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Environmental assessment of electricity transmission using input-output analysis

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Master of Energy Use and Energy Planning

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MASTER THESIS

for

Student
Tord Munro Valheim

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Environmental assessment of electricity transmission using input-output analysis

*Miljøvurdering av kraftoverføring ved hjelp av kryssløpsanalyse***Background and objective**

Substantial investments in electricity transmission will be needed in coming decades in order to extend transmission capacities and to refurbish or replace old components. One reason for this is the need to accommodate higher electricity demands. Another reason is an increasingly important role played by variable wind and solar energy in power systems. The temporal and spatial distribution of wind and solar energy outputs are determined or influenced by weather, and cannot easily be adjusted to follow demand. These characteristics of wind and solar energy make their large-scale integration into power systems challenging, as power demand must be met at all times and for all locations. Transmission grid extensions and upgrades represent part of the solution to this problem, by helping utilities take advantage of geographical variations in the timing of generation and demand across regions.

A fair number of life cycle assessments (LCAs) of electricity transmission are available in literature, including work done at NTNU [1-6]. Most of these studies are process-LCAs, however, based largely on the composition of materials in components and not considering “service” type activities that are best represented by input-output analysis (IOA). Whether the process- LCAs sufficiently capture emissions associated with manufacturing is also unclear. It would be desirable better understand the impacts associated with transmission grid as estimated by IOA, and to compare these impact estimates to corresponding results obtained from process- LCAs.

The objective of this thesis is to provide an environmental evaluation of selected transmission grid technologies or projects by using IOA, with the case to be decided in the first weeks of the work.

The following tasks are to be considered:

1. Present a brief review of LCA literature on transmission grid technologies, and a brief discussion on the need for electricity grid upgrades and extensions in the future.
2. Decide on a case or several cases to study. Compile monetary data on investments into transmission grid for this case, and implement these data in an IOA framework.
3. Perform an environmental evaluation for the selected case, using IOA. Make a comparison with corresponding results found in process-LCA studies.
4. Optional: Expand on the analysis as you wish (e.g., by performing sensitivity analysis, by exploring the importance of geographical variations for the IOA results), bearing in mind the overall background and objective as stated in this assignment text.

Literature cited:

- [1] Jorge R, Hawkins T, Hertwich E. Life cycle assessment of electricity transmission and distribution—part 1: power lines and cables. *The International Journal of Life Cycle Assessment*. 2012;17(1):9-15.
- [2] Jorge R, Hawkins T, Hertwich E. Life cycle assessment of electricity transmission and distribution—part 2: transformers and substation equipment. *The International Journal of Life Cycle Assessment*. 2012;17:184-91.
- [3] Jorge RS, Hertwich EG. Environmental evaluation of power transmission in Norway. *Applied Energy*. 2013;101:513-20.
- [4] Jorge RS, Hertwich EG. Grid infrastructure for renewable power in Europe: The environmental cost. *Energy*. 2014;69(0):760-8.
- [5] Arvesen A, Nes R, Huertas-Hernando D, Hertwich E. Life cycle assessment of an offshore grid interconnecting wind farms and customers across the North Sea. *The International Journal of Life Cycle Assessment*. 2014;19(4):826-37.
- [6] Arvesen A, Hauan IB, Bolsøy BM, Hertwich EG. Life cycle assessment of transport of electricity via different voltage levels: A case study for Nord-Trøndelag county in Norway. *Applied Energy*. 2015;157:144-51.

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

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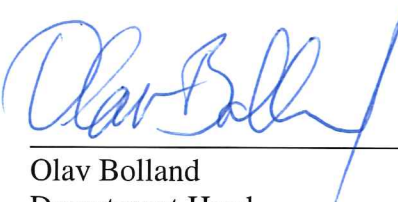
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- Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
- Field work

Department of Energy and Process Engineering, 19. January 2016



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Co-supervisor: Anders Arvesen, EPT

Preface

With this master thesis I complete my MSc degree in Energy Use and Energy Planning at the Norwegian University of Science and Technology (NTNU)

I would like to thank my supervisor Anders Hammer Strømman for giving me the opportunity to work on this thesis, and my co-supervisor, Anders Arvesen, for his guidance and helpfulness.

Trondheim, June 27, 2016

Tord Munro Valheim

Abstract

The purpose of this master thesis was to present an environmental assessment of impacts related to electricity transmission. This was done with the use of two different case studies and by conducting an input-output analysis (IOA). An important transmission route located in Germany, and extensions of transmission lines contributing to renewable energy integration until year 2030 was chosen as case studies. Transmission technologies investigated in detail was overhead lines (OHL) and subsea cables, although other components such as underground cables (UGC) and air insulated substations (AIS) was also included in the assessment.

In the impact assessment, emissions of greenhouse gases (GHG), nitrogen oxides (NO_x), total suspended particles (TSP), sulphur oxides (SO_x), carbon monoxide (CO), and non-methane volatile organic compound (NMVOC) was calculated, with the main focus being on greenhouse gas (GHG) emissions.

The results showed a total impact of 92.5 Mton CO₂-equivalents for developing the transmission grid to accommodate for integrating renewable energy to the electrical power grid. The subsea cable emerged as the main culprit, with 67% of the total CO₂-eq emissions. The largest CO₂-eq intensive transmission technology was found to be UGC, with six times more emissions per km compared to OHLs, and subsea cable with more than twice as high emissions, resulting in OHL as the least CO₂-eq intensive transmission technology per km. For subsea cables, cable materials and installation represented the largest share of emissions, mainly due to the operation of marine vessels. For OHLs, activities related to constructing foundations for masts, erecting the masts and stringing the conductors represented the largest share of OHL emissions. Metal products and usage of electricity, generated from coal, was especially important contributors affecting the various types of emissions from OHLs.

Sammendrag

Målet med denne masteroppgaven er å presentere en miljøvurdering av utslipp relatert til kraftoverføring. Dette ble gjort ved å undersøke to forskjellige case-studier. Dette ble utført ved å bruke en input output analyse (IOA). Den ene case-studien som ble undersøkt omhandlet en viktig kraftoverføringsstrekning i Tyskland. Den andre baserte seg på utbyggelse av kraftoverføringsnett i Europa for å imøtekomme integreringen av fornybare energikilder frem til 2030. De forskjellige overføringsteknologier som ble undersøkt var luftledning, sjøkabel og jordkabel, i tillegg til transformatorstasjon.

I konsekvensutredningen ble utslipp av drivhusgasser, nitrogenoksider (NO_x), total suspended particles (TSP), svoveloksider (SO_x), karbonmonoksider (CO) og flyktige organiske forbindelser med unntak av metan (NMVOC) kalkulert med ekstra fokus på drivhusgassutslipp.

Resultatene viste et utslipp på totalt 92.5 Mton CO_2 -ekvivalenter fra utbyggelsen av kraftoverføringsnett. Her utmerket sjøkabelen seg som var hovedårsaken til størstedelen av utslippet (67% av det total CO_2 -ekvivalent utslippet). Den mest intense CO_2 -ekvivalent overføringsteknologien var jordkabel, med seks ganger mer utslipp per kilometer sammenlignet med luftledning. Sjøkabel hadde to ganger så høye utslipp sammenlignet med luftledning som resulterer i lavest CO_2 -ekvivalent utslipp per kilometer for luftledning. For sjøkabelen, så hadde kabel materiell og installasjon den høyeste andelen utslipp, hovedsakelig på grunn av bruken av marine fartøy. For luftledning, så var aktiviteten av å konstruere fundamenter for master, montering av master, og strekking av ledere den med høyest andel utslipp for luftledning. Metallprodukter og bruk av kullbasert strøm var spesielt bidragsytende til utslippene fra luftledninger.

Table of contents

Preface.....	I
Abstract	III
Sammendrag.....	V
Table of figures	IX
List of tables	X
Abbreviations	XI
1 Introduction	1
1.1 Problem definition	1
1.2 Objective.....	3
2 LCA literature on transmission grids and discussion of future aspects of electricity transmission and distribution	4
2.1 Literature review.....	4
2.2 Electricity transmission and distribution in the future.....	10
3 Methodology	11
4 Case descriptions.....	12
4.1 Case 1, South-West interconnector	12
4.2 Case 2, TYNDP 2014 projects contributing to RES integration	13
5 Life cycle inventory	14
5.1 Overhead lines	15
5.2 Subsea cables.....	16
5.3 Underground cables.....	17
5.4 Substations.....	18
5.5 Allocation of cost data to product groups.....	19
6 Results and analysis	20
6.1 Case 1	20
6.2 Case 2	25
7 Discussion and comparison with other studies	31
8 Conclusions and future work.....	34
References	36
Appendix A The harmonised index of consumer prices	39
Appendix B Final demand vectors.....	40
Appendix B.1 Overhead lines.....	40
Appendix B.2 Subsea cable	47
Appendix B.3 Underground cable	51

Appendix B.4 Substations 53

Table of figures

Figure 6.1: Share of total emissions from OHLs and AISs..... 20

Figure 6.2: Share of total emissions from each activity in the modelled system 21

Figure 6.3: Share of investments to each activity. 21

Figure 6.4: Share of emissions from the most important product groups to each emission category in case 1. 24

Figure 6.5: Share of emissions from each technology. 25

Figure 6.6: Overview of correlation between extension lengths in km and the share of required investments. 25

Figure 6.7: Share of total emissions from each activity related to subsea infrastructure..... 26

Figure 6.8: Amount of investments required for each subsea cable activity in MEUR 2007.. 27

Figure 6.9: Share of emissions from the most important product groups to each emission category in case 2. 29

Figure 7.1. Share of CO₂-eq emissions when modelled separately with equal final demand for the product group Sea and coastal water transportation services. 33

List of tables

Table 2.2: Overview of results from references.....	8
Table 5.1: Overview of total length of extensions from each transmission technology (ENTSO-E, 2014).....	14
Table 5.2: Overview of new AIS (ENTSO-E, 2014).....	14
Table 5.3: Total monetary investments required to each activity related to OHL infrastructure for both cases.....	16
Table 5.4: Total monetary investments required to each activity related to subsea cable infrastructure.....	17
Table 5.5: Total monetary investments required to each activity related to UGC infrastructure.....	18
Table 5.6: Total monetary investments required to each activity related to AIS infrastructure for both cases.....	19
Table 6.1: Total emissions from each category from case 1.....	20
Table 6.2: Total emissions from each category from case 2.....	25
Table 8.0.1: Procedure to obtain conversion rates from the harmonised index of consumer prices using data from (Eurostat, 2016).....	39
Table 9.0.2: Final demand price vector for case 1 OHLs located in Germany.....	40
Table 0.3: Final demand price vector for case 2 OHLs, divided between geographical locations.....	45
Table 0.4: Geographical locations of case 2 AC OHL extensions (ENTSO-E, 2014).....	46
Table 0.5: Geographical locations of case 2 DC OHL extensions (ENTSO-E, 2014).....	46
Table 0.6: Final demand price vector for case 2 subsea cables, divided between geographical location.....	49
Table 0.7: Geographical locations of AC subsea cable extensions (ENTSO-E, 2014).....	49
Table 0.8: Geographical locations of DC subsea cable extensions (ENTSO-E, 2014).....	50
Table 0.9: Final demand price vector for UGCs, divided between geographical locations.....	51
Table 0.10: Geographical locations of AC UGC extensions (ENTSO-E, 2014).....	52
Table 0.11: Geographical locations of DC UGC extensions (ENTSO-E, 2014).....	52
Table 0.12: Final demand price vector for case 1 AISs located in Germany.....	53
Table 0.13: Final demand price vector for case 2 AISs, divided between geographical locations.....	54
Table 0.14: Geographical locations of planned AISs (ENTSO-E, 2014).....	55

Abbreviations

COP21	21 st Conference of the parties
GHG	Greenhouse gas
°C	Degrees Celsius
EU	European union
CO ₂	Carbon dioxide
T&D	Transmission and distribution
ENTSO-E	European network of transmission system operators for electricity
TYNDP	Ten-year network development plan
RES	Renewable energy sources
kWh	kilowatt hour
LCA	Life cycle assessment
IOA	Input output analysis
SF ₆	Sulphur hexafluoride
CC	Climate change
kg	kilogram
g	gram
CO ₂ -eq	Carbon dioxide equivalent
gCO ₂ -eq	gram carbon dioxide equivalent
tCO ₂ -eq	ton carbon dioxide equivalent
MWh	Megawatt hour
HV	High voltage
DC	Direct current
AC	Alternating current
GWP	Global warming potential
Mton	Megaton
kton	Kiloton
OHL	Overhead line
UGC	Underground cable
AIS	Air insulated substation

GIS	Gas insulated substation
km	Kilometre
kv	Kilovolt
EEIOA	Environmentally extended input output analysis
MREEIOT	Multi-regional environmentally extended input output table
IO	Input output
NO _x	Mono-nitrogen oxide
TSP	Total suspended particle
SO _x	Sulphur oxide
CO	Carbon monoxide
NMVOC	Non-methane volatile organic compound
IOT	Input output table
GBP	British pound sterling
EUR	Euro
HICP	Harmonised index of consumer prices
OPGW	Optical ground wire
MEUR	Million euro
MEUR 2007	Million euro 2007 value
O&M	Operation and maintenance
PCI	Project of common interest

1 Introduction

1.1 Problem definition

On the 21st Conference of the Parties (COP21) which was held in Paris in December 2015, the governments agreed on long term goals for reducing greenhouse gas (GHG) emissions. The goals aim on keeping the global average temperature well below 2°C, limit the increase to 1.5°C, and use the best available technology for rapid reductions GHGs (European Commission, 2015).

The European Union (EU) was the first major economy to submit its intended contribution to the new global climate agreement, the 2030 climate and energy framework. The framework sets three key targets; at least 40% reductions in greenhouse gas emissions, that at least 27% of energy consumption shall originate from renewable energy and at least a 27% improvement in energy efficiency. The aim is to achieve a more competitive, secure and sustainable energy system. (European Commission, 2014).

Because about 2/3 of all GHG emissions originates from the energy sector, effective actions in this sector is essential to tackling the climate change problem (International Energy Agency, 2015a). In 2005, energy supply and use contributed to around 80% of the CO₂ emissions (Johansson et al., 2012). Other emissions linked to energy supply and use are nitrogen and sulphur oxides, carbon monoxide, total suspended particles and non-methane volatile organic compounds that can lead to increased acidification, eutrophication, ozone and particulate matter.

As a result of the growing global energy demand, driven by population growth, increasing economic prosperity and more energy-intensive technologies, and the increasingly important role of renewable energy in power systems, there is a need for substantial investments of extension and refurbishment of the current transmission and distribution (T&D) network (Johansson et al., 2012).

To support the EU's ambitious energy and climate framework, the European Network of Transmission System Operators for Electricity (ENTSO-E) developed the Ten-Year Network Development Plan (TYNDP). The report acknowledges the environmental challenges and is a contributor to the future development of the European power grid. The TYNDP 2014 (ENTSO-E, 2014) report addresses the current problem with the energy infrastructure, where the majority of the future investments is related to issues with the integration of renewable energy sources (RES).

As a result of expanding RES integration in the European energy system, more grid length will be required to transmit 1 kWh of electricity in the future (R. S. Jorge & Hertwich, 2014). In recent years, there has been an increasing interest for life cycle assessments (LCA) studies on T&D. However, despite the growing interest concerning environmental performances of T&D, limited available literature covering the subject (Arvesen, Hauan, Bolsoy, & Hertwich, 2015; Arvesen, Nes, Huertas-Hernando, & Hertwich, 2014; Harrison, Maclean, Karamanlis, & Ochoa, 2010; R. Jorge, Hawkins, & Hertwich, 2012a; R. S. Jorge & Hertwich, 2013, 2014; Turconi, Simonsen, Byriel, & Astrup, 2014). To the author's knowledge, there is no

environmental assessment of T&D performed with the use of Input-Output Analysis (IOA), which will be the approach utilised in this study.

