NTNU – Trondheim
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Environmental Assessment of Electricity Transmission Grid Upgrades Triggered by the Increasing Utilization of Variable and Remote Renewable Energy

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MASTER THESIS

for

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Environmental Assessment of Electricity Transmission Grid Upgrades Triggered by the Increasing Utilization of Variable and Remote Renewable Energy

Vurdering av miljøkonsekvenser knyttet til oppgradering av kraftnett som resultat av økt bruk av variable fornybar kraft

Background and objective

Climate policy aims to reduce greenhouse gas emissions also by replacing fossil power stations with renewable forms of energy, with a significant share of wind and solar power foreseen in many energy scenarios. The characteristic of such intermittent or variable sources is that utilities have less control over the timing of electricity production. Significant research attention and engineering effort has gone into finding solutions that allow grid to utilize a large degree of variable renewable energy, e.g. through back-up fossil power, energy storage, demand control, and overcapacity plus curtailment of overproduction. One key idea is the integration of production and demand across larger regions, taking advantage of differences in the timing of generation and demand and the flexibility offered by larger grid areas. To a significant measure, the relatively unproblematic high penetration of wind power in the Danish national grid is due to the integration of that grid with the other Nordic countries, which provide regulating capacity. Such grid extensions have been studied for many regions and in some futuristic proposals even across continents (utilizing the differences in time zones).

There has historically been little interest in the LCA of electricity transmission and distribution, as T&D have a small impact on the environment compared at fossil power generation. The need to upgrade and extend grids to transport electricity over much larger distances, combined with the dramatic reduction of impacts offered by renewable power, have increased the importance of impacts from transmission in particular compared to those of generation. In addition, some of the environmental concerns, such as the use of materials and land, are similar to those triggered by renewables. Some of the most recent and up-to-date life cycle inventories for equipment for electricity transmission were produced by Raquel Jorge (2013) in her PhD thesis, and have been adopted by the new EcoInvent 3 database. At the same time, grid companies and electrical engineering institutes have a renewed interest in life cycle aspects and their importance in the determination of the optimal electricity system under different climate policies. Current LCAs of T&D, however, are process analyses, based mostly on the composition of components of the grid and not taking into account those "service" type activities that are best represented by input-output analysis. Given that hybrid LCAs of renewable energy technologies have shown that conventional process LCA underestimates some of the environmental impacts by a factor of 2, it would be desirable to better understand the

The objective of this thesis is to provide a hybrid life cycle assessment of a transmission grid upgrade and extension serving to integrate variable or remote renewables, with the case to be decided in the first weeks of the work.

The following tasks are to be considered:

1. Review of literature on electricity grid upgrades and extensions in relationship to the introduction of more variable supply.
2. Explanation of hybrid LCI methods.
3. Identification and review of life cycle inventory and cost data of components of transmission grids with the aim to produce hybrid inventories.
4. Initial evaluation of proposed solutions through back-of-the-envelope calculations.
5. Development and analysis of a detailed inventory of a selected project or case study.
6. Interpretation of the case study, recommendations and need for further work.

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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.

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

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

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Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

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The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

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

Department of Energy and Process Engineering, 14. January 2014

Olav Bolland
Department Head

Edgar Hertwich
Academic Supervisor

Research Advisor: PostDoc Anders Arvesen

Preface

This master thesis work was developed during last semester of study within MSc programme for Industrial Ecology.

I would like to whole-heartedly thank my supervisor, Edgar Hertwich, and my co-supervisor, Anders Arvesen, for showing exceptional patience and exercising individual approach during writing of the thesis.

Thank you very much, the opportunity to finish my MSc in IndEcol means a whole world for me.

I would also like to thank Raquel Jorge for provision of support and original data.

Rustem Saitov.

October 2014, Moscow

Abstract

This study aims to perform hybrid life cycle assessment of potential environmental implications due to expansion of electricity transmission grid which would allow to including intermittent energy sources.

Existing studies in this field of research employ process-based life cycle assessment techniques which inevitably suffer from truncation errors. This can potentially cause underestimation of significant share of impacts. Hybrid tiered analysis performed for the case project seeks to redress this gap.

The results showed that total impacts generated in physical (process-LCA) sub-system are nearly four times higher than that of monetary one (Input-Output). The share of monetary sub-system related impacts are lower than expected, but are significant nevertheless.

The structure of this report is as follows. In chapter 1 introduction into the topic is given, followed by literature review, case identification and methods description in next chapter. Chapter 3 covers life cycle inventories and cost data adapted to perform life cycle impact assessment. In the following chapter, the results of such assessment are reported, while chapter 5 provides discussion on obtained results. Finally, chapter 6 concludes this study and lists potential improvements for next work.

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1. Introduction

1.1. Problem definition

One of the biggest achievements of modern civilization is pervasive sophisticated energy systems. Thanks to seemingly abundant and affordable natural resources, they have been producing, transforming and delivering energy tirelessly in order to ensure social, economic and technological progress. Meanwhile, exponential population growth during the 20th century coupled with rising well-being aspirations and development of technology proved that current setup of the global energy system is not suitable for a new millennium due to a number of implications.

For one, current rates of resources extraction are projected to lead to the depletion of fossil fuels and mineral resources that are critically important for healthy functioning of the world economy [1]. Moreover, as accessibility and economics of reserves would continue to decline in future, energy intensity in primary metal production is going to rise which would translate into respective surge in emissions to the nature [2]. Secondly, the energy systems produce a plethora of environmental stressors ranging from greenhouse gas emissions (e.g. carbon dioxide and methane) to those that are toxic to human and ecosystems (such as 1,4-dichlorobenzene). For instance, from the climate change perspective, 84% of total global CO2 emissions and 64% of anthropogenic global greenhouse gas (GHG) emissions are produced by energy systems [3].

These factors along with ageing of infrastructure act as strong drivers for a transformation of the global energy system in place. Revamped system is expected to become sustainable which implies, among others, more efficiency and less pollution [4]. The magnitude of this challenge is tremendous considering environmental goal of containing global temperature rise at 2 C° while providing energy services to 3 billion people lacking it [3]. No single solution, so to say “silver bullet”, is there to address it wholly, however researchers and policy-makers around the world proposed a set of dedicated technologies and policies [5].

Electricity transmission systems that can incorporate intermittent and unevenly located renewable energy sources can be perceived as an important part of such answer. Its uniqueness lies in the potential to address a wide range of issues by employing a combination of technologies, approaches and applications. Such electricity systems are vital part of the Smart Grid which was defined as the next step in evolution of power (electricity) grid taking a shape of a convergence of communication and information technologies (ICT) [6, 7, 8].

Extension and development of the power grid require significant financial and material investments. For instance, it was estimated that EU would have to provide means for transmission and distribution for 250 GW of new generation, which is roughly a quarter of net installed capacity as of 2012 [9]. The effect of such investments should be thoroughly assessed on different levels in order to gauge benefits and identify potential drawbacks of the implementation.

In the meantime, quantitative analyses of environmental benefits and trade-offs have been largely concentrated on life cycle assessments of renewable generation [10, 11, 12] as there are only a few available papers investigating the transmission and distribution part of the power systems [13, 14, 15, 16] which were instrumental in estimation of impacts in connection with infrastructural changes required to accommodate renewables. When weighting related pros and cons, it should be taken into account that enhancement of existing electricity grid happens on wide scale, so that process-based methodology may not capture the entirety of environmental repercussions. The truncation errors are intrinsic to process-built life cycle assessments, and implementation of hybrid techniques [17, 18] can address this issue, which would improve our understanding of increasing scarcity of mineral resources, energy and emission intensity of primal metal production since it. The downside of this method is its complexity, however, this work represents a conscious effort to implement hybrid LCA unlike other studies in this field of research.

1.2. Objective

The main goal of this study is to undertake hybrid life cycle assessment of the case project in the power transmission grid expansion dedicated to incorporate variable sources of renewable energy. We are first intended to review a literature about projects in this field and identify case for subsequent analysis. Then, the reports that documented life cycle inventories and cost data on sub-components of transmission infrastructure would be discovered and adapted to the case study. After that life cycle impacts assessment would be performed with results reported and interpreted. Ultimately, conclusions are to be presented along with suggestions for further research into this area.

2. Literature review, case identification and hybrid assessment under tiered LCI framework

2.1. Overview of literature and case identification

This chapter is intended to cover existing literature related to extensions of transmission grid with respect to accommodation of new capacity of intermittent sources of energy, which is followed by identification of case study or project of interest.

To begin with, we provide brief opening about basic energy systems as described in the Global Energy Report [19]. A schematic diagram of the energy system with its elements is presented in Figure 2.1.

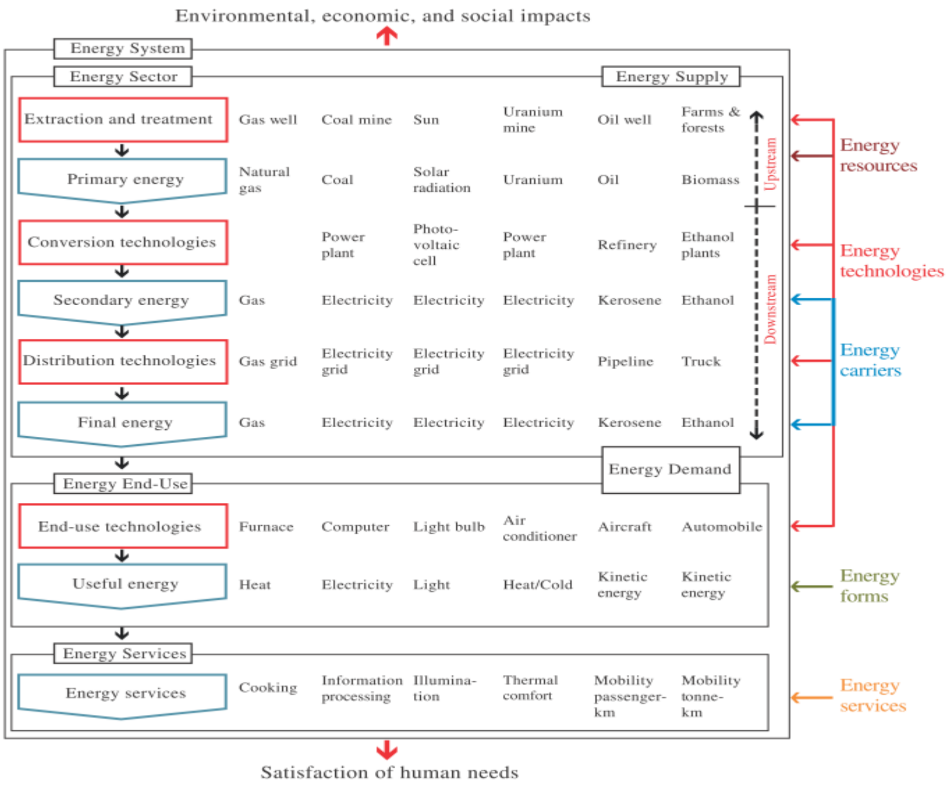


Figure 2.1. Diagram of the energy system. Source: [19]

As we can see from the figure above, there are three main steps: production, conversion and use of energy, to which all elements of the energy system are related. In the energy supply sector the chain of activities is initiated with extraction of primary energy resources (such as drilling of oil and natural gas). Next, these resources undergo transformation by dint of technologies into different energy carriers (i.e. liquefied natural gas). At this step energy is in secondary form so it could be distributed more effectively to places where energy demand occurs. That is where it is finally used as useful energy in end-use applications in order to deliver various energy services to end-users.

Given the framework of the energy system, it is handy to associate it to the power grid architecture. Electricity (or power) grid is conceptually presented as a unidirectional system (see Figure 2) where electrical energy is produced by power plants, transformed and transmitted through network of power lines and substations to customers. From the energy system perspective, electricity grid can be related to both energy supply (where secondary energy is electrical energy) and energy demand parts. It is easy to see, that part of the power grid stretching from the central generation to the distribution network refers to the

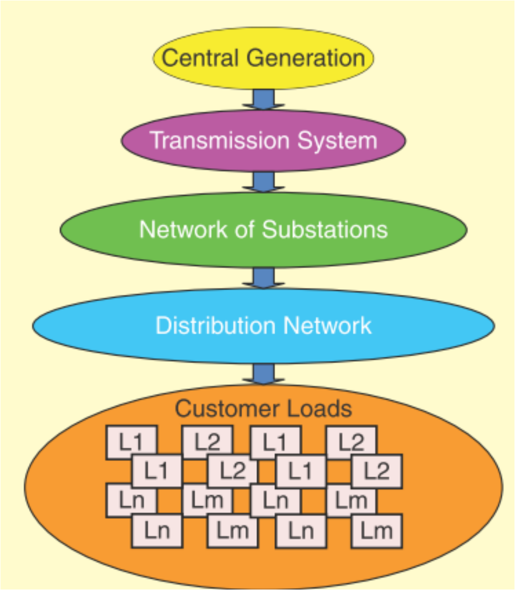


Figure 2.2. Current structure of the power grid. Source [6]

conversion and distribution technologies of the energy supply sector. At the same time, end-use technologies of the energy demand sector are basically customer loads in the power grid.

With increased concerns about detrimental effect that conventional energy production has on environmental conditions globally and improving competitiveness of less carbon-intensive means of energy production, there emerges a drive for structural change of current electricity transmission infrastructure given the intermittent nature of new generation.

