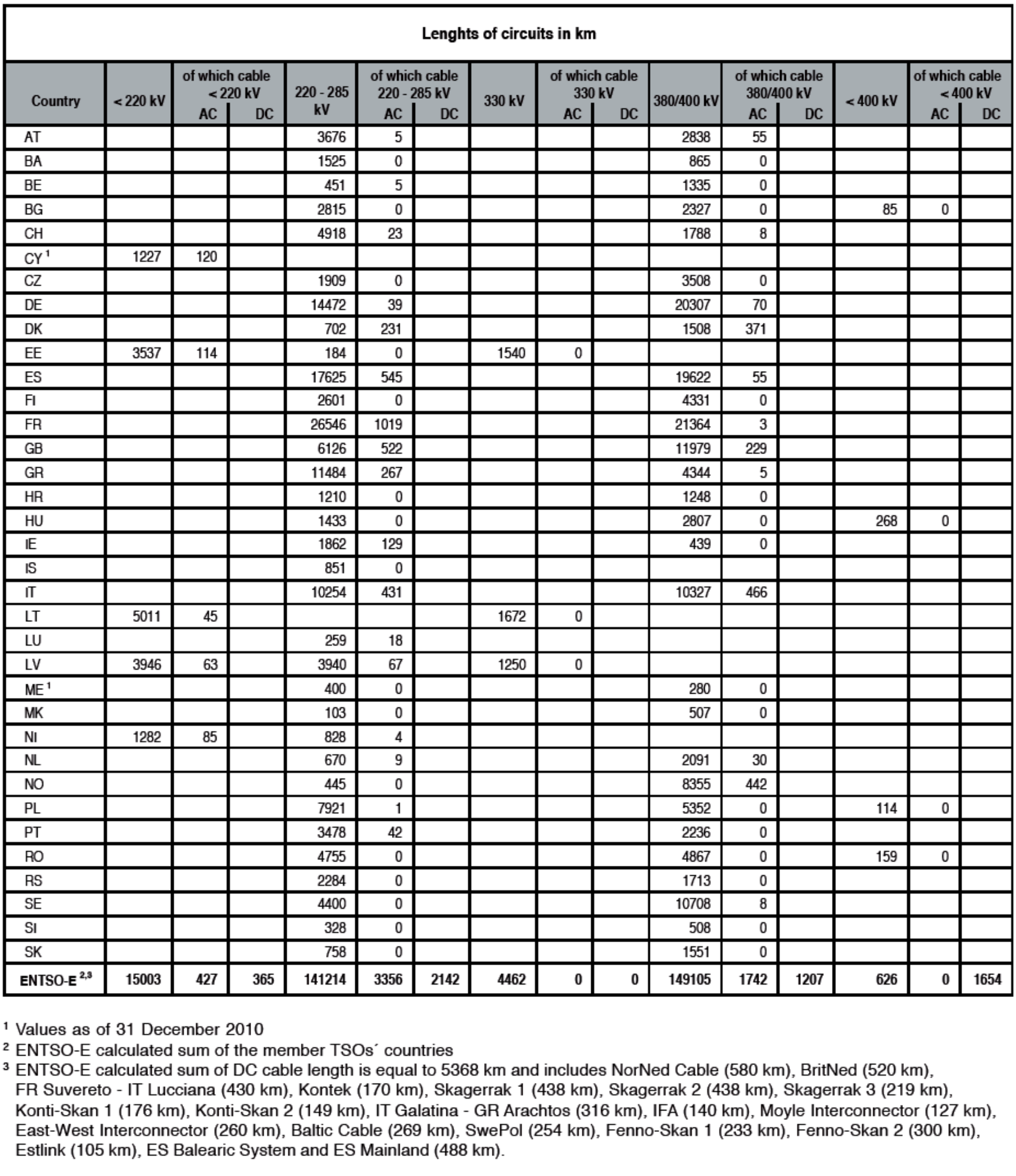


Figure 3: Sensitivity analysis of the results for OHLs to different assumption for recycling, for selected impact categories. The scenarios correspond to recycling rates of metal parts of 0%, 50% and 90% respectively.



Appendix

Table A.1 - Inventory of transmission equipment installed in Europe as per December 2011 (source: Statistical Yearbook 2011, ENTSO-E).



