Master's thesis

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

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Revenue-Weighted Life Cycle Assessment of two Nordic Energy companies

Exploring a simplification of Organizational LCA as a proxy for Organizational Impact through comparisons with company sustainability reports and third-party impact data

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Abstract

Accurate and comparable organizational impact data that is manageable to compute is essential for organizations to understand and mitigate their impact. Organizational Life Cycle Assessment (O-LCA) frameworks face challenges in setting organizational boundaries for the assessment in the goal and scope phase. O-LCA is further limited in its application by not allowing for inter-organizational comparisons. This study proposes Revenue Weighted LCA (RW-LCA) as a simplification to address challenges within O-LCA. By excluding supplemental activities and narrowing the scope of LCA to organizations' product offerings, RW-LCA removes complexity and opens the door for comparisons between organizations. RW-LCA is applied to two companies, Statkraft and Vattenfall. The Product LCAs use secondary data from published studies as inputs. P-LCA results are then aggregated by revenue to arrive at RW-LCA for the companies. The LCA uses the Simapro software, Ecoinvent 3, and the default Hierarchical (H) ReCiPe 2016 v1.1 midpoint impact assessment method.

The products assessed are electricity generated from wind power, hydropower, nuclear power, and natural gas, the results of which were 5.74, 6.90, 20.8, and 414 g CO_2-eq., respectively. Generally, reproducing LCA results based on published LCAs is difficult due to the limited availability of complete and transparent life cycle inventories. Still, in this thesis, the global warming results of the original studies were reproduced with a certain preciseness. The RW-LCA company results unmistakably show that Vattenfall has a larger impact than Statkraft per kWh (and per revenue) for all impact categories. The RW-LCA global warming results for Vattenfall were 79.2 g CO_2-eq./kWh, approximately four times larger than those of Statkraft at 21.7 g CO_2-eq./kWh. Natural gas power production causes most of the global warming impacts for both companies.

The RW-LCA results were compared to the GHG emissions from the companies' sustainability reports and the Net Impact Data provided by the Upright Project. The global warming RW-LCA results almost exactly replicate the GHG emissions from the company reports. The similarity of the results strengthens the validity of outside-in estimation of a company's impacts with LCA using secondary data as input and the product LCA's representativeness of the company products. However, differences arise when comparing RW-LCA with Net Impact Data, which estimated global warming impacts at approximately 25% of the RW-LCA results for both companies. As both the results and the reports are LCA-based and gave similar results, the differences in results are likely caused by the differences in methodology. Upright's top-down approach allocates each impact exactly once across all products in the Upright product taxonomy, resulting in lower impacts on a product level by avoiding double-counting. Further differences may be driven by Upright's more comprehensive product sets, undisclosed aspects of the NLP at the core of Upright's model, or uncertainty related to the top-down nature of Upright's methodology.

As a simplification of O-LCA, the RW-LCA solves some challenges regarding the complexities of supplemental activities. The method is based on P-LCA, allowing inter-organizational comparisons for organizations with similar products. For similar organizations with at least one overlapping product, it may be reasonable to compare RW-LCA results. The comparisons of organizations with complex and different products still contain challenges analogous to those found in O-LCA. However, the solution is the exclusion of supplemental activities, which is only reasonable if the impacts of supplemental activities are negligible. Future research can explore the inclusion of supplemental activities in O-LCA in comparison to RW-LCA results and perform more comparisons of Upright's Net Impact Data. Collaboration between private impact data providers and academia may provide mutual learning benefits and advance organizational impact assessment.

Sammendrag

Nøyaktige og sammenlignbare organisasjons impact data som er håndterbare å beregne er avgjørende for at organisasjoner skal kartlegge og redusere deres impact. Rammeverk for Organisatorisk livsløpsanalyse (O-LCA) har utfordringer med å sette organisatoriske systemgrenser i fasen for Fastsettelse av hensikt og omfang. O-LCA er ytterligere begrenset i sin anvendelse ved ikke å tillate sammenlikninger på tvers av organisasjoner. Denne studien foreslår Revenue Weighted LCA (RW-LCA) som en forenkling for å løse utfordringer innen O-LCA. Ved å ekskludere tilleggsaktiviteter og begrense omfanget av LCA til organisasjoners produkter, fjerner RW-LCA kompleksitet og åpner døren for sammenligninger mellom organisasjoner. RW-LCA brukes på to selskaper, Statkraft og Vattenfall. Produkt-LCAene bruker sekundærdata fra publiserte studier som input. P-LCA resultatene aggregeres deretter etter inntekt for å komme frem til RW-LCA for selskapene. Livsløpsanalysen bruker Simapro programvaren, Ecoinvent 3, og standard Hierarchical (H) ReCiPe 2016 v1.1 midpoint impact assessment metoden.

De analyserte produktene er elektrisitet generert fra vindkraft, vannkraft, kjernekraft og naturgass, hvor resultatene var henholdsvis 5.74, 6.90, 20.8 og 414 g CO_2-ekv. Generelt er det vanskelig å reprodusere LCA resultater basert på publiserte LCAer på grunn av den begrensede tilgjengeligheten av komplette og transparente livsløpsregnskap. Likevel, i denne oppgaven, ble resultatene for Global Warming fra de originale studiene gjenskapt med en viss nøyaktighet. RW-LCA resultatene viser umiskjennelig at Vattenfall har større impact enn Statkraft per kWh (og per inntekt) for alle påvirkningskategorier. RW-LCA resultatene for global oppvarming for Vattenfall var 79.2 g CO_2-eq./kWh, omtrent fire ganger større enn Statkrafts på 21.7 g CO_2-eq./kWh. Kraftproduksjon fra naturgass forårsaker mesteparten av impact på global warming for begge selskapene.

RW-LCA-resultatene ble sammenlignet med klimagass utslippene rapportert i selskapenes bærekraftsrapporter og Net Impact Data fra selskapet Upright Project. RW-LCA global warming resultatene hadde nærmest identiske verdier som selskapenes bærekraftsrapporter. Likheten mellom resultatene styrker validiteten med å gjenskape en bedrifts impact med LCA ved kun å bruke sekundærdata som input, samt produkt LCAens representativitet av bedriftens produkter. Forskjeller ble funnet i sammenlikningen av RW-LCA med Net Impact Data, som estimerte global warming impacts til omtrent 25% av RW-LCA-resultatene for begge selskapene. Siden både resultatene og selskapsrapportene er LCA-baserte og ga lignende resultater, er de potensielle manglene i Net Impact Dataen sannsynligvis forårsaket av forskjellene i metodikk. Uprights top-down tilnærming allokerer hver impact nøyaktig én gang på tvers av alle produktene i Upright databasen, noe som resulterer i lavere impact per produkt ved å unngå dobbelttelling. Ytterligere forskjeller kan være drevet av Uprights mer omfattende produktsett, unevnte aspekter ved NLP i kjernen av Uprights modell, eller usikkerhet knyttet til top-down naturen til Uprights metodikk.

Som en forenkling av O-LCA løser RW-LCA noen utfordringer angående kompleksiteten til tilleggsaktiviteter. Metoden er basert på P-LCA, som tillater sammenligninger på tvers av organisasjoner med lignende produkter. For lignende organisasjoner med minst ett overlappende produkt kan det være rimelig å sammenligne RW-LCA-resultater. Sammenligninger av organisasjoner med komplekse og ulike produkter fører fortsatt med seg utfordringer like de man finner i O-LCA. Løsningen foreslått her er imidlertid en eksklusjon av tilleggsaktiviteter, noe som bare er rimelig hvis impact av tilleggsaktiviteter er ubetydelige. Fremtidig forskning kan utforske inkludering av tilleggsaktiviteter i O-LCA sammenlignet med RW-LCA-resultater og utføre flere sammenligninger med Uprights Net Impact Data. Samarbeid mellom private leverandører av impact data og akademia kan gi gjensidige læring og fremme utviklingen av organisatorisk impact data.

Preface

This thesis was written in the spring of 2023 at the Faculty of Engineering (IV) at the Norwegian University of Science and Technology (NTNU) as the final work of the Master's degree in Energy and Environmental Engineering with a specialization in Industrial Ecology at the Department of Energy and Process Engineering (EPT).

This thesis has been written in collaboration with the Finnish company, the Upright Project, which the author of this thesis has had an employment engagement with. Upright is not paying for the work done in this thesis and is not the initiator of this research. The topic of this thesis was developed primarily by the author in collaboration with the supervisors. Efforts have been made to minimize bias and subjectivity on the author's side. Still, the working relationship is flagged here to ensure transparency and openness around this thesis.

I want to extend my gratitude to my supervisor at NTNU, Prof. Edgar Hertwich, and to Lisa Jackson at Upright, for their guidance during the writing of this thesis.

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Nomenclature

ABBREVIATIONS	
EOL	End-Of-Life
EPD	Environmental Product Declaration
FU	Functional Unit
GHG	Greenhouse Gas emissions
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
OEF	Organization Environmental Footprint
OEFSR	Organisation Environmental Footprint Sector Rules
P-LCA	Product Life Cycle Assessment
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rules
RW-LCA	Revenue Weighted Life Cycle Assessment
SETAC	Society of Environmental Toxicology and Chemistry
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Program

IMPACT CATEGORIES		**UNITS**	
GW	Global warming	bcm	Billion cubic metres of natural gas
IR	Ionizing radiation	CO	Carbon Monoxide
FPMF	Fine particulate matter formation	CO_2-eq.	Carbon Dioxide equivalents
TA	Terrestrial acidification	kWh	Kilowatt hours
FE	Freshwater eutrophication	m^3	Cubic meters
ME	Marine eutrophication	MW	Mega watt
TE	Terrestrial ecotoxicity	NO_x	Oxides of nitrogen
FEc	Freshwater ecotoxicity	PM	Particulate Matter
ME	Marine ecotoxicity	SO_2	Sulphur dioxide
HCT	Human carcinogenic toxicity		
HNCT	Human non-carcinogenic toxicity		
LU	Land use		
MRS	Mineral resource scarcity		
FRS	Fossil resource scarcity		
WC	Water consumption		

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1 Introduction

The topic of this thesis is organizational impact data, specifically investigating the application of Life Cycle Assessment (LCA) to companies by simplifying the method of Organizational LCA (O-LCA). The purpose of this thesis is to calculate the Revenue Weighted LCA (RW-LCA) of two Nordic energy companies, Statkraft and Vattenfall, to explore the validity, potential, and limitations of organizational impact data based only on the revenue-weighted Product LCA (P-LCA) results of the companies offering. Through comparisons with Upright's Net Impact Data and the proprietary sustainability reports of the companies, light is shed on the difference between the methods of the results to provide broader insight into how to measure the impact of companies. The first part of the introduction provides background and actualization. Then is presented the purpose and research questions. Finally, an overview of this thesis's structure and scope is outlined.

1.1 Background and actualization

Climate change is perhaps the most critical challenge for humanity to solve. The IPCC has made it crystal clear that the anthropogenic emissions of Greenhouse Gases (GHG) must be reduced to limit the temperature increase below 1.5 or 2.0 degrees (IPCC, 2023). Reducing the emissions of GHGs is extremely important to avoid severe increases in extreme weather, significant sea rise leading to millions of climate refugees, and all the geopolitical implications of such disruptions (IPCC, 2023). Simultaneously, reducing GHG emissions is not enough. The earth is on the verge of ecological collapse, with more and more species facing extinction because of land-use change leading to decreasing wild habitats (WWF, 2022). Pollution of metals, chemicals, and nutrients is also harming our planet in various ways. The Brundtland Commission defined sustainable development already in 1987 as one whichëxtit ”... meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland Commission, 1987, p. 6). Currently, we are not on the path to achieving this definition. While there have been efforts to reduce our anthropogenic environmental footprint, there have not yet been significant improvements, and GHG emissions continue to increase (IPCC, 2023). Mitigating the over-exploitation of the earth requires action from companies, governments, regulators, and individuals.

One sensible pathway for reducing anthropogenic impacts is mitigating the impacts of organizations, as the impacts of human activities are attributable to the consumption of goods and services, which in turn are provided by organizations. Thus, organizations have the possibility and the responsibility to reduce their impact by changing their product offerings, production methods, or operations (Martínez-Blanco and Finkbeiner, 2018). The motivation of organizations to mitigate their impacts has increased dramatically in recent years, with sustainability being increasingly on the agenda everywhere. Organizations are under pressure from their investors, customers, suppliers, stakeholders, and employees, to have a positive impact. Another factor contributing to the motivation of organizations to mitigate their impacts is the increasing amount of sustainability regulations. There has been an increase in the amount of sustainability-related regulation of organizations, particularly in the European Union (EU). The European Commission (EC) has launched the EU Sustainable Finance regulations, making it mandatory for investors and large companies in the EU to report quantitatively on their sustainability (EC, 2019, 2020, 2022). The Securities and Exchange Commission (SEC) in the US has also proposed regulation for mandatory disclosures on the carbon footprint of companies (SEC, 2022).

Given the motivation for organizations to reduce their impacts, the challenge becomes how to measure and mitigate organizational impact. Organizations would ideally be able to measure their impact accurately with a manageable amount of effort and time investment. There already exists a range of different methodologies commonly used for reporting the environmental performance of organizations, primarily for voluntary reporting. These include Environmental Management Systems (EMS), Corporate Sustainability Reporting (CSR) following the Global Reporting Initiative (GRI), and Life Cycle Assessment (LCA) often in the form of Environmental Product Declarations (EPD) or carbon footprints (Martínez-Blanco and Finkbeiner, 2018). Methods like these are commonly used by organizations but consider a limited amount of necessary aspects. Carbon footprints only consider one impact dimension, CSR and EMS do not include a Life-Cycle perspective, and LCA is designed for products and product systems. LCA is the dominant global tool for assessing the environmental impacts of products and product systems (Bjørn, Owsianiak, Molin and Laurent, 2018). These methodologies are evaluated in more detail in the Literature review. There exists a trend of development in LCA to make it simpler and more flexible (Bjørn, Owsianiak, Molin and Laurent, 2018). One approach for simplification is the single-dimension impact assessment, allowing for faster assessments and increased comparability. Carbon footprinting is the most prominent and has already become quite common both for products and organizations. Carbon footprinting is standardized by the ISO 14064 standard and many organizations follow the Greenhouse Gas Protocol's scope 1, 2, and 3 definitions (ISO, 2018, 2019a, 2019b; WRI and WBCSD, 2004). Single-dimension impact assessment differs from LCA, which necessitates the assessment of multiple impact dimensions (ISO, 2006b, 2006c).

Organizational Life Cycle Assessment (O-LCA) is one method for an organizational impact assessment that includes a life-cycle perspective and is multi-impact. O-LCA adapts the fundamentals of product LCA to be applied instead to organizations. Multiple frameworks for O-LCA exist, most notably the ISO/TS 14072 standard, the UNEP Guidance on O-LCA, and the EC's Organizational Environmental Footprint (EC, 2021a; ISO, 2014b; UNEP, 2015). The two latter build on the first one, and there is a significant overlap between the three frameworks. While these frameworks provide guidance on how to apply LCA to organizations, none of them have yet seen widespread adoption. This may be due to the complexities and challenges of O-LCA. Martínez-Blanco et al. (2020) point out some of these challenges based on the road testing of the UNEP O-LCA guidance. They highlight in particular the increased complexities in defining the Goal and Scope for an organization due to the increased complexities of system boundaries for organizations. Additional challenges include data collection of sufficient quality from external suppliers and customers. A high-quality O-LCA requires detailed data from the organization's entire value chain, which leads to high time and effort requirements. Currently, the O-LCA frameworks do not allow for comparisons between companies (ISO, 2014b; UNEP, 2015). O-LCA is suggested to only be compared within the same company between different years. There is a clear need for company-level environmental impact data that measures multiple dimensions and is comparable between companies, while still being manageable to compute, which has not yet been achieved with O-LCA.

Based on the need for comparable impact data there have emerged private companies providing novel types of impact data. One of these is the Upright Project, a Finnish startup founded in 2017 on a mission to help companies optimize their Net Impact (Upright Project, n.d.-b). Upright aims to provide comprehensive scientific company impact data, which is multi-impact, takes a life-cycle perspective, and is comparable between companies. The Net Impact of a company is defined by Upright as the *"net sum of all the costs and benefits a company creates"* (Upright Project, n.d.-c). To measure Net Impact, Upright has created a new framework, the Net Impact framework. The framework aims to capture comprehensively the positive and negative impact companies have on the world through its 19 impact categories grouped within Society, Health, Knowledge, and Environment. Upright's data is being used by corporations such as Securitas, Nokia, and Cargotec and institutional investors such as Nordea, LGT Capital Partners, and RBC BlueBay. Upright has released the world's first openly available database of freely available impact data on 10000+ companies.

Upright models the impact of companies based on the products and services offered by a company and their impact macromodel (Upright Project, n.d.-c). Their method requires little extra effort on the side of the company to arrive at their Net Impact Data. Companies receive aggregated impact scores based on their revenue-weighted product sets. The details of the company's product offering are covered by the high level of granularity of Upright's product taxonomy. The assumption made by Upright is that the products and services offered by a company are causing the majority of its impacts. Upright further suggests that the ability to compare impact data between companies is essential. If there is no impact data allowing for comparisons, then the decisions of companies, investors, and consumers will be based on other factors. Upright suggests that we need to dare to make data that allows comparisons between companies, to provide the best possible basis for decisions. A more in-depth description of how Upright calculates Net Impact Data is provided in the Methods section.

The way Upright uses the company product sets as the vantage point for measuring impact is the inspiration for the method explored in this thesis. The idea is that the products and services offered by a company are likely to be responsible for the majority of the impacts of the company. Would the exclusion of operational and supplemental organizational activities make the impact assessment more manageable while still providing accurate impact data? One way to simplify O-LCA would be narrowing the impact assessment down to cover the products and services of organizations, neglecting operational and supplemental activities. This could allow for a more meaningful comparison between organizations. It would also likely lead to a loss of detail, neglecting parts of the impact of the organizations assessed. As the frameworks for O-LCA have not yet seen broad adoption towards creating meaningfully comparable organizational impact data it may be worthwhile to take inspiration from new types of impact data, such as that of Upright.

1.2 Purpose and research questions

The aims of this thesis are as follows: Firstly, to examine the current challenges and limitations of applying LCA to organizations. Second, to perform the Revenue Weighted LCA (RW-LCA) of two Nordic energy companies, Statkraft and Vattenfall. The third aim is to compare the RW-LCA results with the companies' proprietary sustainability reporting and Upright's Net Impact Data. The fourth aim is to examine the usefulness of the RW-LCA method as a proxy for companies' impacts. Based on the aims the following research questions are defined:

1. What are the current challenges and limitations of O-LCA?
2. What are the results of the RW-LCAs of Statkraft and Vattenfall?
3. How and why do the RW-LCA results vary from the proprietary sustainability reporting and the Net Impact Data?
4. To what degree do the RW-LCAs give a fair picture of the impacts of the company?
5. What challenges of O-LCA does the RW-LCA approach solve?

1.3 Structure and scope of this thesis

The structure of this thesis is as follows:

- **Introduction**: The introduction presents the topic of this thesis as well as the background, actualization, purpose, and research questions.

- **Literature review**: The literature review explores and summarizes the literature on Life Cycle Assessment, footprints, Organizational LCA and its challenges, and fundamentals of the energy-producing technologies that are assessed with LCA in this thesis.

- **Methods**: In the methods, the method for LCA based on the ISO standards is detailed and the selection of companies for assessment is described. Then is presented the method of Revenue-Weighted LCA, as well as the methods and modeling choices for Product LCA of the four energy technologies. Finally is described the LCA data sources as well as the data used for comparisons, the Net Impact Data, and the company sustainability reports.

- **Results**: The results first summarize the key limitations of O-LCA as found in the literature review. Second, are presented the Life Cycle Inventories and the Product Life Cycle Impact Assessments of the four products. Third is presented the RW-LCA company results and its comparison to the Net Impact Data and the company reports.