1.2 Objective

The objective of this study is to investigate the environmental impacts associated with the infrastructure of electricity transmissions. In the first part of this thesis a review of literature relevant to this subject will be performed and identify a case, or several cases, for the following analysis. Further, an Input-Output Analysis approach will be utilised to assess impacts from activities related to monetary investments into the transmission grid. The results of the present study will then be compared with previous process based LCA and hybrid LCA studies.

2 LCA literature on transmission grids and discussion of future aspects of electricity transmission and distribution

As a basis for a comparison of the case study results, a literature review on previous electricity T&D LCA's is conducted. As is mentioned, there is limited literature in this field of study, but 10 references contained relevant data and are hence presented the next subchapter.

2.1 Literature review

Life cycle assessment of transport of electricity via different voltage levels: A case study for Nord-Trøndelag county in Norway (Arvesen et al., 2015).

Arvesen et al. (2015) studied the Norwegian T&D grid. The study was conducted using an LCA case study of electricity transportation to consumers in Nord Trøndelag county. A Hierarchist ReCiPe impact assessment was applied. The assessment covered impacts associated with production, transport, and installation of components, power grid losses and losses of sulphur hexafluoride (SF₆).

The results showed that the local distribution grid caused higher impacts to climate change (CC) than both regional and national transmission grids. The local distribution grid cause emissions of 4.8 kg CO₂-equivalent (CO₂-eq) per MWh, regional transmission grid 1.6 kg CO₂-eq per MWh, and the national transmission grid cause emissions of 1.4 kg CO₂-eq per MWh. Power losses is responsible for 43% of the CC emissions when assuming Norwegian electricity mix. The percentage increases significantly if considering Nordic or European electricity mix.

Finally, a comparison between electricity T&D and electricity generation was investigated for the Norwegian, Nordic and European electricity mix. The study concluded that although the electricity T&D caused less environmental impacts than electricity generation, the impact is too high to be neglected.

Life cycle assessment of an offshore grid interconnecting wind farms and customers across the North Sea (Arvesen et al., 2014).

Arvesen et al. (2014) investigated impacts associated with the Windspeed project. Two different scenarios were compared. The assessment included power cables, ancillary electrical equipment and structures and excluded the offshore wind turbines. The impacts modelled a life cycle perspective, building, operating and dismantling the grid with a lifetime of 30 years.

A hybrid LCA method was utilized, combining process-based LCA and IOA. Developing, operating and dismantling the grid caused emissions of 2.5 g CO₂-eq per kWh. The HVDC cables contributed most to the environmental impacts with almost half of total climate change effects. The report did not take into account power losses or benefits from recycling of components.

Life cycle assessment of electricity transmission and distribution – part 1: power lines and cables (R. Jorge et al., 2012a).

Jorge et al. (2012a) provides a life cycle inventory data and results for power lines and cables to the larger community of LCA practitioners. The study aimed to answer two questions: how large was the impacts resulting from power losses in the equipment and how large was share of impacts associated to each of the life cycle stages. In this first part the report examined power lines and cables. A process based LCA method and Hierarchist ReCiPe impact assessment was utilised.

The results showed that power losses were the dominant process for almost all the impact categories, contributing with up to 99% to climate change impacts. After power losses, the production of metals for masts and conductors for lines were generating the most impacts. For cables, infrastructure impacts are dominated by cable production, and recycling of cable materials did not always compensate for the other impacts generated at the end of life.

Life cycle assessment of electricity transmission and distribution – part 2: transformers and substation equipment (R. Jorge, Hawkins, & Hertwich, 2012b).

Jorge et al. (2012b) assessed the environmental performance of different main components in the electrical grid. This part assessed the impacts of transformers and substation equipment. The process-based life cycle assessment method is used and for the impacts assessment method, ReCiPe Midpoint Hierarchist perspective is used. European power mix is used. Life cycle stages included in this paper is: raw materials production, transportation, use/maintenance, and end of life.

The results showed that for transformers, power losses were the process that have the highest impacts to almost all the impact categories, with climate change impacts of 96%. Within the different life cycle stages, raw materials production had highest contribution to all impact categories. Recycling had benefits to the majority of impact categories. Substation equipment using SF₆ gas showed that leakages contributed up to 78% of the total global warming potential (GWP) score.

Environmental evaluation of power transmission in Norway (R. S. Jorge & Hertwich, 2013).

Jorge et al. (2013) utilised process LCA to estimate and characterize the environmental impacts of the Norwegian transmission system. The impact assessment method used was ReCiPe midpoint for three perspectives: egalitarian, hierarchical and individualistic. Processes included were: production of materials, installation, operation/maintenance and end-of-life. Power losses were modelled for Norwegian supply mix, Nordic mix and average European mix.

The results showed emissions of 1.3-1.5 gCO₂-eq per kWh transmitted assuming Norwegian electricity mix and 10.6-11.8 gCO₂-eq per kWh assuming European mix. Results from the hierarchical perspective showed that raw materials have the largest contribution to GWP but almost half was gained from recycling at the end-of-life stage, resulting in power losses as the largest contributor with 68%. Switching electricity mix to Nordic mix and European mix

increased the power loss contribution to CC. Excluding losses, overhead lines contributed most to CC followed by SF₆ emissions and transformers.

Grid infrastructure for renewable power in Europe: The environmental cost (R. S. Jorge & Hertwich, 2014).

Jorge et al. (2014) investigated what modifications were required to upgrade the European transmission grid in order to develop the renewable energy capacity in the European region and performed an LCA to estimate the consequences associated with the grid extensions and upgrades. The method used was process based LCA and impact assessment method was ReCiPe midpoint-oriented, Hierarchical perspective. Power losses in this study were excluded.

The results showed a contribution of 10.7 Mton CO₂-eq. 8.7 Mton CO₂-eq from new lines and 2 Mton CO₂-eq from renovation or upgrading existing lines. In 2020, electricity transmission will be more material intensive, with about a 10% increase in metal use per kWh transmitted.

Life cycle assessment of the transmission network in Great Britain (Harrison et al., 2010).

An assessment of the life cycle carbon emissions of the entire high voltage transmission network in Great Britain is presented by Harrison et al. (2010) The boundary considered all energy inputs and carbon emissions from extraction of raw materials to the disposal at the end-of-life phase. The functional unit was defined as impact per kWh electricity transmitted but also presented the result for an alternative functional unit, namely impact per km. The method used was process-based LCA.

The GWP of the transmission network was 11 gCO₂-eq per kWh electricity transmitted or alternatively 6,300 tCO₂-eq per km. 96% of the impacts emerged from the operational/use phase, where the highest contributor was power losses with 85%, a significant impact from SF₆ gas was also mentioned.

Life cycle assessment of the Danish electricity distribution network (Turconi et al., 2014).

The aim of this study by Turconi et al. (2014) was to evaluate the potential importance of environmental impacts associated with distribution, in current and future electricity systems. The assessment focused on the Danish distribution network and provides comparisons to the generation and transmission of electricity. The article defined the functional unit as impact per kWh electricity transmitted and a process-based LCA methodology was used. Impact assessment categories from the ReCiPe methodology was used, but the perspective was not specified.

The results showed a non-negligible contribution from electricity T&D, where impacts from the distribution network was 1.6-2.5 times larger compared to transmission network for all impact categories. This was because of lower voltage caused higher losses and distribution networks are more complex. It is also concluded the importance of impacts from electricity distribution are likely to increase in the future because of expansions of RES.

Life-cycle assessment of electricity in Portugal (Garcia, Marques, & Freire, 2014).

This article by Garcia et al. (2014) assessed the life cycle environmental impacts of electricity generation and supply in Portugal from 2003 to 2012. A process-based LCA methodology was used. The T&D infrastructure comprised of OHLs, underground cables, substations and transformers. All the life cycle stages were included along with power losses and SF₆ leakages. The lifetime of each component in the system is modelled with a lifetime of 40 years.

Total power losses ranged between 6.3% and 9.6% whereas the majority originated in the distribution grid, 80% of total, and 20% in the transmission grid. SF₆ leakages was also larger in the distribution grid with 175.4 kg SF₆ per year compared to 46.7 kg SF₆ per year in the transmission grid. For emissions contributing to global warming, the transmission grid had more impacts, 0.64 g CO₂-eq per kWh electricity transmitted, than the distribution grid, 0.53 g CO₂-eq per kWh electricity transmitted.

Life cycle assessment of overhead and underground power distribution (Bumby et al., 2010).

Bumby et al. (2010) studied the environmental impacts from overhead lines (OHL) and underground cables (UGC) in southern California on a distribution level and used process-based LCA methodology. The entire life cycle of the components was assessed including benefits from recycling. Operational lifetime is different for the two technologies, OHLs was 40 years, and UGC was 30 years. The functional unit was defined as impacts per circuit over one mile (1.609 km) per year.

The results were presented in different scenarios, baseline, best and worst case. The baseline scenario showed for OHLs a GWP of 1,419 kg CO₂-eq per mile per year and for UGC 7,683 kg CO₂-eq per mile per year.

Main findings

The literature collected in the present thesis have all assessed potential environmental effects of transmission and/or distribution OHLs, underground and subsea cables as well as substations, transformers and switchgear. Some common results among the literature was non-negligible impacts from T&D networks, and the majority of impacts was related to power losses. Some references also included statements of scarcity in LCA literature on T&D. The methods used was mainly process-based LCA. An exception is Arvesen et al. (2014) which included IOA in a hybrid LCA. The voltage levels in the literature review differs in many ways. Different countries operate with different voltage levels, as well as the difference of transmission network and distribution network. The greater part of the articles clearly defines their functional unit as impact per kWh electricity transmitted, but impact per MWh, impact per km and total impact is also used. Components included in the articles assessments depends on the scope of each article and varies accordingly. Generally, OHLs and cables for various voltage levels, substations, switchgear and transformers is consistently included in the assessments. Jorge et al. (2013) acknowledges the importance of recycling at the end-of-life phase and the positive contribution it had on the overall system. Jorge et al. (2012a) argues that subsea cables are recycled but in reality is not due to high cost. References (Arvesen et al., 2015; R. Jorge et al., 2012a; R. S. Jorge & Hertwich, 2013) shows that emissions from power losses will vary

depending on the electricity generation mix. In Arvesen et al. (2015) and Jorge et al. (2013), when assuming Norwegian supply mix, both studies estimated rather low power loss contributions to climate change, with 43% and 51% respectively, compared to European production mix where power loss contribution was 99% in Jorge et al. (2012a) and 94% in Jorge et al. (2013). In Jorge et al. (2012a), the highest contributor to CC impacts was power loss with a contribution of 99%.

Reference	Voltage level/technology	Power loss	Recycling benefits	SF ₆	Emissions	Functional unit	Lifetime (years)	Method
(Arvesen et al., 2015)	Main transmission	Yes	No	Yes	1.4 kgCO ₂ -eq	MWh	40	Process LCA
(Arvesen et al., 2014)	33 kV, 450 kV	No	No	No	2.5 gCO ₂ -eq	kWh	30	Hybrid LCA
(Arvesen et al., 2014)	450 kV DC subsea cable	No	No	No	215 tonCO ₂ -eq	Km	30	Hybrid LCA
(R. Jorge et al., 2012a)	AC 400 kV OHL	Yes	Yes	No	525 tonCO ₂ -eq	Km	40	Process LCA
(R. Jorge et al., 2012a)	HVDC subsea cable	Yes	Yes	No	125 tonCO ₂ -eq	Km	40	Process LCA
(R. Jorge et al., 2012b)	420 kV gas insulated substation (GIS)	Yes	Yes	Yes	930 tonCO ₂ -eq	Unit	40	Process LCA
(R. S. Jorge & Hertwich, 2013)	Transmission grid, 132 kV – 420 kV	Yes	Yes	Yes	1.3-1.5 gCO ₂ -eq	kWh	100	Process LCA
(R. S. Jorge & Hertwich, 2014)	Transmission	No	Yes	Yes	10.7 MtonCO ₂ -eq	System	40	Process LCA
(Harrison et al., 2010)	Transmission	Yes	Yes	Yes	11 gCO ₂ -eq	kWh	40	Process LCA
(Harrison et al., 2010)	Transmission	Yes	Yes	Yes	6300 tonCO ₂ -eq	Km	40	Process LCA
(Turconi et al., 2014)	Distribution	Yes	Yes	Yes	28.5 gCO ₂ -eq	kWh	40	Process LCA
(Garcia et al., 2014)	Distribution and transmission	Yes	No	Yes	0.64 gCO ₂ -eq	kWh	40	Process LCA
(Bumby et al., 2010)	Distribution, OHL	No	Yes	No	1419 kgCO ₂ -eq	Mile/year	40	Process LCA
(Bumby et al., 2010)	Distribution, UGC	No	Yes	No	7683 kgCO ₂ -eq	Mile/year	30	Process LCA

Table 2.1: Overview of results from references.

Conclusions

This literature review considered LCA studies related to environmental impacts from T&D networks. Although the assessments differ in geographical locations, voltage levels, and T&D technologies (cables, overhead lines, AC and DC), important results are obtained and can be compared with results in this study.

The majority of the reviewed articles, (Arvesen et al., 2015; Arvesen et al., 2014; Harrison et al., 2010; R. Jorge et al., 2012a; R. S. Jorge & Hertwich, 2013, 2014; Turconi et al., 2014), mention the limited amount of research aimed at environmental assessments and life cycle data related to the T&D network. In all articles, except for Arvesen et al. (2014), the process-based LCA method was used. Even though this particular method is widely used, it has some limitations such as truncation errors which leads to underestimation of environmental impacts (Majeau-Bettez, Strømman, & Hertwich, 2011). Arvesen et al. (2014) utilised a tiered hybrid methodology, which is a combination of process-based LCA and IOA. Process LCA also suffer from cut-off errors and difficulties of defining system boundaries (Suh et al., 2004). And IOA have high level of aggregation which leads to increased uncertainty (Majeau-Bettez et al., 2011). Because there is advantages and disadvantages related to each of the two methods, the Hybrid LCA aims at combining the strengths of both methods (Suh et al., 2004). This results in an improved system boundary completeness (Crawford, 2008) and reduce uncertainty (E. D. Williams, Weber, & Hawkins, 2009).

In every article except Garcia et al. (2014), where power losses was included in the assessment, the importance of power losses related to environmental impacts was identified as the largest contributor of CO₂-eq emissions, ranging from 43% to 99% of total contributions. Additionally, the electricity mix used affected the power loss contribution because of the CO₂ concentration is higher in European electricity mix compared to the Norwegian. Specifically Arvesen et al. (2015) and Jorge et al. (2013), illustrated this in a clear manner by implementing Norwegian, Nordic and European electricity mixes in their assessments to compare the differences. Hence, resulting in a considerably lower impact percentage when Norwegian electricity mix was assumed.

The references that accounted for recycling benefits, that is recycling of materials that outweighs the sum of impacts generated by other end-of-life processes, generally showed a positive impact on CC impact potential. An exception is Jorge et al. (2012a), revealing negative impacts on CC for recycling of land cables.

SF₆ gas, which is an extremely potent greenhousegas, only affect results for climate change potential. The amount of contribution to CC depends on how much gas insulated switchgear equipment is used in the substations, but the majority stem from the transmission grid (Arvesen et al., 2015; Garcia et al., 2014; Turconi et al., 2014). According to Turconi et al. (2014), an expected increase in the use of SF₆ gas when the deployment of smart grids is to take place.

2.2 Electricity transmission and distribution in the future

In the coming years, the demand for electricity will grow driven by factors like population growth, increased economic prosperity, expanding middle class and more energy intensive technologies (International Energy Agency, 2015b), along with a potential electrification of heat and transport sector (Berrill, Arvesen, Scholz, Gils, & Hertwich, 2016). In order to maintain a steady course of decarbonising the energy sector and to adjust for more power generation, an expansion of renewable energy sources is needed along with phasing out electricity generated from fossil fuels. This, as well as renewable technologies' increasing competitiveness (International Energy Agency, 2015b), will introduce an increasing amount of renewable energy penetration to the electrical T&D grid.