Lenghts of circuits in km

Country	< 220 kV	of which cable < 220 kV		220 - 285 kV	of which cable 220 - 285 kV		330 kV	of which cable 330 kV		380/400 kV	of which cable 380/400 kV		< 400 kV	of which cable < 400 kV	
		AC	DC		AC	DC		AC	DC		AC	DC		AC	DC
AT				3676	5					2838	55				
BA				1525	0					865	0				
BE				451	5					1335	0				
BG				2815	0					2327	0		85	0	
CH				4918	23					1788	8				
CY[1]	1227	120													
CZ				1909	0					3508	0				
DE				14472	39					20307	70				
DK				702	231					1508	371				
EE	3537	114		184	0		1540	0							
ES				17625	545					19622	55				
FI				2601	0					4331	0				
FR				26546	1019					21364	3				
GB				6126	522					11979	229				
GR				11484	267					4344	5				
HR				1210	0					1248	0				
HU				1433	0					2807	0		268	0	
IE				1862	129					439	0				
IS				851	0										
IT				10254	431					10327	466				
LT	5011	45					1672	0							
LU				259	18										
LV	3946	63		3940	67		1250	0							
ME[1]				400	0					280	0				
MK				103	0					507	0				
NI	1282	85		828	4										
NL				670	9					2091	30				
NO				445	0					8355	442				
PL				7921	1					5352	0		114	0	
PT				3478	42					2236	0				
RO				4755	0					4867	0		159	0	
RS				2284	0					1713	0				
SE				4400	0					10708	8				
SI				328	0					508	0				
SK				758	0					1551	0				
ENTSO-E[2,3]	**15003**	**427**	**365**	**141214**	**3356**	**2142**	**4462**	**0**	**0**	**149105**	**1742**	**1207**	**626**	**0**	**1654**

[1] Values as of 31 December 2010

[2] ENTSO-E calculated sum of the member TSOs´ countries

[3] ENTSO-E calculated sum of DC cable length is equal to 5368 km and includes NorNed Cable (580 km), BritNed (520 km), FR Suvereto - IT Lucciana (430 km), Kontek (170 km), Skagerrak 1 (438 km), Skagerrak 2 (438 km), Skagerrak 3 (219 km), Konti-Skan 1 (176 km), Konti-Skan 2 (149 km), IT Galatina - GR Arachtos (316 km), IFA (140 km), Moyle Interconnector (127 km), East-West Interconnector (260 km), Baltic Cable (269 km), SwePol (254 km), Fenno-Skan 1 (233 km), Fenno-Skan 2 (300 km), Estlink (105 km), ES Balearic System and ES Mainland (488 km).

Table A.2 - Total planned km of overhead lines (OHL) by voltage level and type, for projects contributing to RES integration in Europe (source: TYNDP 2012).

	OHL (AC)							OHL (HVDC)	
Voltage (kV)	**200**	**330**	**330+110**	**380**	**400**	**400+150**	**400+200**	**380**	**450**
Simplex (km)	62	295	682	95	6427				
Duplex (km)	318	143		3650	12772	160	434	760	14

Table A.3- Total planned km of land cables by voltage level and type, for projects contributing to RES integration in Europe (source: TYNDP 2012).

	Land cables (AC)			Land cables (HVDC)					
Voltage (kV)	**200**	**330**	**400**	**150**	**220**	**300**	**320**	**380**	**450**
Cable length (km)	121	13	89	151	90	675	1857	120	113

Table A.4 - Total planned km of sea cables by voltage level and type, for projects contributing to RES integration in Europe (source: TYNDP 2012).

	Sea cables (AC)	Sea cables (HVDC)						
Voltage (kV)	**155**	**132/150**	**200/220**	**300**	**320**	**400**	**450**	**500**
Cable length (km)	147	205	1224	673	2224	77	710	3007

Table A.5 - Additional transformers by transformer type for projects contributing to RES integration in Europe (source: TYNDP 2012).

Transformer type			
220/380 kV	**380/110 kV**	**400/120 kV**	**400/230 kV**
2	32	2	8

Table A.6 - Additional substations and switchgear infrastructure, facilitating RES integration projects in Europe (source: TYNDP 2012).

Voltage (kV)	200	380	400
Switchgear			7
Substations	7	45	104

Table A.7 - Reconductoring and reinsulating existing OHLs (source: TYNDP 2012).