- **Discussion**: The results are discussed in relation to the research questions. Firstly, are discussed the limitations of reproducing LCAs based on secondary data. Secondly, the company result comparisons are discussed, exploring how and why the results vary. Thirdly, findings on the method of RW-LCA as a proxy for organizational impact are discussed. Finally, the limitations of the results and methods, as well as suggestions for further work.

- **Conclusion**: The conclusion summarizes the findings and answers the remaining research questions.

The scope of this thesis is limited to environmental impacts and does not include any social impact categories. Multiple impact categories are evaluated in the LCAs, but for the comparisons between the company results and other data sets, only the global warming impact category is considered.

2 Literature review

Based on the purpose of this thesis as outlined, a literature review was carried out. This chapter summarizes relevant literature on the key topics of importance for this thesis. The first section introduces the general framework for LCA, its development, its standardization by the International Organization for Standardization, and some of the limitations remaining in LCA. Then follows an introduction to single impact dimension LCA, focusing on the carbon footprint. Then follows an introduction to Organizational LCA and its three leading frameworks, the ISO/TS 14072, the UNEP O-LCA Guidance, and the European Commission's Organizational Environmental Footprint (OEF). Then, are described what changes from product LCA to O-LCA before presenting some of the current limitations and challenges within O-LCA within the three frameworks specifically, and for comparisons between organizations. Lastly, follows an introduction to the four energy-producing technologies assessed in this thesis, describing their fundamental workings, inputs, and impacts.

2.1 Life Cycle Assessment

Life Cycle Assessment can be defined as *"... a science-based, comparative analysis and assessment of the environmental impacts of product systems."* (Klöpffer, 2014, p. 2). There are two distinctive features of LCA: The Functional unit and the cradle-to-grave perspective. The functional unit (FU) is the vantage point for all inputs and system modeling and is defined to best reflect the intended use of the product system. LCA allows for comparison between results for products with a similar FU. From the functional unit, the entire life cycle of the product system is modeled. LCA is a bottom-up approach to impact assessment, meaning that it starts from the perspective of a single product and measures all the relevant inputs, direct emissions, and indirect emissions. The Cradle-to-grave perspective entails that the entire life cycle of the product system is considered, including all upstream inputs and downstream end-of-life impacts. Another important aspect is that an LCA following the ISO 14040 standard should cover multiple impact categories (Bjørn, Owsianiak, Molin and Laurent, 2018; Klöpffer, 2014).

2.1.1 History and development of LCA

The precursors of today's LCA methods were conceived of and developed in the 1960s when limited access to resources and environmental degradation started becoming concerns. The early methods were known as Resource and Environmental Profile Analysis (REPA) (Hunt et al., 1992) or Ecobalances (Ahbe et al., 1990). These first LCA methods were inspired by material flow accounting, with an emphasis on physical flows, energy savings, and resource conservation, instead of on pollution (Bjørn, Owsianiak, Molin and Hauschild, 2018; Klöpffer, 2014). As the complexity of inventories increased, the physical flows were translated into contributions to a range of environmental impact potentials, such as climate change, eutrophication, and resource scarcity (Bjørn, Owsianiak, Molin and Hauschild, 2018). A lot of the terminology still used today originated from an influential Dutch report published by the Institute of Environmental Sciences at Leiden University (Heijungs et al., 1992). Their methodology was called CML92 and was the first impact assessment methodology to comprehensively assess a set of midpoint impact categories, as they are known today. The early LCAs already contained the two distinctive features of LCA, the functional unit and cradle-to-grave analysis (Klöpffer, 2014). The first major steps towards the standardization of LCA were led by the Society of Environmental Toxicology and Chemistry (SETAC), starting with the workshop called “A technical Framework for Life Cycle Assessment” in 1990 (SETAC, 1991). Then followed multiple LCA methodology workshops by SETAC (1991, 1992, 1993a, 1994) leading up to the first SETAC World Conference in Lisbon 1993 which culminated in the publication of “A Code of Practice for LCA” (SETAC, 1993b). The period from 1990 to 1993 has been called the ‘heroic time of SETAC’, as it was the time when the first standardized structure for performing LCA was created (Fava et al., 2014). At this point, the LCA structure had developed to include its four components: Goal Definition and Scoping, Inventory Analysis, Impact Assessment, and Improvement Assessment (SETAC, 1993b). The SETAC ‘Code of Practice’ from 1993 was immediately a success and served as the blueprint for the following standardization by the ISO (Fava et al., 2014).

During the early 1990s, multiple life cycle inventory databases were created. The initial focus was on expanding the limited coverage and increasing the data quality to cover different industrial sectors. A large improvement came with the release of the first Ecoinvent database (Version 1), which aimed for consistent data standards and quality, providing coverage of all industrial sectors (Ecoinvent, n.d.-b). The rise of complicated product systems and the abundance of Life Cycle Inventory (LCI) data and impact assessment methodologies necessitated the development of specialized LCA software. As a result, the first iterations of SimaPro and GaBi, two popular software programs, emerged in the early 1990s (Bjørn, Owsianiak, Molin and Hauschild, 2018; PRé-Sustainability, 2016).

During the rest of the 1990s, the SETAC working groups regularly published their recommendations for further developments of methodological elements, focusing particularly on the inventory modeling and impact assessment phases (Bjørn, Owsianiak, Molin and Hauschild, 2018). After its launch in 2002, the UNEP/SETAC Life Cycle Initiative with its working groups took over the developments, gaining a more authoritative status through a more formalized review procedure. Building on the years of accomplishments in LCA consensus building following the SETAC Code of Practice from 1993 (SETAC, 1993a), the International Organization of Standardization (ISO) initiated a formal standardization process to develop a global standard for LCA.

2.1.2 Standardization of LCA

The first international standard for LCA was mentioned in print already in 1997 (Marsmann, 1997). In this editorial, Marsmann suggested that the standard structure with its four components *“... will remain a valid orientational framework for a long period of time”* (Marsmann, 1997, p. 122). This prediction was largely correct, as with only a minor update in 2006 (ISO, 2006b, 2006c) the ISO 14040 and ISO 14044 standards have become the dominant globally relevant international standard on LCA. The ISO standards established a common language for LCA and provided a clear perspective on what LCA can and cannot do, making the limitations of LCA transparent (Finkbeiner, 2014a). This increased trust in LCA, in turn increasing its useability as a tool to support decision-making for private and public organizations.

The two most important ISO standards for LCA are the ISO 14040 and the ISO 14044 standards (ISO, 2006b, 2006c). The ISO 14040 is a guidance standard, describing the principles of LCA and providing general guidelines. The ISO 14044 standard is a more operational document and contains all the technical requirements for an ISO-compliant LCA. The ISO standards for LCA define the methodology of LCA in four distinct steps: (1) Goal and scope definition, (2) Inventory Analysis, (3) Impact Assessment, and (4) Interpretation.

The Goal and scope definition phase as defined in ISO 14040 and ISO 14044 contains the following key steps: defining the goal, defining the scope, choosing the functional unit, and setting the system boundary (ISO, 2006b, 2006c). This initial phase is essential for defining the direction of the assessment and ensuring its quality. The LCI analysis *"involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system."* (ISO, 2006b) At this stage a product system should be drawn for assessment, displaying the relations between the inputs and outputs. The Life Cycle Impact Assessment (LCIA) phase connects the inventory data to environmental impact categories. This phase has multiple mandatory steps, the selection of impact categories, classification of LCI results, and characterization. Secondary steps such as normalization, grouping, and weighting are optional. The final phase is the Life Cycle Interpretation, which connects each of the previous phases iteratively. Interpretation can take place between each phase and lead to changes in the analysis to improve it. This phase contains the identification of significant issues. It includes checks of completeness, sensitivity check, and consistency check. It also includes conclusions, limitations, and recommendations. The pattern of Interpretation between each phase is illustrated by the arrows in the schematic in Figure 3 in the Methods chapter where the steps of LCA according to the ISO standards are further outlined.

As the ISO standards still left too many possibilities for ambiguity, the International Reference Life Cycle Data System (ILCD) Handbook was developed by the EC's Joint Research Centre's Institute for Environment and Sustainability (EC-JRC, 2010). The purpose of the Handbook is to cover the remaining open methodological choices within ISO 14040 and 14044 standards. Adherence to the guidelines is intended to increase the comparability of LCA results between studies by ensuring consistent and reproducible results (Bjørn, Owsianiak, Molin and Hauschild, 2018).

2.1.3 Limitations and challenges remaining in LCA

The selection of an appropriate functional unit is an inherent challenge in LCA influenced by changing consumption patterns, intricate economic systems, and the complexity of products with multiple functionalities (Finkbeiner et al., 2014). Different functional units can lead to varying results for the same product system, making a strict functional equivalent insufficient in capturing reality. Modeling is further complicated by factors like lifetime, performance, system dependency, and non-quantifiable aspects. Curran (2014) suggests that this challenge can be solved by proper education and training in applying the tool of LCA.

Data quality in LCA refers to the *"...characteristics of data that relate to their ability to satisfy stated requirements... "* (ISO, 2006c). Limitations affecting data quality in LCA include insufficient data, incorrect measurements, and model assumptions. Consensus on a systematic methodology for assessing data quality is lacking, leading to inconsistent application in LCA studies (Finkbeiner et al., 2014). Various approaches exist for data quality analysis, but no universally accepted scheme exists. Due to the limited robustness of data quality analysis, caution is needed when interpreting study findings. Data quality analysis overlaps with uncertainty analysis, which is not standardized within the LCA community either (Finkbeiner et al., 2014). Uncertainty analysis involves uncertainty within parameters, scenarios, and models. Currently, a systematic methodology for assessing uncertainty is lacking, leaving the choice of method to practitioners which increases the level of subjectivity.

The bottom-up nature of LCA hinders the macroeconomic scale-up from product system to region, country, or organization (Finkbeiner et al., 2014). Process-based LCA typically does not include industrial dynamics or production structures and usually excludes macroeconomic infrastructure and its impacts. Reproducing LCA results based on previous LCAs is challenging due to the individual modeling choices, system definitions, and datasets. Usually, published LCAs don't supply all the data in transparent ways that allow for reproducing the results (Finkbeiner et al., 2014). Different LCA tools have also been shown to produce significantly different results (Silva et al., 2017). Other challenges that exist within LCA such as those relating to weighting, allocation, and impact assessment methods are not highlighted here (Finkbeiner et al., 2014).

2.2 Footprints - single-impact dimension LCA

Recent years have seen the emergence of single impact dimension LCA, more commonly known as environmental footprints (Rosenbaum et al., 2018). The most popular is the carbon footprint which is a narrow-scoped LCA examining only the Global Warming Potential impact category. Typically, organizations that report on carbon footprints follow the GHG Protocol which builds on the ISO 14064 standard (ISO, 2018, 2019a, 2019b; WRI and WBCSD, 2011b). Other common footprints include the Ecological footprint, the Cumulative Energy Demand (CED), and the Water Footprint (Frischknecht et al., 2015; ISO, 2006d; Wiedmann and Barrett, 2010).

2.2.1 ISO for carbon footprint

The ISO 14064 standards describe the quantification and reporting of the GHG emissions of projects and organizations (ISO, 2018, 2019a, 2019b). The intention of the ISO 14060 series is that it *"... provides clarity and consistency for quantifying, monitoring, reporting and validating or verifying GHG emissions and removals ...* " (ISO, 2018, p. vi). The standards define principles and requirements for organizational GHG emissions. The characterization factor to be used is the latest IPCC's Global Warming Potential (GWP) with a time horizon of 100 years. The ISO recommends defining a base year for organizations to compare themselves to over time, reminiscent of the recommendations for comparisons within the O-LCA frameworks.

2.2.2 GHG Protocol

The GHG protocol initiative is a partnership led by the World Resources Institute (WRI) and The World Business Council for Sustainable Development (WBCSD). The GHG protocol was published in 2004 and is an international standard for corporate carbon footprint reporting (WRI and WBCSD, 2004). Many organizations have started using the GHG protocol to report on their GHG emissions. The protocol builds on the ISO/TS 14064, with the most notable new concept being the definition of Scope 1, 2, and 3 emissions (WRI and WBCSD, 2011a). Scope 1 emissions include the direct emissions occurring within owned assets and operations of the organization. Scope 2 emission includes the indirect emissions from purchased energy and electricity. Scope 3 emissions include indirect emissions both upstream and downstream.

2.2.3 Limitations of single-impact footprints

Footprints have the narrow scope of a single impact dimension, which facilitates easier interpretation, comparisons, and goal setting, by removing the ambiguity, and subjectivity related to comparing different impact categories (Rosenbaum et al., 2018). Simultaneously, assessing only a single impact dimension can easily lead to problem shifting (Finkbeiner and König (2013) and Laurent et al. (2012)). Single impact dimension approaches are attractive to corporations wanting to pick a single dimension to communicate as footprints are more understandable for the general public. However, this advantage is somewhat negated by the fact that footprints are not recommended for decision support (Rosenbaum et al., 2018). In addition to the already existing challenges of double-counting within LCA as described by Lenzen (2008), on an organizational level, the scope 3 carbon footprints as defined by the GHG protocol are exposed to double-counting effects. The double-counting is inherent to the scope 3 definitions within the GHG protocol (WRI and WBCSD, 2004). The reason is that scope 3 emissions include indirect emissions, thus the scope 3 emissions of one company overlap with the scope 1 or 2 emissions of another company.

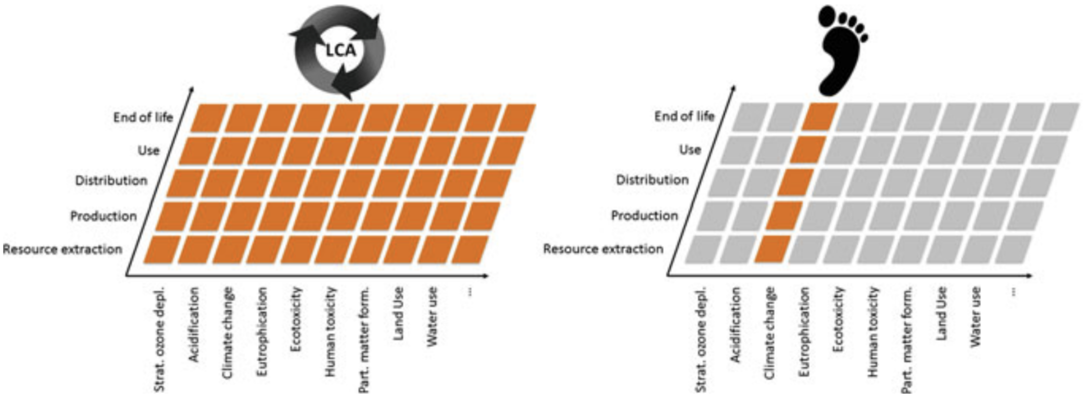

Figure 1: Difference in scope and completeness between LCA and footprints, from Rosenbaum et al. (2018, p. 197)

2.3 Organizational LCA

While LCA has been designed for products and product systems its benefits and potential can be extended to organizations, as many environmental concerns are handled at the organizational level (Martínez-Blanco and Finkbeiner, 2018). The first steps towards organizational impact assessment were taken in the 1990s by Clift and Wright (2000), Finkbeiner et al. (1998) and Taylor and Postlethwaite (1996)) and by combining Input-Output analysis with LCA (Huang et al., 2009; Lave, 1995). Today some of the most common methodologies for reporting the environmental performance of organizations are environmental management systems (EMS), Corporate Sustainability Reporting (CSR), and carbon footprints (Martínez-Blanco and Finkbeiner, 2018). Corporate sustainability reporting follows the standards created by the Global Reporting Initiative (GRI). EMS assessments commonly follow the ISO 14001 or the European equivalent EMAS, while carbon footprints usually follow the ISO 14060 series or the GHG Protocol (ISO, 2013, 2015, 2018, 2019a, 2019b; WRI and WBCSD, 2004). Methods like EMS are designed for organizations and consider multiple impacts, but do not include the life-cycle perspective. Carbon footprint methods include the life-cycle perspective and are applicable to organizations, but it only considers one impact dimension. Organizational LCA is the first method for organizations that is multi-impact and includes a life-cycle perspective. (Martínez-Blanco and Finkbeiner, 2018). This triple overlap characterizing O-LCA is illustrated in the center of the venn diagram in Figure 2. Many companies also use EPDs based on LCA for communicating the environmental impact of their products, which have been standardized by the ISO 14025 standard (ISO, 2006a; Schmincke and Grahl, 2007). In recent years, several initiatives have created frameworks for Organizational LCA. Next follows an overview of the three most prominent frameworks.

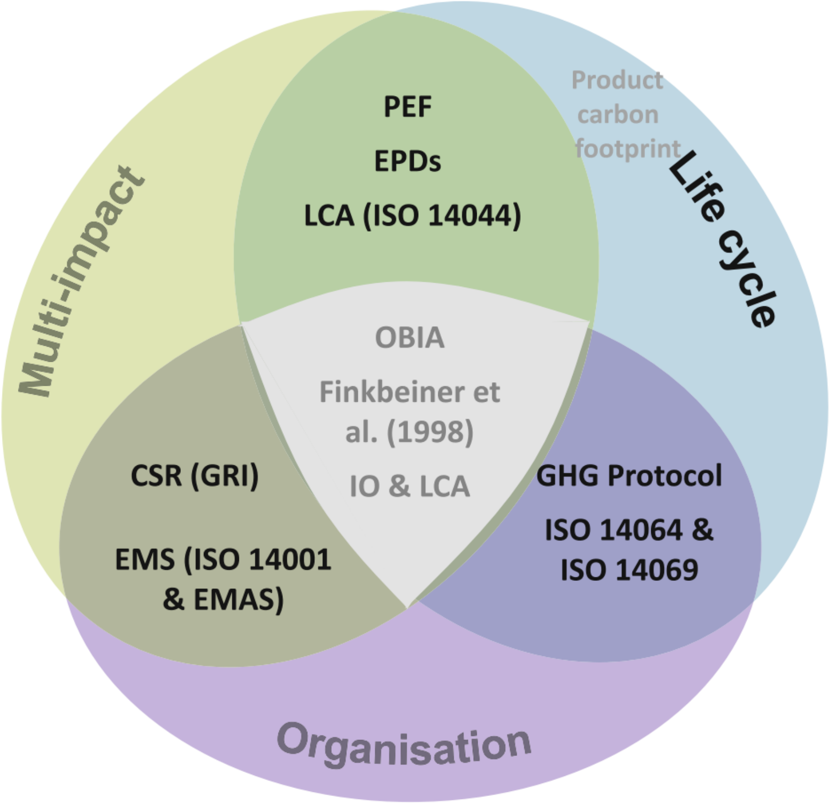

Figure 2: The organization's environmental toolbox: precursory approaches. Figure from Martínez-Blanco and Finkbeiner (2018), originally adapted from Martínez-Blanco et al. (2016).

2.3.1 ISO/TS 14072 - Requirements and Guidelines for Organizational Life Cycle Assessment

The ISO/TS 14072 has been developed as the global standard of requirements and guidelines for performing an O-LCA (ISO, 2014b). It adapts and builds on the ISO 14040 and 14044 standards to bring LCA to organizations. The fundamental four-phase methodology is unchanged and the majority of requirements remain unchanged from the ISO 14044 and 14044 standards (Finkbeiner and König, 2013; Martínez-Blanco, Inaba and Finkbeiner, 2015). The Functional Unit and The Reference Flow are changed into Reporting Organization and Reporting Flow for an O-LCA, specifying the type, quality, and quantity of products within a reference period, usually one year. The scope of an O-LCA requires additional clarifications on exactly what parts of the organization are part of the assessment.