The existing T&D infrastructure is aging, and have problems with congestion, peak-loads, power losses and reliability, and was not built for an electricity mix with high penetration of renewable energy (Johansson et al., 2012). With this comes intermittent and variable electricity supply from wind and solar power, which can lead a decrease in security of supply. Conventional power plants generate a steady flow of electricity, as for solar and wind energy, the supply is influenced by weather and cannot easily be adjusted to follow demand at all times. Hence, the grid must develop flexibility in the system to accommodate for more volatile energy generation. Originally, T&D grids were optimised for regional self-sufficiency and developed for a more centralised generation, and interconnections between regions was created for mutual support, which can explain the current congestion problems and bottlenecks, due to lack of capacity, between European countries (Hammons, 2008). Additionally, renewable energy sources are located far away from consumption areas, e.g. offshore windfarms, and thus require more infrastructure leading to larger mineral resource depletion impacts than fossil fuel systems, and more land occupation impacts than systems based on natural gas (Berrill et al., 2016).

In order for the T&D grid address these challenges, there is a need for huge investments and development of new policies (International Energy Agency, 2015a). Upgrades of current lines to accommodate for higher loads and reducing network losses. Extensions of transmission lines and interconnections between regions to avoid congestion problems and bottlenecks. The ability of transportation of electricity over longer distances to support regions with imbalance supply and demand, and to integrate a distributed renewable energy system to the T&D grid. A future T&D grid will rely more on implemented technology like data communication between source and end-users, additional surveillance and better control capabilities to more efficient operation of power generation (Johansson et al., 2012). Smart grid technologies are also part of a futuristic T&D network, that be connected or disconnected to the T&D grid, contributing to optimise grid operations and can have a relieving effect on the network in terms of lower loads and network losses because of the power is generated near consumption areas (International Energy Agency, 2015b). Smart grids provide also the opportunity to support the increasing electrical vehicle fleet as an electricity storage option (International Energy Agency, 2015b). Other measure like energy storage, that is pumped hydro and battery banks, also adds to the flexibility and optimisation of the T&D network (International Energy Agency, 2015b).

3 Methodology

In the present study, Environmentally Extended Input-Output Analysis (EEIOA) method is utilised, using a top-down approach to assess the environmental impacts from two product systems, a specific project in Germany and an aggregation of European projects contributing to RES integration. This method uses monetary data to estimate environmental impacts based upon economic activities, which in this case, is economic outputs from product groups.

The Input-Output database that will be used is Exiobase. This is a global, detailed multi-regional environmentally extended input output table (MR EE IOT) created in the EXIOPOL project (Richard et al., 2014; Tukker et al., 2013). The database covers 43 countries, 5 regions, 200 products and 163 industries. Whereas in this analysis specific countries in the European region is utilized. The IO table used is product by product for the year 2007.

For the impact assessment, the CML 2001 (Institute of Environmental Science, Leiden University) method is used ("CMLCA, "). Environmental impact categories and stressors that are analysed is CC, mono-nitrogen oxides (NO_x), total suspended particles (TSP), sulphur oxide (SO_x), carbon monoxide (CO) and non-methane volatile organic compound (NMVOC). The reason for including these particular non-greenhouse gas pollutants is related to their contribution to air pollution, giving negative effects like increased acidification, eutrophication, ozone and particulate matter. The results are obtained using the LCA software tool Arda, developed by the Industrial Ecology Programme at NTNU ("Industrial Ecology Programme (IndEcol),").

The goal of this part of the thesis is to perform an environmental assessment of electricity transmission using input-output analysis. More specific, two cases will be studied. The first case will focus on a current transmission extension project in Germany and assess the environmental impacts. The next case will use the TYNDP 2014 as a basis to assess environmental impacts of planned extensions in the European transmission network until year 2030. Considering the investigation of two different cases, there will also be different scope. To make it easier to differentiate, they will be identified as Case 1 and Case 2. Case 1 being selected sections of the South-West interconnector project located in Germany. Case 2 is the aggregation of projects contributing to RES integration in Europe from the TYNDP 2014.

For case 1, the scope is the product system consisting of OHLs and substations related to the project. For case 2, the scope is the product system consisting of OHLs, land and sea cables and substations.

The systems functional unit would optimally be presented in impacts per unit electricity delivered. This would make it easier to compare results with previous studies on the subject. However, this will not be the case due to little or no information on transmission power flows. Therefore, for both cases, the functional unit will be the product system itself. The lifetime of the grid, and all components, is assumed to be 40 years, which is based on the literature review. End of life and power losses is not included in the assessment due to little or no data. Benefits or impacts from recycling is likewise not considered.

4 Case descriptions

4.1 Case 1, South-West interconnector

When selecting a case, some criteria were established in order to narrow down potential projects. Firstly, it had to be part of the TYNDP and contribute to RES integration. Secondly, it was preferred that it was important on local and regional scale.

The selected case is mentioned in the European network of transmission system operators for electricity's "ten-year network development plan" for 2010, 2012, 2014 and 2016 (ENTSO-E, 2010, 2012, 2014, 2016). The project was also selected as a project of common interest (PCI) by the European Commission (European Parliament and the Council of the European Union, 2006). Another major factor contributing to the importance of this project is the decommissioning of the Grafenrheinfeld nuclear reactor (D. Williams, 2015). This would lead to a lack of power supply in Southern Germany, and the South-West Interconnector is part of the solution that will transfer wind power from the north to the south, and will further contribute to the transition to a more renewable based generation of electricity. This emphasizes some of the importance of the development of this transmission line.

The project is called the South-West interconnector and has the intention of connecting Bad Lauchstädt to Schweinfurt via a 380 kV AC overhead line (50Hz). The project is also referred to as Halle/Saale-Schweinfurt. The project stretches over three regions, Saxony-Anhalt, Thuringia and Bavaria and couples the control areas of two independent transmission system operators, 50Hz Transmission GmbH in the North-East Germany and TenneT TSO GmbH in the South-Western part. 50Hz has the responsibility within the Saxony-Anhalt and Thuringia region, meaning the stretches from Bad Lauchstädt to Vieselbach, from Vieselbach to Altenfeld and from Altenfeld to the state border between Thuringia and Bavaria. From this state border, TenneT has the responsibility for the transmission line from the state border to Redwitz and from Redwitz to Schweinfurt.

To simplify this project to some degree, this case will only include the part of the project that is within the responsibility of 50Hz, in the regions of Saxony-Anhalt and Thuringia. This is the stretch from Bad Lauchstadt to state border between Thuringia and Bavaria. The project is divided into three sections with different completion dates. Section 1, Bad Lauchstädt to Vieselbach, consists of 80 km of double circuit 380 kV OHLs. Section 2, Vieselbach to Altenfeld, consists of 57 km of double circuit 380 kV OHLs. Section 3, Altenfeld to Thuringian state border, consists of 26 km of double circuit 380 kV OHLs.

4.2 Case 2, TYNDP 2014 projects contributing to RES integration

The planned extensive development of the European transmission grid in the coming future requires billions of euros in investments. As part of the solution to the European climate project, to reduce greenhouse gas emissions and increase renewable energy consumption, the TYNDP 2014 have developed an overview of electricity transmission projects until 2030. These extension has a variety of purposes like improving security of supply and market integration, increasing renewable energy source integration, reducing congestion and intensifying competition (ENTSO-E, 2014).

Every project listed in the TYNDP 2014, has an assessment of RES integration for four different future visions. Visions 1 and 2, “Slow Progress” and “Money Rules” respectively, assume a slower start before an acceleration after 2030, while Vision 3 and 4, “Green Transition” and “Green Revolution” respectively, assume to maintain a regular pace until 2050 (ENTSO-E, 2014). Forward, this study will assess the environmental impacts from projects that is estimated to increase RES integration in Europe for all four visions and will subsequently include the majority of the listed projects. Components assessed in the transmission grid extension is OHLs, subsea cables, underground cables and substations. The listed projects are all located in different countries, and this will be reflected in the final demand. The IOT does not cover every country, hence some countries will be combined and presented as a region.

Although the timeline of the projects is listed to be built between 2014 and 2030, it is assumed that all projects are built and completed at present time and do not account for future benefits from improved technology.

5 Life cycle inventory

This chapter presents the compilation of monetary data of the two cases. Cost data for various transmission technologies is a challenge to attain, and more so, finding data from credible sources.

Monetary data related to OHLs, UGCs and subsea cables are obtained from a costing study done by Parsons Brinckerhoff (Parsons Brinckerhoff, 2012) and will be the foundation of the cost estimates for overhead lines, subsea cables, underground cables and converter stations. The report has through communications with companies established cost estimates for various scenarios and presents allocation of costs within a project. The attributed cost data from this source is firstly converted from British Pound Sterling (GBP) to Euro (EUR) using the average 2012 exchange rate of 1.2338 (European Central Bank, 2016) and secondly, using the Harmonised Index of Consumer Prices (HICP) to further convert the 2012 EUR value to 2007 EUR value (Eurostat, 2016), in order to be coherent with the Exiobase database. A more detailed view of the HICP conversion is provided in Appendix A

Cost data acquired for substations are obtained from (Balzer & Schorn, 2015) and (Alberta Electric System Operator, 2013), and provides life cycle costs for a 380 kV and 240 kV Air-Insulated Substation (AIS). The cost data will be a combination of data from these sources to present a more complete system. For monetary conversion of Canadian dollar (CAD) to EUR, the average 2013 exchange rate of 0.7315 (European Central Bank, 2016) was used and further converted to 2007 EUR value with HICP.

When line and cable lengths were not specified in the TYNDP 2014 (ENTSO-E, 2014), it was then estimated by a distance calculator tool by Google Maps Api (Google Maps Api, 2016)

TRANSMISSION TECHNOLOGY	LENGTH (KM)	
	CASE 1	CASE 2
OHL AC	163	11,918
OHL DC		1,500
SUBSEA CABLE AC		375
SUBSEA CABLE DC		12,431
UNDERGROUND CABLE AC		32
UNDERGROUND CABLE DC		299
TOTAL	163	26,555

Table 5.1: Overview of total length of extensions from each transmission technology (ENTSO-E, 2014).

SUBSTATIONS	AMOUNT	
	CASE 1	CASE 2
	2	40

Table 5.2: Overview of new AIS (ENTSO-E, 2014).

5.1 Overhead lines

The acquired cost data for OHLs is for double circuit 400 kV, and it is further assumed no price difference between 400 kV and 380 kV (where 400 kV is the transmission voltage in Great Britain and 380 kV is the transmission voltage in Germany). In case 1, that is the construction of 163 km of OHLs in Germany, the extension of OHLs is carried out as three separate projects. In the cost estimate this is implemented but the data are presented as total costs.

As for case 2, the European transmission grid extension, the planned construction of OHLs varies in length, voltage and number of conductors and there is also a geographical dispersion. Also here, it is assumed no price difference between the following voltage levels 380/400 kV and 275/330 kV. Using this cost estimate for OHLs with lower voltages and single conductor contributes to some uncertainties. The average length of the total planned extensions for each voltage and conductor category is used when establishing a cost estimate. For example, the double circuit 380/400 kV OHL have a total planned extension of 8,904.1 km from 89 separate projects in 19 countries. The cost estimate will then be based upon 89 projects of about 100 km each, and the costs will further be divided in the final demand vector between countries where extensions are planned.

Costs of construction for overhead lines consists of multiple different activities and components where (Parsons Brinckerhoff, 2012) have estimated and distributed the costs to relevant activities. This includes cost of materials, construction, planning, operation and maintenance and contingencies. The following paragraph explains the activities related to the construction of overhead lines and it is also the basis of costs allocated to product groups in Exiobase.

Mobilisation extras is the associated cost for transportation of personnel, equipment and supplies along with establishment of site office. *Tower materials*, cost of constructing the tower and transportation to site. *Conductors and OPGW materials*, cost of conductors and OPGW cable and transportation to site. Including joint boxes. *Access roads* includes construction of access roads, necessary improvements to existing roads, managing topsoil and reinstatement process following the completion of the project. *Insulators and fittings materials* is the cost of insulator strings, steel and aluminium conductor fittings and transportation to site. *Foundations, erection of towers and stringing*, cost of labour activities and crane transport and use and cost of material and plant. *Engineering and safety*, costs of site-based engineering, management, safety and design. *Project launch and management* encompass costs of early designs, applications and project management. *Build contingency* cover unexpected costs that may arise during the construction period. *Operation and maintenance* cover costs from route patrols and inspections, vegetation management, painting of towers and other maintenance work. (Parsons Brinckerhoff, 2012).

ACTIVITIES	MEUR 2007	
	Case 1	Case 2
	163 km	13,417.7 km
MOBILISATION EXTRAS	8.37	395.73
TOWER MATERIALS	29.14	1,910.56
CONDUCTORS AND OPGW MATERIALS	24.66	1,726
ACCESS ROADS TOTAL	39.94	2,823.61
INSULATORS AND FITTINGS MATERIALS	12.23	844.11
FOUNDATIONS, ERECTION OF TOWERS AND STRINGING	87.22	5,741.44
ENGINEERING AND SAFETY	40.34	2,670.85
PROJECT LAUNCH AND MANAGEMENT	24.19	1,610.97
BUILD CONTINGENCY	24.19	1,610.97
OPERATION AND MAINTENANCE	10.60	777.1

Table 5.3: Total monetary investments required to each activity related to OHL infrastructure for both cases.

5.2 Subsea cables

Subsea cables are only in the scope of case 2. There is a total of 12,798 km of planned subsea cable extensions. Using the same approach as the previous subchapter, with regards to using average lengths, when establishing the cost estimate. The cost data are obtained from (Parsons Brinckerhoff, 2012) and is further modified depending on the voltage level and cable length. An explanation of the activities required to constructing a subsea cable are presented in the following paragraph.

Cable studies and assessments, is the cost of the pre-build assessments of the landing sites. *Cable landing costs and materials*, is the cost of coming ashore and termination of the cable. *Cable mobilisation and demobilisation costs*, includes mobilising and fitting out the marine vessels and crew cost. *Cable contractor project management*, is the cost of the cable and cable installation management. *Cable studies and assessments*, cost of route assessments, desktop studies, utility surveys and sonar scans. *Cable materials and installation*, is the main cost of cable works, materials, manufacture and installation. *Marine insurance (cable)*, insurance cost. *Cable project launch and management*, cost of early designs, applications and management. *Cable system build contingency*, covers unforeseen costs that may arise. *Operation and maintenance*, is the cost of maintaining the subsea cable. (Parsons Brinckerhoff, 2012).

ACTIVITIES	MEUR 2007
	12,797.8 km
CABLE LANDING COSTS AND MATERIALS	2,130.23
CABLE MOBILISATION/DEMOBILISATION COSTS	201.30
CABLE CONTRACTOR PM	1,193.74
CABLE STUDIES AND ASSESSMENTS (FIXED + VARIABLE)	3,571.78
CABLE MATERIALS AND INSTALLATION	1,7424.51
MARINE INSURANCE (CABLE)	825.81
CABLE PROJECT LAUNCH AND MANAGEMENT	2,990.04
CABLE SYSTEM BUILD CONTINGENCY	4,488.07
OPERATION AND MAINTENANCE	8,398.14

Table 5.4: Total monetary investments required to each activity related to subsea cable infrastructure.

5.3 Underground cables

The unground cables are additional to subsea cables only in the scope of case 2. The planned extensions are 331 km. The cost data was obtained from (Parsons Brinckerhoff, 2012), and further modified based on voltage level and cable length. An explanation of the activities required to constructing underground cables are presented in the following paragraph.