Voltage (kV)	**Type**	**Upgrade**	**Total length (km)**
220	Simplex	Reconductoring	260
275	n.a.	Reconductoring	485
400	Duplex	Reconductoring	380
275	n.a.	Reinsulating to 400 kV	168

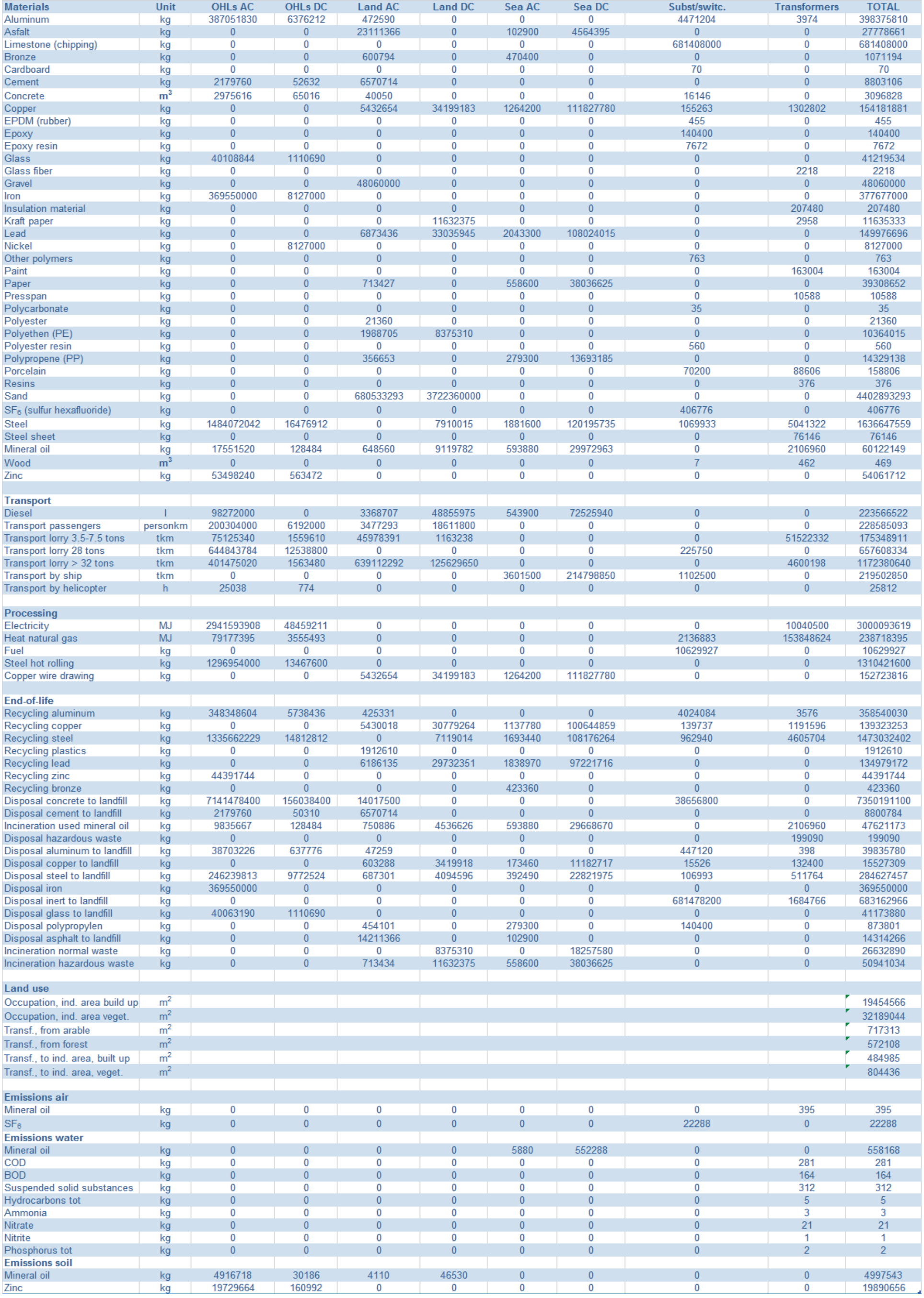
Table A.8 - Decommissioning of old OHLs required for projects contributing to RES integration according to the TYNDP 2012.

Voltage (kV)	**Decommissioning length (km)**
150	87
200	198

Table A.9 - OHL (AC) upgrades for capacity increase (source: TYNDP 2012).