2.3.2 UNEP Guidance on O-LCA

The UNEP Guidance on Organizational Life Cycle Assessment (UNEP, 2015) was created as a supplement to the ISO/TS 14072 standard to show the potential of the methodology and support more widespread application (Martínez-Blanco, Inaba, Quiros et al., 2015). It builds on the specifications of the ISO/TS 14072 and aims to be a complementary document providing more detailed guidelines on how to perform an O-LCA. There are very few differences between the guidance and the ISO standard apart from the spelling of the acronym O-LCA. It included a pilot study with 11 organizations, which gave some initial insight into the benefits of the guidance (UN, 2017). Martínez-Blanco et al. (2020) highlight some challenges and lessons learned based on the road testing of the O-LCA guidance, which will be discussed further in Section 2.3.5.

2.3.3 Organizational Environmental Footprint (OEF)

After the ILCD guidelines were released in 2012, the EU Commission introduced the Product Environmental Footprint (PEF) and Organisational Environmental Footprint (OEF) Guidelines, as a part of its Roadmap to a Resource Efficient Europe (EC, 2011). These guidelines are abbreviated and slightly modified versions of the ILCD guidelines, also taking into consideration the ISO 14040 series and the Greenhouse Gas Protocol (EC, 2021a, 2021b). The Environmental Footprint (EF) methods aim to increase the comparability for companies and organizations reporting on their environmental performance by providing more strict guidelines for each sector (EC, 2021b). This is done by defining, for the PEF method, Product Environmental Footprint Category Rules (PEFCR). These product category rules define specific requirements of EF assessments of groups of products. The PEFCR removes some of the modeling choices left by previous standards, by fixing requirements, providing standardized inventories, and providing benchmark values. Parallel to the PEFCR, the OEF defines Organisation Environmental Footprint Sector Rules (OEFSR). These provide specifications at the sector level for organizations with the aim of making results more comparable. The OEFSR allows for comparisons between organizations within the same sector or within the same organization between different years. Another proposed benefit is to have benchmark organizations' EFs for each sector. The EC suggests that the PEFCR and OEFSR can increase the relevance, reproducibility, and consistency of EF results. Additionally, the rulesets will reduce the effort and the cost of performing the EF analysis.

2.3.4 Going from product to organization

Product LCA forms the foundation of O-LCA, thus most principles and requirements from P-LCA applies also to organizational LCA, but there are some key differences when moving from a product to an organizational perspective. Some of the inherent limitations within P-LCA are directly carried over into O-LCA, such as those relating to data quality, weighting, allocation, impact assessment, and uncertainty analysis (Finkbeiner et al., 2014). The majority of the differences are found in the Goal and Scope definition phase, which can have large effects on the rest of the assessment (Martínez-Blanco, Inaba and Finkbeiner, 2015). For an O-LCA, the Functional Unit as known from P-LCA is replaced by the Reporting Unit. In the UNEP/SETAC O-LCA Guidance the Reporting Unit as defined from the ISO/TS 14072 is further broken down into the reporting organization and the reporting flow (ISO, 2014b; UNEP, 2015). The reporting organization should describe the unit of analysis, namely the description of precisely what should be considered "the organization". The reporting flow is the quantification of the products portfolio, expressed e.g. per unit, by weight, or by volume, defined for a set reporting period which is often one year.

In O-LCA one considers two sets of boundaries; the system boundary and the organization boundary. The UNEP Guidance suggests defining the system boundary based on the reporting organization. It should include direct and indirect activities and their associated impacts. The OEF Guide and the GHG Protocol define two system boundaries, one covering direct activities and one including the value chain to cover the whole system. Martínez-Blanco, Inaba and Finkbeiner (2015) propose that having a single term for system boundary covering both direct activities and the value chain as suggested by the UNEP Guidance is sufficient in O-LCA.

2.3.5 Challenges of O-LCA

Despite the existence of multiple frameworks, O-LCA has not yet seen widespread adoption. Perhaps due to its limitations and challenges, which are summarized here based on the existing literature. The inherent limitations of P-LCA are carried over to O-LCA as P-LCA is the foundation of O-LCA. The challenges relating to the FU, data quality, and uncertainty analysis as well as issues relating to double-counting are all equally relevant in O-LCA as in P-LCA.

Building on Martínez-Blanco, Inaba and Finkbeiner (2015), Martínez-Blanco et al. (2020) point out challenges with the UNEP O-LCA guidance and their suggestions for solutions in their paper: *Challenges of O-LCA: Lessons learned from road testing the guidance on organizational life cycle assessment.* The article is based on a published report on the O-LCA road testing of a group of companies in the piloting phase of the guidance (UN, 2017). Martínez-Blanco et al. (2020) point to the difficulty of choosing the correct subset of an organization for analysis in the Goal and Scope phase. Limiting the analysis to a subset of the organization is allowed by the UNEP guidance if properly justified. Simultaneously, the guidance recommends the inclusion of supporting activities. The guidance suggests defining the reporting flow based on the nature and amount of products in the organization's offering in a set reporting period (UNEP, 2015). On this point Martínez-Blanco et al. (2020) recommend flexibility over rigidity on the part of the organization. Supporting activities are commonly excluded under the assumption of their low relative importance. These include e.g. capital equipment, employee commuting, business travel, design, and marketing.

Both the UNEP Guidance and the OEF suggest splitting organizational activities into three groups to identify where impacts are caused: Direct, Indirect upstream, and Indirect downstream. The Direct and Indirect upstream are mandatory, while the Indirect Downstream is excluded both in O-LCA Guidance, OEF, and ISO (EC, 2021a; ISO, 2014b; UNEP, 2015). The three groups of products are somewhat analogous to Scope 1, 2, and 3 of the GHG protocol, where only Scope 1 and 2 are mandatory (WRI and WBCSD, 2004). The grouping of company activities does not always match these three categories (Martínez-Blanco et al., 2020). Especially for service providers or other complex products, how to draw the system boundaries becomes less clear. Upstream, downstream as well as capital investments, production, and EOL phases become more entangled. Certain activities fall between the categories, some may be grouped together, and others such as capital equipment remain difficult to categorize. Terminology is an additional barrier to the splitting of activities, as the terms direct/indirect emissions can be confused with direct/indirect activities. An organization may for example have direct control over electricity production, which has indirect emissions. Mapping the data needed and effective data collection remains a challenge. A lot of the activities of an organization cannot be covered and assessed with collected data. Martínez-Blanco et al. (2020) suggest that LCI databases can help cover the parts of the data that cannot be collected. They suggest that database providers should expand from materials and processes to goods and services. For organizations, local impacts may be of significant importance. In a global generic assessment of products such local impacts may be of little importance, but for local stakeholders, the impacts may be of large importance. Including a more specific impact assessment of the local burdens could be beneficial, as the location for direct emissions is generally known in O-LCA.

2.3.6 Comparing organizations with O-LCA

While product LCA can be used for comparison between products with the same function, O-LCA is explicitly not intended for public comparisons between different organizations (ISO, 2014b;

UNEP, 2015). The reasoning is that the unit of comparison is not consistent between different organizations. The product portfolio and the overall organization can vary a lot depending on factors such as the sector, the organization's size, or the location. The OEF differs in this regard by allowing for comparisons within the same sector, for organizations that are subject to the same OEFSR (EC, 2021a). Increased comparability was the purpose of the PEF/OEF frameworks which they aimed to achieve by setting additional requirements (EC, 2021a). There have since been criticisms of the frameworks claiming that they do not achieve this goal. If OEF has not reached this goal there is no O-LCA framework that allows for intra-organizational comparisons.

Part of the purpose of the PEF/OEF methods was to increase comparability within sectors by setting stricter requirements within each sector. The frameworks thus represent an effort towards comparability within LCA and specifically, O-LCA. Before examining further the comparison of organizations within O-LCA, some general challenges within the PEF/OEF methods found in the literature are highlighted.

Analogous to P-LCA and O-LCA, the PEF method is the foundation of the OEF method which makes its limitations central to evaluating the limitations of the OEF method. In 2014 in an Editorial in the International Journal of Life Cycle Assessment Finkbeiner (2014b) concluded that the PEF and OEF methods do not achieve their outlined objectives, even suggesting that the frameworks may damage further integration of LCA with environmental policy. Finkbeiner (2014b) highlights a list of issues with the PEF and OEF methods. Firstly that the PEF method is not harmonized with the ISO 14044 standard as advertised, by not meeting several of its reporting requirements and allowing for comparative PEF assertions after weighting. According to Finkbeiner (2014b) the ISO 14044 standard does not allow for comparative assertions if the results have been weighted. Further, the OEF allows for comparisons within sectors, directly at odds with ISO/TS 14071. Other critiques include not using internationally agreed terminology, suggested to lead more to proliferation than harmonization of terminology. In a response to Finkbeiner's editorial, Galatola and Pant (2014) defended the PEF/OEF frameworks. They highlighted the urgency of creating comparable LCA frameworks in the EU. Noting how these methods are measurement tools as part of the policy, not standards. They highlighted the large interest in the methods in terms of companies and pilot proposals, indicating the iterative improvements to the methods following the pilot phase. The authors describe the importance of a public discussion on weighted comparisons, as weighting and comparisons are already being done e.g. in single-impact footprinting. Comparative assertions of different products are already being made without publication in decision-making. The authors suggest that the comparisons of the PEF/OEF methods do follow ISO standards, as the ISO 14044 standard allows for "Comparisons between systems" when the systems are comparable. Pedersen and Remmen (2022) performed a review of the PEF method and identified some central challenges along similar lines as Finkbeiner (2014b). They pointed out how the success of the PEF framework hinges on the ability of the PEFCRs to allow for better comparisons within product categories. Further, they indicate that the FUs are not achieving this purpose as some of the PEFCRs don't include relevant quality and performance aspects.

The PEF method indicates specific impact assessment methods to be used, in contrast to the ISO 14044 standard where there are no specific requirements (Lehmann et al., 2015). Finkbeiner (2014b) critiqued some of the mandatory impact methods as not being scientifically valid. Pedersen and Remmen (2022) suggest that the provision of specific impact categories and methods neglects the difference in maturity between the different impact categories. The selection of broad and more uncertain impact categories was commented on in the response to Finkbeiner's editorial, by stating the importance and aim to cover a comprehensive range of impacts, despite some impact categories having more uncertain methodologies (Galatola and Pant, 2014). The authors conclude their defense of the methods by highlighting again the 3-year pilot phase and their technical advisory board aimed to figure out and improve on the remaining challenges of the methods (Galatola and Pant, 2014). Pedersen and Remmen (2022) further suggest that the PEF method should cover social impacts in order to be used in policy or communications. There has been a very limited amount of pilots and usage of the methods in general in the past decade, with only 19 PEFCR pilots having been published by the EC (EC, 2021b). The fundamental difficult question arising in the disagreements about the PEF/OEF frameworks is whether additional requirements to an LCA framework in fact increase the comparability, or if the inflexibility and limitations the requirements impose are more detrimental than beneficial.

Now onto inter-organizational comparisons under the ISO/TS 14072 and the UNEP O-LCA guidance. Both frameworks explicitly state that O-LCA results are not intended for comparisons between organizations because the unit of comparison (reporting unit) is different between organizations (ISO, 2014b; UNEP, 2015). Martínez-Blanco, Inaba and Finkbeiner (2015) and Martínez-Blanco and Finkbeiner (2018) both note that O-LCA is best suited for the performance tracking and continuous measurement of the improvements of organizations over time, maintaining the unit of comparison fixed to the same organization. They highlight how O-LCA may fulfill other goals such as intra-organizational comparisons and informing strategic decisions and voluntary corporate sustainability reporting. Even comparing the performance of an organization over time can be ambiguous if the reporting unit or scope otherwise changes. To manage this Martínez-Blanco et al. (2020) suggest that the reporting flow should depict the product portfolio in acute detail. A baseline period should be established for the first year with reliable data which can be compared to. Additional measures can be made to keep the changing factors of the reporting flow between years more comparable such as setting a fixed amount of units a mass. An impact intensity, either per dollar or per worker, could also facilitate better tracking and interpreting of results over time. The authors suggest that this kind of impact intensity tracking may also inspire action in the organization. Although O-LCA is time-consuming, one should make sure to spend enough time on the interpretation phase. Fewer impact categories make interpretation easier, but it is important to ensure a broad set of impacts to understand the complete picture (Martínez-Blanco et al., 2020). The trend of carbon footprint reporting in organizations may be making comparability between organizations more manageable, but it is neglecting a broad range of other impact categories which potentially leads to problem shifting (Finkbeiner and König, 2013; Laurent et al., 2012).

The remaining challenges within O-LCA have likely contributed to hindering the adoption of the method. The restriction on comparing different organizations further limits some of the usefulness of O-LCA. The main use cases for O-LCA currently are therefore intra-organizational comparisons, decision support, and voluntary reporting.

2.4 Energy producing technologies

This section presents a short introduction to the four energy technologies that will be assessed using LCA in the ensuing chapters. The energy technologies are wind power, hydropower, nuclear power, and natural gas power. These introductions describe briefly, for each energy technology, how the technology works, the amount of global production, the range of GHG emissions from previous studies, and other potential environmental impacts.

2.4.1 Wind power

Wind power is a renewable energy technology that harnesses the power of wind to generate electricity. Wind turbines convert the kinetic energy of wind into electricity through rotating blades that drive a generator. Wind power generated 1588.6 TWh of electricity globally in 2020 (IRENA, n.d.-c). The vast majority comes from onshore wind power, but offshore wind is growing rapidly and reached 6.3% of global wind power production in 2020 (IRENA, n.d.-c). A review of LCAs of wind power found the GHG emissions of wind power to be in the range of 3.0 to 45 g CO_2-eq./kWh and the median to be 11 g CO_2-eq. (Dolan and Heath, 2012). Wind power has essentially no operational environmental impacts, the majority of impacts come from the material inputs used in the windmill, its foundations, and the generator (UNECE, 2021). These include, among others steel, different metals, cement, and rare earth elements (Razdan and Garrett, 2017). The impact of wind power on birdlife has been documented by Marris, Fairless et al. (2007) and Thaxter et al. (2017), but put in context these values are often a small fraction of bird fatalities caused by other anthropogenic infrastructure (Sovacool, 2013). In Scandinavia, there have been challenges regarding the land conflict with indigenous people (Lawrence, 2014).

2.4.2 Hydropower

Hydropower is a renewable energy technology that generates electricity by harnessing the energy of falling or flowing water using turbines to turn kinetic energy into electrical power. There are two main types of hydropower plants: reservoir hydropower, which can regulate its production through large dams, and run-of-river hydropower, which doesn't have this possibility and are usually smaller. Hydropower is one of the most cost-efficient energy sources and is the largest source of renewable electricity generation worldwide with a production of 4355,8 TWh in 2020 (IRENA, n.d.-b). In Europe, hydropower is particularly prominent in mountainous countries such as Norway and Switzerland (Flury and Frischknecht, 2012; IRENA, n.d.-b). Gemechu and Kumar (2022) performed a review of LCAs applied to hydropower where they found reported life-cycle GHG emissions to be in the range of 1.5 to 3747.8 g CO_2-eq./kWh. The authors suggest reasons for the wide range of GHG emissions to be caused by data limitations, challenges in modeling End-Of-Life, (EOL) and variations in reservoir emissions. The reservoir emissions vary because of different characteristics between reservoirs and because of different methods used for the LCAs. Of other environmental impacts hydropower has been suggested to have ecological impacts due to habitat change of aquatic ecosystems caused by dams and river flow disruptions (UNECE, 2021).

2.4.3 Nuclear power

Nuclear power is a non-renewable energy technology that generates electricity from the energy released during the fission process of radioactive isotopes such as uranium or plutonium. Nuclear power plants use this process to heat water and produce steam that drives turbines, which then generate electricity. Nuclear power accounts for approximately 10% of global electricity production, with the largest producers being the United States, France, and China (IRENA, n.d.-a). In a review of the GHG emissions of nuclear electricity generation Lenzen (2008) found the range of GHG intensities to be between 10 to 130 g CO_2-eq./kWh. Another literature review by Warner and Heath (2012) found that the range of GHG emissions was 3.8 to 140 g CO_2-eq./kWh when normalized for plant lifetime. The study found the mean and median to be 20 and 15 g CO_2-eq./kWh, respectively. While nuclear power is a low-carbon source of energy, it has significant environmental impacts, including the production of radioactive waste and the potential for nuclear accidents (McCombie and Jefferson, 2016). The disposal of radioactive waste is a major challenge for nuclear power, as it remains radioactive for thousands of years and requires careful management to prevent contamination of the environment. Nuclear accidents, such as the Chernobyl disaster in 1986 and the Fukushima disaster in 2011, have highlighted the potential risks associated with nuclear power production. Although the risks of nuclear accidents have diminished, some severe accidents are still likely to occur in the future (Wheatley et al., 2016). The fear of nuclear power plant accidents has soured the support for expanding nuclear power production. Many are unproportionally fearful of these big accidents, although fossil fuels are much more lethal per kWh (McCombie and Jefferson, 2016). The environmental impact of uranium mining is also a concern, as it can lead to the release of radioactive materials into the environment harming both the environment and human health (Srivastava et al., 2020).

2.4.4 Natural gas power

Natural gas power production involves the burning of natural gas to produce electricity. The process involves the combustion of natural gas in a turbine, which drives a generator to produce electricity. Natural gas power production is a significant contributor to global energy production, with natural gas accounting for approximately 24% of global electricity production in 2020 (IRENA, n.d.-a). O'Donoughue et al. (2014) performed a systematic review of the Life-Cycle GHG emissions of electricity production from conventionally produced natural gas. Examining Natural Gas Combined Cycle (NGCC) plants they found that previous studies estimate the emissions to be within the range 420 to 480 g CO_2-eq./kWh. Jarre et al. (2016) assessed two Italian NGCC power plants, finding the operational emissions to be 412.6 g CO_2/kWh. Natural gas also emits significant amounts of carbon monoxide (CO) and nitrogen oxide (NO_x) (Jarre et al., 2016). Additionally, the extraction and transportation of natural gas can result in methane leaks, which are also a potent greenhouse gas (O'Donoughue et al., 2014). The role of natural gas power production is a topic of ongoing debate, with some arguing that natural gas can serve as a transition fuel to renewable energy sources, while others argue that the environmental impacts of natural gas production and consumption outweigh its benefits. Natural gas is for example included as a transitionally sustainable activity in the EU Taxonomy (EC, 2020).

3 Methods

The following chapter describes the methods of this thesis. Firstly, is described the general method of LCA according to the ISO standards. Then follows a description of the choice of companies for the analysis and the data sources used to arrive at the revenue-weighted product sets for each company. Next is described the method of Revenue Weighted LCA, which aggregates the P-LCA results by company revenue. Next the methods of each Product LCA are detailed, including the data sources used, the Goal and Scope definitions, modeling choices, and preliminary limitations. Then is outlined the data sources, databases, and tools used for this analysis. Finally, the data to be used for comparisons are described, the Upright Net Impact Data and the company reports.

3.1 Framework for LCA - ISO

The general method for the LCA in this thesis follows the steps of the ISO 14040 and 14044 standards. The four distinct steps of an LCA following the ISO standards are (1) Goal and scope definition, (2) Inventory Analysis, (3) Impact Assessment, and (4) Interpretation (ISO, 2006b, 2006c).