Cable terminal compound, is the construction of terminal compound at each end of the cable. *Cable terminations and testing*, is the build cost of supplying and erecting cable terminations along with the costs of testing. *On route cable system materials*, is the costs of cable materials. *On route cable installation*, is the cost of excavation and cable installation. *Reactor costs*, is the cost of reactive compensation equipment. *Special constructions*, is the cost of those works considered to be over and above that required to install the cable. *Build contingency*, covers unforeseen costs. *Project launch and management*, is the costs of routeing surveys, soil samples, predesign, consultants and management. *Operation and maintenance*, is the cost of cable maintenance. (Parsons Brinckerhoff, 2012).

ACTIVITIES	MEUR 2007
	330.8 km
CABLE TERMINAL COMPOUND	50.61
CABLE TERMINATIONS AND TESTING	22.96
ON ROUTE CABLE SYSTEM MATERIALS	1,657.99
ON ROUTE CABLE INSTALLATION	2,346.84
REACTOR COSTS	324.55
SPECIAL CONSTRUCTIONS	281.786
BUILD CONTINGENCY	660.44
PROJECT LAUNCH AND MANAGEMENT	1,012.68
OPERATION AND MAINTENANCE	55.7

Table 5.5: Total monetary investments required to each activity related to UGC infrastructure.

5.4 Substations

Two substations are incorporated in case 1. Vieselbach and Altenfeld substation. Due to little-to-non data available on former or current technical aspects of the two substation, further assessment will be based on the assumption that two new 380 kV Air-Insulated Substations (AIS) will be constructed in these locations.

In case 2, it is also assumed air-insulated substations. A total of 40 substations will be built to facilitate RES integration. The number may be higher as some of the described extensions contained uncertain formulations as for example “several”. 38 substations will reduce voltage levels from 380/400 kV. The cost of refurbishment and upgrade of substations are not included, only planned to be constructed substations are included.

The substations consist of plant, where minor components are aggregated like busbars, dead ending, portals, etc., five circuit-breakers, one power transformer, 25 disconnectors, 15 instrument transformers and five bays (Balzer & Schorn, 2015). This is the general content of a substation. In addition to the equipment cost data for components from (Balzer & Schorn, 2015), products from construction of buildings, commissioning and engineering will be added (Alberta Electric System Operator, 2013). An explanation of activities required to build substations are presented in the following paragraph.

Plant, is the cost of manufacturing and installing minor components in the system. *Circuit breaker*, manufacturing and installation cost. *Power transformer*, manufacturing and installation cost. *Disconnecter*, manufacturing and installation cost. *Instrument transformer*, manufacturing and installation cost. *Secondary equipment*, manufacturing and installation cost of the equipment required to protect and control the entire substation. *Structures*, construction cost of substation facilities. *Commissioning*, covers the cost of testing, inspections and procurement. *Engineering*, covers the cost of design, studies and management. *Operation and maintenance*, is the cost of operating and maintaining the substation.

ACTIVITIES	MEUR 2007	
	Case 1	Case 2
	2 substations	40 substations
PLANT	10.86	213.94
CIRCUIT-BREAKER	1.2	23.64
POWER TRANSFORMER	5.66	111.50
DISCONNECTOR	2.1	41.37
INSTRUMENT TRANSFORMER	2.78	54.77
SECONDARY EQUIPMENT	1.04	20.49
STRUCTURES	2.5	49.25
COMISSIONING	0.44	8.67
ENGINEERING	1	19.70
OPERATION AND MAINTENANCE	8.72	171.78

Table 5.6: Total monetary investments required to each activity related to AIS infrastructure for both cases.

The monetary investments are not exactly 20 times higher, this is because two substations (in case 2) have lower voltage level, 220 kV and 275 kV.

5.5 Allocation of cost data to product groups

The allocation of monetary outputs from various product groups related to activities, are based on own assumptions and explanations of costs associated with the different activities from (Parsons Brinckerhoff, 2012). To further allocating costs between countries (this only applies for case 2, where several countries are involved), the fraction of cable lengths in each country is used. A total overview is provided in Appendix B.

6 Results and analysis

This chapter presents the result of the input-output analysis based on the LCI from the previous chapter. The first subchapter studies the first case, with in-depth analysis of emissions from OHLs and AISs. The second subchapter presents the results from future grid extensions with an in-depth analysis of subsea cable.

6.1 Case 1

The system is disaggregated into two distinctive parts. Namely, overhead lines and substations. Table 6.1 display the total life cycle emissions from selected impact categories and stressors for the extension of 163 km overhead lines and two air insulated substations, and Figure 6.1 shows the share of emissions represented by OHLs and AISs. The largest share of the emitting pollutants originates from OHLs, as is evident from Figure 6.1, with between 88% and 90%.

IMPACT/STRESSOR	UNIT	TOTAL
CLIMATE CHANGE (CC)	Kg CO ₂ -eq	2.45E+08
NITROGEN OXIDES (NO _x)	Kg	4.26E+05
TOTAL SUSPENDED PARTICLES (TSP)	Kg	8.08E+04
SULFUR OXIDE (SO _x)	Kg	4.49E+05
CARBON MONOXIDE (CO)	Kg	9.84E+05
NON-METHANE VOLATILE ORGANIC COMPOUND (NMVOC)	Kg	3.24E+05

Table 6.1: Total emissions from each category from case 1.

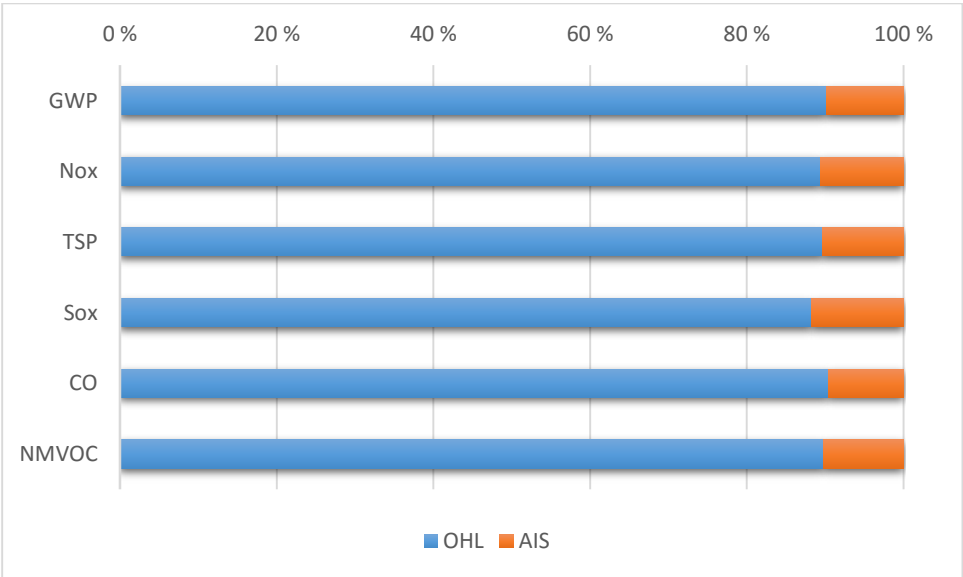


Figure 6.1: Share of total emissions from OHLs and AISs.

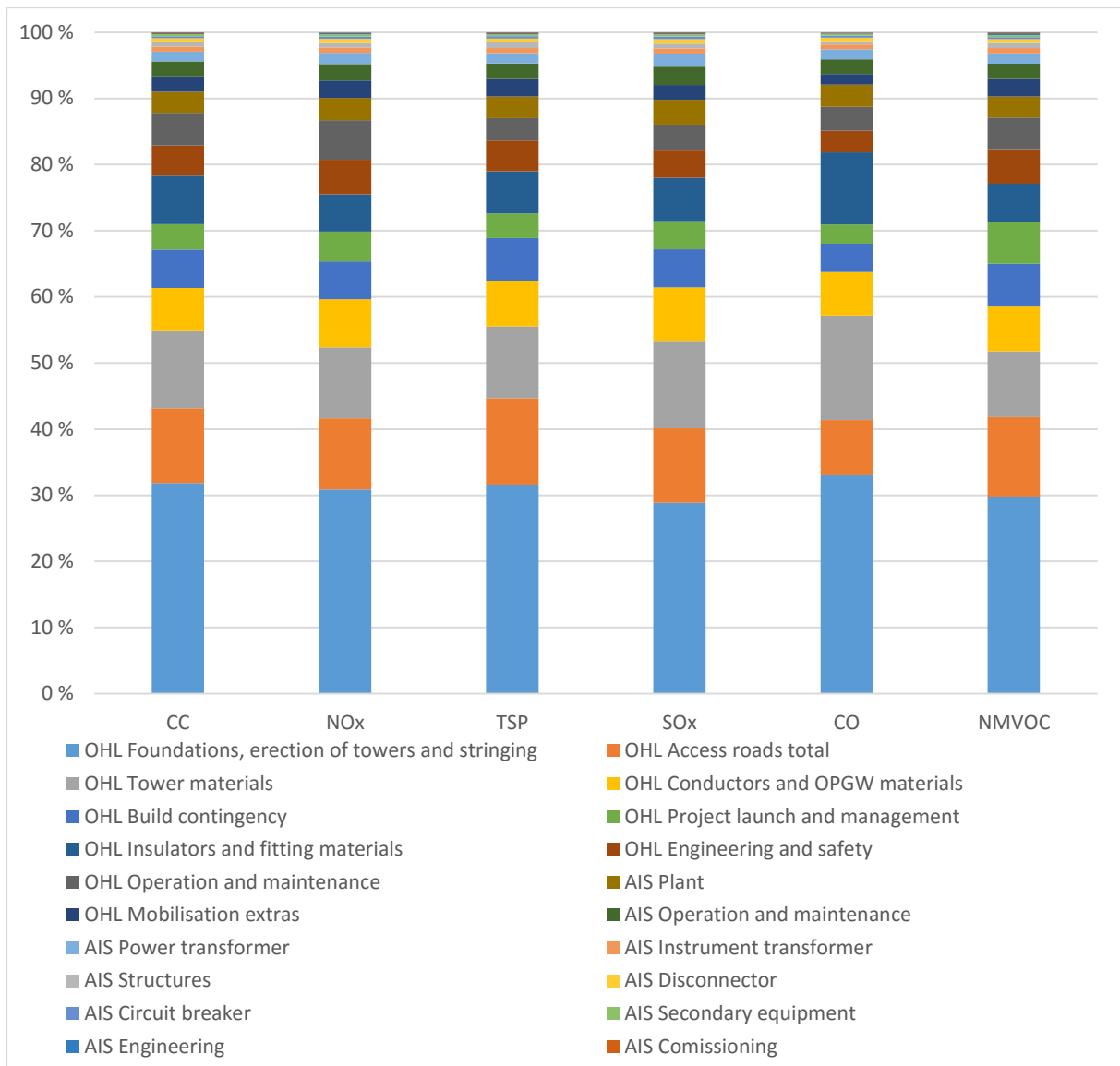


Figure 6.2: Share of total emissions from each activity in the modelled system.

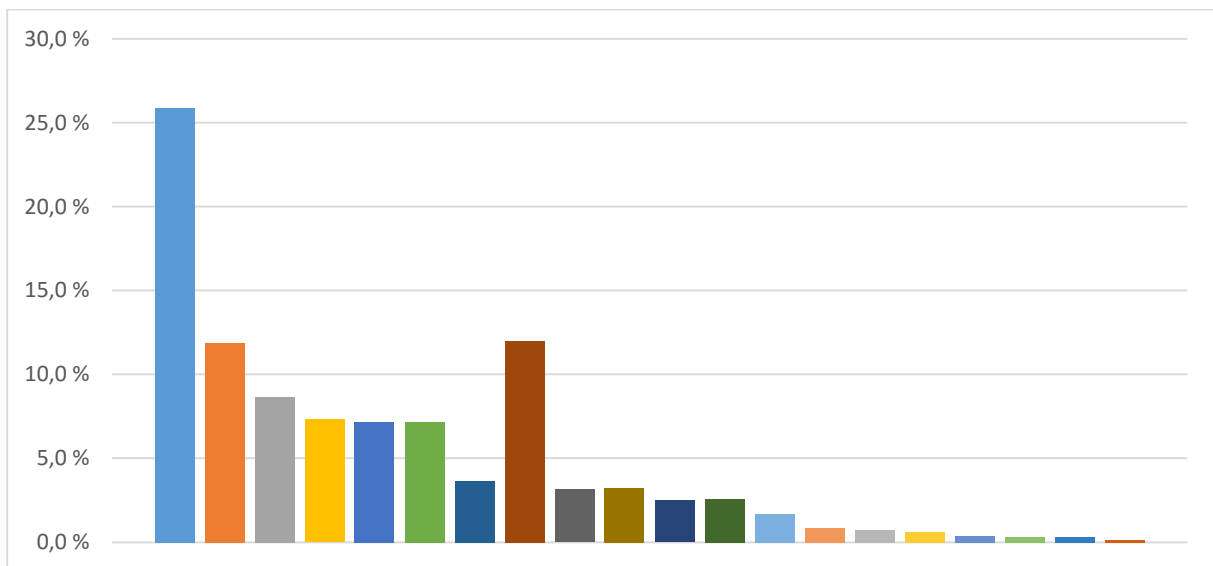


Figure 6.3: Share of investments to each activity.

Figure 6.2 displays the share of impacts represented by each activity in the system. This illustration clearly shows the dominating contribution of emissions from OHL infrastructure. Figure 6.3 shows the investments to each activity. The highest emissions stem from the activity OHL foundations, erection of towers and stringing, with 29% to 33% of total emissions. Emissions from this activity originates primarily from the use of steel, cement, transport and operation of heavy equipment. Whereas emissions from cement and steel products represents most contribution to CC. For NO_x emissions, transportation, steel and cement represents the largest shares. TSP emissions originates mostly from manufacturing of cement and is followed by fabrication of steel. Further, SO_x emissions has the highest contribution from generation of electricity by coal. The electricity is further used in steel manufacturing and various construction work. Also, sea and coastal water transportation contributes to SO_x emissions with at least 11%. CO emissions originate mostly from manufacturing of steel products, with over 60%. Lastly, NMVOC emissions is dominated by crude petroleum and services related to crude oil extraction which is further processed and converted to gas/diesel oil. Gas/diesel oil are then used in construction work by heavy equipment, and in land transportation.

Next, emerges tower materials and construction of roads as second and third highest contribution to the impact categories. Tower materials for the masts varies between 10% and 16% emissions of total. Whereas the CO₂-eq emissions mainly originates from the production process of steel followed by the generation of electricity from coal, NO_x emissions derives from generation of electricity from coal as the largest contributor and sea and coastal water transportation services. TSP emissions has, similarly to CC emissions, largest contribution from the production process of steel and generation of electricity from coal. SO_x emissions arise mainly from generation of electricity by coal with at least 33%, and is followed by the production process of steel with at least 17% of the emissions. Over half of the tower material total CO emissions occur from steel production. Emissions of NMVOC is mainly due to crude petroleum and services related to crude petroleum, fabrication of steel products and manufacture of other bituminous coal. The activity of constructing access roads is one of the top contributors to the total amount of emissions. The construction work emits between 8% and 13% from the various categories.

The conductor and OPGW materials have lower emissions than expected. Mainly due to the aggregated product sector in the IOT. 7%-8% of the emissions is related to manufacturing of conductors and OPGW materials. Generating electricity from coal comprise of about 20% of CC, NO_x and TSP emissions and peaks at 41% of SO_x emissions. Manufacturing of basic iron and steel contributes to the highest share of CO emissions with 42% followed by CC emissions of 20%. And has lesser share of TSP and SO_x emissions of 12% and 10%, respectively. Sea and coastal water transportation services contributes to 19% of NO_x emissions and is then the second most important product group to NO_x emissions. It also contributes to TSP and SO_x emissions with 8% and 10%. Aluminium and aluminium products is the product group with the second largest CO emissions with 11% of total. NMVOC emissions originates primarily from crude petroleum and services related to crude oil extraction with 22% of the emissions. And to a lesser extent from chemicals and other bituminous coal.