From		**To**		
Voltage (kV)	**Type**	**Voltage (kV)**	**Type**	**Length (km)**
110/132	n.a.	n.a.	n.a.	44
132	n.a.	220	n.a.	2,73
150	Simplex	150 + 400	n.a.	106
220	n.a.	380	n.a.	514
220	Simplex	400	n.a.	350
220	Duplex	400	n.a.	1018
220	Simplex	n.a.	n.a.	448
220	n.a.	n.a.	n.a.	265
275	n.a.	400	n.a.	263
300	n.a.	420	n.a.	185
300	Simplex	n.a.	n.a.	718
380	Simplex	380	Duplex	108
380	Duplex	n.a.	n.a.	380
400	Simplex	400	Duplex	503
400	Simplex	n.a.	n.a.	1005
400	Duplex	n.a.	n.a.	778

Table A.10 - Life cycle inventory (LCI) for projects corresponding to construction of new assets for the European transmission grid (as described in tables A.2-A.6).



Materials	Unit	OHLs AC	OHLs DC	Land AC	Land DC	Sea AC	Sea DC	Subst/switc.	Transformers	TOTAL
Aluminum	kg	387051830	6376212	472590	0	0	0	4471204	3974	398375810
Asfalt	kg	0	0	23111366	0	102900	4564395	0	0	27778661
Limestone (chipping)	kg	0	0	0	0	0	0	681408000	0	681408000
Bronze	kg	0	0	600794	0	470400	0	0	0	1071194
Cardboard	kg	0	0	0	0	0	0	70	0	70
Cement	kg	2179760	52632	6570714	0	0	0	0	0	8803106
Concrete	m^3	2975616	65016	40050	0	0	0	16146	0	3096828
Copper	kg	0	0	5432654	34199183	1264200	111827780	155263	1302802	154181881
EPDM (rubber)	kg	0	0	0	0	0	0	455	0	455
Epoxy	kg	0	0	0	0	0	0	140400	0	140400
Epoxy resin	kg	0	0	0	0	0	0	7672	0	7672
Glass	kg	40108844	1110690	0	0	0	0	0	0	41219534
Glass fiber	kg	0	0	0	0	0	0	0	2218	2218
Gravel	kg	0	0	48060000	0	0	0	0	0	48060000
Iron	kg	369550000	8127000	0	0	0	0	0	0	377677000
Insulation material	kg	0	0	0	0	0	0	0	207480	207480
Kraft paper	kg	0	0	0	11632375	0	0	0	2958	11635333
Lead	kg	0	0	6873436	33035945	2043300	108024015	0	0	149976696
Nickel	kg	0	8127000	0	0	0	0	0	0	8127000
Other polymers	kg	0	0	0	0	0	0	763	0	763
Paint	kg	0	0	0	0	0	0	0	163004	163004
Paper	kg	0	0	713427	0	558600	38036625	0	0	39308652
Presspan	kg	0	0	0	0	0	0	0	10588	10588
Polycarbonate	kg	0	0	0	0	0	0	35	0	35
Polyester	kg	0	0	21360	0	0	0	0	0	21360
Polyethen (PE)	kg	0	0	1988705	8375310	0	0	0	0	10364015
Polyester resin	kg	0	0	0	0	0	0	560	0	560
Polypropene (PP)	kg	0	0	356653	0	279300	13693185	0	0	14329138
Porcelain	kg	0	0	0	0	0	0	70200	88606	158806
Resins	kg	0	0	0	0	0	0	0	376	376
Sand	kg	0	0	680533293	3722360000	0	0	0	0	4402893293
SF$_6$ (sulfur hexafluoride)	kg	0	0	0	0	0	0	406776	0	406776
Steel	kg	1484072042	16476912	0	7910015	1881600	120195735	1069933	5041322	1636647559
Steel sheet	kg	0	0	0	0	0	0	0	76146	76146
Mineral oil	kg	17551520	128484	648560	9119782	593880	29972963	0	2106960	60122149
Wood	m^3	0	0	0	0	0	0	7	462	469
Zinc	kg	53498240	563472	0	0	0	0	0	0	54061712
Transport										
Diesel	l	98272000	0	3368707	48855975	543900	72525940	0	0	223566522
Transport passengers	personkm	200304000	6192000	3477293	18611800	0	0	0	0	228585093
Transport lorry 3.5-7.5 tons	tkm	75125340	1559610	45978391	1163238	0	0	0	51522332	175348911
Transport lorry 28 tons	tkm	644843784	12538800	0	0	0	0	225750	0	657608334
Transport lorry > 32 tons	tkm	401475020	1563480	639112292	125629650	0	0	0	4600198	1172380640