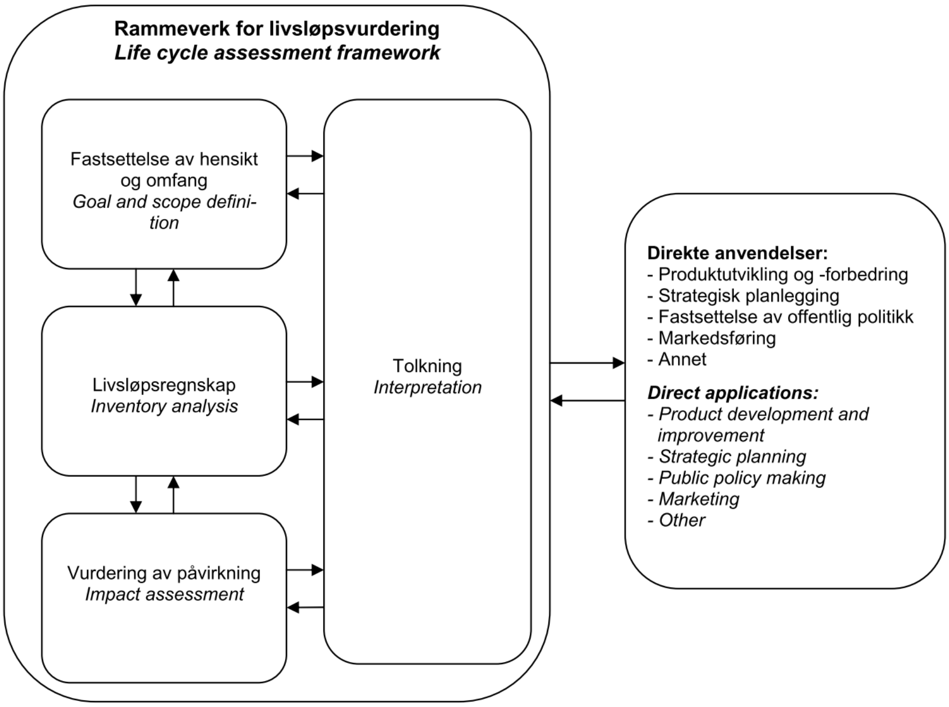

Figure 3: Steps of an LCA (ISO 14040)

The Goal and scope definition phase, as defined in the ISO standards, entails the following key steps: defining the goal, defining the scope, choosing the functional unit, and setting the system boundary. This initial phase is essential for determining the direction of the assessment and ensuring its quality. The Life Cycle Inventory analysis "*... involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system.*" (ISO, 2006b, p. 18). At this stage, a product system should be drawn for assessment, displaying the relations between the inputs, outputs, and the functional unit. The Life Cycle Impact Assessment (LCIA) phase connects the inventory data to environmental impact categories. This phase has multiple mandatory steps:

selecting impact categories, classifying LCI results, and characterization. Secondary steps such as normalization, grouping, and weighting are optional. The final phase is the Life Cycle Interpretation, which connects each previous phase iteratively. Interpretation can take place between each phase and lead to changes in the analysis to improve it. This phase contains the identification of significant issues and includes checks of completeness, sensitivity checks, and consistency checks. It also contains conclusions, limitations, and recommendations. The steps of an LCA are outlined in Figure 3, where the iterative nature of interpretation between each phase is illustrated clearly. Lastly, an internal or external expert may perform a critical review to increase credibility and trust in the LCA results.

3.2 Selection of companies

The companies chosen for this analysis are two Nordic energy companies, the Norwegian company Statkraft and the Swedish company Vattenfall. There were a few main reasons for the selection of companies. Their relatively low amount of product offering, specifically energy production, with significant overlap between the companies. The familiarity of the author with energy-producing technologies made the analysis more manageable. Energy production is somewhat uncomplicated with regards to the use-phase and downstream impacts, and literature is abundant on both the technology, their inputs, and their impacts. The companies are also covered by the public coverage of the Upright project, meaning that Upright had both financial and Net Impact Data readily available for comparison. The proprietary sustainability reporting of the companies includes life-cycle carbon footprints, providing yet another source of comparison.

The primary input data from the companies used in this analysis is their product sets, which is the list of yearly revenue percentages per product. These product sets are the same sort of company input data that Upright uses to calculate Net Impact Data. The product sets used in this thesis, and those of Upright are based primarily on the financial reporting of the two companies (Statkraft, 2022; Vattenfall, 2022). For the purposes of this thesis, the product sets used were slightly simplified, excluding small products in companies' offerings, to reduce the number of products to assess. The product sets used by Upright in their modeling are slightly more comprehensive due to the nature of their methodology. For example, Upright uses products such as 'Construction of hydropower plants' in addition to 'Electricity produced from hydropower' in their product sets, in contrast to the LCA as performed here where both are handled within the functional unit for hydropower electricity. The exact product sets used by Upright are not provided here, as they are not publicly available information. Figure 1 and Figure 2 shows the product sets used in this analysis and the complete product weights as reported by the companies' electricity production. In these product sets it is assumed that all electricity has the same price regardless of production source. Electricity prices have little variance between production technologies apart from minor differences relating to low-carbon electricity or market fluctuations. For this analysis, it is assumed that electricity from different sources is priced the same. Following this assumption, the yearly production by technology is parallel to the yearly revenue from each product.

3.2.1 Statkraft revenue-weighted product set

Statkraft is a Norwegian energy production company that gets most of its revenue from energy production. Table 1 shows the generation by power source for Statkraft as of their financial reporting for the year 2021, and for the simplified case where minor products not assessed in this analysis are neglected. Only a small amount of production was neglected in the simplification as

'Other' power generation only accounted for 0.14% of the production. The two largest producing sources are hydro and wind power, accounting for 90.26% and 5.59% of their yearly production in 2021, respectively (Statkraft, 2022). The 'Percentage simplified' column in Table 1 shows the percentages for the product set used in this analysis, where the remaining products were scaled up to sum to 100% to account for the neglected products.

Generation by power source	**TWh**	**Percentage**	**Percentage simpl.**
Hydropower	63.0	90.26%	90.5%
Wind power	3.9	5.59%	5.6%
Natural gas power	2.7	3.87%	3.9%
Other (biomass and solar power)	0.2	0.14%	-
Total generation	69.8	100%	100%

Table 1: Statkraft yearly electricity production in 2021 (Statkraft, 2022).

3.2.2 Vattenfall revenue-weighted product set

Vattenfall is a Swedish energy production company, which similarly to Statkraft gets almost all its revenue from energy production(Vattenfall, 2022). The generation per power source for the year 2021 is shown in Table 2. The largest electricity production sources are Hydropower and Nuclear Power. The generation from Biomass and waste was neglected as they together only accounted for 0.4% and allowed fewer products to be assessed in this analysis. All that Vattenfall calls fossil power is assumed to be electricity production from natural gas. This choice was made to limit the scope of the product LCA to a single product to cover fossil fuel production. Upright models this product as fossil fuels generally. The 'Percentage simplified' column in Table 2 shows the percentages for the product set used in this analysis, where the remaining products were scaled up to account for the neglected products.

Generation by power source	**TWh**	**Percentage**	**Percentage simpl.**
Hydropower	40.9	36.7%	36.9%
Nuclear power	40.4	36.3%	36.4%
Natural gas power	18.4	16.5%	16.6%
Wind power	11.2	10.1%	10.1%
Biomass and waste	0.5	0.4%	-
Total generation	111.4	100 %	100%

Table 2: Vattenfall yearly electricity production in 2021 (Vattenfall, 2022)

3.3 Revenue-Weighted LCA

In the introduction, it was asserted that there is a clear need for robust and comparative impact data of organizations. As found in the literature review, P-LCA is the best tool we currently have for measuring the environmental impact of products and product systems (Bjørn, Owsianiak, Molin and Laurent, 2018). Further, it was found that O-LCA in its current form has not yet seen widespread adoption, and the frameworks that exist still contain challenges (Martínez-Blanco et al., 2020). For further progress in O-LCA, there are different paths to take. One possibility is the iteration on improvements to the specific challenges of the frameworks and methods to better handle the complexities of organizational boundaries in O-LCA. Another approach is to move towards simplification, for example by excluding supplemental activities to focus exclusively on the products offered by the organization. The second route is the one explored in this method. For this simplification, one would consider the current challenges in O-LCA somewhat inherent to the complexity of organizations and choose instead to leverage the strength of P-LCA. Martínez-Blanco and Finkbeiner (2018) highlighted the complementary nature of P-LCA and O-LCA and suggested that a *"... proxy organizational LCA could be calculated by the weighted summation of the product LCAs for the products in the organization's portfolio (plus supporting activities)"* (Martínez-Blanco and Finkbeiner, 2018, p. 485). In this suggestion, the authors still include supplemental activities in contrast to the simplification to be suggested in this method. The method of Revenue Weighted LCA explores the exclusion of the supporting activities in order to simplify O-LCA. Using the definitions from the UNEP O-LCA Guidance, this means setting the reporting unit in O-LCA equal to the reporting flow (UNEP, 2015). Further, the reporting period of one year to quantify the reporting flow of the organization is the same in this method as in O-LCA. If the vast majority of an organization's impacts come from its product offering, such that the impact of the supplemental activities is negligible, RW-LCA becomes a good proxy for the impacts of the organization. Upright models the Net Impact of companies under this assumption - that the products and services offered by a company are causing the majority of the impacts (Upright Project, n.d.-c). The way Upright uses product sets to aggregate from product impacts to company impacts is analogous to the revenue weighting of LCA results in this method.

From this line of thinking we arrive at the method of Revenue Weighted LCA (RW-LCA) which will be performed in this thesis. The method will be executed on the two selected Nordic energy companies, Statkraft and Vattenfall. RW-LCA is defined in this thesis as the yearly revenue-weighted product LCA of an organization. The method excludes supplemental organizational activities by measuring the impact of an organization exclusively based on the impacts of its product offering. The method builds on the fundamental methods of LCA for products known from the ISO 14040 and ISO 14044 standards. The first step of the method is the choice of companies and the identification of their product sets. This includes understanding exactly what products the company offers and the relative revenue share of each product. The second step of the method is performing product LCAs to assess the environmental impacts of all the products identified in the product sets of each company. The third step is the aggregation of impacts based on each product's relative revenue share for each organization. This step entails the multiplication of the revenue share for each product with its impacts. The method covers the same impact categories as the underlying P-LCA and does not include any further weighting or normalization apart from the revenue weighting.

3.4 Product LCA

This section outlines the methods for the P-LCA performed in this thesis. As described in the RW-LCA methods, the results from the product LCAs are the building blocks to arrive at the company results. The goal of the following Product LCAs is to evaluate the potential environmental impacts of the product for it to be used to understand the impacts of the companies. The P-LCAs will be performed by extracting LCI data from existing studies, relying only on published data and LCA databases. This allows for building on previous works, limiting the time requirements for the creation of the inventory generally, and the depth needed for the data collection. The only specific inputs from the companies are the product sets derived from their public financial reporting and Upright's data. The scope of the P-LCAs includes the majority of the cradle-to-grave life cycle of all the products. The products are modeled generally, within a European context where possible. The

LCAs are attributional and process-based approaches. Based on the physical material and energy flows, the potential environmental impacts are calculated for the range of LCA impact categories as outlined in Section 3.5.2. The generic fashion of the P-LCAs allows for an exploration of the reproducibility of LCA results and an exploration of the feasibility of using the impact of 'generic' P-LCAs to understand the impact of the specific products of companies. In the following four sections are outlined the Goal and Scope definitions of each P-LCA performed in this analysis. Each part includes summaries of the Goal and Scope definitions as well as other relevant methods from the studies the analysis of each product is based on. Then is described how the analysis in this thesis differs from the studies where there are notable differences.

3.4.1 Wind power LCA

The study chosen to model wind power is an LCA of a virtual 100MW wind power plant with 3.45MW rated Vestas wind turbines performed by Vestas (Razdan and Garrett, 2017). The study is hereby called the Vestas LCA. Vestas is one of the worlds leading wind turbine producers and have been conducting LCAs of their turbines since 2001. The report conforms to the ISO standards ISO 14040 and 14044 and has undergone a critical review according to ISO 14071, performed by Prof. Dr. Mathias Finkbeiner (ISO, 2006b, 2006c, 2014a). This report was chosen due to its comprehensiveness and the availability of the life-cycle inventory in the study. It is worth noting that the size of the wind turbines is on the larger side, representing more accurately the average size of new wind power plants built today (IRENA, n.d.-c).

Description	**Unit**	**Quantity**
Lifetime	years	20
Rating per turbine	MW	20
Generator type	-	Induction
Turbines per power plant	pieces	29
Plant size	MW	100
Hub height	metres	94
Rotor diameter	metres	112
Wind class	-	High (IEC1A)
Tower type	-	Steel
Foundation type	-	LGWL
Production @ 7.5 m/s (low wind)	MWh per turbine per year	-
Production @ 8.5 m/s (medium wind)	MWh per turbine per year	-
Production @ 10.0 m/s (high wind)	MWh per turbine per year	15725
Grid distance	km	20
Plant location	-	Europe
Vestas production location	-	Global average

Table 3: Baseline wind plant assessed, from Razdan and Garrett (2017)

Next follows a summary of the Goal and Scope definition from the study. The goal of the study was to evaluate the potential environmental impacts of a 'virtual' 100 MW wind power plant, consisting of twenty-nine 3.45 MW turbines. Modeling a European scenario without making comparative assertions to other plants or technologies. The study was intended for environmental reporting, decision support within the company, and as marketing materials. The main audience were customers, the company internally, investors, and other stakeholders. The scope of the study is a cradle-to-grave LCA. The life-cycle phases include manufacturing, wind plant setup, site operation, and end of life. The manufacturing phase includes the production of all parts as well as the import of components not produced by Vestas. Transport is included both for raw materials and component transportation. The wind plant setup includes the transportation of components to the site and installation. The site operation phase includes power production, servicing and maintenance, and replacement parts. The End-of-life phase considers the whole power plant including the decommissioning activities, dismantling, recycling, and landfill/incineration. The functional unit is defined as: "*1 kWh of electricity delivered to the grid by a 100MW wind power plant*" (Razdan and Garrett, 2017, p. 27). The plant is considered to have a lifetime of 20 years, dividing up the impacts of the plant over the total energy production over the lifetime of the plant. Table 3: *Baseline wind plant assessed* from the study is included here and gives the basic information and assumptions for the whole power plant. The system includes the wind turbines, as well as the power plant including site cables and site transformers up until the point of the existing grid. The data collection builds on the years of previous studies and data performed by Vestas. The cut-off criteria used in the study is 1% for mass and energy inputs and for environmental impacts. The End-of-life recycling rate for the most plentiful metals in the analysis (steel, aluminum, copper) is modeled to be 92%. In the study, there is no quality difference between recycled and primary metals. Most of the remaining EOL collected materials are landfilled while some are incinerated. For more details, we refer to the complete study (Razdan and Garrett, 2017).

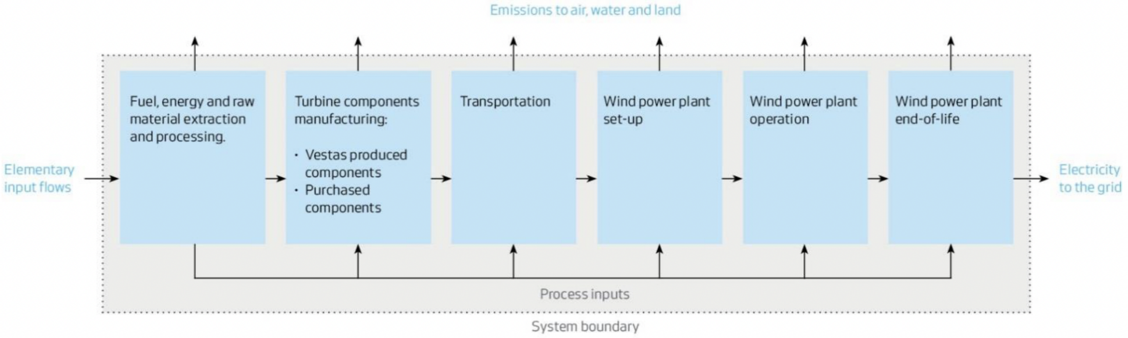

Figure 4: Wind power product system drawing, from Razdan and Garrett (2017)

The wind power P-LCA in this study is modeled directly after the Vestas LCA. The complete inventory of the Vestas power plant was used to create the Inventory used for this analysis. The functional unit is the same for this analysis. The purpose of the wind power product LCA is the same as that of Vestas, to examine the potential environmental impacts of a 100 MW wind power plant consisting of twenty-nine 3.45 MW turbines. The analysis considers the same life-cycle phases as the Vestas LCA and the inventory includes all the material and energy inputs disclosed in the study. A range of LCA environmental impact categories was assessed, as outlined in Table 6. The scope of this analysis is cradle-to-grave, including the same life-cycle phases as outlined above according to the Vestas Study. Based on the inventory tables from the Vestas LCA, an almost complete LCI of all the inputs required for all life cycles of the wind power plant was created. Each material was mapped from Vestas' description to a corresponding process in Simapro/Ecoinvent. The complete Inventory used is presented in Table 9. The mapping between the Vestas study material/emissions descriptions and Ecoinvent processes is shown in Table 16 and 17 in the Appendix. The materials were modeled in mass units on a per kWh basis, converting between metric units where necessary. Some materials were excluded in the mapping process as no suitable processes were found for modeling in Simapro. The excluded materials are marked as yellow rows in Tables 16 and 17.

3.4.2 Hydropower LCA

The hydropower product LCA is performed similarly to the wind power LCA by extracting inventory data from an existing study, with the same reasoning of building on previous works. The study chosen for hydropower is a report commissioned by the Öko-Institute (Institute for Applied Ecology) (Öko-Institute, n.d.), an independent research and consulting institution based in Germany. The study, "Life Cycle Inventories of Hydroelectric Power Generation," aimed to estimate the environmental impacts of hydroelectric power plants in Switzerland (Flury and Frischknecht, 2012). The study is hereby called the hydro LCA study. It examines different types of hydropower plants from a cradle-to-grave perspective and uses datasets compliant with Ecoinvent V2.2 guidelines. The study included reservoir, pumped reservoir, run-of-river, and small-scale hydropower plants. For the purposes of this analysis, we focus only on the reservoir hydropower plant part of the study. The goal of the hydro LCA study is to evaluate the potential environmental impacts of hydropower production in Switzerland. The study did not intend to examine a single hydropower plant, but rather to use average data representative of Switzerland and also other countries. The functional unit of the study was '1 kWh of electricity delivered to the grid by a hydropower plant'. The life-cycle phases in the study include construction, operation, and deconstruction. The construction phase includes reservoirs, dams, associated buildings, and the transformer. Land transformation and water occupation are modeled in the operation phase, together with operational inputs from the technosphere and direct emissions to air, soil, and water. The study assumed the hydropower plants to be replaced, including the deconstruction phase activities within the construction phase. The study used a wide range of data sources, combining the work of consultants, previous assessments, and literature. The study focused on data from 52 dams with storage hydropower and 6 small hydropower stations, used to create average energy and material data for the different types of power plants. The study assessed storage hydropower stations, pumped storage hydropower stations, run-of-the-river hydropower stations, and small hydropower stations. Based on the data, a life cycle inventory is created, results are calculated, and then an LCIA is performed. A range of environmental impacts are considered. Land occupation and water disruption impacts were included in the study in the operational phase. For more in-depth descriptions we refer to the Hydro LCA study (Flury and Frischknecht, 2012).