Furthermore, considering the AISs, highest emitting activities is the construction of plant and power transformer, and operation and maintenance. This applies for emission categories. The components incorporated in the activity "AIS plant", represents from 31% to 35% of the total AIS emissions. Manufacturing of basic iron and steel products continues as an important

product group for its high contribution of CC, TSP, SO_x and CO emissions. And so does generation of electricity from coal which has high emissions of CC, NO_x, TSP and SO_x. Sea and coastal water transportation services has its highest contribution to NO_x emissions of 18%, and a minor contributing factor of TSP and SO_x emissions. Aluminium and aluminium products have non-negligible emissions only of CO with 10%. NMVOC emissions is similar to the previously analysed activities, with crude petroleum and services related to crude oil extraction as the top emitting product group. Further, chemicals and other bituminous coal is also important emitters.

Operating and maintaining the AISs emerges as the second largest emitter of the various emission categories and is followed by power transformer as the third. Also here, a similar pattern occurs with the same product groups as the main culprits. This is due to the majority of demand required from the same product group, electrical machinery and apparatus, giving a predictable allocation of emissions.

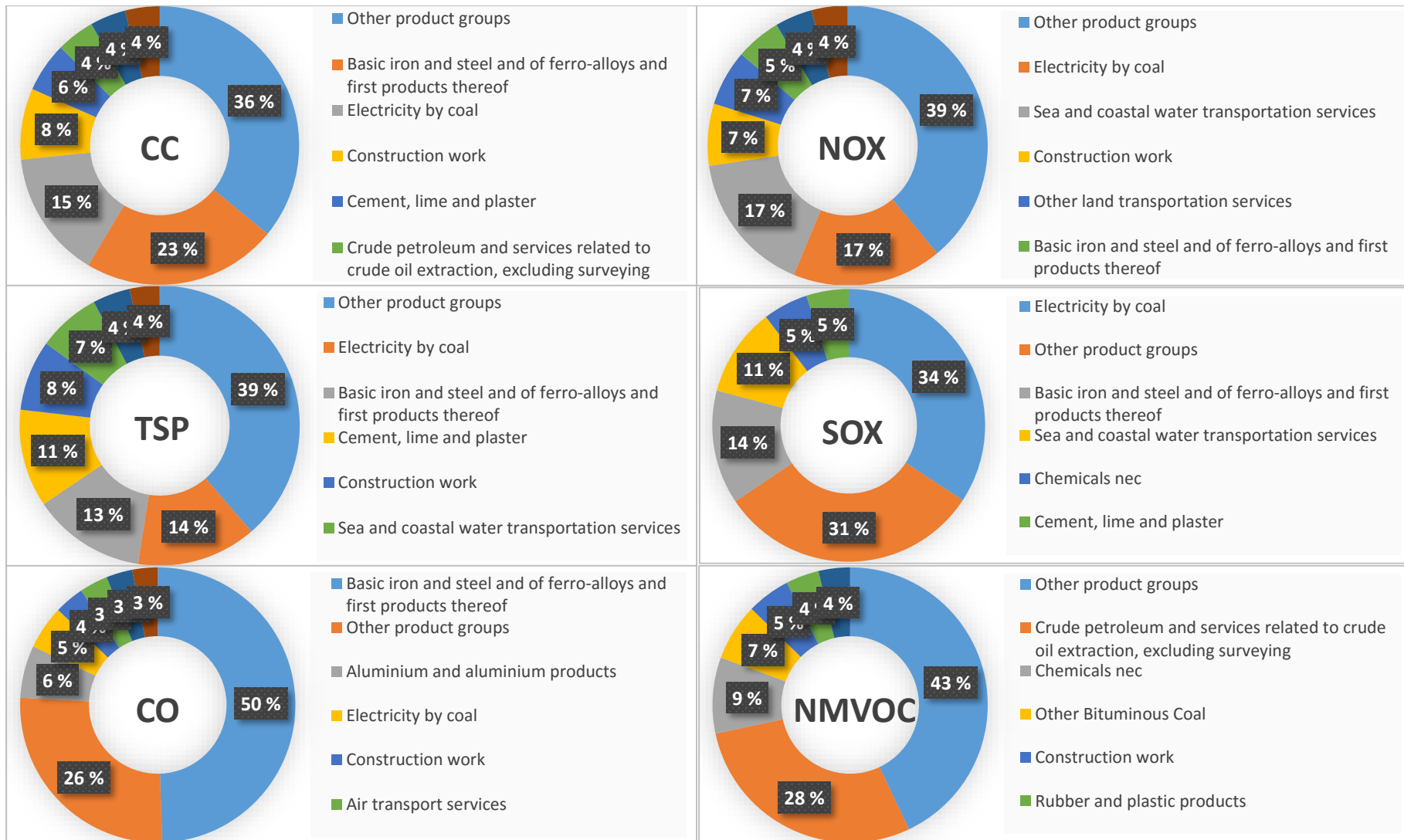


Figure 6.4: Share of emissions from the most important product groups to each emission category in case 1.

6.2 Case 2

IMPACT/STRESSOR	UNIT	TOTAL
CLIMATE CHANGE (CC)	Kg CO ₂ -eq	9.25E+10
NITROGEN OXIDES (NO _x)	Kg	9.52E+08
TOTAL SUSPENDED PARTICLES (TSP)	Kg	8.84E+07
SULFUR OXIDE (SO _x)	Kg	7.07E+08
CARBON MONOXIDE (CO)	Kg	3.03E+08
NON-METHANE VOLATILE ORGANIC COMPOUND (NMVOC)	Kg	1.12E+08

Table 6.2: Total emissions from each category from case 2.

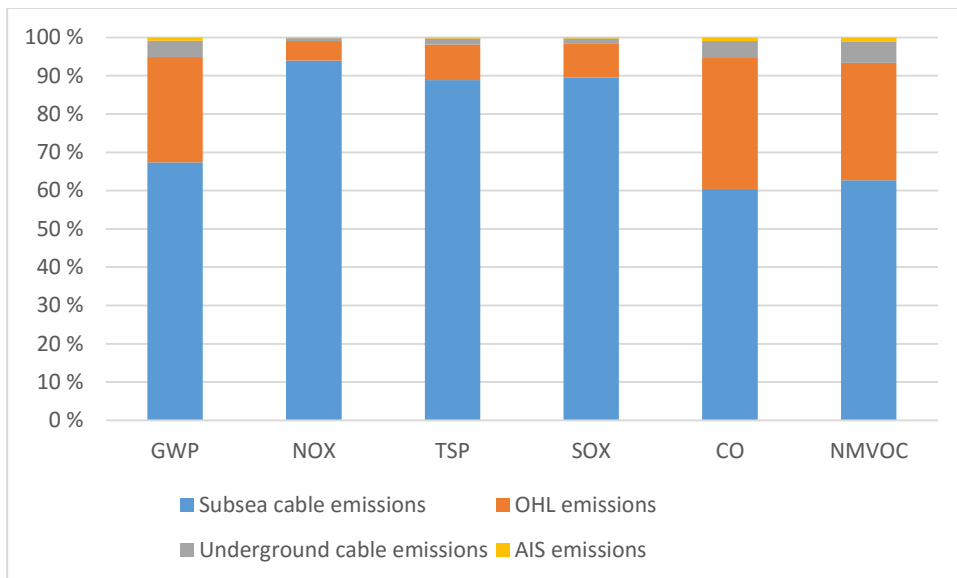


Figure 6.5: Share of emissions from each technology.

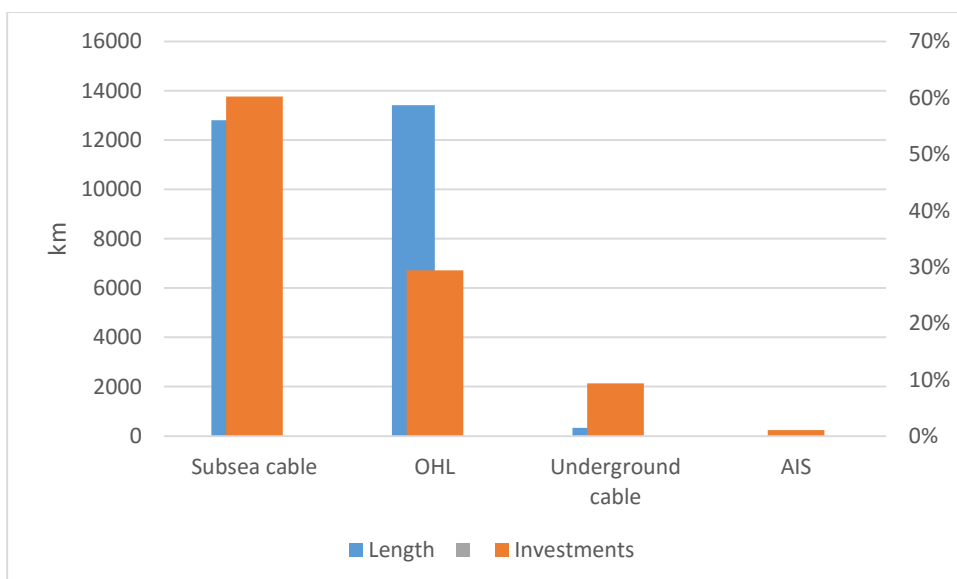


Figure 6.6: Overview of correlation between extension lengths in km and the share of required investments.

As is seen in Figure 6.5, an overwhelming majority of emissions is related to the subsea cables, from 60% of CO emissions to 94% of NO_x emissions. The remaining bulk of emissions is largely from OHLs and further negligible results from UGCs and AISs. Although the LCI comprised of almost equal length of extensions for OHLs and subsea cables, the two technologies differ in every aspect of emissions, where subsea cables emit far more.

From Figure 6.6, a comparison between cable/line lengths and the costs reveals that UGC is most cost intensive followed by subsea cable, and OHL is the cheapest transmission technology.

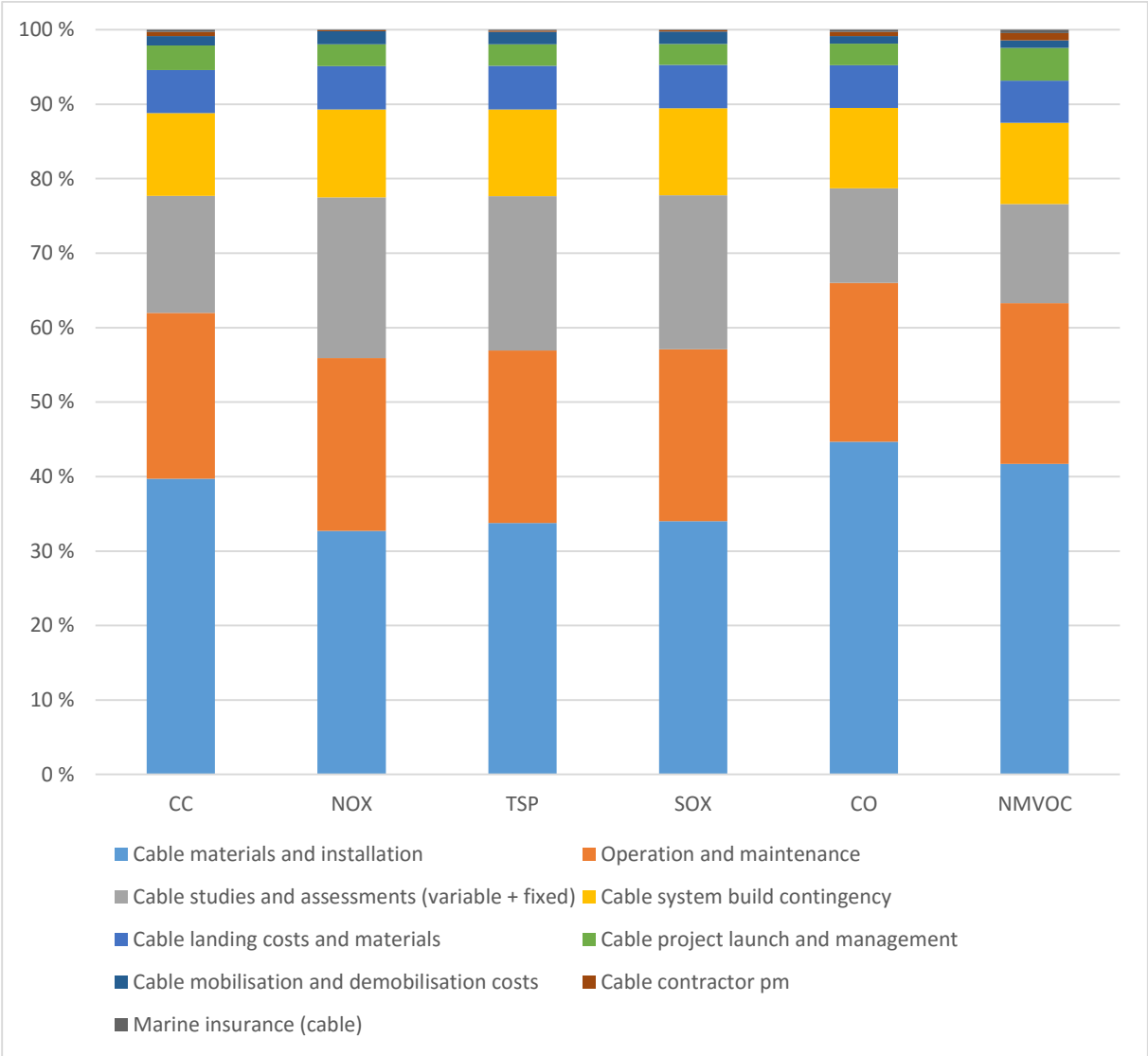


Figure 6.7: Share of total emissions from each activity related to subsea infrastructure.

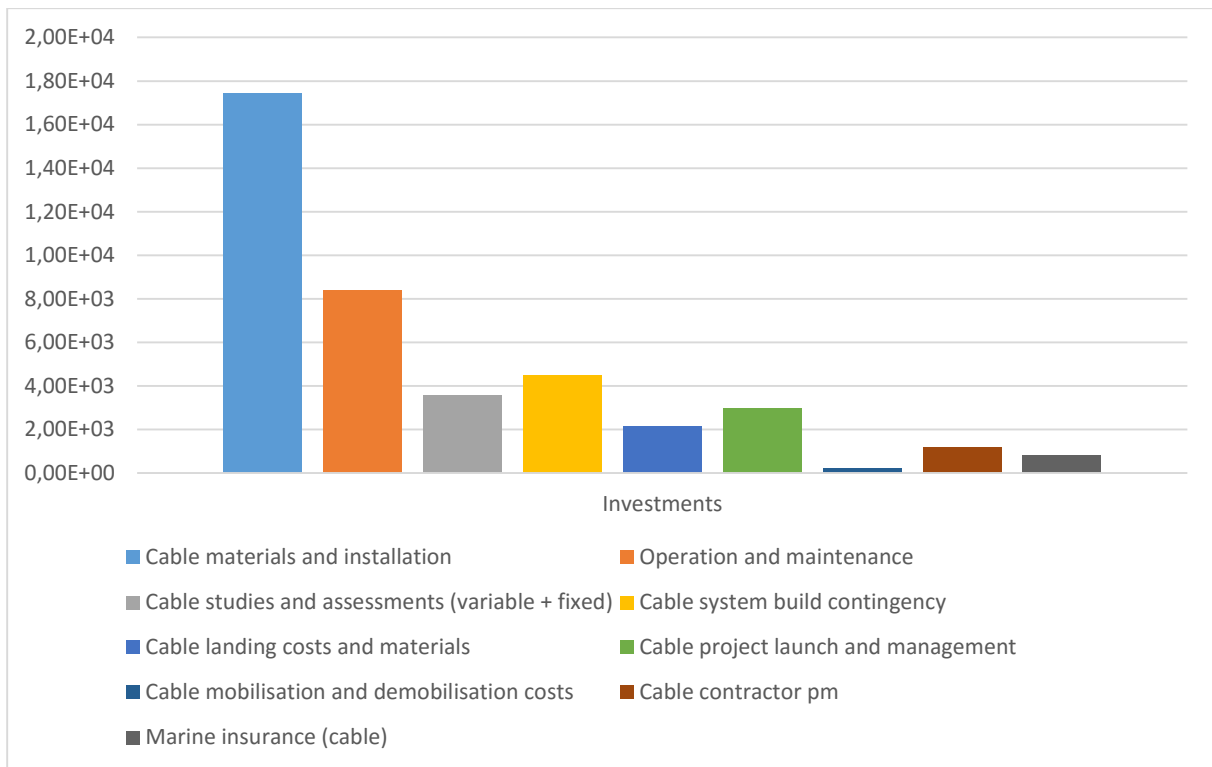


Figure 6.8: Amount of investments required for each subsea cable activity in MEUR 2007.