Transport by ship	tkm	0	0	0	0	3601500	214798850	1102500	0	219502850
Transport by helicopter	h	25038	774	0	0	0	0	0	0	25812
Processing										
Electricity	MJ	2941593908	48459211	0	0	0	0	0	10040500	3000093619
Heat natural gas	MJ	79177395	3555493	0	0	0	0	2136883	153848624	238718395
Fuel	kg	0	0	0	0	0	0	10629927	0	10629927
Steel hot rolling	kg	1296954000	13467600	0	0	0	0	0	0	1310421600
Copper wire drawing	kg	0	0	5432654	34199183	1264200	111827780	0	0	152723816
End-of-life										
Recycling aluminum	kg	348348604	5738436	425331	0	0	0	4024084	3576	358540030
Recycling copper	kg	0	0	5430018	30779264	1137780	100644859	139737	1191596	139323253
Recycling steel	kg	1335662229	14812812	0	7119014	1693440	108176264	962940	4605704	1473032402
Recycling plastics	kg	0	0	1912610	0	0	0	0	0	1912610
Recycling lead	kg	0	0	6186135	29732351	1838970	97221716	0	0	134979172
Recycling zinc	kg	44391744	0	0	0	0	0	0	0	44391744
Recycling bronze	kg	0	0	0	0	423360	0	0	0	423360
Disposal concrete to landfill	kg	7141478400	156038400	14017500	0	0	0	38656800	0	7350191100
Disposal cement to landfill	kg	2179760	50310	6570714	0	0	0	0	0	8800784
Incineration used mineral oil	kg	9835667	128484	750886	4536626	593880	29668670	0	2106960	47621173
Disposal hazardous waste	kg	0	0	0	0	0	0	0	199090	199090
Disposal aluminum to landfill	kg	38703226	637776	47259	0	0	0	447120	398	39835780
Disposal copper to landfill	kg	0	0	603288	3419918	173460	11182717	15526	132400	15527309
Disposal steel to landfill	kg	246239813	9772524	687301	4094596	392490	22821975	106993	511764	284627457
Disposal iron	kg	369550000	0	0	0	0	0	0	0	369550000
Disposal inert to landfill	kg	0	0	0	0	0	0	681478200	1684766	683162966
Disposal glass to landfill	kg	40063190	1110690	0	0	0	0	0	0	41173880
Disposal polypropylen	kg	0	0	454101	0	279300	0	140400	0	873801
Disposal asphalt to landfill	kg	0	0	14211366	0	102900	0	0	0	14314266
Incineration normal waste	kg	0	0	0	8375310	0	18257580	0	0	26632890
Incineration hazardous waste	kg	0	0	713434	11632375	558600	38036625	0	0	50941034
Land use										
Occupation, ind. area build up	m^2									19454566
Occupation, ind. area veget.	m^2									32189044
Transf., from arable	m^2									717313
Transf., from forest	m^2									572108
Transf., to ind. area, built up	m^2									484985
Transf., to ind. area, veget.	m^2									804436
Emissions air										
Mineral oil	kg	0	0	0	0	0	0	0	395	395
SF$_6$	kg	0	0	0	0	0	0	22288	0	22288
Emissions water										
Mineral oil	kg	0	0	0	0	5880	552288	0	0	558168
COD	kg	0	0	0	0	0	0	0	281	281
BOD	kg	0	0	0	0	0	0	0	164	164
Suspended solid substances	kg	0	0	0	0	0	0	0	312	312
Hydrocarbons tot	kg	0	0	0	0	0	0	0	5	5
Ammonia	kg	0	0	0	0	0	0	0	3	3
Nitrate	kg	0	0	0	0	0	0	0	21	21
Nitrite	kg	0	0	0	0	0	0	0	1	1
Phosphorus tot	kg	0	0	0	0	0	0	0	2	2
Emissions soil										
Mineral oil	kg	4916718	30186	4110	46530	0	0	0	0	4997543
Zinc	kg	19729664	160992	0	0	0	0	0	0	19890656