When it comes to public information on this topic, European Union is at the forefront, with the United States of America following EU closely. Most of the reports contextualize transmission grid upgrades within Smart Grid platform [references], however, one notable exception from that is Ten-Year Network Development Plan (TYNDP) by the European Network of Transmission System Operators for Electricity (ENTSO-E). This document "..deliver a structure, systematic and comprehensive vision for grid development in the coming 10 years in Europe.." [9], where complete framework for assessment of investments in European transmission grid expansion projects with description of methodology and scenarios are formulated in dedicated chapters. Most importantly, large part of the infrastructure expansion is envisaged to be a basis for providing grid access to renewable generation. Description of the projects is structured into several columns that contain, among others, classification of projects, outline of technical details, transfer capacity enhancement, environmental benefits, etc. [9].

Having accepted this report as a basis for selection of case project, all portfolio was investigated in order to determine project with (1) ample description, i.e. length of transmission lines and voltage ratings are included; and with (2) adequate scope, i.e. we avoided multi-project clusters, and project should have RES integration designation. The absolute majority of the projects did not met the outlined criteria, however, one project related to provision of electricity infrastructure for Romanian pumped-storage hydro power plant Tarnita -

Lapustesti was successfully selected [9]. The summary of the project is given the chapter 3.

2.2. Methods. Hybrid tiered life cycle analysis

To begin with, we are providing a brief overview of the *life cycle assessment* method.

Life cycle assessment (LCA) is commonly used in quantification of environmental aspect of products and services. International Standard Organisation developed the framework for this technique, ISO 14 040 and 14 044 standards [20, 21]. This method considers the entirety of a product's life cycle "from-grave-to-cradle", so that environmental performance is evaluated systematically, and there is no transfer (or shift) of impacts from one stage to another.

The procedure for LCA follows four consecutive steps (see Figure 3.1):

1). Goal and scope definition, 2). Inventory analysis, 3). Impact assessment, 4.)

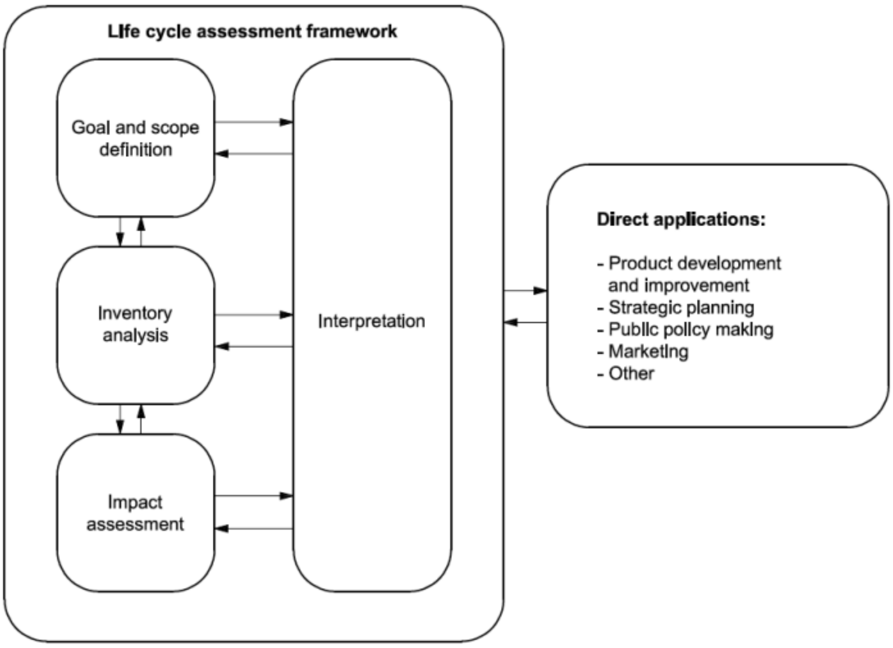


Figure 3.1. Life cycle assessment phases. Source: [20]

In first phase the proposed intention, motivation, functional unit and system boundaries are specified. Next step, inventory analysis, is to construct inventory with energy and material flows which present inputs and outputs of the system. The outcome of the previous phase, which takes form of environmental stressors, is used to quantify impact across chosen categories. This is done in order to gauge the contribution of system components or stages to the total environmental impact. Life cycle impact assessment can be based on the ReCiPe methodology [22]. The respective results are presented in 18 midpoint indicators and can be shaped within three contexts: egalitarian, individualistic and hierarchical, that accounts for uncertainty. Finally, conclusions and recommendation are made based on calculations which are related to the aims of the analysis.

Next we account for the hybrid tiered LCA method as first described in [23] and then in [18, 24].

Hybrid assessment uses input output analysis postulated by Wassily Leontief jointly with LCA. The IOA is used to analyse inter-industry relations in the economy, which in its turn can be employ to account for direct and indirect environmental stressors. Mathematical apparatus is similar to that of LCA which facilitate its co-implementation under hybrid methodology.

Hybrid tiered LCA starts with construction of A, matrix of requirements, which is presented in Figure 3.2, where two sub-systems are connected to the foreground process –based model, A_{ff}, via respective requirements matrices A_{nf} (IO-based) and A_{bf} (process-LCA) with the background databases A_{nn} (monetary) and A_{bb} (physical).

$$\begin{bmatrix} A_{ff} & 0 & 0 \\ A_{nf} & A_{nn} & 0 \\ A_{bf} & 0 & A_{bb} \end{bmatrix}$$

Figure 3.2. Hybrid A matrix

The major merits of this method is that it covers incomplete system boundaries present in process-determined LCA sub-system with economic activities among different sectors, hence minimizing truncation errors. On the flip side, this introduces double-counting issue into the model, which can be resolved by undertaking following steps. At first, we need to assign foreground processes (A_{ff}) to IO sectors, which is performed in synthetic H_{nf} concordance matrix. Multiplication of monetary dataset (Ann) with concordance matrix and price vector would yield temporary sub-matrix A_{nf}. Finally, Z_{nf} is a sub-matrix constructed to account for which sectors of IO are double-counted (meaning that respective intersection of sector and foreground process has zero value), and Z_{nf} is multiplied with temporary A_{nf} to obtain final sub-matrix linking foreground processes to monetary background.

3. System definition and hybrid inventories

Previous chapters were dedicated to identification of potential case study and to establishing methodological framework. With that being achieved, this chapter aims to bring these bodies of knowledge together to perform life cycle inventory analysis, i.e. explore and determine applicable life cycle inventories and cost data required for creation of hybrid inventories for this study.

3.1. System definition

The case project is identified as a part of massive plan for extension of electrical grid in EU called “10-Year Network Development Plan 2012” developed by The European Network of Transmission System Operators for Electricity (ENTSO-E), and take place in Cluj County, Romania. Rationale for selection of the project for case study was provided in Chapter 1. We start defining the system for this project with a brief listing of the projects basic technical details, which are presented in Table 3.1.

Table 3.1. Description of the project chosen for case study adopted from [9]

Investment number	Element of project	Expected date of commissioning
108.A134	New 145 km double circuit 400 kV OHL Tarnita - Mintia	2018
108.A135	New 40 km double circuit 400 kV OHL Tarnita – Cluj E - Gadalin	2018
108.A136	New 400 kV substation Tarnita	2018

According to the description outlined in [25] the main goal of this project is the grid connection of pumped-storage hydraulic power plant (SPHPP) Tarnita – Lapustesti that is going to be built on Somesul Cald River in Cluj County. This power plant is designed to have 1000 MW capacity and should have profound effect on power balancing in the country. Development of the Romanian grid on a period from 2001 to 2017 as planned by Transelectrica, Romanian transmission operator, is presented in Figure 3.1.

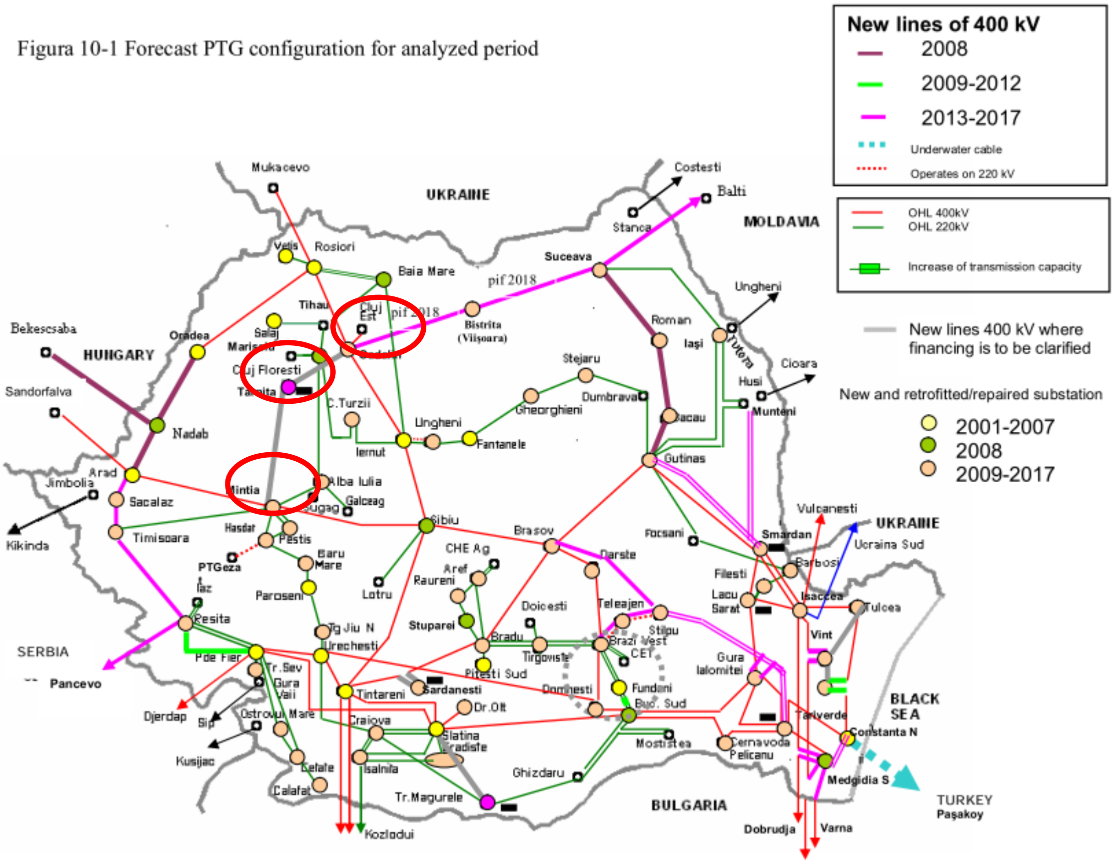


Figure 3.1. Map of the Romanian grid development from 2001 to 2017 with highlighted cluster of projects chosen as case study. Source: [25]

While power grid is generally comprised of many elements pertaining to a number of technologies for transmission and distribution of electricity [26], this part of the study would focus only those that are relevant to the scope of case project: OHL and substation equipment.

Thus, the system is comprised of double circuit 400 kV overhead transmission lines and substation with gas-insulated equipment. When it comes to the functional unit, the product system is chosen to be the functional unit itself. This decision is based on the fact that there was no access to the power flows data, hence it was not possible (without introduction of large uncertainties) to connect functional unit with kWh of electricity transmitted which is commonplace for LCA studies related to energy generation. The simplified system is shown in Figure 3.2.

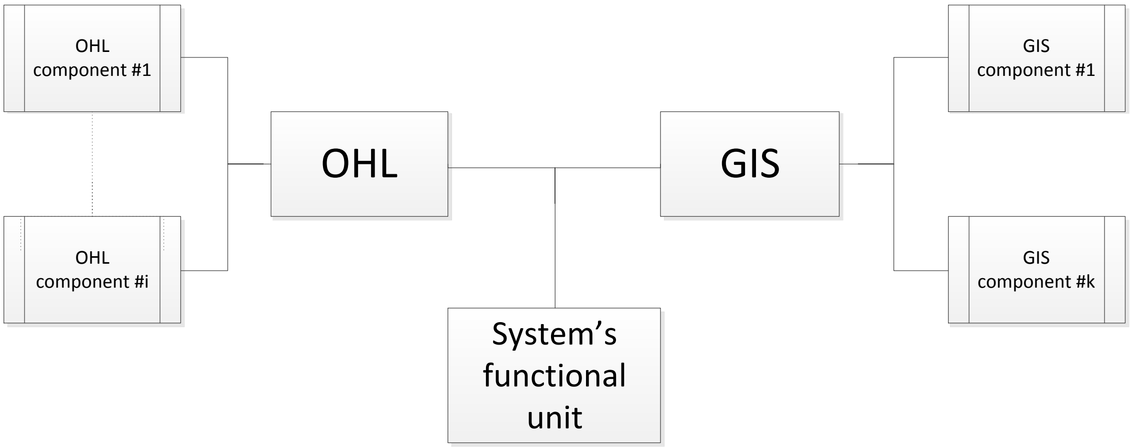


Figure 3.2. Simplified product system for the case project with generic number of components in OHL and GIS categories

Generally, the functional unit and system definition are followed by selecting system boundary. On the power grid level, when considering goal and scope of this study, it seems obvious that the system includes only transmission of electricity from generation units to other parts of Romanian power grid, but the generation of electricity on SPHPP Tarnita – Lapustesti and further T&D to the end users is beyond the scope of the work. As to the equipment level, we will first look closer at life cycle inventorying for OHL and GIS substation categories defining which element are part of analysis and which are not. Once it is done, it would be possible to clearly outline system boundary highlighting all relevant elements.

The lifetime of the system elements is adopted from [Raquel] as 40 years.

Importantly, power losses are not considered due the fact that the power flow analysis within TYNDP report is not available hence assuming general power load and deriving losses from this calculation can distort final results significantly.

3.2. Data compilation. Physical inventories

Previous section of this chapter lays out the order in which system and inventories are designed to be reported. This sub-chapter describes life cycle inventories for transmission lines and gas-insulated substation, refining which elements of these categories are considered in the study.