Figure 6.8 illustrates the breakdown of subsea cables during its operational lifetime. Two activities contribute to over half of the emissions in every category. The top contributing activities have all considerable investments to products from marine vessel services which may be the cause of the large emissions from these activities.

Cable materials and installation emerges as the highest contributing activity to CC, NO_x, TSP, SO_x, CO and NMVOC emissions ranging from 33% to 45% of total emissions. Breaking down the emission results, sea and coastal water transportation services appears as the main contributor of these emissions. The use of products from this particular product group emits nearly the entire NO_x, TSP and SO_x emissions for this activity with a considerable proportion, 91%, 84% and 84% respectively. Of CC emissions, it emits nearly half of the emissions, and for CO and NMVOC, just above 30%. Because of the dominating emissions from sea and coastal water transportation services, the contribution from some product groups appears to be suppressed and appear almost negligible. The next product group with relevant emissions is basic iron and steel with as much as 29% of the CO emissions and 11% of CC. Generation of electricity from coal have only a contribution of just under 10% of the CC and SO_x emissions. Lastly, crude petroleum and services related to crude oil extraction emits 20% of the NMVOC emissions.

The second highest impacts derive from operating and maintaining the subsea cable during its 40-year lifetime. Like the preceding mentioned activity, O&M follows the same pattern of emission contribution from product groups where Sea and coastal water transportation services increases its contribution by a few percentage-points. This also applies for the variable and fixed cable studies and assessments.

It is not necessary to further present the disaggregated results from OHLs, as this was thoroughly described the previous subchapter, case 1, along with AIS.

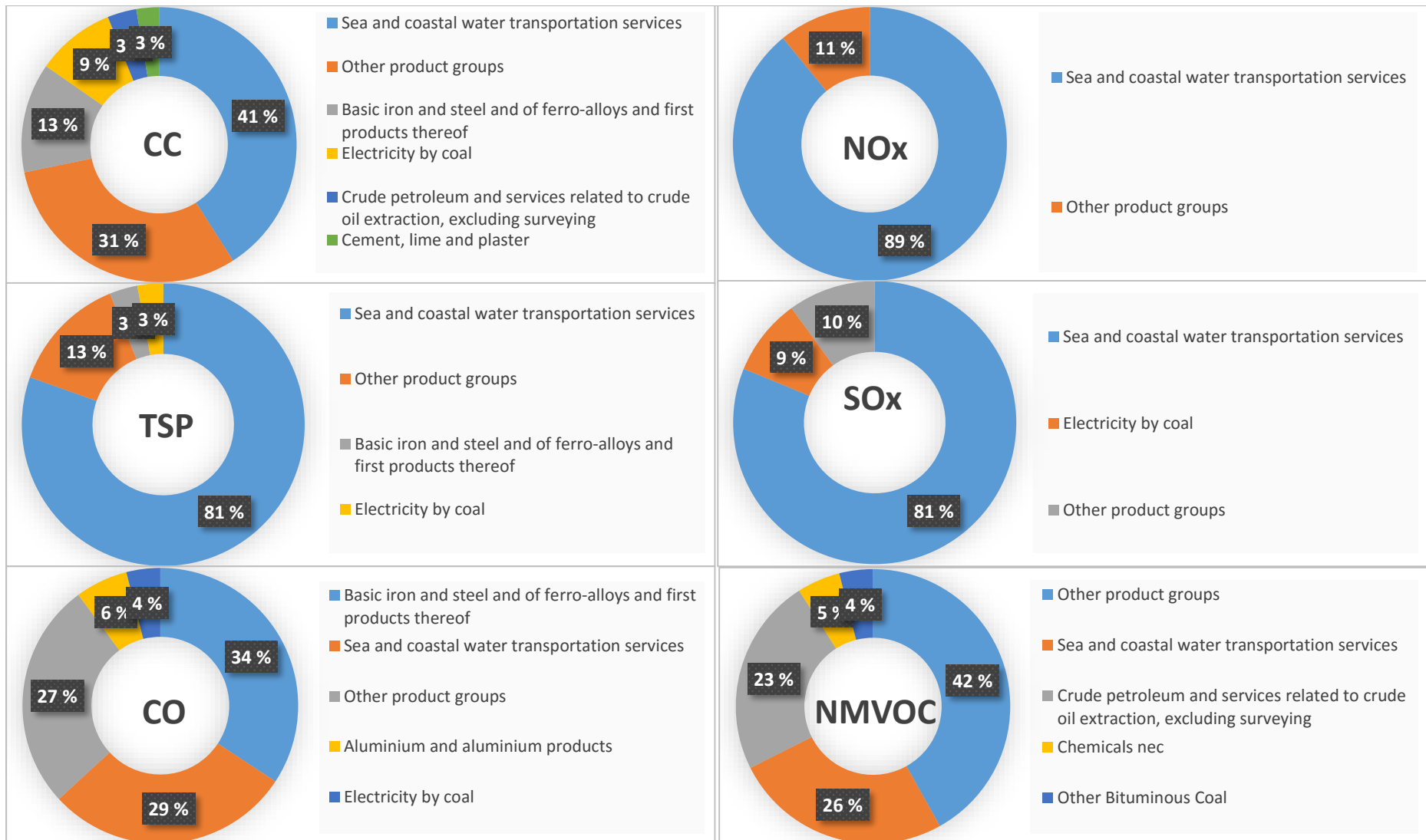


Figure 6.9: Share of emissions from the most important product groups to each emission category in case 2.

7 Discussion and comparison with other studies

The resulting CC emissions over the life cycle of the 163 km of 380 kV AC OHL and two AISs, is 0.25 Mton CO₂-eq. There are no other research papers with an IOA on OHL, or other electrical transmission technologies. Although, Saitov et al. (2014) explored a similar case, in his master thesis, with a hybrid approach, presented a roughly equal result. Further comparisons with other LCA studies on electricity transmission technologies will require a different functional unit, as this thesis uses the system as a functional unit, and lacking the data to convert to emission per kwh electricity transmitted.

When measured OHL CO₂-eq per km of cable length the carbon footprint is 1.35 kton CO₂-eq/km. For comparison, Jorge et al. (2012a) estimated a 0.55 kton CO₂-eq/km, neglecting the benefits from end-of-life. Even with an underestimation of the process-based LCA results (Lenzen & Dey, 2000), the difference is much.

From the results, we also see that OHL foundations, erection of towers and stringing was the activity with highest emissions to CC, and surprisingly, conductors and OPGW lines was outside the top three ranking emission activities. This could be a result from various uncertainties and limitations. Firstly, the allocation of investments to product groups which was largely based on personal assumptions and experience. Secondly, the aggregated IOT, where products of interest were aggregated to product groups involving other products of somewhat similar material composition but the allocation from the product group to the subcategories can result in under/over estimation. Such discrepancies must however be expected when aggregating every product of a nation to only 200 product groups.

A further breakdown of results shows that products from basic iron and steel and of ferro-alloys and first products thereof is the highest emitting product group of CO₂-eq. After performing a structural path analysis, it can be seen that most of the emissions stem from required inputs from its own product group. It also shows minor inputs from other countries as far as from the 4th tier. Fabricated metal products, except machinery and equipment appears to be the product group with second largest emissions in which basic iron and steel products emits through. The basic iron and steel inputs is required for the construction of masts. Next, is emissions from basic iron and steel inputs to electrical machinery and apparatus which is required to construct the conductors and OPGW line. Here we see that constructing the transmission masts is more metal (not including aluminium) intense than the construction of conductors and explains the ranking/CO₂-eqs emitted from these categories. It appears to be an underrepresentation of aluminium product inputs to the electrical machinery and apparatus product group when modelling for high voltage electric conductors. Although, this can be balanced with modelling of direct investments to the aluminium product group. However, this was not conducted. For the next four product groups, all emissions are largely related to construction work which is the product group that is modelled for activities related to OHL foundations, erection of towers and stringing, and access roads.

Looking at emissions from generation of electricity from coal, an important aspect to have in mind is the increasing renewable energy penetration to the European electricity generation which will decrease the use of coal for electricity generation and further reduce its overall environmental emissions.

Referring again to Jorge et al. (2012a), where the results from OHLs showed dominant contribution from materials to masts and conductors, and foundations came third. Whereas in this analysis, foundations are combined with two other activities and emerge as top contributor to all emissions. Tower and conductor materials is ranked 3rd and 4th, but as stated earlier in the discussion, discrepancies may occur due to aggregation issues. The activity of constructing access roads is not part of Jorge et al.'s. (2012a) analysis, but emerge as an important activity to the contribution of emissions.

Another surprising result occurred, with high NO_x emissions from coastal water and transportation services. Although high NO_x emissions from operation of marine vessels is expected. The emissions appear to be almost evenly distributed among the main product groups in tier 0, construction work, other land transportation, basic iron and steel, fabricated metal products, and electrical machinery and apparatus, but NO_x emissions from marine vessels related to construction work is highest and electrical machinery and apparatus as the lowest.

From the system, where the goal was to estimate the emissions from the extensions of transmission lines related to RES integration (case 2), the total carbon footprint was 92.5 Mton CO₂-eq. The modelled system comprised of 13,418 km of OHLs, 12,798 km of subsea cables, 331 km of underground cables and 40 substations. This gives an overall length of 26,547 km. Jorge et al. (2014) conducted a similar research on the environmental cost of Europe's extension of transmission lines based on the TYNDP 2012. The approach that was used was different, process-LCA, and the inventory comprised of a longer total length, 45,300 km, and 156 substations. The total impact was estimated at 10.7 Mton CO₂-eq. The system from Jorge et al. (2014) comprised of almost 20 000 km longer lines and cables and over 100 more substations, and still, the calculated CO₂-eq emissions represented only 12% of this study's modelled system.

Subsea cables, even though OHLs was estimated at almost equal lengths, had a dominating contribution to all emission categories, with 67% of the total CO₂-eq emissions. This corresponds to 4.9 kton CO₂-eq/km and is almost 3 times more CO₂ intensive than OHLs. Although it is more CO₂ intensive, DC subsea cables from a certain point of length has less resistance giving lower power losses. And as is mentioned, power losses are the largest contributor to emissions of greenhouse gases. From Arvesen et al. (2014), the subsea export cable (HVDC 450 kV) which is a part of the assessment, have a length of 39,800 km. The method used was hybrid LCA. Per km of cable length, the emissions were 0.43 kton CO₂-eq/km. Another study by Jorge et al. (2012a), using process LCA, also calculated subsea cables emissions, with a comparative functional unit. The cable, a HVDC 150 kV, emitted 0.13 kton CO₂-eq.

The product group sea and coastal water transportation services have an overwhelming contribution to emissions from all emission categories and is therefore the main reason of the high emissions. Explanations of why the per km emissions of subsea cable is remarkably higher can be argued with an overestimation of investments to this product group. From the cost make-up, (Parsons Brinckerhoff, 2012), large amount of investments is required for the operation of sea vessels, which has a key role both before and during the installation phase. Other factors that affect emissions from subsea cables is the conductor cross section, type of cable and transmission capacity. It is also concluded in Arvesen et al. (2013), that process-based LCA tends to underestimate emissions from sea vessels. And by Majeau-Bettez et al. (2011), that

CO₂ embedded in transport was systematically underestimated in process-based LCA. Additional results from Arvesen et al. (2014), showed only 13% of the GHG emissions was generated from transport while it is considerably higher in this assessment, 41%.

The per unit GHG emissions from a 380 kV AIS is estimated at 12 kton CO₂-eq per unit. In comparison, Jorge et al. (2012b) estimated emission from a 420 kV GIS (transformer excluded) to be 0.93 kton CO₂-eq/unit, using process LCA, and Saitov (2014) for a 400 kV GIS emitted 23 kton CO₂-eq/unit, using a hybrid method. The GIS from Saitov et al. (2014) comprised of four power transformers which can explain its high emission. In Harrison et al. (2010), general emissions from substations (GIS and AIS) is 2.6 kton CO₂-eq/unit, using process LCA, and concludes that AIS embodies more CO₂-eq than a GIS.

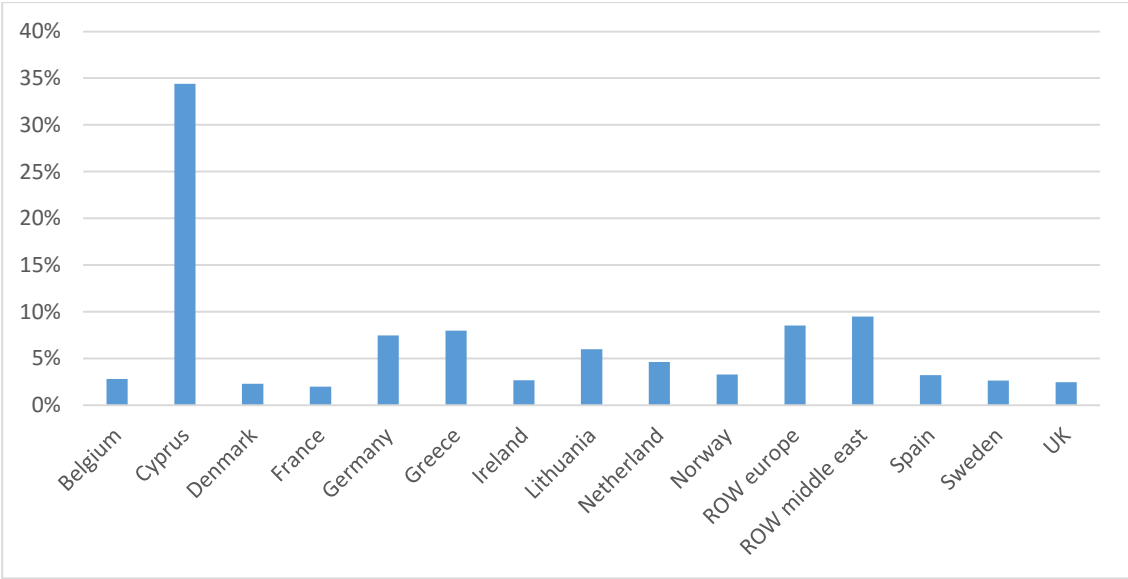


Figure 7.1. Share of CO₂-eq emissions when modelled separately with equal final demand for the product group Sea and coastal water transportation services.

It is also performed an analysis exploring the geographical variations of CO₂-eq emissions with equal final demand vector to the same product group, Sea and coastal water transportation services. This product group was chosen for its large impacts which is previously discussed. It is apparent that emissions for equal final demand are noticeably higher when modelled for Cyprus. This can be because it is an island and is largely dependent on import of products.

8 Conclusions and future work

As a result of the increasing RES development, an expansion and improvement of the current T&D network in Europe is needed. This development will result in environmental costs, but also benefits like cleaner electricity mix. However, with more renewable energy generation, a larger share of the impacts from energy supply sector can be related to the T&D grid.

This report stands out with its exclusively use of IOA to estimate environmental impacts from the transmission grid. Other studies either use process LCA or a combination of these methods, hybrid LCA. To the author's knowledge, it does not exist an environmental impact study of T&D infrastructure using only IOA.