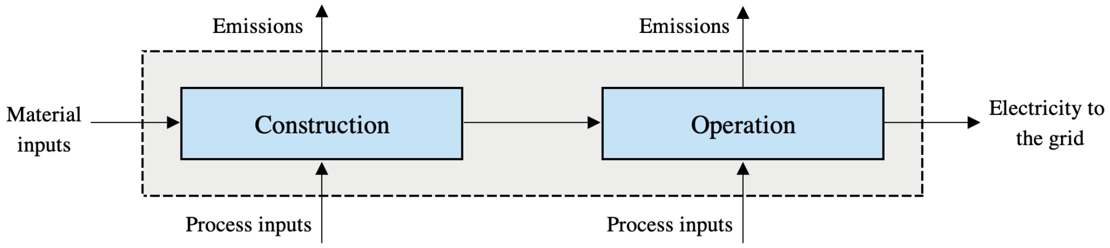

Figure 5: Hydro power product system drawing

The hydropower product LCA in this thesis follows the hydro LCA study in most aspects. This analysis aims to quantify the potential environmental impacts of typical hydropower production in the Nordics, with the basis in the inventory from the Hydro LCA. For this P-LCA, the product examined is a reservoir hydropower plant. The data used from the hydro LCA is the specific unit inventory data of the modeled reservoir hydropower plant in Switzerland. The functional unit of this analysis is *"1 kWh of electricity delivered to the grid by a 95 MW hydropower plant"*. The study assesses hydropower production in Switzerland, which in this analysis is considered reasonably representative of the Nordics where the two companies analyzed operate. Switzerland resembles the Nordics in its abundance of mountains with plentiful hydro resources. Both being in Europe, large parts of the supply chains are the same between Switzerland and the Nordics. The scope of this analysis includes the construction and operation phases as in the hydro LCA study but excludes deconstruction. In the study inventories on deconstruction were included within the construction inventory, as amounts of steel and concrete that were recycled or disposed of. The study also assumes 100% recycling of metals at EOL. The study noted that how to allocate the end-of-life impacts of hydropower plants like this one with a 150-year lifetime is still an open question. For this analysis, the deconstruction parts of the inventory were excluded, meaning no modeling of disposal or recycling at EOL. The complete impact of all material inputs is allocated to the power production of the lifetime of this power plant. Thus the impacts of the metal inputs were allocated evenly over the lifetime power production of the power plant. The disposal EOL flows from the study originally modeled under construction were neglected. These flows are marked in yellow in Table 18. One additional material input was neglected in the construction phase, thovex (explosives), as no representative material flow was found in Ecoinvent/Simapro. This material is also marked in yellow in Table 18. The transport relating to both materials and operations is included in the inventories from the hydro LCA study. The Hydro LCA study assumes that the plant's location will be reused for a new hydropower plant after the EOL. Given that assumption, one could argue that the land and water occupation impacts should be allocated over all future power plants. On the other hand, one could argue that it makes more sense to allocate these impacts to the first one because it is the one that causes the occupation from the beginning and because of the long lifetime of 150 years. The latter argument was followed here, allocating all the land and water occupation impacts to this hydro plant.

3.4.3 Nuclear power LCA

The Nuclear power product LCA is based on an inventory from Pomponi and Hart (2021), a study that assesses the environmental impacts of a European pressurized nuclear reactor nuclear power plant. The study is hereby called the nuclear LCA study. The study was chosen for two reasons. It assesses a European nuclear power plant that reasonably represents the Nordics. Secondly, it provides detailed information on its life-cycle Inventory. The study uses three methods, process-based LCA, input-output analysis, and hybrid life cycle assessment. For this analysis, only the process-based LCA scenario of the study is considered. The goal of the study was to provide more insight into the GHG emission intensity of new nuclear reactors, where the previously found range of emissions is very broad. The study considers the construction of a specific nuclear power plant project by EDF Energy in Somerset, England called Hinkley Point C (EDF Energy, 2016). The nuclear power plant consists of two European Pressurized Reactors that will each have a maximum output of 3.2 GW. The study is based on a combination of self-reporting by EDF on the power plant and publicly available information. The scope of the study is a cradle-to-grave perspective, including construction, operation, and End-Of-Life phases. The study highlights the complexity of nuclear plants and their material inputs, therefore choosing the main material inputs for construction as the starting point of the life-cycle inventory. The study extracts a lot of primary data for the inventory from the EPD report on the HPC power plant but also supplements it from other sources to ensure the quality of the data (EDF Energy, 2016). Due to the complexity and range of options in modeling EOL for nuclear power plants, the study models EOL in two scenarios based on suggestions from the literature. The two scenarios model EOL impacts as 35% and 10% of construction impacts, respectively. Using the construction phase to model EOL replicates material inputs well, but is limited in its ability to measure aspects related to handling radioactive waste at EOL. The functional unit of the analysis is "1 kWh of electricity delivered to the grid by the

Description	Scenario A	Scenario B	Scenario C
Capacity (GW)	1.6	1.6	1.6
Capacity factor	74%	84%	92%
Lifetime output (kWh)	8.30E+11	1.41E+12	1.55E+12

Table 4: Nuclear power plant lifetime output scenarios from Pomponi and Hart (2021).

nuclear power plant". The lifetime production of the power plant strongly affects the FU and the environmental impacts. Because of this, the study examines three scenarios for lifetime production, displayed in Table 4. Scenario A is a cautious scenario based on existing facilities, with a 74% capacity factor and a lifetime of 40 years. Scenario B assumes 84% capacity factor and 60 years lifetime. Scenario C is the reactor developers' view, assuming a 92% capacity factor and a lifetime of 60 years. For more in-depth details we refer to the study (Pomponi and Hart, 2021).

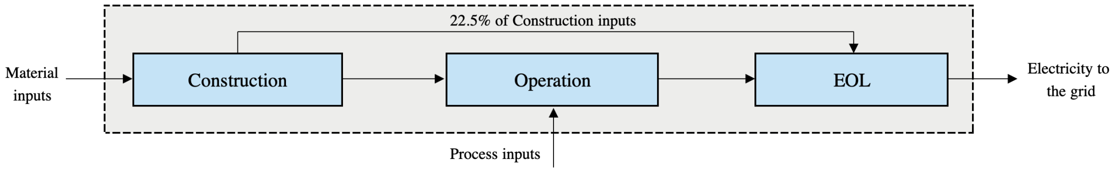

Figure 6: Nuclear power product system drawing

The Nuclear power product LCA in this study follows the nuclear LCA study closely. The goal of the analysis is to quantify the potential environmental impacts of electricity production from a nuclear power plant in the Nordics. The data used for the analysis are the inventories provided by the nuclear LCA study. The FU is the same as in the study. The scope of the analysis is cradle-to-grave, including the same life-cycle phases as the study. Construction and operation phases are modeled directly after the inventories provided by the study. The complete inventories are displayed in Table 12. The EOL inventory is modeled as 22.5% of the construction inventory, taking the average of the two scenarios from the study. For the lifetime production of the nuclear power plant, scenario B from the study is chosen, which is displayed in Table 4. The mapping between material descriptions from the nuclear LCA study and Ecoinvent is shown in the Appendix in Table 20. In this mapping process, certain modeling choices were made. The material inputs were divided by the lifetime production of the power plant to arrive at inputs per kWh. Concrete for the construction phase was converted to a volumetric unit to match the suitable Ecoinvent process, using a density of 2400 kg/m3 based on Neville et al. (1995). The input described as Natural Uranium in the nuclear LCA study is excluded similarly as was done in the study, where the reasoning was that the 'Enriched uranium' process covers this material input. The Electric motors were mapped to Ecoinvent material 'Electric component, active' with an assumed weight of 10 kg per machine. Pipe welding in the construction phase was not included as no suitable matching product was found in Ecoinvent. The excluded input rows are marked yellow in Table 20 showing the mapping from the materials to the Ecoinvent processes.

3.4.4 Natural gas power LCA

The goal of the Natural Gas power product LCA is to evaluate the potential environmental impacts of electricity production from a natural gas power plant in the Nordics. The LCA was modeled from multiple data sources for the different parts of the life-cycle phases. The gas power plant modeled is a conventional Natural Gas Combined Cycle (NGCC) power plant. The analysis takes a cradle-to-gate perspective, excluding EOL. The scope of the study includes natural gas extraction/production, processing construction, and operation. The scope includes material inputs for the mentioned life cycles and direct emissions for the operation phase.

The natural gas production and processing phases were modeled from the inventories of Schori and Frischknecht (2012). The inventory from this study includes the natural gas production platform and processing. Schori and Frischknecht (2012) built the inventory from European data, primarily from Norway, Russia, Germany, and the Netherlands. Of the different natural gas production plants in their study, their offshore production plant was chosen for this analysis. The offshore plant has a service lifetime of 11 years and a total production of 27.7 bcm natural gas, which corresponds to 289935.9 GWh (Education, n.d.). This results in an allocation of 1/2.89E11 of the production plant impact to each kWh produced. The inventory from Schori and Frischknecht (2012) does not include exploration activities or natural gas transportation infrastructure.

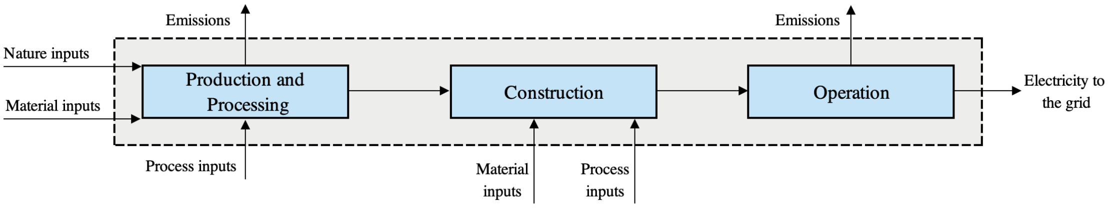

Figure 7: Natural gas power product system drawing

The construction phase of the natural gas power plant was modeled using data from Ecoinvent, specifically the process ”Gas power plant, combined cycle, 400MW”. This process models all the inputs for the construction of one natural gas combined cycle power plant. The power plant construction impacts were allocated per kWh of electricity produced over the lifetime of the power plant. The production and lifetime of the power plant are modeled after data from Singh et al. (2011) on a 400 MW NGCC power plant. The lifetime is 25 years and the full load hours are 8000 h/year, resulting in 400*25*8000 = 4.4E10 kWh yearly electricity production. This value is used to allocate 1/4.4E10 of the construction of the power plant to each produced kWh.

The operation phase models the combustion of natural gas in the NGCC plants using operational emissions data for CO_2, NO_x, and CO. The data is based on Jarre et al. (2016), who assessed the operations of selected Italian NGCC power plants looking both at their energy performance and pollutant emissions. The purpose of the study was to provide operational data on the NGCC-based plants. For this analysis, the emission factor data from the Moncalieri power plants from the year 2014 was used. The study found emission factors to be 412.6 g CO_2/kWh, 0.122 g NO_x/kWh, and 0.160 g CO/kWh (Jarre et al., 2016, p. 312). These emission intensities were used as the direct emissions in the operation phase.

Methane leakage is not included in this analysis based on the reasoning of O’Donoughue et al. (2014), who chose to exclude considerations of methane leakage in their literature review when harmonizing the results from different LCAs. The reasoning was that the methodologies and results for methane leakage vary widely, and how to estimate methane leakage from natural gas infrastructure still remains an open scientific question. Brandt et al. (2016) similarly found a large variance between methane leakage results in the literature and further suggests that the extreme distribution of values for methane leakage mayanalysis’s make them unsuitable for compounding average values.

Description	Value
Capacity	400 GW
Lifetime	25 years
Yearly load hours	8000
Lifetime production	4.4E10 kWh

Table 5: Natural gas power plant basic data from Singh et al. (2011).

The Life-cycle Inventory for the natural gas construction phase is given in Table 14. Inventory for Operation is given in Table 15. No inventory is used for the construction phase, instead an Ecoinvent process was used, "Gas power plant, combined cycle, 400MW".

3.5 LCA data sources

The following section describes the tools and data sources used for LCA in this thesis. It includes some background, the reasons for choosing them, and the data choices made.

3.5.1 Simapro

SimaPro 9.4.0.3 is the LCA program used for the analysis performed in this thesis. Simapro was developed by PRé Sustainability in the 1990s and is today one of the world's leading LCA software solutions (PRé-Sustainability, n.d.). The program is flexible, with a lot of features allowing for a range of applications, such as sustainability reporting using LCA, footprinting, or EPDs. Simapro is a transparent software with detailed information and documentation on all processes. The program comes with multiple impact assessment methods and multiple impact categories for the user to choose from. Simapro was selected due to its relative ease of use, availability of documentation, and completeness in terms of databases.

3.5.2 Ecoinvent

Ecoinvent 3 is used for the background LCI data for this analysis, which comes included in Simapro. Ecoinvent is a not-for-profit organization based in Switzerland with the aim of making high-quality data for sustainability assessment available worldwide (Ecoinvent, n.d.-a). The Ecoinvent Database contains more than 18000 processes covering a range of sectors and geographic locations. The Database strives to be transparent, allowing the user to examine the details of each process to trace impacts along the value-chain and understand the entirety of the process. The Database includes several impact assessment methods and impact categories.

3.5.3 ReCiPe

ReCiPe was chosen as the impact assessment method for this analysis. ReCiPe is a harmonized method for LCA impact assessment across impact categories that quantifies impact on both mid-point and endpoint levels (Goedkoop et al., 2009). The ReCiPe method comes with three different perspectives that group consistent sets of subjective choices. The three perspectives are identified by the names: hierarchist (H), individualist (I), and egalitarian (E). For the LCA in this thesis,

Impact category	**Abbreviation**	**Unit**
Global warming	GW	kg CO_2 eq
Ionizing radiation	IR	kBq Co-60 eq
Fine particulate matter formation	FPMF	kg PM2.5 eq
Terrestrial acidification	TA	kg SO_2 eq
Freshwater eutrophication	FE	kg P eq
Marine eutrophication	ME	kg N eq
Terrestrial ecotoxicity	TE	kg 1,4-DCB
Freshwater ecotoxicity	FEc	kg 1,4-DCB
Marine ecotoxicity	ME	kg 1,4-DCB
Human carcinogenic toxicity	HCT	kg 1,4-DCB
Human non-carcinogenic toxicity	HNCT	kg 1,4-DCB
Land use	LU	m2a crop eq
Mineral resource scarcity	MRS	kg Cu eq
Fossil resource scarcity	FRS	kg oil eq
Water consumption	WC	m^3

Table 6: Impact categories included from the ReCiPe 2016 v1.1 midpoint hierarchist (H) method

the default ReCiPe 2016 v1.1 midpoint method, hierarchist (H) version was chosen (Huijbregts et al., 2016). A range of the impact categories covered by this analysis is given in Table 6.

3.6 Data for comparisons

The RW-LCA company results will be compared to two other data sources to answer the second research question of this thesis. The results will be compared to comparable dimensions within the Net Impact Data provided by Upright. And to the GHG emissions intensities reported by the companies in their proprietary sustainability reporting. In the following two sections, these two datasets are presented, and the methodology behind the Net Impact Data is explained in detail.

3.6.1 Upright Net Impact Data

The primary components of the Upright net impact framework are the macromodel and the company model. The company model uses product information from various financial and non-financial reporting sources to generate product sets. The product sets consist of the revenue weights of the products and services offered by the company and are analogous to the product sets used for RW-LCA in this analysis. For input data, the macromodel uses a database of 200M+ scientific articles as well as statistics from the OECD, World Bank, WHO, and Eurostat. The model consists of three main algorithms. The first algorithm uses a deep neural network to extract causal links between products and impacts. The second algorithm generalizes scientific knowledge by building a hierarchical product taxonomy. This step allows the inclusion of impacts at different product detail levels. A very simple example to illustrate this algorithm is that impacts that relate generally to apples should also apply to green apples. The third algorithm is an allocation of impact across the value-chain following the principle of participating value-add. This allocation method allocates the impacts of product x to its value-chain in proportion to its value-add contribution to product x. Upright uses a top-down approach to allocate impacts across the product taxonomy. Following the three algorithms described above, the macromodel allocates the total global impacts within each category exactly once across all products in the product taxonomy. Using a top-down approach allows Upright to count all impacts exactly once, to avoid the challenge of double-counting inherent in bottom-up approaches like LCA. Upright models Net Impact across 19 impact categories, measuring both positive and negative impacts. For the comparisons in this thesis, only the negative GHG emissions will be examined, as the impact category quite accurately matches the Global Warming impact category in LCA. Upright's Net Impact Data mainly aims to show relative impact scores, quantifying impact per unit of company revenue. Additionally Upright provides the total impact within a year and physical units such as CO_2-eq. for GHG emissions. (Upright Project, n.d.-c)

Upright quantifies the total amount of CO_2-eq. emissions for Statkraft and Vattenfall to be 0.359 Mtonnes and 1.35 Mtonnes, respectively. Dividing these yearly emission figures by each company's total electricity production, we arrive at 5.16 g CO_2-eq. / kWh for Statkraft and 12.17 g CO_2-eq. / kWh for Vattenfall. (Upright Project, n.d.-a

3.6.2 Company sustainability reports

Statkraft and Vattenfall both provide proprietary sustainability reporting. The reports contain environmental, social, and governance assessments with an emphasis on their strategies toward a sustainable future. Both companies have performed LCAs to assess the carbon footprints of their electricity production, which will be used for comparisons with the RW-LCA results.

In Statkraft's report, they place emphasis on their commitment to becoming a leading renewable energy company (Statkraft, 2022). The company reports on GHG emissions, contribution to the Sustainable Development Goals, and management of governance aspects. Statkraft reports following the Global Reporting Initiative Standards, with one of the dimensions assessed being climate change mitigation. The company reported on their Scope 1, 2, and 3 GHG emissions. The reported average carbon intensity of their power production was 21 g/kWh for the year 2021. Additional environmental impacts covered in the report include biodiversity impacts and waste generation.

The headline of Vattenfall's sustainability report is "Fossil-free living within one generation." The company reports on GHG emissions, contribution to the Sustainable development goals, and management of governance aspects (Vattenfall, 2022). Additionally, Vattenfall reports on their Net Impact with data provided by Upright, noting how the Net Impact data "... captures the impact of our business in a more comprehensive way, ... than we could achieve internally". The company reported on their Scope 1, 2, and 3 GHG emissions. In their sustainability report, Vattenfall reports an average carbon intensity of their power production of 81.5 g/kWh for the year 2021. In addition to GHG emissions, the company reports on total NO_x, SO_2, and PM emissions from their operations.

4 Results

This chapter presents the results found in this analysis. The first section summarizes the key findings from the literature review on the limitations of O-LCA and answers the first research question. The second section contains the Life-Cycle Inventories for the four products analyzed. The third section displays the product LCA results and the LCIA of the results, focusing primarily on the global warming impacts. The fourth section presents the RW-LCA company results for the two companies Statkraft and Vattenfall, answering the second research question of this thesis. The company results for the global warming impact category are then presented in comparison to the company report values and Upright's Net Impact Data, answering the first part of the third research question.

4.1 Limitations of Organizational LCA

The frameworks for O-LCA do not allow for comparisons between organizations, which limits the use of O-LCA results beyond the individual organization. This is inherent to the ISO/TS 14072 and the UNEP O-LCA guidance, which are specifically not intended for intra-organizational comparisons (ISO, 2014b; UNEP, 2015). The OEF framework allows for limited comparisons, only between organizations within the same sector (EC, 2021a). Finkbeiner (2014b) and Pedersen and Remmen (2022) highlighted how the PEF/OEF did not achieve their aims to make O-LCAs more comparable using stricter sectorial requirements. Central challenges of O-LCA are highlighted by Martínez-Blanco et al. (2020), many of which relate to difficulties in the Goal and Scope phase. These include choosing system boundaries and choosing the correct subset of the organization for the analysis. Grouping of company activities within direct/indirect and upstream/downstream categories is challenging for activities such as capital investment and other supporting activities. The terminology itself of these two dimensions is a barrier to O-LCA application. Data collection and mapping are challenging for organizations as it requires cooperation with suppliers, partners, and customers. All these challenges have been part of hindering the broader adoption of O-LCA.

4.2 Product Life Cycle Inventories

The complete tables of life-cycle Inventories used for the analysis of the four energy technologies are displayed in the Appendix. Table 9 shows the complete unit inventory for the wind power plant, including energy resources, material inputs, and direct emissions. Table 10 shows the inventory for the construction of the hydropower plant and Table 11 shows the inventory for the operation of the hydropower plant. Table 12 shows the complete inventory for the nuclear power plant, separated into construction and operation inputs. Tables 13, 14, 15, show, respectively, the complete inventories for production, construction, and operation of the natural gas power plant. The material/process descriptions in all the inventory tables represent the materials as given in the original data sources. Tables for the mapping between these materials and the Ecoinvent processes are given for all the inventories in the Appendix in Tables 16, 17, 18, 19, 20, 21. All units in the inventory tables are given on a per kWh basis. The neglected flows are marked as yellow in the mapping tables and excluded from the inventory tables.