The life cycle inventories for this case project are based on the work performed by [27] with all original inventory and supplementary files kindly provided by authors. This paper looked into all projects related to RES integration into European power grid. Various elements of this inventory are sourced from different papers and reports, which were considered as well. Since the scope of this study confined to one investment TYNPD project, only part of this inventory is used.

3.2.1. LCI of overhead transmission lines

When it comes to overhead transmission lines original inventory does not contain double circuit 400/400 kV OHL, instead, the closest match is double circuit 400/150 kV OHL which is used as proxy for this work. Next, we are intended to analyse its structure and explain how it was adopted in our inventory, as shown in Figure 3.3.

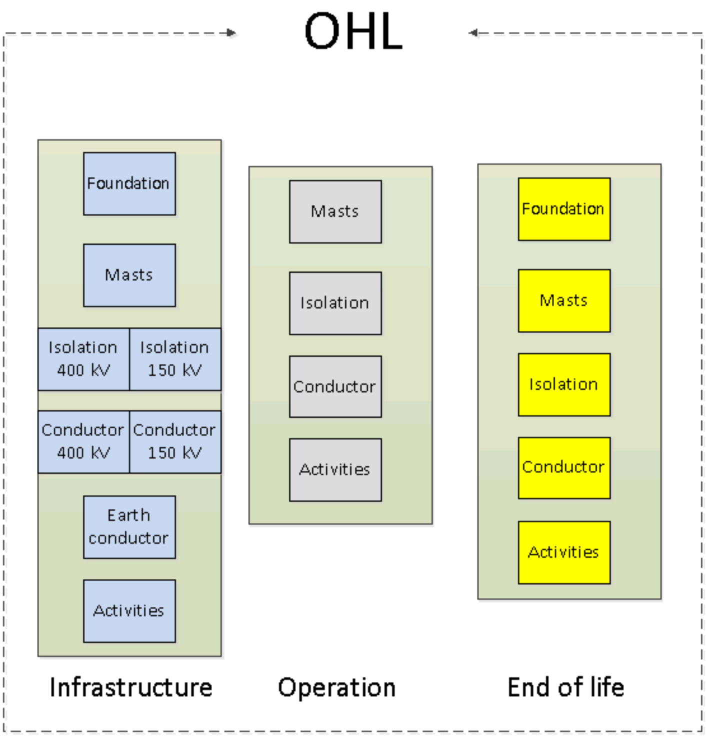


Figure 3.3. Structure of original OHL inventory as constructed in [27]

As can be seen in Figure 3.3, OHL unit processes represent major elements of the transmission lines:

- foundations;
- masts;
- conductors (400 and 150 kV separately);
- isolation (400 and 150 kV separately);
- earth conductor;
- activities.

Figure 3.4 illustrates typical high-voltage alternating current transmission line.

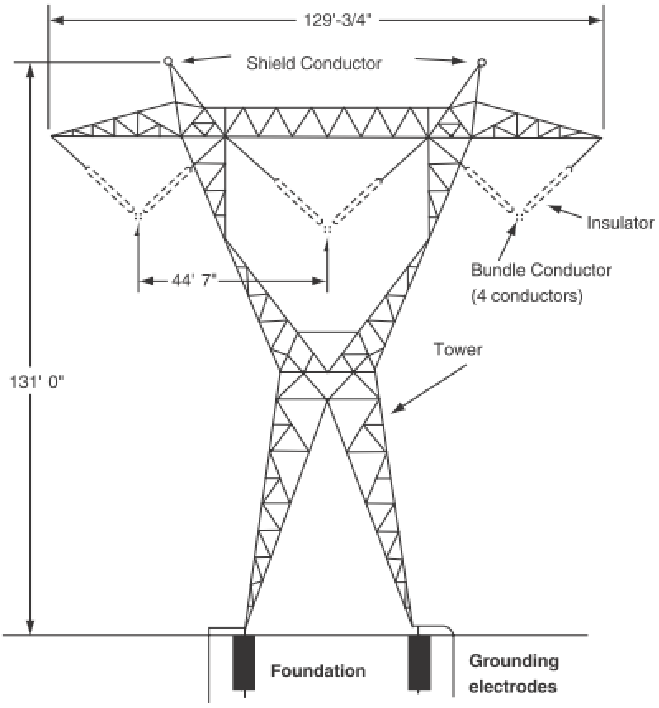


Figure 3.4. Illustration of generic OHL with major elements. Source: [28]

Overhead transmission line process itself disaggregated into three life cycle stages: infrastructure, operation and end-of-life. Infrastructure stage covers all energy and material flows due to raw materials extraction, manufacturing, assembly, installation and related transport activities. Next stage is operation, which includes maintenance and other assets management activities such as on-site inspections with related transport activities. Last stage describes processes related to disposal and recycling of unit processes.

In the following section these unit processes would be given brief technical description along with procedure of its implementation in life cycle inventory.

Foundations is a part of the transmission line that carries over mechanical loads of the whole structure to a ground. There are a number of types of foundations, and its selection depends on soil characteristics, weather conditions and type of transmission tower [Foundations for transmission lines]. Details of foundations for OHL were not specified in the [29] report, but considering materials required for its construction, we can assume that generic concrete foundation with steel framework for steel towers was used. The data source [29] provides bill of quantities for double circuit 400/150 kV OHL, hence when using its information we had to scale inputs for foundations. No literature was identified that could support implementation of scaling coefficient, therefore the choice of 1.5 multiplier was confined to exercising own judgment with consideration given to increased inputs of other OHL elements.

Table 3.2 provides inputs of materials required for construction of concrete foundations per 1 km of OHL

Table 3.2. Material inputs for construction of concrete foundations per 1 km of OHL

Material	**Quantity**
Concrete with density 2400 kg/m^3, m^3	180
Iron, kg	22,500

Masts or towers (another term is pylon) serve to provide mechanical support for energized conductors and isolate them from each other (phase-to-phase), from ground (phase-to-ground) and structure (phase-to-tower). Main features of the tower design can include its basic dimensions, conductor spacing and span between adjacent towers and is a subject to many parameters including stresses from conductors, wind and other weather conditions, grid topology, and other site characteristics. The most common type of transmission towers is suspension one, where conductors do not apply sideways force to the supporting structure. In case lateral loads are present, angle towers are installed which allows to changing an angle of the line route. Naturally, that means that angle towers are heavier than suspension ones so that the former is more material-intensive than the latter. Speaking about materials, transmission towers can be made from steel, concrete and wood, and in practice, the all three are widely-used. [30]

According to the report [29], each OHL *mast* is made of steel with anti-corrosion protection (hot dip coated with zinc) and assumed to be of suspension type with average span of 333 m. Pre-eminence of suspension towers is somewhat detached from real situation where transmission line has to change its angles depending on the route, however, no estimates for difference between suspension and angle towers were found. One last important point that was addressed in this study is that OHL of the Romanian case project is designed to have two 400 kV circuits per one tower, whereas in original data it is one circuit has voltage rating of 400 kV and the other one is 150 kV. Similarly to foundations, procedure for scaling from 150 kV to 400 kV in terms of materials has not been determined, so that an estimate that the inputs would be two times higher for the case tower was applied. Throughout the OHL lifetime, zinc coating would be washed away from the surface of steel structure so that reapplication of zinc is required during operation of OHL.

Table 3.3 shows what materials are being consumed during construction and operation of OHL masts.

Table 3.3. Material inputs for construction and operation of steel suspension towers per 1 km of OHL

Material/Stage	Infrastructure	Operation
Steel, kg	106,000	-
Zinc, kg	3,200	1,280

Typical *conductors* have outerlaying aluminium strands encircling steel core with a gap between them filled with heat-resistant oil or grease. Such arrangement is engineered to strengthen a conductor cable (where strength to weight ratio is the key parameter), which improves thermal elongation performance allowing having bigger tower spans. The number of shapes and patters of conductors is large, and, along with cross-section thickness, depend on weather loads, designed power transmission parameters (capacity, thermal tolerance, electro-dynamic forces, etc.) and other design considerations. One notable point is that conductors for HV OHL are bundled into two (duplex), three (triplex) and more conductors, to reduce corona effect which is a source of significant power losses. Along with these conductors, lightning protection measures necessitate another group of wires to be installed on top of main conductors. This shielding conductors can be called ground (or shied) conductors, and due to analogous technology are considered to be a part of this components (which is in contrast to [Raquel Paper], cf. Figure 3.3). [30]

As stated in the report [29], the 400 kV part of the double circuit OHL has duplex *conductors* with 772 mm^2 diameter in cross-section. For the case project we disregard values given for 150 kV part of OHL and use twice the amount of materials required for 400 kV circuit, which is shown in table 3.4. It ought to be mentioned that zinc coating of steel core of conductors is disregarded in a view of its insignificance compared to that of used for steel sections for masts. Heat-resistant lubricant applied to the steel core of conductors can leach off, and therefore require regular replenishment during lifetime of OHL, which explains inputs in during operation stage.

Table 3.4. Material inputs for construction and operation of conductors per 1 km of OHL

Material/Stage	Infrastructure	Operation
Aluminium, kg	24,714	-
Steel, kg	10,032	-
Mineral oil, kg	798	356

Insulators are called those parts of equipment that insulate conductors from surroundings prevent occurrence of faults, and are attached to cross-arms of transmission tower. They are combined into set of strings with a number of insulators depending on the dielectric requirements. The classification of insulators follows that of the tower one (i.e. suspension, angle) and reflects design peculiarities. Materials that insulators can be produced with include glass, porcelain and cast epoxy. [31]

Eltra report [29] specifies that insulators for the given OHL is made from toughened glass and are of suspension type. Similarly to conductors, only data for 400 kV set of insulators is employed in this study, and the amount of materials is doubled to account for double circuit 400 kV OHL, as can be seen in Table 3.5.

Table 3.5. Material inputs for construction and operation of insulators per 1 km of OHL

Material/Stage	Infrastructure	Operation
Cement, kg	126	0.4
Glass, kg	2,700	13
Steel, kg	1,632	10

One last element of OHL inventory is the transport that is required to during all life cycle stages. These transport *activities* are presented in Table 3.6 and include delivery of all finished products from supplier to construction site, supervision and operation of machinery and equipment, aerial monitoring, service and maintenance field trips and finally disposal at the end of life.

Table 3.6. Material inputs for construction, operation and end-of-life of transport activities per 1 km of OHL

Material/Stage	**Infrastructure**	**Operation**	**End of life**
Lorry for conductors, km	35,000	-	-
Lorry for foundations (concrete) and steel sections, km	15,240	-	14000
Lorry for insulators, km	4,500	-	30
Transport for supervision	1,500	9,000	1,500
Diesel for machinery and equipment on construction site	2,250	1,500	2,250
Aerial transport (helicopter monitoring)	-	2	-

When this overview of OHL elements accounted for two major life stages, construction and operation, this was generally not the case for inputs that take place during decommissioning of OHL (in other words, end-of-life) with exception of inputs described within activities process. The reason for that is that original study [27] modelled recycling of the majority of inputs, however, we exclude recycling from LCI with all materials being disposed at the end of its life. Although, being a realistic assumption, recycling of materials can be, yet, another source of uncertainty that has a positive effect on emissions occurring during construction and operation life stages (i.e. the environmental burden associated with processes is decreased), which ultimately can obscure overall performance of investigated system. On the other hand, it is also understood that the absence of recycling, per se, brings in uncertainty since, in reality, recycling of materials (especially metals) does take place at some rates.

Replacement of materials during operation stage is subtracted from end-of-life stage, and 60% of initial value of heat-resistant lubricant is supposed to disposal stae. Finally, all materials that are disposed at the end of life stage excluding those pertaining to transport activities, are summarized in Table 3.7.

Table 3.7. Materials disposed at the end-of-life per 1 km of OHL

Material/Stage	Infrastructure
Concrete, kg	432,000
Steel and iron, kg	140,164
Aluminium, kg	24,714
Zinc, kg	3,200
Cement, kg	126
Toughened glass, kg	2,700
Mineral oil, kg	479

Other elements that can be a part of OHL transmission lines are excluded from the analysis.

3.2.2. LCI of gas-insulated substation

High voltage substation is complex engineering installation with array of electrical equipment serving to accept, transform and distribute electrical power. A large number of technologies are employed for creating high voltage substations with power transformer and switchgear being two most important among them. Insulation media that can be used in substation equipment include air, vacuum, dielectric oil and dielectric gas. GIS term presumes usage of sulphur hexafluoride (very potent greenhouse gas) as insulator within metal enclosed modules. [28]

According to the grid development plan of Romanian TSO, Transelectrica, [25] for the planned 400 kV Tarnita substation there would be installed four power transformers 400/15.75 kV (primary voltage rating to secondary) with capacity 280 MVA each. A unit of switchgear that accommodate transmission line circuits is sometimes called substation bay, and is generally comprised of circuit breakers, disconnectors, current and voltage instrumental transformers and surge arrestor [28]. While the number of bay on 400 kV Tarnita substation is not explicitly stated an estimation can be performed given the availability of data on incoming transmission lines and installed transformers. Thus, total number of connections to the switchgear equals to 8 (four transformers and two double circuit transmission lines). Assuming that the substations layout is designed as a breaker-and-a-half scheme (i.e. 3 circuit breakers per 2 connections), the case project substation will have 12 substation bays. When comparing case substation with original substation inventories developed by [27], it ought to be mentioned that there were described GIS switchgear 275/400 kV and power transformer 400/135 kV with capacity 250 MVA. While it is understood that using these proxies in the project's LCI would bring down accuracy of the impact assessment, its effect should be limited, and that pertains to the difference in material and energy inputs required to manufacture secondary side of the transformer, in particular, 15.75 kV as opposed to 135 kV. Moreover, the lack of data of power transformer LCI does not permit to consider alternatives.