This study presented an environmental assessment of electricity transmission with the use of input-output analysis. The resulting environmental impacts from a 163 km transmission line and two air insulated substations was estimated to be 0.25 Mton CO₂-eq. Expanding the European transmission grid in order to accommodate for future renewable energy integration correspond to a total impact of 92.5 Mton CO₂-eq.

For OHLs, the activity of constructing foundations for masts, erecting the masts and stringing the conductors represented the largest emissions for all stressors. Two product groups, basic iron and steel, and electricity from coal, are identified as important contributors of GHGs, NO_x, TSP, SO_x and CO emissions. This indicates that metal products and use of electricity are significantly affecting the emissions. Regarding the use of electricity, the analysis is modelled with static technology throughout its lifetime. Realistically, advancing technology will contribute to a less CO₂ intensive electricity mix in the future, resulting in less environmental impacts from this type of energy, hence, this illustrates the importance of reducing fossil fuels in the energy mix.

For subsea cables, cable materials and installation represented the largest share of emissions. Operation of marine vessels (sea and coastal water transportation services) emerges as the most important emitting product group to all stressors except CO. Basic iron and steel products represents the majority of CO emissions. Effective emission reductions from subsea cables can be achieved by integrating new and more efficient technology in marine vessels.

Per km, underground cable has the highest GHG emissions (12 kton CO₂-eq/km) followed by subsea cable (5 kton CO₂-eq/km) and lastly overhead line (2 kton CO₂-eq/km). Subsea cables are almost three times more CO₂-eq intensive than OHLs.

Although the UGC have more than twice the CC impacts per km compared to subsea cable, it has not been further analysed. This was because of the negligible environmental impacts due to the short length of UGC cables required (331 km) for the integration of renewable energy resources.

Additional work can be done to improve our understanding of the relevant emission sources. In the context of this report, it has its limitations and can be improved to investigate T&D infrastructure on a more complete level. By, including power losses which is known to represent the major share of emissions, including end-of-life and its potential benefits. The results would also be improved by a more precise allocation of investments, referring to the conductor's underrepresentation of aluminium for OHLs and copper for subsea cables. Another important

improvement can be achieved by combining IOA and LCA into a hybrid LCA with additional incorporation of future technology variations. With a hybrid LCA, it can better cover the system boundary and reduce overall uncertainty.

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APPENDIX A THE HARMONISED INDEX OF CONSUMER PRICES

The harmonised index of consumer prices is used to convert 2012 EUR and 2013 EUR values to 2007 EUR values, in order to be coherent with the Exiobase database. To convert from 2012 values, a conversion rate of 1.1352 is used, and a conversion rate of 1.1667 is used from 2013 values as is apparent from Table 8.0.1.

YEAR	HICP	ANNUAL RATE OF CHANGE	CONVERSION RATE FROM YEAR TO 2007 EUR VALUES
2015	100	0,0 %	1,1928
2014	99,2	0,8 %	1,1832
2013	97,8112	1,4 %	1,1667
2012	95,1703	2,7 %	1,1352
2011	92,0297	3,3 %	1,0977
2010	90,0971	2,1 %	1,0746
2009	88,9258	1,3 %	1,0607
2008	85,7245	3,6 %	1,0225
2007	83,8385	2,2 %	1

Table 8.0.1: Procedure to obtain conversion rates from the harmonised index of consumer prices using data from (Eurostat, 2016).

APPENDIX B FINAL DEMAND VECTORS

APPENDIX B.1 OVERHEAD LINES

Product group	MEUR 2007
Products of forestry, logging and related services	5,30E-01
Ceramic goods	7,95E+00
Basic iron and steel and of ferro-alloys and first products thereof	1,30E+01
Fabricated metal products, except machinery and equipment	2,91E+01
Electrical machinery and apparatus n.e.c.	2,47E+01
Transmission services of electricity	4,24E+00
Construction work	1,26E+02
Other land transportation services	1,91E+01
Air transport services	2,12E+00
Research and development services	1,94E+01
Other business services	5,46E+01

Table 9.0.2: Final demand price vector for case 1 OHLs located in Germany.

Country/Region	Product group	MEUR 2007
Spain	Products of forestry, logging and related services	2,05E+00
Portugal	Products of forestry, logging and related services	3,40E+00
Belgium	Products of forestry, logging and related services	1,35E-01
Luxemburg	Products of forestry, logging and related services	2,63E-02
GB	Products of forestry, logging and related services	3,42E-01
Ireland	Products of forestry, logging and related services	7,61E-01
Denmark	Products of forestry, logging and related services	2,04E-01
Lithuania	Products of forestry, logging and related services	5,24E-01
Finland	Products of forestry, logging and related services	7,38E-01
Latvia	Products of forestry, logging and related services	4,05E-01
Estonia	Products of forestry, logging and related services	7,74E-01
Poland	Products of forestry, logging and related services	2,15E+00
Czech Republic	Products of forestry, logging and related services	2,38E+00
Romania	Products of forestry, logging and related services	2,22E+00
Bulgaria	Products of forestry, logging and related services	1,86E+00
RoW Europe	Products of forestry, logging and related services	4,09E+00
Greece	Products of forestry, logging and related services	3,03E-01
Switzerland	Products of forestry, logging and related services	1,35E+00
Germany	Products of forestry, logging and related services	1,38E+01
France	Products of forestry, logging and related services	4,84E-01
Italy	Products of forestry, logging and related services	8,50E-01

Spain	Ceramic goods	2,96E+01
Portugal	Ceramic goods	4,89E+01
Belgium	Ceramic goods	1,94E+00
Luxemburg	Ceramic goods	3,79E-01
GB	Ceramic goods	4,93E+00
Ireland	Ceramic goods	1,09E+01
Denmark	Ceramic goods	2,94E+00
Lithuania	Ceramic goods	7,54E+00
Finland	Ceramic goods	1,06E+01
Latvia	Ceramic goods	5,83E+00
Estonia	Ceramic goods	1,11E+01
Poland	Ceramic goods	3,09E+01
Czech Republic	Ceramic goods	3,43E+01
Romania	Ceramic goods	3,19E+01
Bulgaria	Ceramic goods	2,68E+01
Row Europe	Ceramic goods	5,88E+01
Greece	Ceramic goods	4,36E+00
Switzerland	Ceramic goods	1,94E+01
Germany	Ceramic goods	1,88E+02
France	Ceramic goods	6,97E+00
Italy	Ceramic goods	1,22E+01
Spain	Basic iron and steel and of ferro-alloys and first products thereof	4,89E+01
Portugal	Basic iron and steel and of ferro-alloys and first products thereof	8,09E+01
Belgium	Basic iron and steel and of ferro-alloys and first products thereof	3,21E+00
Luxemburg	Basic iron and steel and of ferro-alloys and first products thereof	6,27E-01
GB	Basic iron and steel and of ferro-alloys and first products thereof	8,15E+00
Ireland	Basic iron and steel and of ferro-alloys and first products thereof	1,81E+01
Denmark	Basic iron and steel and of ferro-alloys and first products thereof	4,86E+00
Lithuania	Basic iron and steel and of ferro-alloys and first products thereof	1,25E+01
Finland	Basic iron and steel and of ferro-alloys and first products thereof	1,76E+01
Latvia	Basic iron and steel and of ferro-alloys and first products thereof	9,64E+00
Estonia	Basic iron and steel and of ferro-alloys and first products thereof	1,84E+01
Poland	Basic iron and steel and of ferro-alloys and first products thereof	5,11E+01
Czech Republic	Basic iron and steel and of ferro-alloys and first products thereof	5,68E+01
Romania	Basic iron and steel and of ferro-alloys and first products thereof	5,28E+01
Bulgaria	Basic iron and steel and of ferro-alloys and first products thereof	4,43E+01
Row Europe	Basic iron and steel and of ferro-alloys and first products thereof	9,73E+01
Greece	Basic iron and steel and of ferro-alloys and first products thereof	7,21E+00
Switzerland	Basic iron and steel and of ferro-alloys and first products thereof	3,21E+01
Germany	Basic iron and steel and of ferro-alloys and first products thereof	2,73E+02
France	Basic iron and steel and of ferro-alloys and first products thereof	1,15E+01
Italy	Basic iron and steel and of ferro-alloys and first products thereof	2,02E+01
Spain	Fabricated metal products, except machinery and equipment	1,10E+02

Portugal	Fabricated metal products, except machinery and equipment	1,81E+02
Belgium	Fabricated metal products, except machinery and equipment	7,20E+00
Luxemburg	Fabricated metal products, except machinery and equipment	1,40E+00
GB	Fabricated metal products, except machinery and equipment	1,83E+01
Ireland	Fabricated metal products, except machinery and equipment	4,06E+01
Denmark	Fabricated metal products, except machinery and equipment	1,09E+01
Lithuania	Fabricated metal products, except machinery and equipment	2,79E+01
Finland	Fabricated metal products, except machinery and equipment	3,93E+01
Latvia	Fabricated metal products, except machinery and equipment	2,16E+01
Estonia	Fabricated metal products, except machinery and equipment	4,13E+01
Poland	Fabricated metal products, except machinery and equipment	1,14E+02
Czech Republic	Fabricated metal products, except machinery and equipment	1,27E+02
Romania	Fabricated metal products, except machinery and equipment	1,18E+02
Bulgaria	Fabricated metal products, except machinery and equipment	9,92E+01
RoW Europe	Fabricated metal products, except machinery and equipment	2,18E+02
Greece	Fabricated metal products, except machinery and equipment	1,62E+01
Switzerland	Fabricated metal products, except machinery and equipment	7,18E+01
Germany	Fabricated metal products, except machinery and equipment	5,75E+02
France	Fabricated metal products, except machinery and equipment	2,58E+01
Italy	Fabricated metal products, except machinery and equipment	4,53E+01
Spain	Electrical machinery and apparatus n.e.c.	9,12E+01
Portugal	Electrical machinery and apparatus n.e.c.	1,51E+02
Belgium	Electrical machinery and apparatus n.e.c.	5,99E+00
Luxemburg	Electrical machinery and apparatus n.e.c.	1,17E+00
GB	Electrical machinery and apparatus n.e.c.	1,52E+01
Ireland	Electrical machinery and apparatus n.e.c.	3,37E+01
Denmark	Electrical machinery and apparatus n.e.c.	9,06E+00
Lithuania	Electrical machinery and apparatus n.e.c.	2,32E+01
Finland	Electrical machinery and apparatus n.e.c.	3,27E+01
Latvia	Electrical machinery and apparatus n.e.c.	1,80E+01
Estonia	Electrical machinery and apparatus n.e.c.	3,43E+01
Poland	Electrical machinery and apparatus n.e.c.	9,53E+01
Czech Republic	Electrical machinery and apparatus n.e.c.	1,06E+02
Romania	Electrical machinery and apparatus n.e.c.	9,85E+01
Bulgaria	Electrical machinery and apparatus n.e.c.	8,25E+01
RoW Europe	Electrical machinery and apparatus n.e.c.	1,81E+02
Greece	Electrical machinery and apparatus n.e.c.	1,34E+01
Switzerland	Electrical machinery and apparatus n.e.c.	5,98E+01
Germany	Electrical machinery and apparatus n.e.c.	6,15E+02
France	Electrical machinery and apparatus n.e.c.	2,15E+01
Italy	Electrical machinery and apparatus n.e.c.	3,77E+01
Spain	Transmission services of electricity	1,64E+01
Portugal	Transmission services of electricity	2,72E+01

Belgium	Transmission services of electricity	1,08E+00
Luxemburg	Transmission services of electricity	2,11E-01
GB	Transmission services of electricity	2,74E+00
Ireland	Transmission services of electricity	6,09E+00
Denmark	Transmission services of electricity	1,63E+00
Lithuania	Transmission services of electricity	4,19E+00
Finland	Transmission services of electricity	5,90E+00
Latvia	Transmission services of electricity	3,24E+00
Estonia	Transmission services of electricity	6,19E+00
Poland	Transmission services of electricity	1,72E+01
Czech Republic	Transmission services of electricity	1,91E+01
Romania	Transmission services of electricity	1,78E+01
Bulgaria	Transmission services of electricity	1,49E+01
RoW Europe	Transmission services of electricity	3,27E+01
Greece	Transmission services of electricity	2,42E+00
Switzerland	Transmission services of electricity	1,08E+01
Germany	Transmission services of electricity	1,10E+02
France	Transmission services of electricity	3,87E+00
Italy	Transmission services of electricity	6,80E+00
Spain	Construction work	4,77E+02
Portugal	Construction work	7,89E+02
Belgium	Construction work	3,13E+01
Luxemburg	Construction work	6,11E+00
GB	Construction work	7,95E+01
Ireland	Construction work	1,76E+02
Denmark	Construction work	4,74E+01
Lithuania	Construction work	1,21E+02
Finland	Construction work	1,71E+02
Latvia	Construction work	9,40E+01
Estonia	Construction work	1,80E+02
Poland	Construction work	4,98E+02
Czech Republic	Construction work	5,53E+02
Romania	Construction work	5,15E+02
Bulgaria	Construction work	4,32E+02
RoW Europe	Construction work	9,48E+02
Greece	Construction work	7,03E+01
Switzerland	Construction work	3,12E+02
Germany	Construction work	2,59E+03
France	Construction work	1,12E+02
Italy	Construction work	1,97E+02
Spain	Other land transportation services	7,03E+01
Portugal	Other land transportation services	1,16E+02
Belgium	Other land transportation services	4,62E+00

Luxemburg	Other land transportation services	9,02E-01
GB	Other land transportation services	1,17E+01
Ireland	Other land transportation services	2,60E+01
Denmark	Other land transportation services	6,99E+00
Lithuania	Other land transportation services	1,79E+01
Finland	Other land transportation services	2,52E+01
Latvia	Other land transportation services	1,39E+01
Estonia	Other land transportation services	2,65E+01
Poland	Other land transportation services	7,35E+01
Czech Republic	Other land transportation services	8,16E+01
Romania	Other land transportation services	7,60E+01
Bulgaria	Other land transportation services	6,37E+01
RoW Europe	Other land transportation services	1,40E+02
Greece	Other land transportation services	1,04E+01
Switzerland	Other land transportation services	4,61E+01
Germany	Other land transportation services	3,70E+02
France	Other land transportation services	1,66E+01
Italy	Other land transportation services	2,91E+01
Spain	Air transport services	8,22E+00
Portugal	Air transport services	1,36E+01
Belgium	Air transport services	5,40E-01
Luxemburg	Air transport services	1,05E-01
GB	Air transport services	1,37E+00
Ireland	Air transport services	3,04E+00
Denmark	Air transport services	8,17E-01
Lithuania	Air transport services	2,09E+00
Finland	Air transport services	2,95E+00
Latvia	Air transport services	1,62E+00
Estonia	Air transport services	3,10E+00
Poland	Air transport services	8,59E+00
Czech Republic	Air transport services	9,54E+00
Romania	Air transport services	8,88E+00
Bulgaria	Air transport services	7,44E+00
RoW Europe	Air transport services	1,64E+01
Greece	Air transport services	1,21E+00
Switzerland	Air transport services	5,39E+00
Germany	Air transport services	5,52E+01
France	Air transport services	1,94E+00
Italy	Air transport services	3,40E+00
Spain	Research and development services	7,26E+01
Portugal	Research and development services	1,20E+02
Belgium	Research and development services	4,77E+00
Luxemburg	Research and development services	9,30E-01

GB	Research and development services	1,21E+01
Ireland	Research and development services	2,69E+01
Denmark	Research and development services	7,21E+00
Lithuania	Research and development services	1,85E+01
Finland	Research and development services	2,60E+01
Latvia	Research and development services	1,43E+01
Estonia	Research and development services	2,73E+01
Poland	Research and development services	7,58E+01
Czech Republic	Research and development services	8,42E+01
Romania	Research and development services	7,84E+01
Bulgaria	Research and development services	6,57E+01
RoW Europe	Research and development services	1,44E+02
Greece	Research and development services	1,07E+01
Switzerland	Research and development services	4,76E+01
Germany	Research and development services	4,04E+02
France	Research and development services	1,71E+01
Italy	Research and development services	3,00E+01
Spain	Other business services	2,04E+02
Portugal	Other business services	3,38E+02
Belgium	Other business services	1,34E+01
Luxemburg	Other business services	2,62E+00
GB	Other business services	3,40E+01
Ireland	Other business services	7,56E+01
Denmark	Other business services	2,03E+01
Lithuania	Other business services	5,20E+01
Finland	Other business services	7,33E+01
Latvia	Other business services	4,02E+01
Estonia	Other business services	7,69E+01
Poland	Other business services	2,13E+02
Czech Republic	Other business services	2,37E+02
Romania	Other business services	2,20E+02
Bulgaria	Other business services	1,85E+02
RoW Europe	Other business services	4,06E+02
Greece	Other business services	3,01E+01
Switzerland	Other business services	1,34E+02
Germany	Other business services	1,14E+03
France	Other business services	4,81E+01
Italy	Other business services	8,44E+01

Table 0.3: Final demand price vector for case 2 OHLs, divided between geographical locations.