4.3 Product Life Cycle Impact Assessment

The complete LCIA profile for the four products is presented in Table 7. The classification and characterization of LCI results within each Impact Category were done in Simapro. Figure 8 displays, in a bar chart, all impact categories of the four LCA results. In this figure, the bars for each impact category are scaled as percentages of the product with the largest impact. This figure allows for visual comparison between products within individual impact categories but not across impact categories, as there is no endpoint weighting. The figure shows significant variations in the sizes of the impacts for the products. For the majority of impact categories, Nuclear power has the largest impact per kWh. For the impact categories Ionizing radiation and Marine eutrophication, the Nuclear power impacts make the impacts of the other products essentially negligible. For the impact category of Land use, wind power has the largest impact. In all impact categories, hydropower was found to have either the lowest or second lowest impact of all the products. For the impact category of global warming, natural gas power has by far the largest impact. The global warming impacts were found to be 5.74, 6.90, 20.8, and 414 g CO_2-eq. for hydropower, wind power, nuclear power, and natural gas power, respectively. As one could expect, the only fossil fuel power source, natural gas, has the largest global warming impacts, almost two orders of magnitude larger than that of hydro- and wind power.

Impact category	**Unit**	**Hydro power**	**Wind power**	**Nuclear power**	**Nat. Gas power**
Global warming	kg CO_2 eq	5,74E-03	6,90E-03	2,08E-02	4,14E-01
Ionizing radiation	kBq Co-60 eq	2,94E-04	1,08E-04	9,24E-01	5,93E-05
Fine particulate matter formation	kg PM2.5 eq	7,16E-06	2,24E-05	5,97E-05	1,91E-05
Terrestrial acidification	kg SO_2 eq	1,57E-05	6,24E-05	9,36E-05	5,62E-05
Freshwater eutrophication	kg P eq	1,86E-06	8,77E-06	1,33E-05	1,26E-06
Marine eutrophication	kg N eq	1,01E-07	2,93E-07	1,66E-05	6,14E-08
Terrestrial ecotoxicity	kg 1,4-DCB	5,25E-02	3,16E-01	5,55E-01	4,08E-02
Freshwater ecotoxicity	kg 1,4-DCB	7,39E-04	5,79E-03	6,01E-03	6,74E-04
Marine ecotoxicity	kg 1,4-DCB	9,47E-04	7,33E-03	7,79E-03	8,58E-04
Human carcinogenic toxicity	kg 1,4-DCB	4,55E-04	7,77E-04	2,68E-03	3,73E-04
Human non-carcinogenic toxicity	kg 1,4-DCB	1,04E-02	7,46E-02	1,75E-01	8,86E-03
Land use	m2a crop eq	1,40E-04	1,63E-03	3,88E-04	6,69E-05
Mineral resource scarcity	kg Cu eq	8,86E-05	2,64E-04	1,06E-03	5,84E-05
Fossil resource scarcity	kg oil eq	7,57E-04	8,32E-04	5,82E-03	4,65E-04
Water consumption	m3	6,44E-05	4,19E-05	2,84E-04	1,04E-05

Table 7: Product LCA results, unit is per kWh as per the FU

4.3.1 Wind power results

The wind power Global Warming LCA results were 6.9 g CO_2-eq./kWh as compared to the LCA result in Vestas' original study of 5.3 g CO_2-eq./kWh. The results are 30.5% larger than the Vestas study, which is larger than expected given the limited changes in the modeling for this analysis. For the wind power LCA, the complete unit LCI from the Vestas study was used without much adjustment. The reason for using the complete inventory was modeling challenges in EOL when recreating the whole system step by step. The complete inventory used likely contributed to the

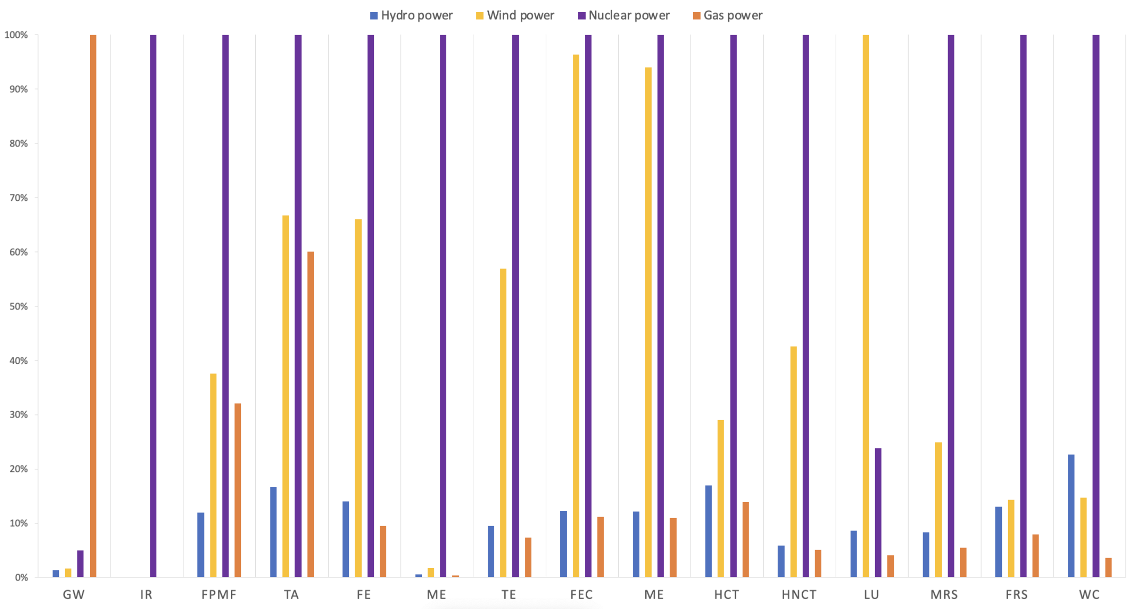

Figure 8: LCA Product results for hydropower, wind power, nuclear power, and natural gas power

relative proximity between the results. There are a few aspects that may explain the differences between the results, such as the different impact assessment methods, the different LCA software, and the input and emission mapping. This analysis used impact assessment based on Ecoinvent and Simapro while the study used CML and the Gabi LCA software. The potential mismatches in the mapping of inputs and emissions between the Vestas descriptions and Ecoinvent processes may have caused parts of the differences. The mapping is provided in the Appendix in Tables 16 and 17. As described in the section on wind power in the literature review, a suggested range of global warming impact intensities found by Dolan and Heath (2012) was 3.0 to 45 g CO_2-eq. / kWh. The LCA results are well within the range, albeit on the lower end. The wind turbines modeled were 3.45 MW which is on the larger side of the global existing wind power turbine size, which generally leads to lower emissions per kWh (IRENA, n.d.-c). Further, the Vestas LCA assumed the highest of their wind production scenario, which makes the denominator of the FU larger than it would be for a lower wind production scenario.

4.3.2 Hydropower results

The hydropower LCA resulted in the lowest overall impacts of the products, with global warming impacts of only 5.74 g CO_2-eq./kWh. The result was only 4.15% higher than the global warming results of the study used for the inventory, at 5.513 g CO_2-eq./kWh. (Flury and Frischknecht, 2012). The close replication of the global warming results is likely due to the highly similar modeling of the inventory. The exclusion of the deconstruction phase likely increases the results in comparison to the hydro LCA study. The input data from the hydro LCA models a reservoir hydropower plant in Switzerland. Most hydropower-related conditions are likely to be similar between Switzerland and the Nordics, given the similar alpine landscape and European context. The study models a reservoir hydro plant. Although the companies both produce different types and sizes of hydropower plants, the majority of their plants are reservoir hydropower plants (Statkraft, 2022; Vattenfall, 2022). Modeling all hydropower of the companies with a large reservoir hydro plant should reduce most impacts per kWh as larger plants are more effective, but also lead to larger area occupation impacts. As mentioned in the Literature review, Gemechu and Kumar (2022) performed a review of LCAs applied to hydropower finding reported life-cycle GHG emissions to be in the range of 1.5 to 3747.8 g CO_2-eq./kWh. Most of the studies reviewed were closer to the range of 0 - 100 g CO_2-eq. / kWh. The results found in this analysis are thus within the range of the literature, albeit on the smaller end of the range.

4.3.3 Nuclear power results

The nuclear power global warming results were 20.8 g CO_2-eq./kWh. The Nuclear power results from the study used for the inventory were 16.531 and 16.825 g CO_2-eq./kWh for the two EOL scenarios of 10% and 35% of construction impacts, respectively. The LCA results in this thesis used the average of the two, 22.5% of construction impacts, as described in the methods section. Accordingly, the results of the analysis are compared to the average of the two results from the study for reasonable comparability, at 16.678 g CO_2-eq./kWh. Compared to this value, the LCA results were 24.7% higher than the study used for the inventory. There are two inherent limitations of the original study worth highlighting. The EOL phase is modeled as a percentage of the construction phase, which is unlikely to provide precisely the same impacts. The EOL phase would include impacts from the processes required to handle nuclear waste, demolition, recycling, and disposal. Simultaneously, the impacts from the input of radioactive isotopes are included in a simplistic manner. The study, and this analysis, count the entire input of enriched uranium allocated over the lifetime of the plants, while in reality, all radioactive materials are likely to be recovered and well handled at EOL. More accurate modeling of EOL was not included in the study, and thus not in this analysis either. The simplistic modeling of radioactive inputs may have contributed to the relatively large nuclear impacts across categories. The mapping choices between input descriptions in the study and processes in Ecoinvent are likely to account for some of the results differences. One of these was the mapping of Electric motors in the study as Electric components in Ecoinvent. Although this was the best available mapping found at the stage of analysis, electric components may have larger impacts than electric motors, per material input. A very limited amount of the differences can be attributed to databases and software, as the study also used Simapro and Ecoinvent. Even when the study used the same software and database, differences remained, pointing to the difficulty of reproducing LCA results. The main limitation is the missing amount of information about the modeling and the inventory. Studies for publication need to limit their comprehensiveness so they do not elaborate on every detail of the modeling or provide pages upon pages of detailed inventories. Ranges for GHG emissions of nuclear power found in the literature were described in the literature review. Lenzen (2008) founs the range to be 10 to 130 g CO_2-eq./kWh while Warner and Heath (2012) found the range to be 3.8 to 140 g CO_2-eq./kWh. The results of 20.8 g CO_2-eq./kWh fall well within this range, and is very close to the mean of 20 g CO_2-eq./kWh reported by Warner and Heath (2012).

4.3.4 Natural gas results

The natural gas global warming results of this analysis were 414 g CO_2-eq./kWh. O'Donoughue et al. (2014) performed a literature review of NGCC plants, finding the range of global warming impacts to be 420-480 gCO_2/kWh. Thus the results of this analysis were just below the range of the literature review but still in its vicinity. The natural gas LCA was modeled based on different studies for each life cycle. The operations phase was modeled based on direct emission values instead of a more complete operation inventory. This modeling choice was made because the operational direct emissions from natural gas power are known to dominate the impacts (O'Donoughue et al., 2014). The operational CO_2 emissions used were 412 g CO_2-eq./kWh based on Jarre et al. (2016). The different sources for the different life-cycle phases may contribute to spreading out the accuracy of the results, relying on different modeling choices and data sources. Neglecting methane leakage is a very likely cause of underestimating the true impacts. However, methane leakage was also neglected by the literature review and does therefore not account for the results falling outside of the emissions range reported by the literature review. A likely reason for falling outside the range is the fact that the operational emissions data was taken from a single LCA, modeling a specific plant (Jarre et al., 2016). This makes the operational emissions vulnerable to the specifics of that one plant and the choices made in their LCA. The EOL phase was not included in this analysis because few useful sources that could be used in conjunction with the other data sources were found. It is clear from the literature that the operational aspects far outweigh all other phases for natural gas electricity production (O'Donoughue et al., 2014). Therefore the neglecting of EOL is likely to be a small error, as its impacts would be dwarfed by the operation phase. A more complete operational inventory including a broader range of emissions may have provided more accurate results, particularly for other impact categories than global warming. Examples include toxic chemicals, PM, SO_2, and potentially other harmful pollutants, which may have contributed to larger impacts across other impact categories. However, the operational emissions relating to Global Warming are likely well covered, as they are dominated by CO_2 emissions.

4.4 RW-LCA company results

Impact category	**Unit**	**Statkraft**	**Vattenfall**
Global warming	kg CO_2 eq	2,17E-02	7,92E-02
Ionizing radiation	kBq Co-60 eq	2,74E-04	3,37E-01
Fine particulate matter formation	kg PM2.5 eq	8,48E-06	2,98E-05
Terrestrial acidification	kg SO_2 eq	1,99E-05	5,55E-05
Freshwater eutrophication	kg P eq	2,23E-06	6,63E-06
Marine eutrophication	kg N eq	1,10E-07	6,12E-06
Terrestrial ecotoxicity	kg 1,4-DCB	6,68E-02	2,60E-01
Freshwater ecotoxicity	kg 1,4-DCB	1,02E-03	3,16E-03
Marine ecotoxicity	kg 1,4-DCB	1,30E-03	4,07E-03
Human carcinogenic toxicity	kg 1,4-DCB	4,70E-04	1,28E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	1,39E-02	7,67E-02
Land use	m2a crop eq	2,21E-04	3,68E-04
Mineral resource scarcity	kg Cu eq	9,72E-05	4,55E-04
Fossil resource scarcity	kg oil eq	7,50E-04	2,56E-03
Water consumption	m3	6,10E-05	1,33E-04

Table 8: RW-LCA results for Statkraft and Vattenfall

The RW-LCA results unmistakably show that the impacts of Vattenfall are significantly larger than those of Statkraft. The complete results for all impact categories for Statkraft and Vattenfall are given in Table 8 and visualized in Figure 9. All impact categories were dominated by Vattenfall, with more than twice the impacts of Statkraft, for all impact categories except for Land use. The source of the differences in results is the different compositions of the product sets for the companies. Figure 10 and Figure 11 shows how much responsibility for the impacts belongs to each product for both companies. The figure shows that Hydropower dominates the bulk of impact categories for Statkraft, accounting for more than 50% of impacts for all categories except

Global Warming where Natural gas contributes more. Wind power is responsible for parts of the impacts, most notably over 30% of Land use impacts, and significant contributions to ecotoxicity impacts, acidification, and eutrophication. In addition to Global warming impacts, nuclear power contributes approximately 9% of Fine Particulate matter formation impacts. Simultaneously, for Vattenfall nuclear power is causing most of the impacts in most impact categories. In categories such as Ionizing radiation, and Marine eutrophication almost the entire company impacts come from nuclear power. For most other impact categories wind and hydro together make up only around 10-20% of the company impacts. For Land use impacts, wind power contributes the most with 45% of impacts. Similarly to Statkraft, natural gas dominates the Global Warming impact category.

The scope for the comparisons of the company results will be limited to the Global Warming impact category, thus we zoom in on the results of this impact category. For Statkraft and Vattenfall the global warming impacts are 21.7 and 79.2 g CO_2-eq./kWh. The approximately four times larger Global Warming impacts of Vattenfall, as compared to Statkraft, is due to the much larger share of natural gas power in the company's product set. Natural gas power production dominates the Global Warming impacts for both companies, accounting for 74.2% and 86.9% of the impacts, for Statkraft and Vattenfall respectively. Symmetrically to the impacts, Vattenfall's revenue share from natural gas is approximately four times that of Statkraft, at 16.6% as compared to 3.9%, further supporting the relation between the natural gas revenue share and the company's Global Warming impacts.

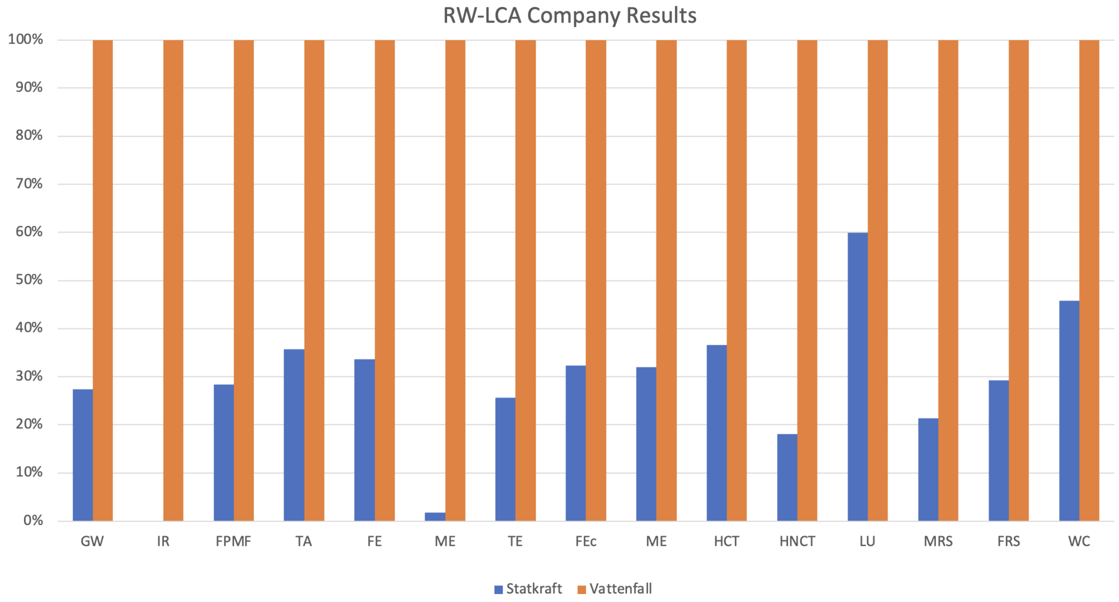

Figure 9: Normalized RW-LCA results for Statkraft and Vattenfall

4.5 Comparisons to Net Impact Data and company reports

Figure 12 shows the company Global Warming Impacts for Statkraft and Vattenfall next to the values from the company reports and the Net Impact Data. The RW-LCA Global Warming results for both companies are almost identical to the company reports, finding the Impacts of Statkraft to be about 25 % of that of Vattenfall. The company sustainability reports contained carbon intensities of 21 and 81.5 g CO_2-eq./kWh for Statkraft and Vattenfall, respectively, as

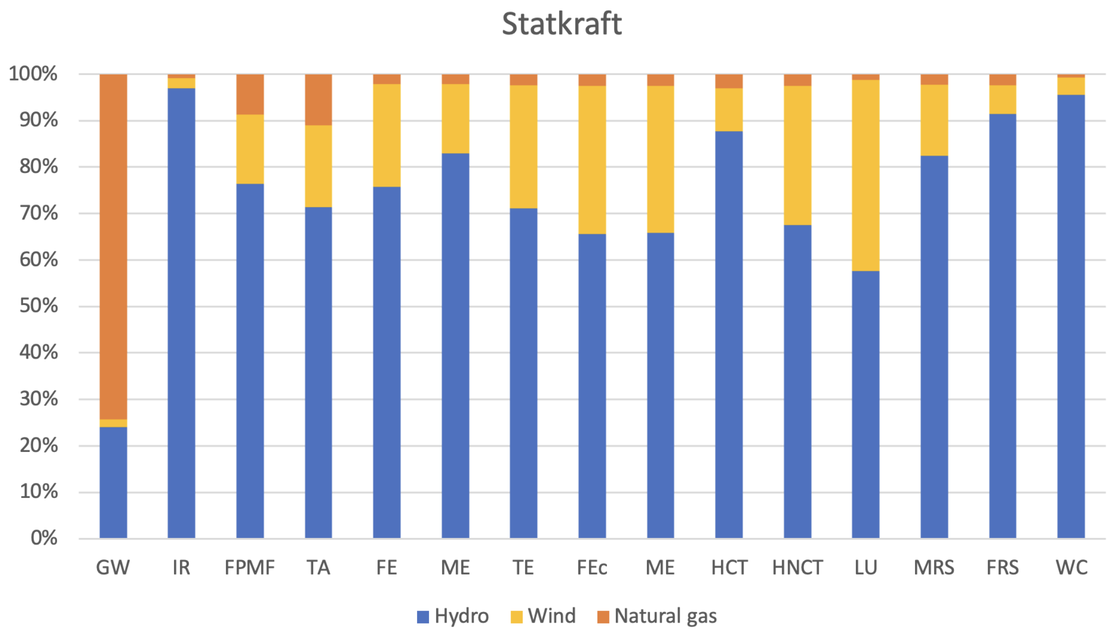

Figure 10: Statkraft RW-LCA impacts by product

compared to the RW-LCA Global Warming results of 21.7 and 79.2 g CO_2-eq./kWh. The Net Impact Data showed much lower values for the Global Warming impacts for both companies, at 5 and 12 g CO_2-eq./kWh for Statkraft and Vattenfall, respectively. However, the relative sizes of the company results indicated a similar comparative conclusion between the companies. The Net Impact scores for Statkraft were approximately 33% of that of Vattenfall.