When modelling substation inventory, the original inventory is arranged so that power transformer and GIS switchgear are examined separately. As to its components, GIS switchgear was dissected into manufacturing and end-of-life stages according with data sourced from study by [16]. Power transformer, on the other hand, accounted for material and energy flows from extraction of virgin materials, transport of raw material to next stage, manufacturing, transport of finished products, maintenance and final disposal. The data for life cycle inventory of transformer was taken from environmental product declaration by global power equipment producer company, ABB [32].

The abovementioned substation life cycle inventories are largely adopted as it is for the case project, however the structure of the substation is designed differently. There are several things in this respect that were modified in order to add clarity and consistency between physical and monetary inventories.

For one, our structure of GIS substation is derived from the report [33], and is shown in Figure 3.5.

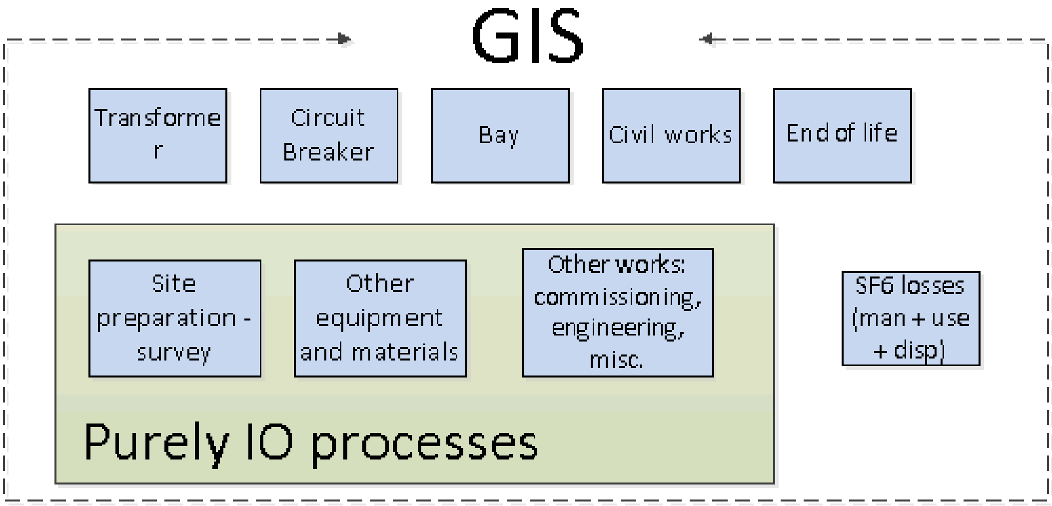


Figure 3.5. Structure of GIS substation inventory for the case project

Most notable feature of this composition of substation elements is that transformer is included into substation rather than being modelled separately. Hence, its inputs during life cycle stages are merged into one process – transformer. This is in contrast to GIS switchgear with is disaggregated into several components. We retained inventory as cited in data source set [16] insofar as the *circuit breaker* is set apart from *substation bay*, whereas the bay itself represents structural frame for the GIS module.

Basic civil engineering renamed into *civil works*. Looking at set [16] it can be interpreted that *Basic civil engineering* values are given for 1 Substation with 8-12 bays. Hence we need to insert value per bay, thus we divide total value on 10 (average number of bays). This is different from [Raquel] study since the total value for substation was used per unit of switchgear. Next, there are three unit processes with no physical data: (1) *Site preparation – survey*; (2) *Other equipment and materials*; (3) *Other works: commissioning, engineering, misc.*. This is due to their sole purpose is to present IO processes. Lastly, SF_6 losses of GIS equipment are taken from [32] and are calculated as direct stressors. Other elements of substation (such as Smart Grid components) and power losses are not accounted for due to the lack of data.

Summary of all material and energy inputs is shown in Table 3.8.

Table 3.8. Material inputs of the life cycle inventory for 1 unit of 400 kV GIS Tarnita substation

Inputs/Processes	**Trafo 250 MVA**	**Circuit Breaker**	**Bay**	**Civil works**	**End of life (disposal of materials)**
Aluminium, kg	1,987	8,400	-	1,080	11,467
Limestone, kg	-	-	-	201,600	-
Concrete, density 2400 kg/m^3, m^3	540	-	16	3	1,341,020
Copper profile, kg	23,837	1,800	-	-	Copper total: 26,028
Copper wire, kg	391	-	-	-	
Steel sheet, kg	38,074	-	-	-	Steel total: 116,238
Steel profile, kg	7,500	3,500	-	-	
Electrical steel, kg	67,165	-	-	-	
Glass fiber, kg	1,109	-	-	-	-
Kraft paper, kg	1,479	-	-	-	-
Presspan, kg	5,294	-	-	-	-
Porcelain, kg	2,009	-	-	-	-
Paint, kg	95	-	-	-	-
Transformer oil, kg	48,000	-	-	-	48,000
Resins, kg	188	-	-	-	-
Epoxy, kg	-	1,800	-	-	1,800
Electricity, kWh	116,750	-	-	-	-
Natural gas,	1,788,938	-	-	-	-
Transport lorry 3.5-7.5 tons, t/km	1,106,935	-	-	-	-
Transport lorry >32 tons, t/km	98,834	-	-	-	-
Disposal inert to landfill, kg	-	-	-	-	226,841
Disposal hazardous waste, kg	-	-	-	-	2,315

3.3. Data compilation. Monetary inventories

The process of compiling monetary data, i.e. price vector, proved to be strenuous. The cost data of transmission infrastructure is quite heterogeneous, and examined reports vary geographically and have different scopes and goals [33, 34]. As a result the product of such compilation is subject to big uncertainty, however, given the absence of complete data accounts pertaining to European context, it is our believe that this attempt is a step forward for this field of research.

Coming to the categories itself, they were defined in the previous section of life cycle inventory analysis in a process of matching data on physical and monetary inputs. This way the following section of this chapter would first provide details on OHL data compilation and then that of GIS substation.

3.3.1. Cost data for OHL

As to development of cost account for OHL, [34] was used to supply the data. While Romania was not included in that research, we considered several countries with similar geographical features. As can be seen from satellite snapshot of area in Romania where the case project is ought to be developed, which is shown in Figure 3.6, Romanian landscape can be generally characterized as mountainous.

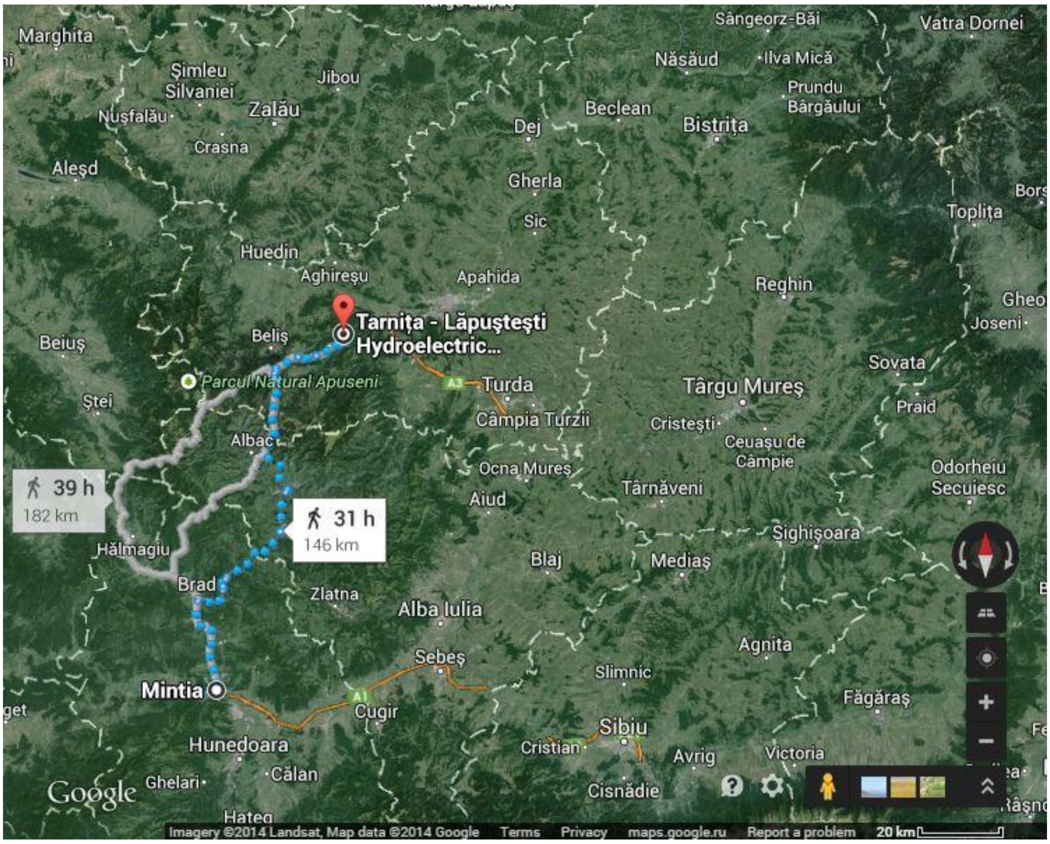


Figure 3.6. Satellite snapshot of Cluj County, Romania showing landscape elevation. Source: [35]

Out of several European countries studied in [34] Austria, Italy and Switzerland were examined as a potential proxy for Romanian cost data. Swiss data was the most suitable for the case project due to proximity of cost categories with that of LCA, and it is presented in Table 3.9 along with relative shares of costs.

Table 3.9. Costs of construction double circuit 380 kV OHL in Switzerland and derived relative cost shares, year 2002. Source: [34]

OHL component	Costs, Euro	Relative cost share of OHL components
Foundations	123,000.00	19.3%
Towers	151,000.00	23.7%
Conductors	75,000.00	11.8%
Insulators	41,000.00	6.4%
Labour	247,000.00	38.8%

The reason why we transformed absolute cost values into percentages of total OHL price is due to availability of total price for Romanian OHL. In particular, according to [36] average cost of construction of 1 km of double circuit 400 kV OHL equals to 400,000 Euro per 2002 year prices.

One more step is necessary to obtain data costs for the OHL of the case project. The point is that prices of goods and services are not constant and are subject to inflation (or less commonly to deflation), meaning that the average price per 1 km should be scaled to the base year of Exiopol database [38], 2000. In other words this rate of scaling is called harmonised indices of consumer prices (HICP). These data can be found in Eurostat database on HICP [37]. HICP for EU-27 were applied to maintain consistency with Exiopol database (which is compiled for 27 European countries) [38]. Eurostat database set 1996 as a base year, hence additional calculations were made in order to obtain OHL price for year of 2000. The table 3.10 shows calculations performed to obtain the OHL price, year 2000.

Table 3.10. Procedure for obtaining OHL price Euro per 1 km scaled with HICP for EU-27.

Year, month/Category	**2002M01**	**2000M01**
HICP, EU-27	125.1%	117.6%
Intermediate relative share	106.38%	100%
Price value, 10^3 Euro	0.4	**0.376**

Once the average value of OHL per 1 km for a year of 2000 is found, we can construct OHL part of price vector, as shown in Table 3.11.

Table 3.11. Price vector compiled for OHL components.

OHL component process	Price per unit, 10^6 euro
Foundations - infrastructure	7.26E-02
Masts Infrasctructure	8.91E-02
Insulator 400 kV Infrastructure	2.41E-02
Conductor 400 kV Infrastructure	4.44E-02
Activities Infrastructure	1.46E-01
Masts Operation	1.07E-03
Insulator operation	2.89E-04
Conductor operation	5.32E-04
Activities operation	1.75E-03
Foundations waste	-
Masts waste	-
Insulator waste	-
Conductor waste	-
Activities waste	-

3.3.2. Cost data for GIS substation

Compilation of the price vector for GIS substation is divided into two major sub-tasks: obtaining price value for power transformer and for GIS switchgear components. Report [40] contains information on prices for HVAC 400 kV GIS switchgear and power transformer 400/132 kV with capacity 240 MVA in British pound sterling. Once again, when compared to the case project equipment, transformer’s technical characteristics is slightly different, nevertheless, it can be concluded that the difference is marginal.

Assuming exchange rate of British pound to Euro equals 1.12 (as of 01.01.2010 [41], i.e. as of the issue year of the data source report), we can obtain average price values for transformer and switchgear, as shown in Table 3.12.

Table 3.12. Conversion of average price in British pounds to Euro values for transformer and switchgear as of 01.01.2010

Substation component	Price, 10^6 GBP	Price, 10^6 EUR
Transformer 400/132 kV 240 MVA	2.13	**2.464**
GIS 400 kV switchgear per bay	2.69	**3.136**

Similarly to OHL data cost analysis, for the sake of consistency we need to scale these results to base year of 2000 using harmonised indices of consumer prices, as presented in Table 3.13.

Table 3.13. Procedure for obtaining GIS substation prices Euro per unit scaled with HICP for EU-27.

Year, month/Category	2009M01	2000M01
HCIP, EU-27	146.4%	117.6%
Intermediate relative share	124.49%	100%
Price of transformer 400/132 kV 240 MVA, 10^6 Euro	2.464	**1.98**
Price of GIS 400 kV switchgear, 10^6 Euro	3.136	**2.52**

While the transformer's cost can be used promptly and included in the price vector, that is not the case for the GIS switchgear. The thing is that given the average price, we are yet to disaggregate it into the switchgear components.

As a basis for construction of the structure of GIS switchgear, the T&D costs research by Canadian TSO [33] was employed. It ought to be mentioned though that, arguably, the absolute majority of substations in Alberta, Canada, designed with air- or oil-insulated switchgear equipment. The reason why it is so is that the region occupies Northern part of the Canada where space constraints are rarely included into design considerations. This means that relative shares of GIS substation components are valid for AIS switchgear, and there would be needed additional treatment of these data to improve accuracy of results.