Country	Length (km)	Percentage of total length
Spain	744,11	6,2 %
Portugal	1229,3	10,3 %
Belgium	49,4	0,4 %
Luxemburg	10	0,1 %
GB	123,9	1,0 %
Ireland	275	2,3 %
North Ireland	49	0,4 %
Denmark	74	0,6 %
Lithuania	189	1,6 %
Finland	267,5	2,2 %
Latvia	145	1,2 %
Estonia	280	2,3 %
Poland	776,7	6,5 %
Czech Republic	863,2	7,2 %
Montenegro	196,9	1,7 %
Serbia	493,7	4,1 %
Bosnia Herzegovina	137,23	1,2 %
Croatia	215	1,8 %
Romania	803,7	6,7 %
Bulgaria	673	5,6 %
Albania	238	2,0 %
Macedonia	150	1,3 %
Greece	110	0,9 %
Switzerland	487,8	4,1 %
Germany	2854,15	23,9 %
France	175	1,5 %
Italy	307,4	2,6 %

Table 0.4: Geographical locations of case 2 AC OHL extensions (ENTSO-E, 2014).

DC

Country	Length (km)	Percentage of total length
Germany	1500	100 %

Table 0.5: Geographical locations of case 2 DC OHL extensions (ENTSO-E, 2014).

APPENDIX B.2 SUBSEA CABLE

Country/Region	Product groups	MEUR 2007
Germany	Fabricated metal products, except machinery and equipment	2,79E+01
Greece	Fabricated metal products, except machinery and equipment	1,94E+01
France	Electrical machinery and apparatus n.e.c.	1,53E+03
Spain	Electrical machinery and apparatus n.e.c.	7,87E+02
UK	Electrical machinery and apparatus n.e.c.	4,63E+03
Belgium	Electrical machinery and apparatus n.e.c.	1,65E+02
Ireland	Electrical machinery and apparatus n.e.c.	1,19E+03
RoW Europe	Electrical machinery and apparatus n.e.c.	1,43E+02
Norway	Electrical machinery and apparatus n.e.c.	1,44E+03
Germany	Electrical machinery and apparatus n.e.c.	4,72E+03
Denmark	Electrical machinery and apparatus n.e.c.	1,16E+03
Netherland	Electrical machinery and apparatus n.e.c.	2,68E+02
Sweden	Electrical machinery and apparatus n.e.c.	3,84E+02
Lithuania	Electrical machinery and apparatus n.e.c.	2,68E+02
Greece	Electrical machinery and apparatus n.e.c.	2,34E+03
Cyprus	Electrical machinery and apparatus n.e.c.	8,54E+02
RoW Middle east	Electrical machinery and apparatus n.e.c.	2,53E+02
France	Construction	1,58E+02
Spain	Construction	8,15E+01
UK	Construction	4,80E+02
Belgium	Construction	1,71E+01
Ireland	Construction	1,23E+02
RoW Europe	Construction	1,48E+01
Norway	Construction	1,49E+02
Germany	Construction	4,44E+02
Denmark	Construction	1,20E+02
Netherland	Construction	2,78E+01
Sweden	Construction	3,97E+01
Lithuania	Construction	2,78E+01
Greece	Construction	2,11E+02
Cyprus	Construction	8,84E+01
RoW Middle east	Construction	2,62E+01
France	Other land transportation services	2,27E+01
Spain	Other land transportation services	1,17E+01
UK	Other land transportation services	6,89E+01
Belgium	Other land transportation services	2,45E+00
Ireland	Other land transportation services	1,77E+01

RoW Europe	Other land transportation services	2,13E+00
Norway	Other land transportation services	2,15E+01
Germany	Other land transportation services	6,99E+01
Denmark	Other land transportation services	1,72E+01
Netherland	Other land transportation services	3,99E+00
Sweden	Other land transportation services	5,71E+00
Lithuania	Other land transportation services	3,99E+00
Greece	Other land transportation services	3,46E+01
Cyprus	Other land transportation services	1,27E+01
RoW Middle east	Other land transportation services	3,76E+00
France	Sea and coastal water transportation services	8,30E+02
Spain	Sea and coastal water transportation services	4,27E+02
UK	Sea and coastal water transportation services	2,52E+03
Belgium	Sea and coastal water transportation services	8,95E+01
Ireland	Sea and coastal water transportation services	6,46E+02
RoW Europe	Sea and coastal water transportation services	7,77E+01
Norway	Sea and coastal water transportation services	7,84E+02
Germany	Sea and coastal water transportation services	2,61E+03
Denmark	Sea and coastal water transportation services	6,30E+02
Netherland	Sea and coastal water transportation services	1,46E+02
Sweden	Sea and coastal water transportation services	2,08E+02
Lithuania	Sea and coastal water transportation services	1,46E+02
Greece	Sea and coastal water transportation services	1,30E+03
Cyprus	Sea and coastal water transportation services	4,64E+02
RoW Middle east	Sea and coastal water transportation services	1,37E+02
France	Insurance and pension funding services, except compulsory social security services	6,34E+01
Spain	Insurance and pension funding services, except compulsory social security services	3,27E+01
UK	Insurance and pension funding services, except compulsory social security services	1,92E+02
Belgium	Insurance and pension funding services, except compulsory social security services	6,84E+00
Ireland	Insurance and pension funding services, except compulsory social security services	4,94E+01
RoW Europe	Insurance and pension funding services, except compulsory social security services	5,94E+00
Norway	Insurance and pension funding services, except compulsory social security services	5,99E+01
Germany	Insurance and pension funding services, except compulsory social security services	1,90E+02
Denmark	Insurance and pension funding services, except compulsory social security services	4,81E+01
Netherland	Insurance and pension funding services, except compulsory social security services	1,11E+01
Sweden	Insurance and pension funding services, except compulsory social security services	1,59E+01
Lithuania	Insurance and pension funding services, except compulsory social security services	1,11E+01
Greece	Insurance and pension funding services, except compulsory social security services	9,30E+01

Cyprus	Insurance and pension funding services, except compulsory social security services	3,54E+01
RoW Middle east	Insurance and pension funding services, except compulsory social security services	1,05E+01
France	Research and development services	7,79E-01
Spain	Research and development services	4,01E-01
UK	Research and development services	2,36E+00
Belgium	Research and development services	8,40E-02
Ireland	Research and development services	6,06E-01
RoW Europe	Research and development services	7,29E-02
Norway	Research and development services	7,36E-01
Germany	Research and development services	2,77E+00
Denmark	Research and development services	5,91E-01
Netherland	Research and development services	1,37E-01
Sweden	Research and development services	1,96E-01
Lithuania	Research and development services	1,37E-01
Greece	Research and development services	1,44E+00
Cyprus	Research and development services	4,35E-01
RoW Middle east	Research and development services	1,29E-01
France	Other business services	5,19E+02
Spain	Other business services	2,67E+02
UK	Other business services	1,57E+03
Belgium	Other business services	5,60E+01
Ireland	Other business services	4,04E+02
RoW Europe	Other business services	4,86E+01
Norway	Other business services	4,90E+02
Germany	Other business services	1,63E+03
Denmark	Other business services	3,94E+02
Netherland	Other business services	9,11E+01
Sweden	Other business services	1,30E+02
Lithuania	Other business services	9,11E+01
Greece	Other business services	8,15E+02
Cyprus	Other business services	2,90E+02
RoW Middle east	Other business services	8,59E+01

Table 0.6: Final demand price vector for case 2 subsea cables, divided between geographical location.

Country	Cable length (km)	Percentage of total length
Germany	220	59 %
Greece	155	41 %

Table 0.7: Geographical locations of AC subsea cable extensions (ENTSO-E, 2014).

Country	Cable length (km)	Percentage of total length
France	997	8,0 %
Spain	513	4,1 %
UK	3022	24,3 %
Belgium	108	0,9 %
Ireland	776	6,2 %
North Ireland	93	0,8 %
Norway	942	7,6 %
Germany	2660	21,4 %
Denmark	756	6,1 %
Netherland	175	1,4 %
Sweden	250	2,0 %
Lithuania	175	1,4 %
Greece	1232	9,9 %
Cyprus	557	4,5 %
Israel	165	1,3 %

Table 0.8: Geographical locations of DC subsea cable extensions (ENTSO-E, 2014)

APPENDIX B.3 UNDERGROUND CABLE

Country/Region	Product groups	MEUR 2007
Spain	Fabricated metal products, except machinery and equipment	1,65E+00
Germany	Fabricated metal products, except machinery and equipment	6,77E+00
Luxembourg	Fabricated metal products, except machinery and equipment	7,48E-01
Switzerland	Fabricated metal products, except machinery and equipment	3,51E-01
UK	Fabricated metal products, except machinery and equipment	6,07E-01
Spain	Electrical machinery and apparatus n.e.c.	4,09E+02
Germany	Electrical machinery and apparatus n.e.c.	1,52E+03
Luxembourg	Electrical machinery and apparatus n.e.c.	1,86E+02
Switzerland	Electrical machinery and apparatus n.e.c.	8,72E+01
UK	Electrical machinery and apparatus n.e.c.	1,51E+02
Spain	Construction	4,24E+02
Germany	Construction	1,61E+03
Luxembourg	Construction	1,92E+02
Switzerland	Construction	9,03E+01
UK	Construction	1,56E+02
Spain	Other business services	1,09E+02
Germany	Other business services	4,11E+02
Luxembourg	Other business services	4,95E+01
Switzerland	Other business services	2,32E+01
UK	Other business services	4,02E+01
Spain	Other land transport	4,03E+01
Germany	Other land transport	1,53E+02
Luxembourg	Other land transport	1,83E+01
Switzerland	Other land transport	8,57E+00
UK	Other land transport	1,48E+01
Spain	Research and development services	1,22E+02
Germany	Research and development services	4,60E+02
Luxembourg	Research and development services	5,55E+01
Switzerland	Research and development services	2,61E+01
UK	Research and development services	4,51E+01

Table 0.9: Final demand price vector for UGCs, divided between geographical locations.

Country	Length (km)	Percentage of total length
Germany	32	100 %

Table 0.10: Geographical locations of AC UGC extensions (ENTSO-E, 2014).

Country	Length (km)	Percentage of total length
Spain	57,3	19 %
Germany	182,2	61 %
Luxembourg	26	9 %
Switzerland	12,2	4 %
UK	21,1	7 %

Table 0.11: Geographical locations of DC UGC extensions (ENTSO-E, 2014).

APPENDIX B.4 SUBSTATIONS

Product groups	MEUR 2007
Fabricated metal products, except machinery and equipment	1,95E+00
Electrical machinery and apparatus n.e.c.	2,70E+01
Construction work	5,46E+00
Other land transportation services	4,70E-01
Research and development services	8,50E-01
Other business services	5,90E-01

Table 0.12: Final demand price vector for case 1 AISs located in Germany.

Country/Region	Product groups	MEUR 2007
Spain	Fabricated metal products, except machinery and equipment	9,63E+00
Portugal	Fabricated metal products, except machinery and equipment	4,81E+00
Belgium	Fabricated metal products, except machinery and equipment	1,93E+00
UK	Fabricated metal products, except machinery and equipment	1,93E+00
Ireland	Fabricated metal products, except machinery and equipment	1,93E+00
RoW Europe	Fabricated metal products, except machinery and equipment	2,89E+00
Poland	Fabricated metal products, except machinery and equipment	4,81E+00
Czech rep	Fabricated metal products, except machinery and equipment	1,93E+00
Romania	Fabricated metal products, except machinery and equipment	1,93E+00
Greece	Fabricated metal products, except machinery and equipment	9,63E-01
Germany	Fabricated metal products, except machinery and equipment	5,78E+00
Spain	Electrical machinery and apparatus n.e.c.	1,33E+02
Portugal	Electrical machinery and apparatus n.e.c.	6,64E+01
Belgium	Electrical machinery and apparatus n.e.c.	2,66E+01
UK	Electrical machinery and apparatus n.e.c.	2,66E+01
Ireland	Electrical machinery and apparatus n.e.c.	2,66E+01
RoW Europe	Electrical machinery and apparatus n.e.c.	3,99E+01
Poland	Electrical machinery and apparatus n.e.c.	6,64E+01
Czech rep	Electrical machinery and apparatus n.e.c.	2,66E+01
Romania	Electrical machinery and apparatus n.e.c.	2,66E+01
Greece	Electrical machinery and apparatus n.e.c.	1,33E+01
Germany	Electrical machinery and apparatus n.e.c.	7,97E+01
Spain	Construction work	2,69E+01
Portugal	Construction work	1,35E+01
Belgium	Construction work	5,38E+00
UK	Construction work	5,38E+00
Ireland	Construction work	5,38E+00
RoW Europe	Construction work	8,07E+00
Poland	Construction work	1,35E+01

Czech rep	Construction work	5,38E+00
Romania	Construction work	5,38E+00
Greece	Construction work	2,69E+00
Germany	Construction work	1,61E+01
Spain	Other land transportation services	2,33E+00
Portugal	Other land transportation services	1,16E+00
Belgium	Other land transportation services	4,66E-01
UK	Other land transportation services	4,66E-01
Ireland	Other land transportation services	4,66E-01
RoW Europe	Other land transportation services	7,03E-01
Poland	Other land transportation services	1,16E+00
Czech rep	Other land transportation services	4,66E-01
Romania	Other land transportation services	4,66E-01
Greece	Other land transportation services	2,33E-01
Germany	Other land transportation services	1,40E+00
Spain	Research and development services	4,19E+00
Portugal	Research and development services	2,09E+00
Belgium	Research and development services	8,37E-01
UK	Research and development services	8,37E-01
Ireland	Research and development services	8,37E-01
RoW Europe	Research and development services	1,26E+00
Poland	Research and development services	2,09E+00
Czech rep	Research and development services	8,37E-01
Romania	Research and development services	8,37E-01
Greece	Research and development services	4,19E-01
Germany	Research and development services	2,51E+00
Spain	Other business services	2,89E+00
Portugal	Other business services	1,44E+00
Belgium	Other business services	5,77E-01
UK	Other business services	5,77E-01
Ireland	Other business services	5,77E-01
RoW Europe	Other business services	8,69E-01
Poland	Other business services	1,44E+00
Czech rep	Other business services	5,77E-01
Romania	Other business services	5,77E-01
Greece	Other business services	2,89E-01
Germany	Other business services	1,73E+00

Table 0.13: Final demand price vector for case 2 AISs, divided between geographical locations.

Country	Amount of substations	Percentage of total amount
Spain	10	25 %
Portugal	5	13 %
Belgium	2	5 %
UK	2	5 %
Ireland	2	5 %
RoW Europe	1	3 %
Poland	5	13 %
Czech rep	2	5 %
Croatia	2	5 %
Romania	2	5 %
Greece	1	3 %
Germany	6	15 %

Table 0.14: Geographical locations of planned AISs (ENTSO-E, 2014).