There is a strong consensus between the three data sources that Vattenfall's global warming impacts are multiple times that of Statkraft. The results are robust, as the difference in impact between the companies was so large, and because the results so closely replicate the proprietary reports by the companies. The Net Impact Data for the companies showed much lower values, indicating either limitations in the data or fundamental differences in what is measured. The overall conclusion on the difference in impacts between the companies was reflected in the Net Impact Data, with much larger impacts for Vattenfall than for Statkraft. The majority of impacts for both companies come from their natural gas product. The larger share of natural gas in Vattenfall's product set is the source of the company's larger impacts.

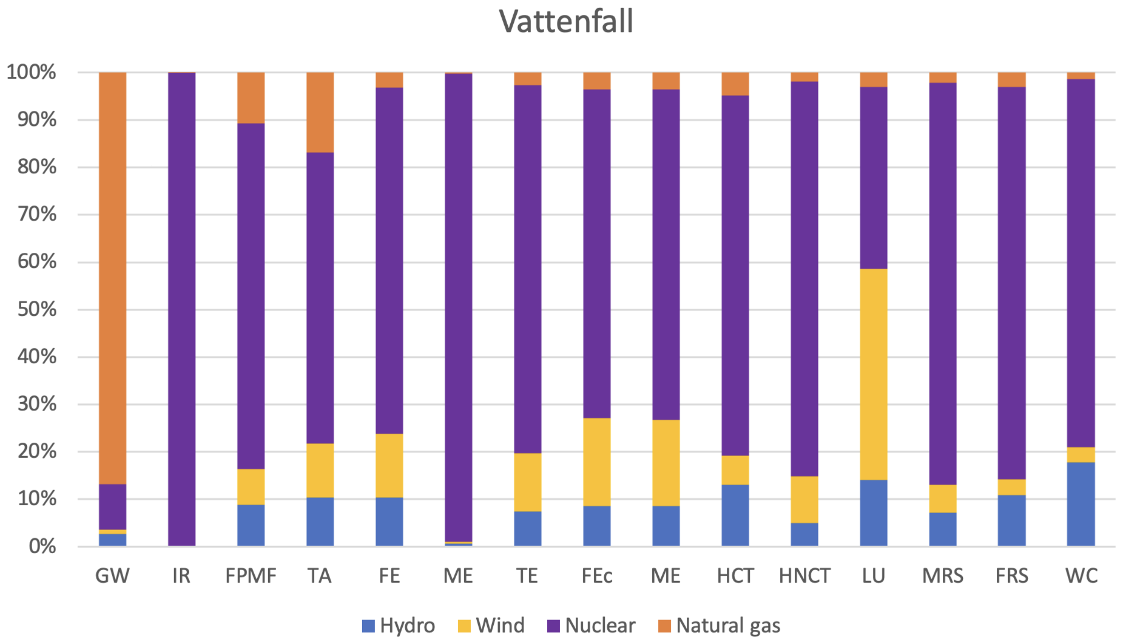

Figure 11: Vattenfall RW-LCA impacts by product

5 Discussion

This chapter discusses the findings from the results and answers the remaining research questions. The first section discusses the Product LCA results and their limitations. The second section discusses the company RW-LCA results and compares them to the Net Impact data and the company reports to answer research question three. The third section discusses the method of RW-LCA, exploring to what degree it is a valid proxy for an organization's impacts based on this analysis and what challenges the method solves, to answer the final two research questions. The fourth section details the limitations of this analysis. The fifth section suggests directions for future work.

5.1 Reproducing LCAs from published studies

Choosing to reproduce LCA results was done to reduce the time and resource requirement of the analysis to make it feasible within the scope of this thesis. Performing LCAs based on secondary data from published studies carries some limitations, both in terms of replicating the original studies and their representativeness of the companies' impacts. The product LCAs form the foundation for the method of RW-LCA, thus their validity has a strong effect on the RW-LCA results.

5.1.1 Reproduction results, usefulness, and limitations

The Product LCA results for Global Warming replicated to a reasonably high degree the results of the studies they were based on. The wind power results were 30.5% larger, the hydropower results were 4.15% higher and the nuclear power results were 24.7% higher. The natural gas operations life-cycle was modeled using emission intensities, which led to the results almost exactly replicating the operational emissions, being only about 0.5% higher. All the product results estimated higher

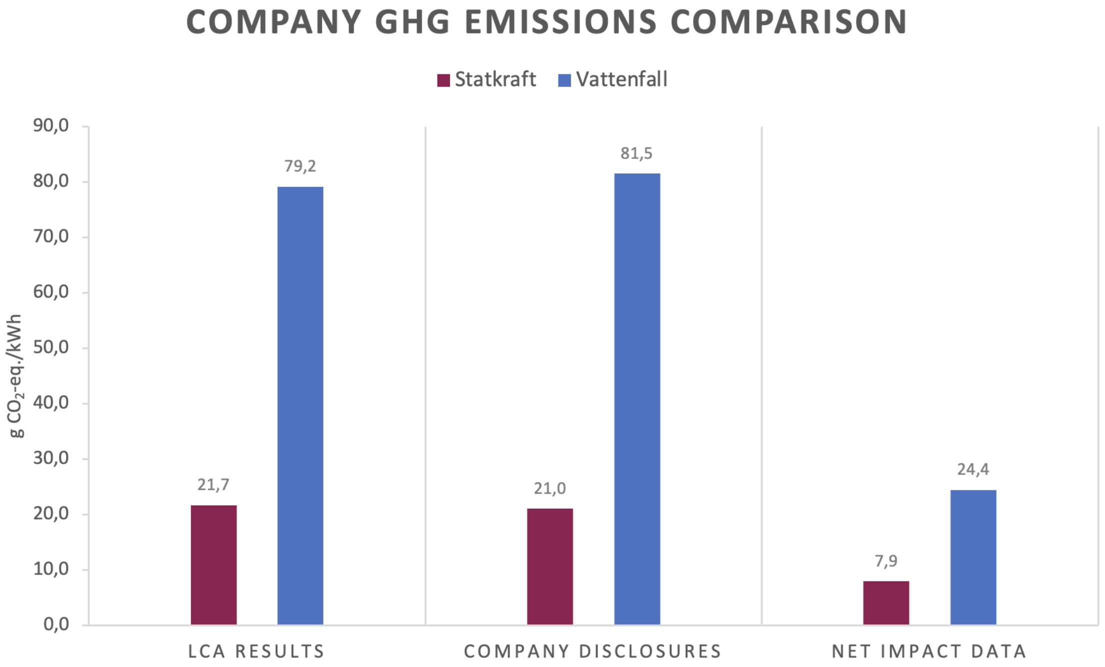

Figure 12: Company results - GHG emissions per kWh for all three sources

impacts than the original study, with the caveat that the natural gas result is compared to operational impacts. The most relevant aspects of each product which may cause the discrepancies were interpreted in the results. The most surprising discrepancy was that of the wind power results, as it was the product with the least modeling changes in this analysis. The hydropower results had very low differences, likely a result of accurate modeling of multiple life-cycle phases in accordance with the original study. The nuclear power differences are perhaps best explained by differences in the software used and databases, while it had some limitations in the EOL modeling stemming from the original study. The natural gas modeling used multiple studies as inputs, thus the comparisons to the studies are less straightforward. The operational CO_2 emissions certainly dominate the Global Warming impacts, thus the results are almost identical to the original study. Its main limitation was the incompleteness of the operational emissions and the exclusion of methane leakage effects.

In this analysis, all the product LCA results were recreated reasonably well, but with varying degrees of precision. Generally, it is challenging to reproduce LCA results from published studies. Few LCA studies actually provide complete LCI data and document all their modeling choices in detail, making it difficult to reproduce results. High-quality studies are transparent and elaborate in the description of their methodologies, but they are usually limited in their comprehensiveness by the publishing format of their publication. Tables upon tables of data are useful for recreating the LCA but are not well-suited for journal articles. The availability of transparent inventory data was one important criterion in the selection of studies, which facilitated the recreation of the LCA results. Some input data or modeling aspects may not be fully disclosed in the studies, and the risk of human error exists in the extraction and mapping of the large inventory tables. Even for these electricity production technologies which have an abundance of literature on their technology and impacts, it proved challenging to reproduce all the LCA results with a high level of accuracy. The results do show a reasonable replication of the results, with the largest difference being 30.5% for wind power, suggesting it is feasible to reproduce LCA results. On the other hand, as the spread in differences can not reliably be attributed to changed modeling choices, it challenges the consistency of reproducing LCA results. The fact that all the products assessed were energy-producing technologies made the reproduction of the results more manageable. The technologies are relatively easy to understand and thus contain low amounts of complexity in setting the scope and boundaries. The main, and perhaps only direct advantage of reproducing LCA results is the lower requirements of time and data collection as well as perhaps opening for a slightly more general way of modeling the impact of products.

Martínez-Blanco et al. (2020) suggested that the availability of LCI databases also expanding to goods and services would be beneficial for future organizational impact assessment to cover issues relating to data collection from outside the organization. Such databases could include LCA results for common products and limit the number of individual product assessments required by organizations, given that the products in the database match well the products of the company. To a degree, efforts of this kind inspired the PEF/OEF frameworks, which provided stricter guidelines for LCA within sectors and even provided benchmarking impacts for the product categories. However, as found in the literature review, PEF/OEF has not seen much adoption and has been criticized for not achieving its aim for increased comparability (Finkbeiner, 2014b; Pedersen and Remmen, 2022). Future efforts toward more standardized LCI databases also extending to goods and services may still prove useful if these challenges are overcome.

5.1.2 Representativeness of the company products

As the input data from the collected studies did not model the company products specifically, the results were likely to vary to a degree from their true impacts. Still, given the care taken in reasonable modeling choices, the results should be fair representations of the impacts of the companies products. Energy-producing technologies are fairly simple with an established body of literature on the technologies and their impacts. Thus, energy products are more reasonable to assess generally than more complex products, suggesting both that the re-creation of LCAs based on published work may be accurate and the products modeled generally are fair proxies of the companies' products. To the degree it was possible, the products were modeled with European data and assumptions in order best to replicate the impacts of the predominantly Nordics-based companies. All the studies used model European conditions. Some differences exist between Europe and the Nordics, but there are significant overlaps in material value-chain and energy markets. It is reasonable to mostly expect European modeling to be quite representative of the Nordics. One exception is the electricity mix, which is generally more fossil dominant in Europe than in the Nordics.

5.2 Company RW-LCA results

This section discusses the results from the comparisons between the RW-LCA results, the company reports, and the Net Impact Data, exploring potential insights from the results in relation to the two other impact data sources. The feasibility of comparisons, the differences between the data types, and their limitations are explored.

5.2.1 Comparisons between companies and their benefits

The apparent need for comparable organizational impact data was established in the introduction, and the fact that O-LCA does not allow for comparisons between organizations was established in the literature review (ISO, 2014b; UNEP, 2015). P-LCAs allow for comparisons between products of similar function, while Net Impact Data allows completely for comparisons between organizations (ISO, 2006b; Upright Project, n.d.-c). The central reason the O-LCA frameworks do not allow for comparisons is the difference in product offering and organizational boundaries between organizations, hindering the comparison of similar units that serve the same function. The RW-LCA results are not an O-LCA, but rather weighted P-LCA results of similar products. Thus there is no need to follow the restrictions of comparison from O-LCA for these results, instead the P-LCA restrictions on comparisons are sufficient. All the products in the companies' offering are electricity production products with matching FUs which makes the organizational boundaries and the product offering for the two companies extremely similar. These factors make comparisons between these particular companies very reasonable.

The benefits of organizational impact data which allows for comparisons between organizations are well described by Upright in their reasoning for creating Net Impact Data. The purpose of their Net Impact Data is to *"... allow individuals to understand what ends their decisions are actually promoting and to make sure that they are in line with their intention"* (Upright Project, n.d.-c). Individuals may include students, consumers, leaders, asset managers, or ministers. Analogously, placing the RW-LCA results for Statkraft and Vattenfall in the hands of individuals could create benefits for society due to the massive differences in impact results between the companies. The company results show that for two companies with very similar product offerings, with overlapping FUs for all their products. There are many companies for which a certain few products dominate the impacts, like natural gas for the two companies assessed, where providing RW-LCA results could instantly guide better decision-making. For companies with only one overlapping product, comparing RW-LCA for the entire company could provide valuable decision support. Based on this analysis, it would, for example, be better to buy wind power from Statkraft than from Vattenfall because then one would be supporting a company with lower overall impacts due to the large impacts of the other products than the overlapping one. This could be useful even if the rest of the products, apart from wind power, did not overlap. Further, comparing RW-LCA results between organizations with very different product sets may not yield great comparative insights. For conventional consumer products, it seems unproblematic to apply Upright's thinking and allow for comparisons of RW-LCA results between companies. Similarly, companies within the same sector would be reasonable to compare. However, for companies with intricate business-to-business products, or products that overlap different value-chains in complex ways, the comparisons become more difficult.

5.2.2 Comparisons with the company reports

The RW-LCA company Global Warming results replicated both company report GHG values almost exactly, as shown in Figure 12. The success in recreating similar values to those found in the reports points to the validity of using generic product information for assessing the life-cycle company Global Warming Potential for these companies. The revenue weighting of products done by the companies in their reports is the same as used in this analysis, as it is based on the yearly electricity production from the same reports (Statkraft, 2022; Vattenfall, 2022). With the same revenue shares as the reports, the individual product LCA results in this analysis are likely to be close to the product LCA results of each company within their reports. Further, the similarity between the results and the values from the reports suggests that the impacts of each type of product were very similar between the two companies. This means there were few differences in the impact of the same products made by either Statkraft or Vattenfall. This further supports the validity of recreating product LCA results from general secondary data.

Reasons for the similarity of the results include that both the LCA results and the company report results are based on product LCA. Inter-organizational comparisons are reasonable and useful between LCAs with the same functional units and similar geography. The company LCAs model the specifics of the products for each company, which both have the majority of their operations in the Nordics. The product LCAs are all primarily based on European input data and assumptions. Further, all the products of the companies are electricity production products. These are well-known technologies with many published studies and well-understood impacts. The nature of the products makes a general assessment of their impacts likely to replicate a specific assessment using primary data such as that of the company reports. Even though, in this case, a generic analysis of the companies' products corresponded well to the companies' proprietary reporting, it is far-fetched to claim from this one case that this would always be the case. It may also be true for other companies with products that are well suited for being assessed in a general way. But for many companies, their products are complex services, new products, or little-known products, for which it would likely be much more difficult to reproduce a general LCA and arrive at comparable results.

5.2.3 Comparisons with the Upright Net Impact Data

The GHG emissions Net Impact Data for Vattenfall and Statkraft show significantly lower impacts than the RW-LCA results and the company reports. For Vattenfall, the Net Impact Data score is 30.8% of the RW-LCA results, and for Statkraft it is 36.4%. As the Net Impact Data differs significantly from the results derived from the two LCA-based methods, it suggests that there may be fundamental differences or deficiencies in the Upright results. Most of the difference is likely caused by the fundamental difference in methodologies between LCA and Net Impact Data. The similarity between the RW-LCA and the company reports, which are both based on LCA, supports this claim. Other potential causes for the differences include uncertainty related to the top-down nature of Net Impact Data, the different product sets used, and the undisclosed inner workings of the NLP driving Upright's model. Additionally, Upright covers all products and services produced by the private sector, implicating a lower level of detail in analyzing each individual product.

The difference in methodology between Net Impact Data and LCA is likely the main contributor to the differences in the results. As described in the Methods section, the Upright Net Impact Data is based on a top-down approach, in contrast to LCA, which is a bottom-up approach. LCA starts from the viewpoint of a single product system defined by the functional unit, including all upstream inputs in terms of materials, energy, transport, and infrastructure. When assessing two different products with LCA, the same piece of infrastructure or transportation may be counted for both products. Performing and comparing LCAs of products at different life-cycle stages would lead to double-counting. For example, in this analysis, if LCAs were performed on both a wind turbine and the wind power plant (as assessed), there would be significant amounts of overlap between the two LCAs. If an LCA is performed for all products in the economy, similarly to the Upright product taxonomy, the sum of all the impacts would be larger than global emissions due to double-counting across products (Lenzen, 2008). Net Impact Data, on the other hand, considers the impact of a product in a different manner than LCA. The Net Impact Data methodology counts global GHG emission impacts exactly once and allocates them across all products and services. Upright's product taxonomy and value-chain allocation model allocate the impacts up and down the value-chain according to the principle of participating value-add (Upright Project, n.d.-c). Thus products for both a wind turbine and a wind power plant can exist in their model without issues of double-counting. The Global Warming Net Impact Data for all products would sum up exactly to total global emissions. The allocation of impacts across all products in the Upright taxonomy results in significantly lower impacts when examining a single product compared to a bottom-up LCA assessment of the same product.

Although Upright's methodology is described in a detailed fashion in the Upright Knowledge base, parts of which have been summarized in the methods of this thesis, there are still some parts of the Net Impact methodology that are not fully disclosed. The fact that there is NLP at the core of Upright's data methodology sets boundaries for the transparency of the method, as all aspects of machine-learning processes can not meaningfully be explained in more detail. (Upright Project, n.d.-c).

The top-down nature of the Net Impact data makes results more uncertain, as more aggregate data and macro-level assumptions are utilized. Correct value-chain relations become highly important for the accuracy of Upright's model in allocating impacts across their product taxonomy. Similar challenges are found with IO-based assessments. The top-down nature of IO allows accounting on a macro level without double-counting for a sector, industry, or even a country. However, inherent to IO is uncertainty due to its linear nature and a large amount of aggregation within sectors (Lenzen et al., 2010; Minx et al., 2009). The Upright database covers all products and services in the private sector, leading to less accurate modeling for each product than LCA.