Table 3.14 presents original costs of 240 kV AIS substation with two power transformers 245 kV 200 MVA and 4 substation bays with 300 kV circuit breakers; and derived relative share of substation components.

Table 3.14. Cost breakdown for AIS Canadian 240 kV substation [33] with derived relative shares

	Substation component	Cost, Canadian dollar	Relative share
Materials	**Transformers**	4 261 795.00	23.607%
	Circuit Breakers	945 704.00	5.238%
	CT_PT	499 162.00	2.765%
	Structure_etc	2 396 145.00	13.273%
	Control Building	398 669.00	2.208%
	SCADA	93 489.00	0.518%
	Controls	681 950.00	3.777%
	Switches	155 000.00	0.859%
Labour	**Commissioning**	466 836.00	2.586%
	Construction	3 982 268.00	22.059%
	Site_Prep - Survey	3 010 207.00	16.674%
	Engineering	1 027 759.00	5.693%
	Misc.	134 196.00	0.743%

In the next following section, we are intended to describe actions taken to obtain final prices of GIS switchgear components. Firstly, since the cost value for power transformer has already been found, it was excluded from further calculations, and percentages of other substation components were rescaled to 100%. Secondly, initial composition of AIS substation was rearranged with some categories merged in order to match with the life cycle inventory of the GIS switchgear. Thirdly, as was mentioned previously, there is a necessity to address the mismatch between air-insulated and gas-insulated technologies which was manifest, which was fulfilled by using cost relation between two solutions [42]. Last step was to find prices of GIS switchgear components as a now known percentage of total GIS switchgear value. The whole procedure is shown in Table 3.15.

Table 3.15. Procedure of obtaining final prices for GIS substation components

Elements of switchgear/Steps of data manipulation	Relative shares for AIS rearranged components [33], %	Cost relation between AIS and GIS Siemens, % (AIS is taken as 100%) [42]	GIS relative shares adjusted from AIS ones, %	GIS percentages rescaled to 100%, % (since we exclude transformers)	Final prices, 10^6 Euro
Circuit Breaker	5.24	120	6.29	11.50	**0.290**
Bay (structure in original cost data)	13.27	60	7.96	14.56	**0.367**
Civil works (construction in original cost data)	22.06	60	13.24	24.20	**0.610**
Site preparation - survey	16.67	80	13.34	24.40	**0.615**
Other equipment and materials: Control Building, CT, PT, SCADA, Controls, Switches	10.13	70	7.09	12.96	**0.327**
Other works: commissioning, engineering, misc.	9.02	75	6.77	12.38	**0.312**
Total	76.39	70	54.68	100.00	**2.519**

Having successfully obtained all of the prices for GIS substation components we can compile the section of price vector related to GIS substation, as presented in Table 3.16.

Table 3.16. Price vector part for GIS substation sub-components

GIS substation component process	Price per unit, 10^6 euro
Power transformer	1.98E+00
Circuit Breaker	2.90E-01
Bay (structure in original cost data)	3.67E-01
Civil works (construction in original cost data)	6.10E-01
Site preparation - survey	6.15E-01
Other equipment and materials: Control Building, CT, PT, SCADA, Controls, Switches	3.27E-01
Other works: commissioning, engineering, misc.	3.12E-01
End-of-life	-
SF6 losses (man + use + dis)	-

Finally, MATLAB scripts is provided in Appendix A; the selection of Ecoinvent processes [38] in physical dataset was to large extent adopted after the original report [27]; and the assumptions and procedure for the double-counting prevention in monetary sub-system is adopted after the research by [24].

4. Results and analysis

This chapter is intended to present the results of the tiered hybrid LCA of electrical grid extension under TYNDP project in Cluj County, Romania. Due to limitations of EXIOBASE developed in EXIOPOL project [39], our final findings encompass only three midpoint categories of impacts [22]: climate change, photochemical oxidant formation and terrestrial acidification. Among these categories the climate change is prioritized in the analysis due to direct relevance to the goal of TYNDP projects – provision of T&D infrastructure for less carbon-intensive generation. Moreover, normalization and weighting steps of LCIA are omitted on the grounds of that they seem to bring little to no benefit to the analysis and discussion. The reason for that is the lack of reference sources and creating even more uncertainty in the relatively underdeveloped area of LCA research. While these judgments can constrain the value of the results, it, nevertheless, is still consistent with the goal and scope of this study, which seeks to create a case for exercising hybrid LCA in the sector of electricity T&D.

The content of this chapter is built upon assessment of balance of power for the total impacts generated in monetary (IO) and physical (LCA-process) subsystems. Ideally, the reported results will both reveal a nature of impacts distribution and provide realistic explanation for it. Following that, the contribution of OHL and GIS components to total impacts is being investigated at first, and, next, relations between monetary and physical datasets of the case in general and with regard to the contributors identified are looked into. These results are complemented by identification of top contributing processes of monetary and physical datasets. Finally, collected evidence is used to interpret distribution of impacts between IO and LCA-process parts of the system.

As it was discussed in previous chapters, the construction of hybrid inventories entails significant number of assumptions and uses of proxy. Along with the quality of the data being accounted for in the Chapter 5, we strive to evaluate to what extent our calculations are prone to uncertainty. This is why the second part of this chapter is dedicated to assessment of the magnitude and characteristics of data variability where three scenarios were developed to reflect upon the conclusions made in the first part of this chapter.

4.1. Environmental impacts of the case project and its origins.

The results of total impacts incurred over life cycles of the double OHL 400 kV Tarnita (RO) - Mintia (RO), double OHL 400 kV Tarnita (RO) - Cluj E - Gadalin (RO) and GIS substation 400 kV are shown in Table 4.1.

Table 4.1. Total impacts of the system.

Total impacts	**Unit**	**Total**	**Share of process-LCA impacts**	**Share of IO-sectors impacts**
Climate change	kg CO_2-Eq	2.23E+08	77%	23%
Photochemical oxidant formation	kg NMVOC	7.58E+05	74%	26%
Terrestrial acidification	kg SO_2-Eq	1.05E+06	77%	23%

It is apparent that our system is disaggregated into two distinctive parts – overhead transmission lines and gas-insulated substation. The point of interest in our contribution analysis is how these parts relate to each other and to the total impacts value. Looking at the distribution of total impacts among the system components presented in the Figure 4.1 we aim to answer the question: “In case there is a sizeable difference, what elements of these subsystems are responsible for that and what elements have negligible influence on overall result?”.

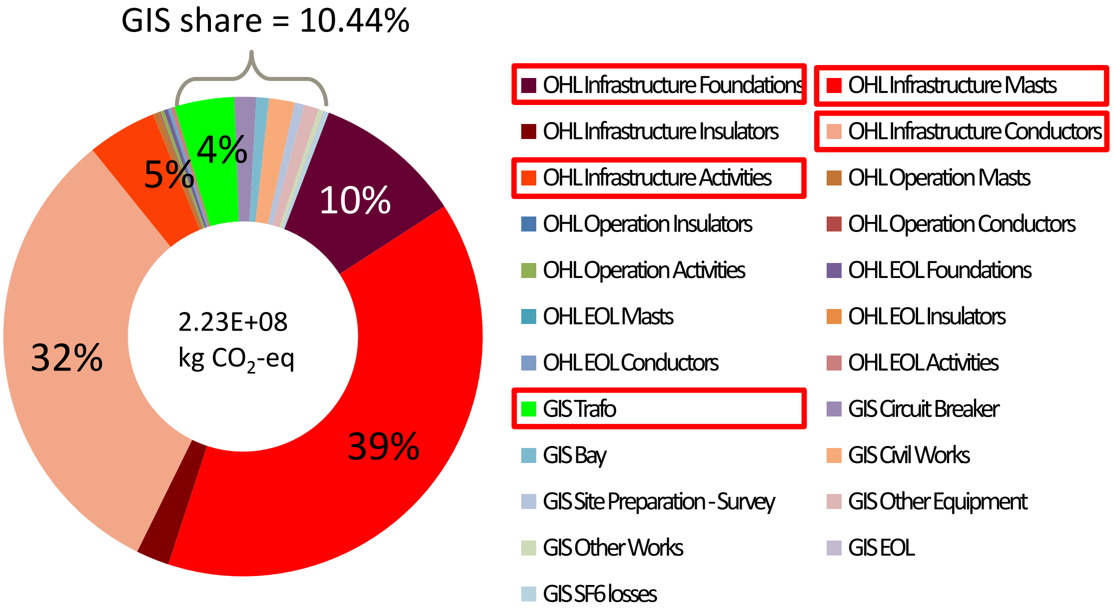
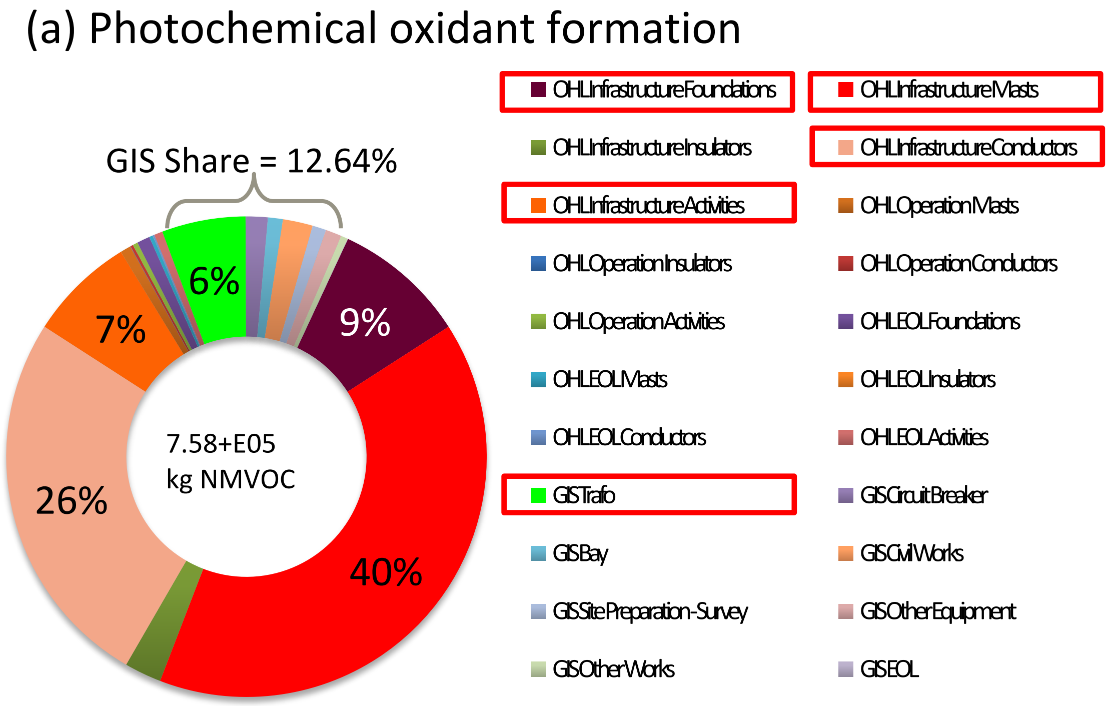
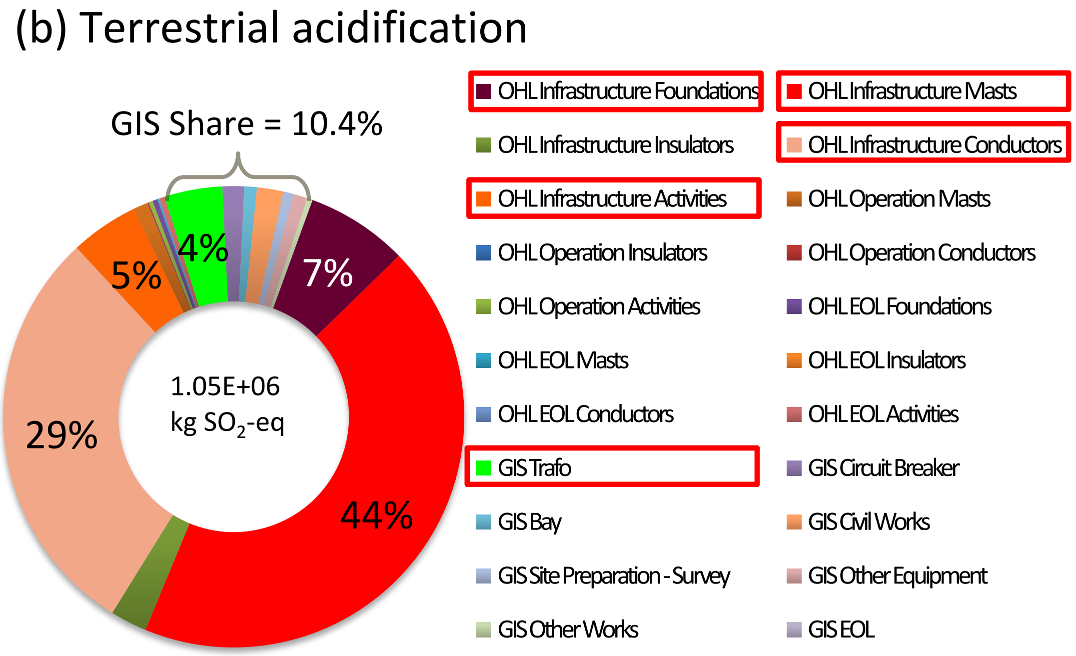


Figure 4.1. Breakdown of the shares of total impacts for climate change category among components of the system

Figure 4.1 shows that the absolute majority of the climate change impacts are associated with the transmission lines, and they are one order higher (2.00E+08) than that of gas-insulated substation ones (2.33E+07 kg CO_2-eq.). It can be seen further that OHL infrastructure is responsible for some 86% of total climate change impacts with masts and conductors components contributing almost three quarters of the total value. Among other important contributors is the construction of foundations and transport activities (delivery of finished and semi-finished products, supervision and monitoring) for OHL infrastructure, while only impacts generated due to 4 power transformers are visible when it comes to GIS contribution. The rest of the elements include OHL operation, OHL EOL and various units of substation and represent negligible 5% of the total value. Contribution of SF_6 leakage modelled as a direct stressor is less than 1% of total impacts value, and constitutes roughly 3% among GIS substation category.

In general, the observations made with regard to the ranking of contributing components are applicable to two other categories: photochemical oxidant formation and terrestrial acidification, and that can be seen in Figure 4.2.


(a) Photochemical oxidant formation



(b) Terrestrial acidification

Figure 4.2. Breakdown of the shares of total impacts for (a) photochemical oxidant formation and (b) terrestrial acidification categories among components of the system

It can be seen in Figure 4.2 that the results for POF and TA categories are strikingly similar to that of climate change one. In particular, OHL infrastructure cluster has retained its overwhelming pre-eminence over other elements. As to the extremes, the construction of masts has peaked at 44% value of terrestrial impacts (4.55E+05 kg SO_2-eq.), just some 6% away from being responsible for a half of overall impacts in this category. While there are some discrepancies, their extent is marginal and the deviations of values lie within a range of 5%. Notably for photochemical oxidant formation category, the impacts due to GIS subset barely reach one eighth of the total value, and the contribution of power transformers stands for 6%, which is still lower than that of OHL Infrastructure activities. Quintessentially, it was found out that the distribution of impacts among elements is homogenous for three chosen ReCiPe impacts categories with small variations in terms of shares of components.

The outcome of impacts calculations for the case TYNPD project is somewhat expected since the composition of the inputs is skewed heavily towards lengthy

(185 km) power transmission lines. Despite the fact that the substation for the pumping storage hydropower plant Tarnita – Lapusesti can be categorized as medium or even large type one, with 12 units of GIS switchgear and 4 power transformers, the project does not take into account end-line substations as they are existing structures. Moreover, the choice of hexafluoride-insulated equipment brings about minimization of the equipment and occupied space, hence reducing the overall need in materials.

It is been argued that integration of LCA and IOA methods under hybrid framework can prove to be value as it employs benefits of both methods while nearly eliminating truncation issues inherent to both LCA and IOA. Therefore this study should showcase achieved ratio of the impacts associated with monetary and physical subsystems and contribute to provision of a rationale for the study results.

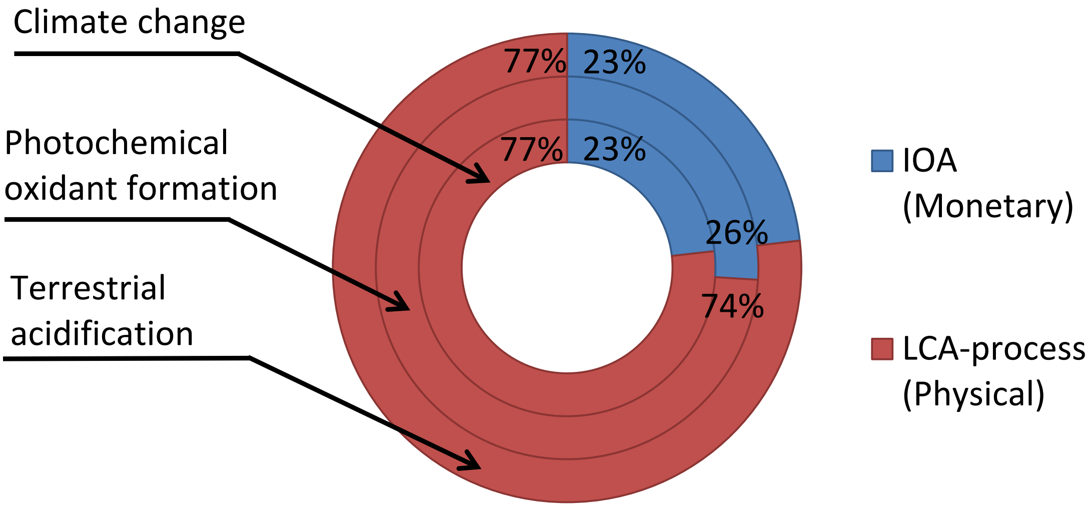


Figure 4.3. Ratio of of physical (LCA-process) subset to monetary (IO) ones for climate change, photochemical oxidant formation and terrestrial acidification impact categories

As shown in Figure 4.3 the share of physical (LCA-process) subset is 4 times higher than that of the monetary (IO) ones for all three impact categories. For climate change and terrestrial acidification impacts associated with physical subsystem are slightly more than 3/4 of the total value, whereas in photochemical impact category it is marginally lower than this threshold.

When it comes to breakdown of impacts for various components we learned from previous part of this work that OHL Infrastructure is the main culprit among all impact categories. Hence, it would be valuable to examine whether our general findings with respect to IOA/LCA impacts ratios hold true for all important components of the system. These data are presented for every part of OHL Infrastructure, for OHL Operation combined with OHL EOL and for total GIS value, as shown in Figure 4.4.

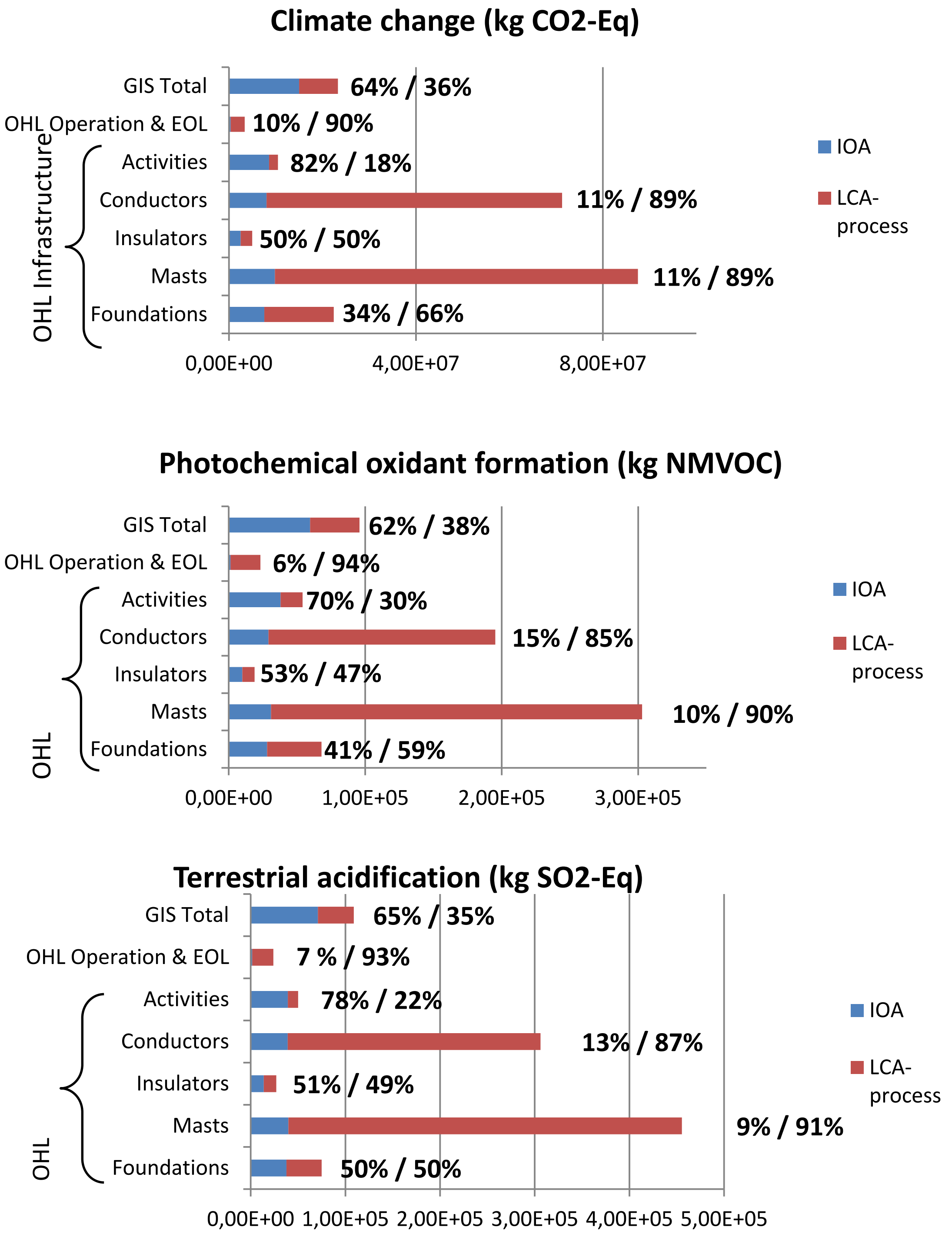


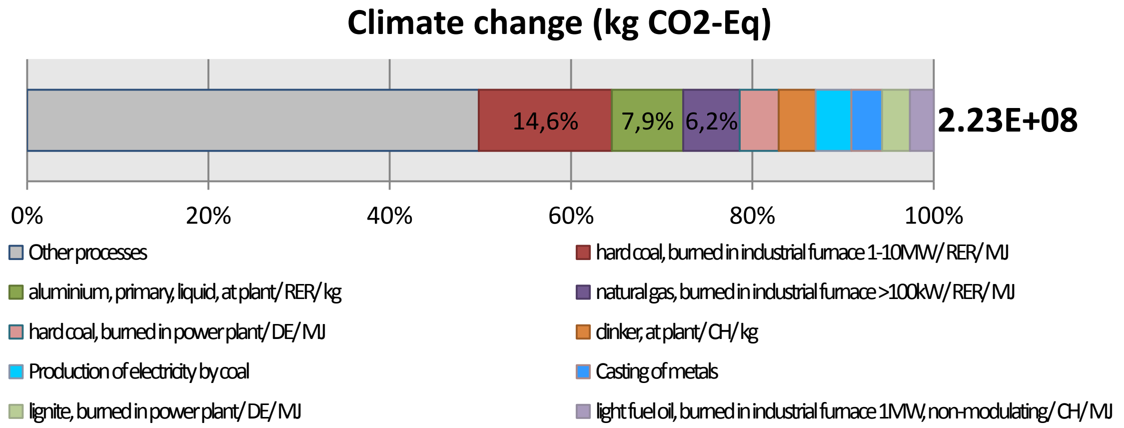
Figure 4.4. Relative share of IO and process-LCA impacts by main components for three indicator categories

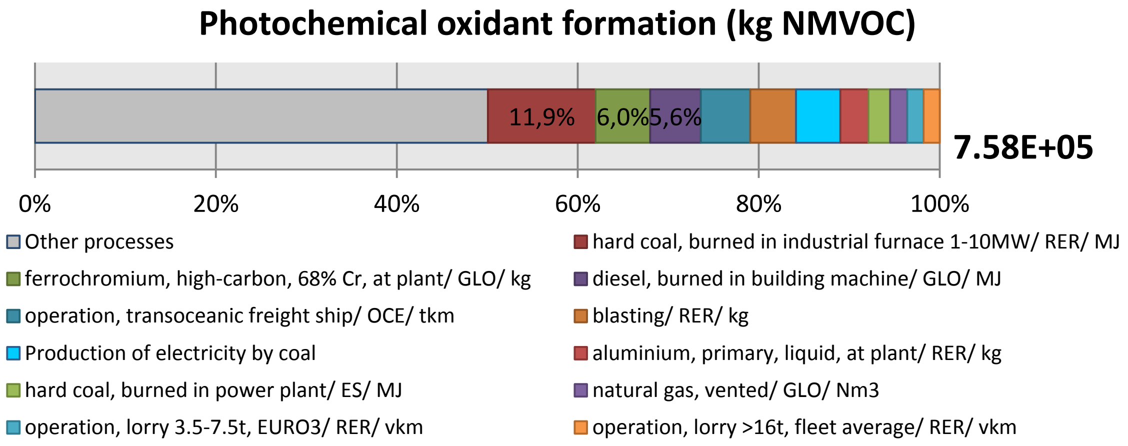
Figure 4.4 reiterates that the distribution of impacts among components is roughly analogous for chosen environmental categories. Further, visualization of relative shares of IO/process-LCA impacts for each component clarify the overall ratios presented in Figure 4.3. The thing is that being the top contributors, masts and conductors of OHL Infrastructure have disproportionately large process-LCA related impacts (approximately 9 to 1), which boost overall share of impacts generated in physical subsystem. Despite the fact that the shares for other components are not similar, the dominance of impacts due to OHL Infrastructure mast and conductors determines the overall profile.

Interestingly enough, monetary subset generates almost 2/3 of total impacts value for all three categories, meaning that a purely process-LCA research of substation electrical equipment and related construction activities may underestimate generated emissions for at least 3 times for these three categories. It ought to be mentioned though that according to [14] power losses have by far the largest impact contribution for transformers, disconnectors and circuit breakers among 12 impacts categories studied (including CC, POF and TA), however, that is determined mostly by electricity mix as was found in [15]. Provided that according to the results the transformer's share in CC impacts induced by gas-insulated substation is roughly 40%, the importance of accounting for monetary part of impacts remains largely unresolved since this paper does not take into account power losses of GIS equipment and OHL.

Other than that, IO relative shares of impacts for other components are substantial for all three categories. One memorable exclusion is OHL Operation and EOL combined where process-LCA share of impacts is in range of 90 to 94% for the chosen categories. As it is assumed in this work that there is no recycling, we can make a conclusion that this situation has to do with the choices made during data compilation for economic subsystem.

Next part of this sub-chapter concludes the contribution analysis of LCA processes and IOA sectors.


Climate change (kg CO2-Eq)
14,6%
7,9%
6,2%
2.23E+08
0%
20%
40%
60%
80%
100%
Other processes
hard coal, burned in industrial furnace 1-10MW/ RER/ MJ
aluminium, primary, liquid, at plant/ RER/ kg
natural gas, burned in industrial furnace >100kW/ RER/ MJ
hard coal, burned in power plant/ DE/ MJ
clinker, at plant/ CH/ kg
Production of electricity by coal
Casting of metals
lignite, burned in power plant/ DE/ MJ
light fuel oil, burned in industrial furnace 1MW, non-modulating/ CH/ MJ


Photochemical oxidant formation (kg NMVOC)
11,9%
6,0%
5,6%
7.58E+05
0%
20%
40%
60%
80%
100%
Other processes
hard coal, burned in industrial furnace 1-10MW/ RER/ MJ
ferrochromium, high-carbon, 68% Cr, at plant/ GLO/ kg
diesel, burned in building machine/ GLO/ MJ
operation, transoceanic freight ship/ OCE/ tkm
blasting/ RER/ kg
Production of electricity by coal
aluminium, primary, liquid, at plant/ RER/ kg
hard coal, burned in power plant/ ES/ MJ
natural gas, vented/ GLO/ Nm3
operation, lorry 3.5-7.5t, EURO3/ RER/ vkm
operation, lorry >16t, fleet average/ RER/ vkm

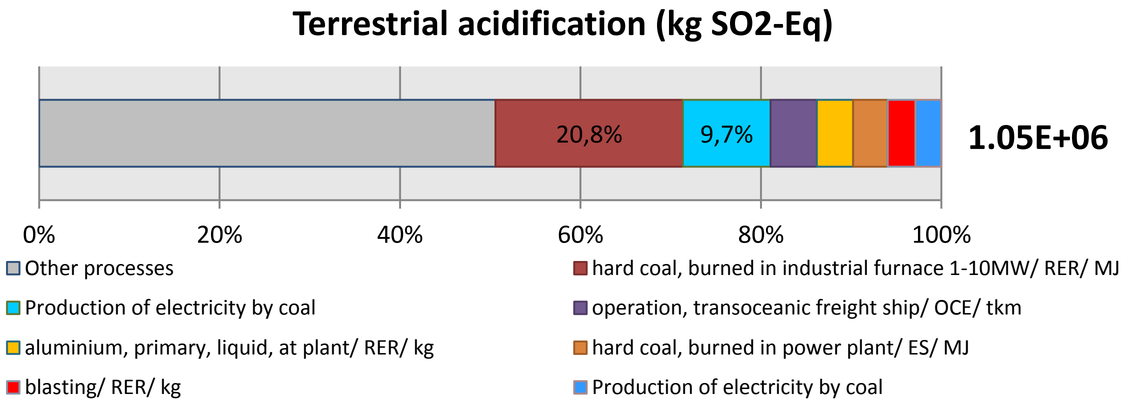

Terrestrial acidification (kg SO2-Eq)
20,8%
9,7%
1.05E+06
0%
20%
40%
60%
80%
100%
Other processes
hard coal, burned in industrial furnace 1-10MW/ RER/ MJ
Production of electricity by coal
operation, transoceanic freight ship/ OCE/ tkm
aluminium, primary, liquid, at plant/ RER/ kg
hard coal, burned in power plant/ ES/ MJ
blasting/ RER/ kg
Production of electricity by coal

Figure 4.5. Contribution analysis of IO sectors and LCA processes for the case TYNPD project for three impact categories

The results of this analysis are shown in Figure 4.5 where top contributors comprising 50% of total value are listed along with other processes and sectors grouped as “Other processes” for each of three impacts categories.

When it comes to climate change it can be seen that almost 15% of impacts occur due to “hard coal, burned in industrial furnace 1-10MW/ RER/ MJ” process which is the most important contributor in this category. Aluminium production as per “aluminium, primary, liquid, at plant/ RER/ kg” comes second, and nearly two times smaller than the first process. Seven out of nine listed contributors belong to process-LCA subsystem, whereas “Production of electricity by coal” and “Casting of metals” are the only distinguishable sectors from IO subsystem. The composition of processes and sectors reveals that a large number of impacts incurred due to electricity generation required by production of steel and aluminium. This corresponds well with the previous parts of the analysis as the system’s components - OHL Infrastructure masts and conductors were found to be responsible for as much as 71% of total CC impacts. One more significant process has to do with the production of concrete for foundations, namely, “clinker, at plant/ CH/ kg”, which is responsible for 4.1% of total value.

As for photochemical oxidant formation, metals production is still dominant part of the overall impacts which occur in processes of electricity generation (“hard coal, burned in industrial furnace 1-10MW/ RER/ MJ”, again, is the biggest contributor with 11.9%) and process of alloys production “ferrochromium, high-carbon, 68% Cr, at plant/ GLO/ kg” coming on the second place (6%). Structural path analysis confirms that the majority of processes listed on the bar can be traced back to the steel production represented by Ecoinvent process ”steel, electric, chromium steel 18/8, at plant/ RER/ kg”. Contribution of other processes, however, becomes visible as well. Overall, “Production of electricity by coal” is the only noticeable IO sector in this part of Figure 4.5, while the rest are due to process-LCA.

Lastly, distribution of processes for terrestrial acidification category resembles that of two other impact categories. “Hard coal, burned in industrial furnace 1-10MW/ RER/ MJ” process now stands for 1/5 of overall impacts, while “Production of electricity by coal” IO sector comes as second with 1/10 of the total value. Notably, there is another “Production of electricity by coal” IO sector (2.9% of total impacts value) that is included in the distribution bar, and explanation for this situation is that the sector with lower share of impacts belongs to Non-EU part of the EXIOBASE, whereas the former one is a part of EU section. It is known that more than three forth of acidification emissions occurs within EU due to domestic EU consumption [39], hence this explains the situation with these IO sectors. In essence, LCA processes associated with metals production remains dominant for this impact category as well.

4.2. Sensitivity analysis.

According to [21] sensitivity check serves as a tool to ascertain reliability of results of the study, so that conclusions based on those results are valid given the uncertainties in the data.

During life cycle inventory compilation a number of assumptions with regard to data were made, mainly, in attempt to adapt raw data from sources and fit it to the study. While sensitivity analysis can be based on a large number of parameters of the system such as recycling rates, lifetime of components, energy mix selection, technological changes, etc., or a combination of several parameters grouped into different scenarios, the choice of parameter(s) should not be arbitrary. Ideally, sensitivity check must be performed for the most influential parameters, which are generally revealed during life cycle impacts assessment or inventory study.

For clarity, this part of thesis deals with performing the sensitivity analysis for three scenarios based on four different geographical conditions that have effect on OHL material and monetary inputs.

When it comes to selection of parameters for the case project we strive to reflect upon results presented and conclusions made in sub-chapter 4.1. To be specific, it was shown that parameters related to the establishment of infrastructure for overhead transmission lines are the determinant of the study outcome.

As to scenarios, it was discussed previously that our physical part of inventory is constructed from the study [27] which employs data on OHL provided by Eltra [29], Danish transmission operator (later merged into “The Energinet.dk Group”). It is not known to what extent material and monetary inputs into construction of OHL in Romania (where the case project should take place at) are different compared to that of Denmark. However, there are several conditions that influence the complexity of construction causing variation of required inputs, and, perhaps, the most applicable parameter is the average tower span which is the horizontal distance between two adjacent electricity pylons.

In LCA performed by Eltra [29] it was assumed that the average tower span of double 400/150 kV overhead transmission line equals to 333 m. It was also stated there that, typically, average tower span can be in range between 400 and 450 m. Hence, scenarios to test sensitivity are developed on difference between tower spans, namely, for values of 333, 400 and 450 m, with 333 m being the reference scenario.

For the physical part of inventory changes of inputs are scaled directly from the relations between the lengths, i.e. 333 to 450, and 333 to 400, and presented in Table 4.2.

Table 4.2. Physical inputs sensitivity parameters of OHL grouped into three scenarios.

Parameter	Long tower span	Normal tower span	Reference tower span
Towers span, m	450	400	333
Physical inputs change	0,74	0,83	1,00

As to the monetary subset, while a number of studies touch upon factors that influence life cycle costs of OHL, we found that [43] provides a superlatively in-depth analysis of sensitivities associated with life cycle costs of different technologies for transmission lines. This information allowed selecting relevant to the case project costs sensitivity parameters which are presented in Table 4.3.

Table 4.3. Cost sensitivity parameters of OHL grouped into three scenarios.

Parameters	Long tower span	Normal tower span	Reference tower span
Route directness	90%	75%	35%
Prices change	0.93	0.95	1.00
Significant crossings	None	3 per 50 km	1 per 5 km
Prices change	0.93	0,95	1.00
Terrain	Flat	Undulated	Hilly
Prices change	0.97	0.98	1.00
Terrain constraints	105%	100%	80%
Prices change	0.94	0.99	1.00
Aggregated prices change	0.79	0.87	1.00

The results of this two-fold sensitivity analysis based on average tower span are shown in Figure 4.6.

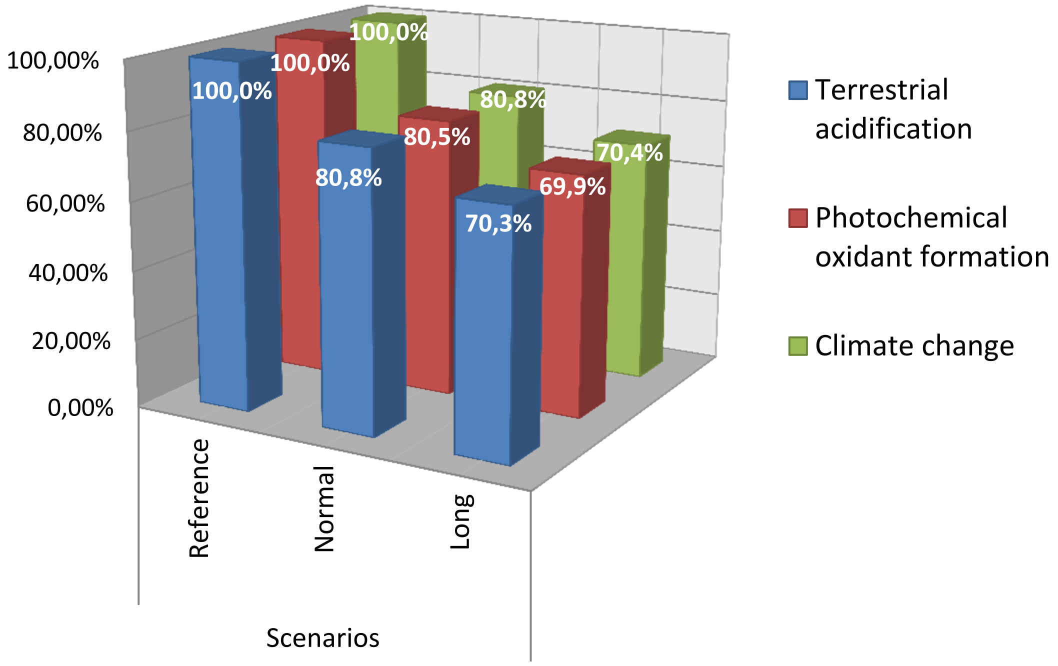


Figure 4.6. Sensitivity analysis of average tower span in relative shares across three impact categories

As shown in Figure 4.6, reduction of the average tower span scales total impacts down in all three categories as a uniform trend. It means that results of LCIA are equally sensitive to average tower span alteration. In particular, per 13% costs and 17% physical inputs decline (representing normal scenario) the total impacts value becomes lower on almost 20%. Basically, that means that rate of change for total impacts is bigger than that of combined inputs, so that gains in material efficiency would translate into greater environmental savings, which is a positive discovery.

This figure, however, does not aid in understanding how total impacts related to process-LCA and IO subsystem are affected. In order to bridge this gap, we showed two separate sensitivity trends: (1) IO impacts towards changes in monetary inventory (2) process-LCA impacts towards changes in physical inventory, for the climate change category on Figure 4.7.

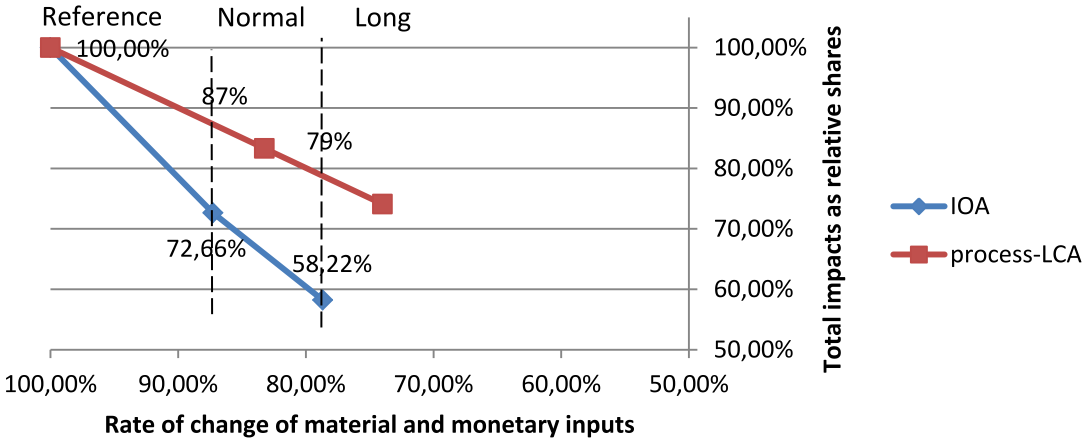


Figure 4.7. Sensitivity analysis of average tower span with physical and monetary trends for climate change impact category

This figure illustrates at least one valuable discovery: impacts associated with IO subsystem are more sensitive towards changes in its part inventory, which can be observed as a steeper slope of IO impacts sensitivity trend compared to process-LCA one. Indeed, if we analyse progression of IO trend at the 87.27% point of horizontal line, we can see that its value is 72.6%, whereas that of process-LCA is 87%. Hence, in case of normal scenario, the difference in sensitivity is 14.4% with IO being exhibiting higher sensitivity which becomes even more pronounced when looking at long scenario where IO trend shows 20% more sensitivity towards changes of chosen parameters.

Given the fact that the share of impacts associated with IO subsystem is roughly 25% for investigated impact categories, we can conclude that uncertainties with regard to the prices of components of OHL, and possibly of GIS, might have tremendous effect on the final results, as these (monetary) impacts are more sensitive than physical one.

5. Discussion

5.1. Interpretation of major findings

Main objective of this study was to explore and construct hybrid life cycle inventories in order to perform hybrid LCA of the case project aiming to expand existing electricity transmission infrastructure to accommodate new renewable energy sources. Broadly speaking, by doing this we intended to continue research efforts in the field of investigating potential benefits and drawbacks of electrical transmission related to facilitation of intermittent energy sources as was documented in reports [12, 27].

In this light, this analysis was designed to specify one ENTSO-E project out of the grid infrastructure en-masse and enhance previous analysis with hybrid life cycle assessment. Since implementation of economic IO inventories addresses truncation errors inherent to process-based life cycle inventories, this analysis can help to showcase share of impacts that could be potentially missing in purely LCA regarding this topic.

As to the results, total impacts elicited over the life cycle of 185 km of the d.c. 400 kV OHL and GIS 400 kV substation are equal to 0.2 Mton CO_2-eq., which is roughly 77% of that related to process-LCA. When benchmarking our findings with the results reported in [12], the outcome is lower than expected, since for the wind offshore farm analysis IO associated impacts were on par with process-LCA ones (52% to 48% respectively). Unfortunately, we identified no papers that performed hybrid LCA of transmission infrastructure solely; hence the only reasonable explanation for such difference is that the juxtaposed scopes and inventories vary dramatically.

Despite this fact, these results can lead to an assumption that process-based LCA of transmission grid projects underestimate emissions on nearly one third of the total value, which seems significant. Following this logic, LCA results obtained by [27] for CC impacts generated by the portfolio of ENTSO-E projects can be increased from 10.7 to 14.26 Mton CO_2-eq. It ought to be noted that this estimate is speculative and serves for illustration only, since, in reality, range of technologies and its composition vary significantly on the case project and overall grid infrastructure level. Nevertheless, such indication of probable underestimation is still valuable.

In fact, it can be argued that hybridization of inventories contributes little to environmental assessment due to aggregation issues related to economic datasets. The point can be valid since compiled during this study hybrid inventories are not consistent. In particular, OHL components are analysed over three life cycle stages, whereas GIS substation components are have only end-of-life stage regarded separately. Nevertheless, given the scope and goal of this study, such eclectic results can be valuable in identification most important contributors and in uncovering relation between IO and process-LCA generated impacts. Further development of life cycle inventories and data costs would harmonize content and structure of analysed components and products, hence this issue will be address.

As to the distribution of impacts between components of infrastructure, share of impacts generated during infrastructure life cycle stage of OHL *masts* and *conductors* (that is from raw materials extraction to manufacturing) is the biggest. Basically, that means that environmental burden associated with steel and aluminium production is the heaviest among other processes. Given the fact that power losses are excluded from analysis due to lack of the data, it becomes obvious that most resource-intensive components would dominate in the structure of total impacts (which holds true for all three categories with minor deviations). Moreover, [Environmental evaluation of power transmission in Norway] showcased that contribution of raw materials category in terms of total impacts can be higher than that of power losses one, but that depends largely on the energy mix. Provided that projections of incremental decrease of carbon-intensity in European energy mix in next decades are to become true [9], more emphasis should be on emissions retaining to life cycle of metals relevant to transmission infrastructure stocks.

When it comes to evaluation of the ratio between environmental gains and drawbacks related to the case project, [9] TYNDP states that examined transmission infrastructure would deliver 1,000 MW of renewable energy, which most likely refer to pumped-storage hydro power plant on the Tarnita Lake, Romania. Given the lifetimes of transmission equipment, it, however, is not possible to assess avoided CO2-eq. impacts without knowing power flows and generation schedule of hydro power plant. A crude estimation environmental benefits could have been made provided that total sum of investments is made publicly available (which is not the case), so that the parameter of kg CO2-eq. per Euro invested could be derived.

Interestingly enough, SF_6 contribution towards climate change impacts were found to be negligible (less than 1% of total value). This is in contrast to the reference research, where the hexafluoride sulphur impacts were almost 6% of total value [27]. One possible explanation for that, yet, once more refer to the difference between composition of inventories on considered levels (project vs. whole grid).

5.2. Uncertainties, data quality and limitations

Assumptions with regard to data and methodology are inherent to any life cycle assessment with hybrid inventories arguable bringing uncertainty to next level. In this sub-section we would discuss some of the most significant choices and assumptions made during this work.

When it comes to physical inventories, *OHL* data was collected for Danish power transmission grid, whereas the case project is to be realized within continental Eastern Europe, in Romania. Technically speaking, construction and maintenance practices would differ between two countries in question, and that would definitely serve as a source of uncertainties. At the same time, both LCA and IO part of our hybrid assessment employ characterization factors and environmental stressors collected with respect to European technological platform. In particular, impacts related to Ecoinvent process "*steel, electric, chromium steel 18/8, at plant/ RER/ kg*" are based upon analysis of production system of 203 electric arc furnaces in Europe [38]. At the same time according to [39] almost 80% of total IO-related impacts take place within Europe as a result of European demand. That is why it can be concluded that while being present, the effect of this uncertainty is limited, and the analysis results remain representative.

As to the life cycle inventory of gas-insulated substation equipment, there are several points about it. On the one hand, data quality for power transformer inventory can be deemed very credible, since it is supplied within producer's environmental product declaration [32], similar to information on material inputs for other substation components such as circuit breakers, substation bay, etc. [16]. On the flip side, substation's layout, selection of vendor, construction policy of general contractor make up for sensible variability of inputs. Overall, it can be argued that technological peculiarities of GIS (or, in general, substation) equipment would be the most important when it comes to impacts associated with substation, therefore, it is largely not possible to assess related uncertainty given the exclusivity of inventories provided by ABB [16].

Cost data of components, unarguably, embrace more assumptions and sources, thus uncertainties for monetary sub-system are larger than that of physical one. Starting with *OHL*, we assumed that Swiss case for valuation of different transmission line components would serve to be valid proxy for Romanian project, however, in-depth knowledge of projects similarities and discrepancies is required to ascertain its applicability. As shown in reviewed literature [33, 34, 36, 42, 43], the number of factors that determine breakdown of costs for particular OHL is large, and each project can be perceived as unique.

Next, the structure of *substation* components was based on Canadian TSO costing study [33] where the closest data identified were sampled for the AIS substation with 2 power transformers 245 kV 200 MVA and 4 substation bays with 300 kV circuit breakers. In the meantime, difference is somewhat significant since we relate this percentages to case project with 4 power transformers 400 kV 250 MVA and 12 bays with 400 kV circuit breakers. Additionally, categories were manipulated to better match with physical inventory of substation and, furthermore, they relative shares were rescaled to realistically represent GIS life cycle costs as reported in [42].

From the consistency perspective, cost data for GIS substation is a subject to large uncertainty, and therefore, the ratio between process-LCA and IO-related impacts can vary significantly.

Inherent to hybrid tiered LCA is uncertainty related to assignment of economic sectors and procedure to avoid-double counting. The essence of this process is the cross-relation of physical inputs (which form process-LCA inventory) with economic sectors as described in [44]. To the most part, this part of research relies on personal assumptions and judgment of authors.

One of the most important limitations of this study is that the LCIA was confined to three impact categories with metal depletion not included. The reason for that is that Exiopol database [39] does not contain data for stressors in this impact category. In the context of importance of steel and aluminium for the grid infrastructure extension, this constraint should be addressed as relevant field of research becomes more developed.

6. Conclusions and need for further work

Ageing of power transmission infrastructure and restructuring of energy generation - in a sense of shifting energy mix towards less carbon-intensive means, bring about inevitable dramatic transformations of the energy system. This study attempted to contribute to existing pool of knowledge with regard to environmental merits and demerits associated with renewable energy integration into current power system. As a result of that hybrid inventories were produced for a project among portfolio of projects aiming to expand European transmission grid.

Under actual assumptions and limitations share of economic-related impacts is less than quarter of total impacts among climate change, photochemical oxidant formation and terrestrial acidification impact categories. Most important contributors are found to be due to infrastructure life cycle stage of overhead transmission towers and conductors. The single most important source of emissions is process of production of steel. Sensitivity analysis with regard to technology of steel production showed that *converter steel* produced with basic oxygen furnaces (BOF) can increase total impacts on 7.5% compated to that of electric steel produced in electric arc furnaces (EAF).

As to potential improvements, there could be a number of them. For one, power losses excluded from current work could draw completely different picture with respect to relation of IO to process-LCA total impacts. Moreover, performing steady-state power flow analysis would allow to calculating potential benefits associated with introduction of 1,000 MW of new renewable energy generation, and compare it on lifetime scale with overall environmental burden due to power grid upgrade. Better access to life cycle inventories and cost data of transmission equipment would definitely improve accuracy of the results and align components allowing to analysing all relevant life cycle stages at the same time. One more important improvement has to do with development of IO-related dataset in order to include other impact categories into assessment.

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Appendix A

MATLAB code:

```
% Matlab script start
clear all; clc
filename='M:\Documents\MASTER THESIS\Working_folder\Inventory.xlsx';
load ('Ecoinvent_2_2_database.mat');
load ('C_large.mat');
% Import of all necessary already established databases:
% EXIOPOL (A_exiopol), Ecoinvent process matrix (A_gen), Ecoinvent
% stressor matrix (F_gen), (modified to take into account EXIOPOL stressors too)
% and C_large - a characterization matrix covering both Ecoinvent and Exiobase stressors.

%% Imports of foreground data
A_f=xlsread(filename,'A','E8:AC4377'); % A_f contains
% A_ff (foreground inter-process requirements matrix) and
% A_nf (matrix of requirements from the foreground to Ecoinvent)
A_f(isnan(A_f))=0; % Making sure all empty fields are 0

y=xlsread(filename,'y','E8:E4377');
y(isnan(y))=0;

H_nf=xlsread(filename,'H_nf','F15:AD272');
H_nf(isnan(H_nf))=0;

p_f=xlsread(filename,'p_f','E6:E30');
p_f(isnan(p_f))=0;

Z_nf=xlsread(filename,'Z_nf','F15:AD272');
Z_nf(isnan(Z_nf))=0;

A_bb=A_gen;
A_nn=xlsread('M:\Documents\MASTER
THESIS\Working_folder\SIOT_2region_pxp.xlsx','A','F15:JC272');
A_nn(isnan(A_nn))=0;

% Create the A_nf (matrix of requirements from the foreground
% to EXIOPOL) matrices

A_nf_adj=A_nn*H_nf*diag(p_f);
```

```
A_nf=Z_nf.*A_nf_adj;

F_ff=xlsread(filename,'F_ff','E4:AC2342'); %SF6 losses included into stressors matrix
F_ff(isnan(F_ff))=0;


%% Construct A-matrix
[m n]=size(A_f);
A=zeros(m,m);
A(1:m,1:25)=A_f;%A_ff
A(26:283,26:283)=A_nn;%Exiopol_inventory
A(284:m,284:m)=A_bb;%Ecoinvent_inventory
A(26:283,1:25)=A_nf;


%% Finding total output
I=eye(size(A));
L=inv(I-A);

x=L*y;


%% Construct F-matrix
S=xlsread('M:\Documents\MASTER
THESIS\Working_folder\SIOT_2region_pxp.xlsx','A','F274:JC999'); %Exiopol stressors matrix
S(isnan(S))=0;
F_large=[S zeros(size(S,1),size(F_gen,2)); zeros(size(F_gen,1),size(S,2)) F_gen]; %Combined
stressors matrix
[r t]=size(F_large);
F=[F_ff F_large];
C_ecoinvent=C_large(:,[1:1613]);
C_exiopol=C_large(:,[1615:end]);
C=[C_exiopol C_ecoinvent];
CF=C*F;

%% Emissions and impacts
% Calculates the vector of total impacts generated for a given external demand
d=CF*x;
D_pro=CF*diag(x);
%% Emissions allocated to foreground processes
D_pro_ff=CF*L*diag(y);% Zeroth tier
D_pro_ff_1stT=CF*L*diag(A*y);% First tier
D_str=C*diag(F*x); % contribution of stressors
```

```
%% Advanced contribution analysis
I_A_f=eye(25,25);
I_A_nn=eye(size(A_nn));
I_A_bb=eye(size(A_bb));

X_f=inv(I_A_f-A_f(1:25,1:25))*y(1:25,1);

M_nf=A_nf*diag(X_f);
X_nf=inv(I_A_nn)*M_nf;
D_pro_nf=C_exiopol*S*X_nf;

M_bf=A_f(284:end,1:25)*diag(X_f);
X_bf=inv(I_A_bb)*M_bf;
D_pro_bf=C_ecoinvent*F_gen*X_bf;


xlswrite(filename,d,'Results','E2:E19');
xlswrite(filename,D_pro,'Results','C23:FLD40');
xlswrite(filename,D_pro_ff,'Results','C44:FLD61');
xlswrite(filename,D_pro_ff_1stT,'Results','C66:FLD83');



% Matlab script end
```