Another potential source for the differences in results is the different product sets utilized by Upright. For RW-LCA, the product sets include only the products according to the yearly electricity production, subsequently quantified by the functional units of 1 kWh produced per product. Upright's Net Impact Data does not use the FU as the vantage point of impact. Thus, the product sets have to be different to model the complete life-cycle of the products. Upright's product taxonomy is highly granular, including more than 100 000 specialized products. Upright's product sets for the companies include products such as 'Electricity produced with hydropower' and 'Construction of hydropower plants.' In contrast, these two products would both be encapsulated within the FU in LCA. The revenue weights between the different products in Upright's product sets are similarly based on collected financial disclosures from the companies (Statkraft, 2022; Vattenfall, 2022). Upright's product sets are built to represent the product offering of the companies and match the granularity of Upright's product taxonomy. Although the product sets are not identical for the two methods, the Net Impact product set represents the most similar starting point possible for comparing the two methods. Nevertheless, the differences in product sets may contribute to the difference between the results. (Upright Project, n.d.-c)

5.3 Method of RW-LCA as a Proxy for an Organization's Impact

The purpose of applying the RW-LCA method to companies was to explore whether the revenue-weighted impacts of the products offered by a company are a good proxy for the impact of the entire company. For companies such as Statkraft and Vattenfall that have energy production as their primary product offering, the impacts of supplemental organizational activities are likely minor in comparison to the impact of the products due to the relatively large impacts of energy production technologies (Dolan and Heath, 2012; Gemechu and Kumar, 2022; O'Donoughue et al., 2014; Warner and Heath, 2012). There are indeed many other companies where this is the case, and the exclusion of supplemental activities has little effect on the overall organizational impacts. Simultaneously, there are other companies for which the impacts of the supplemental activities are significant and maybe even dominate the organizational impacts. Software companies and service companies are good examples of this, as their products have minimal impacts, and their supplemental activities, therefore, account for a more significant part of the organizational impacts.

The RW-LCA method uses revenue-weighted product sets as the vantage point for organizational impact. Relating impact precisely to revenue has some implications on the results. It allows for quantifying impact per dollar of revenue, which then also provides impact per yearly revenue metrics. Quantifying an annual production volume and unit is analogous to the Reporting Unit utilized in O-LCA (ISO, 2014b; UNEP, 2015) For the companies in this analysis, annual energy production was used with the assumption of being equivalent with revenue due to the essentially equal pricing of electricity between energy sources. Measuring organizational impact intensity per unit of revenue allows the pricing of products to affect impact results. Two products with similar purposes and impacts with different pricing would allocate different impacts to their respective organizations. The more expensive product would have lower impacts than the less expensive one. The benefit of using revenue over, e.g., product units, is the comparability between products of different scales and resource intensities. The effects of this aspect are limited in this thesis, as the kWh weighting is equivalent to revenue weighting.

The RW-LCA methods solve the central challenges from O-LCA relating to complexities in the Goal and Scope phase related to setting organizational boundaries. The solution is the exclusion of supplemental activities, which does create the risk of underestimating the impacts. Although the exclusion of supplemental activities solves the challenges, it does not provide any new solutions on how to deal with or assess the impacts of these supplemental activities. The question of what are the impacts of the excluded supplemental activities still remains. Another benefit of the method is the possibility to compare different organizations, with the caveat that P-LCA is suggested only to be compared between similar products. RW-LCA does not solve the challenges of O-LCA related to complex data collection from suppliers and partners unless performed using secondary data. The recreation of LCA results based on secondary data in this analysis provided results that were very near the values in the company reports. If this is the case also for other products, one could explore creating general LCI databases for common products to reduce the time and effort required for the assessment. Challenges relating to double-counting still remain both within RW-LCA and O-LCA, both on a product and an organizational level.

5.4 Limitations

The first clear limitation of the results and findings from this analysis is that all the product LCAs are based on secondary data sources and not on primary data from the companies. The quality of LCAs is generally higher with collected primary data from companies, resulting in more accurate modeling of the exact products to better reflect the impacts of the companies. However, given the similarity between the RW-LCA results and the company reports, this limitation seems unlikely to have played a significant role in this analysis. A second limitation is how the comparisons between data results only examined global warming impacts. Although arguably one of the most critical impact categories, the focus on only a single impact category neglects a lot of potential impacts and may lead to problem shifting. The choice was made because only Global Warming impacts were meaningfully available for all three datasets and because comparisons across different impact categories would introduce additional layers of subjectivity. The simplification to a single impact category for comparability, as performed in this thesis in a way follows the overall development to do the same within corporate sustainability reporting. Another narrowing limitation is the selection of companies. Statkraft and Vattenfall are only two companies out of all that one could examine, providing only two cases for analysis to investigate the more general questions about organizational impact explored in this thesis. A final limitation is that no sensitivity analysis was performed on the results because it was not feasible within the scope and time frame of this thesis. A sensitivity analysis could have aided further exploration of how the modeling choices affect the LCA results and revealed more about the most uncertain aspects of the analysis.

5.5 Further work

Further work could assess the impact of the supplemental activities of organizations that were excluded in the RW-LCA method of this analysis. An in-depth analysis comparing O-LCA results to RW-LCA results could provide additional insight into whether the RW-LCA method is an accurate proxy for organizational impacts. In-depth analysis of single companies as well as large-scale analysis of big groups of companies could be insightful. It would also be beneficial for future work to include multiple impact categories to ensure a complete understanding of environmental impacts and avoid problem shifting. The development of more product and services level LCI databases could facilitate the broader application of LCA for organizations and limit time and resource investments.

Further investigations into ways to make O-LCA more broadly adopted could be worthwhile. Building on LCA is a strength of O-LCA, but the challenges relating to organizational scope and boundaries remain. Other simplifications could be explored, or perhaps stricter sectorial requirements like the PEF/OEF attempted.

The difference in methodologies between the RW-LCA company results and the Upright Net Impact Data resulted in significant differences between the two results. More comprehensive comparisons of Net Impact Data to LCA results could shed more light on the differences, both on a product and an organizational level. Beyond global warming impacts, Net Impact Data also provides a range of other impact categories with both positive and negative impacts that would be interesting to compare with LCA results. Many of the aspects within Upright's methodology relate to LCA and other frameworks, such as IOA, which invites other comparative assessments. Upright's open-access platform with 10000+ companies could provide opportunities for bulk comparisons of organizational impact data.

6 Conclusion

Comparable organizational impact data that is accurate and manageable to compute is urgently needed for organizations to understand and mitigate their impact. It is crucial for organizations to be able to measure and manage their impact in order to satisfy stakeholders, fulfill demands of regulation and make voluntary efforts. Multiple frameworks for reporting on the environmental performance of organizations exist such as EMS, CSR, and EPDs. The existing frameworks cover a limited amount of aspects and are not meaningfully comparable between organizations. Organizational LCA has emerged, leveraging the strengths of LCA on product systems to also extend to organizations. The three most prominent frameworks for O-LCA, the ISO/TS 14072, the UNEP O-LCA guidance, and the OEF do not allow for comparisons between organizations, which limits the use of O-LCA results beyond intra-organizational information and decision support. The PEF/OEF framework allows for limited comparisons between organizations within the same sector but has been criticized for not successfully implementing stricter requirements to strengthen the quality of comparisons (Finkbeiner, 2014b; Pedersen and Remmen, 2022). Central challenges of O-

LCA are highlighted by Martínez-Blanco et al. (2020), most of which relate to difficulties in the Goal and Scope phase. These include the complexities of choosing the organizational system boundaries as well as grouping activities within the categories of direct/indirect and upstream/downstream, and data collection.

The challenges of O-LCA are addressed in this thesis by simplifying the assessment by excluding the supplemental activities that are the source of complexity leading to the majority of the challenges. The central hypothesis of this approach is that the supplemental activities are negligible compared to the impacts of the core product activities of the organization. This way of thinking is the vantage point for the Net Impact Data of the Upright Project, which has inspired the method used in this thesis. With a foundation in the limitations of O-LCA and inspiration from the Upright product sets, the method of Revenue Weighted LCA was performed on two chosen companies, Statkraft and Vattenfall. The method is LCA-based, assessing the products offered by the companies and arriving at the organizational impact by aggregating the P-LCA results using revenue.

The Product LCA results based on published studies found global warming impacts to be within the ranges found in the literature for wind power, hydropower, and nuclear power. The natural gas results showed slightly lower global warming results than the range found in the literature. Further, the product LCA results for impact categories such as Ionizing radiation and Marine eutrophication showed the nuclear power results as the largest. For the impact category of Land use, wind power showed the largest impact. In all impact categories, hydropower was found to have either the lowest or second lowest impact of all the products. For the impact category of global warming, natural gas power has by far the largest impact. The global warming impacts were found to be 5.74, 6.90, 20.8, and 414 g CO_2-eq. for hydropower, wind power, nuclear power, and natural gas power, respectively. Expectedly, the fossil fuel-based electricity source had significantly larger global warming impacts. Reproducing LCA results based on published LCAs is generally difficult due to the limited availability of complete and transparent life cycle inventories, but in this thesis, the global warming results of the original studies were reproduced with fair preciseness. Using secondary data for LCA allowed for more effective calculations while introducing additional uncertainty in the quality and representativeness of the data. As one example of a successful recreation of LCA results the findings do not negate the difficulties of LCA recreation, but point along in the direction as suggested for example by Martínez-Blanco et al. (2020) to develop more comprehensive LCI databases that extend also to goods and services.

The RW-LCA company results unmistakably show that Vattenfall has a larger impact than Statkraft per kWh (and per revenue) for all impact categories. The RW-LCA global warming results for Vattenfall were 79.2 g CO_2-eq./kWh, approximately four times larger than those of Statkraft at 21.7 g CO_2-eq./kWh. The method clearly displays the share of impacts stemming from each product. Natural gas production was clearly the largest source of global warming impacts for both companies. For Statkraft hydropower was responsible for the majority of other impacts across most impact categories, while for Vattenfall nuclear power dominated most of the impact categories.

The RW-LCA global warming results aligned closely with the company reports, displaying an accurate replication of the input LCAs and the product LCA's representativeness of company products. The similarity of the results strengthens the validity of outside-in estimation of a company's impacts with LCA using secondary data as input. The GHG emissions Net Impact Data for Vattenfall and Statkraft were significantly lower than the RW-LCA results and the company report results. As both the company results and the company reports were based on LCA and produced similar results, there may be deficiencies in the Net Impact Data, most of which are likely caused by the differences in methodology. The Net Impact Data is a top-down approach and allocates each impact exactly once across all products in the Upright product taxonomy, which leads to lower impacts on a product level as it avoids double-counting aspects. Further differences may be caused by the fact that Upright uses different product sets, to cover the complete life cycle of the products without having the FU as the vantage point for the analysis. Undisclosed aspects of the NLP at the core of Upright's model may also contribute to the differences.

The RW-LCA as a simplification of O-LCA solves the challenges relating to complex organizational reporting units and system boundaries. As the method is based on P-LCA it allows for inter-organizational comparisons for organizations with similar products. Further, it may also be reasonable to compare RW-LCA results between organizations with only a single similar overlapping product. However, the solution is the exclusion of supplemental activities, which is only reasonable if the impacts of supplemental activities are negligible. Few conclusive remarks can be made on the degree to which RW-LCA is a good proxy for organizational impact, beyond organizations with similar product offerings. Although generally the exclusion of supplemental activities makes comparisons between organizations more reasonable.

Future research opportunities include comparing O-LCA results that include supplemental activities with RW-LCA results for the same organization. The convergence between academia and private companies in organizational sustainability data may provide mutual learning benefits. The private sector is rapidly developing and prototyping solutions tailored to organizations' needs, providing potential new inspiration and directions of development for research. Academia provides the research to validate the methodologies, leaving only the most robust to survive and be adopted with scientific approval. Ultimately this convergence may accelerate progress toward comprehensive organizational impact data through joint efforts.

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Appendix

ENERGY RESOURCES		**EMISSIONS TO AIR**	
Material	**Amount**	**Material**	**Amount**
Crude oil (resource)	5,54E+02	Carbon dioxide	4,79E+03
Hard coal (resource)	5,61E+02	Carbon dioxide (biotic)	2,13E+02
Lignite (resource)	4,25E+02	Carbon dioxide (land use change)	3,98E+00
Natural gas (resource)	4,80E+02	Carbon monoxide	1,67E+01
MATERIAL INPUTS		Nitrogen (atmospheric nitrogen)	8,34E+01
Chromium	5,98E+00	Nitrogen oxides	1,42E+01
Copper	6,88E+00	Oxygen	1,86E+01
Iron	3,16E+01	Sulphur dioxide	1,06E+01
Lead	4,44E+00	Water (evapotranspiration)	1,49E+04
Magnesium	5,21E+00	Water vapour	9,98E+03
Silicon	6,46E+00	Methane	1,07E+01
Zinc	2,03E+01	Clean gas	1,34E+01
Bauxite	2,41E+01	Exhaust	1,33E+04
Clay	5,06E+01	Used air	8,80E+02
Copper	9,41E+01	Particles to air	3,70E+00
Dolomite	2,48E+01	**EMISSIONS TO FRESH WATER**	
Gypsum (natural gypsum)	2,33E+01	Chemical oxygen demand	3,93E+00
Iron ore (56,86%)	4,73E+02	Chloride	5,94E+01
Limestone (calcium carbonate)	1,15E+03	Sodium (+1)	7,03E+00
Natural Aggregate	4,21E+03	Sodium chloride (rock salt)	2,38E+01
Quartz sand (silica sand)	1,63E+02	Sodium sulphate	2,54E+01
Rare-earth ore	1,16E+01	Sulphate	3,35E+00
Sodium chloride (rock salt)	9,60E+01	Waste water	6,97E+03
Shale	5,08E+00	Water (river water from technosphere, rain water)	3,67E+02
Water	4,53E+04		
Air	2,08E+04	Soil loss by erosion into water	8,41E+00
Carbon dioxide	2,09E+02	Solids (suspended)	5,69E+00
Nitrogen	1,16E+01	Radium (Ra226)	1,87E+05
EMISSIONS TO SEA WATER			
Chloride	1,51E+01	Chloride	3,03E+01
5,50E+03	5,50E+03		

Table 9: Wind power inventory for 100 MW power plant, unit is mg/kWh

INPUTS FROM TECHNOSPHERE		
Product	**Unit**	**Amount**
chromium steel 18/8, at plant	kg/kWh	6.39E-05
diesel, burned in building machine	kg/kWh	4.76E-05
gravel, round, at mine	kg/kWh	3.12E-02
cement, unspecified, at plant	kg/kWh	3.58E-03
reinforcing steel, at plant	kg/kWh	6.11E-05
steel, low-alloyed, at plant	kg/kWh	1.43E-04
copper, at regional storage	kg/kWh	1.04E-05
tap water, at user	kg/kWh	1.98E-03
electricity, medium voltage, at grid	kWh/kWh	9.58E-04
transport, lorry 20-28t, fleet average transport, freight, rail	tkm/kWh	1.68E-04
EMISSIONS		
transport, freight, rail	tkm/kWh	9.16E-04
Heat, waste	MJ/kWh	3.45E-03
Particulates, <2.5 um	kg/kWh	3.61E-09
Particulates, >10 um	kg/kWh	7.23E-08
Particulates, >2.5 um, and <10um	kg/kWh	2.05E-08

Table 10: Inventory for Construction of reservoir hydro power plant per kWh

INPUTS FROM TECHNOSPHERE		
Product	**Unit**	**Amount**
sulphur hexafluoride, liquid, at plant	kg/kWh	3.40E-10
lubricating oil, at plant electricity, high voltage, at grid	kg/kWh	3.24E-08
electricity, high voltage, at grid	kWh/kWh	4.40E-02
INPUTS FROM NATURE, LAND		
Transformation, from unknown	m2/kWh	2.44E-05
Transformation, to water bodies, artificial	m2/kWh	2.41E-05
Transformation, to industrial area, built up	m2/kWh	2.41E-07
Occupation, water bodies, artificial	m2a/kWh	3.62E-03
Occupation, industrial area, built up	m2a/kWh	3.62E-05
EMISSIONS TO AIR		
Dinitrogen monoxide	kg/kWh	2.56E-08
Methane, biogenic	kg/kWh	2.64E-07
Carbon dioxide, land transformation	kg/kWh	1.36E-03
Sulfur hexafluoride	kg/kWh	3.40E-10
Heat, waste	MJ/kWh	1.58E-01
Water, CH	kg/kWh	1.75E+00
EMISSIONS TO WATER		
Oils, unspecified	kg/kWh	2.27E-08
EMISSIONS TO SOIL		
Oils, unspecified	kg/kWh	9.76E-09

Table 11: Inventory for Operation of reservoir hydro power plant per kWh

CONSTRUCTION INPUTS		
Input	**Unit**	**Amount**
Concrete	kg/kWh	2.13E-03
Steel rebar	kg/kWh	1.63E-04
Piping	kg/kWh	5.71E-07
Electrical cables	kg/kWh	1.03E-04
Electric motors	kg/kWh	7.09E-09
Electric magnets	kg/kWh	7.09E-12
Zirconium for rods	kg/kWh	1.87E-08
Boron	kg/kWh	6.24E-10
Silver	kg/kWh	1.70E-09
Indium	kg/kWh	3.19E-10
Cadmium	kg/kWh	1.06E-10
Enriched Uranium	kg/kWh	1.84E-07
Gadolinium	kg/kWh	4.61E-09
OPERATION INPUTS		
Enriched Uranium (over 40y)	kg/kWh	2.43E-06
Op. En. Con. (over 40 years) - electric	kWh/kWh	7.73E-04
Op. En. Con. (over 40 years) - thermal	kWh/kWh	7.23E-03

Table 12: Inventory for Nuclear power plant, inputs per kWh

INPUTS FROM NATURE		
Input process	**Unit**	**Amount**
Transformation, from sea and ocean	m2/kWh	5,52E-09
Transformation, to sea and ocean	m2/kWh	5,52E-09
Transformation, from industrial area, benthos	m2/kWh	5,52E-09
Transformation, to industrial area, benthos	m2/kWh	5,52E-09
Occupation, industrial area, benthos	m2a/kWh	6,07E-08
INPUTS FROM TECHNOSPHERE		
diesel, burned in building machine	MJ/kWh	4,00E-04
tap water, at user	kg/kWh	9,76E-06
electricity, medium voltage, production UCTE, at grid	kWh/kWh	7,31E-05
steel, low-alloyed, at plant	kg/kWh	4,52E-05
epoxy resin, liquid, at plant	kg/kWh	2,52E-07
polyvinylchloride, bulk polymerised, at plant	kg/kWh	1,03E-08
aluminium, production mix, at plant	kg/kWh	8,72E-07
cast iron, at plant	kg/kWh	1,04E-09
MG-silicon, at plant	kg/kWh	1,31E-09
copper, at regional storage	kg/kWh	5,24E-11
zinc for coating, at regional storage	kg/kWh	2,70E-08
concrete, normal, at plant	m3/kWh	1,41E-08
transport, lorry 32t	tkm/kWh	6,21E-06
transport, freight, rail	tkm/kWh	9,31E-06
transport, transoceanic freight ship	tkm/kWh	9,69E-06
Heat, waste	MJ/kWh	2,63E-04
EMISSIONS TO WATER		
Aluminum	kg/kWh	7,41E-07
Iron ion	kg/kWh	8,90E-10
Silicon	kg/kWh	1,11E-09
Copper, ion	kg/kWh	4,45E-11
Zinc, ion	kg/kWh	2,29E-08
Titanium, ion	kg/kWh	1,85E-10

Table 13: Inventory for Natural gas production and processing plant

INPUTS FROM NATURE		
Ecoinvent process	**Unit**	**Amount**
Occupation, industrial area	m2a/kWh	3,27E-05
Transformation, from unknown	m2/kWh	9,09E-07
Transformation, to industrial area	m2/kWh	9,09E-07
INPUTS FROM TECHNOSPHERE		
Aluminium, cast alloy {GLO}— market for — Cut-off, U	kg/kWh	3,20E-06
Aluminium, wrought alloy {GLO}— market for — Cut-off, U	kg/kWh	6,80E-06
Ceramic tile {GLO}— market for — Cut-off, U	kg/kWh	9,55E-08
Chromium {GLO}— market for — Cut-off, U	kg/kWh	2,22E-08
Cobalt {GLO}— market for — Cut-off, U	kg/kWh	1,64E-08
Concrete, normal {CH}— market for — Cut-off, U	m3/kWh	1,36E-07
Copper {GLO}— market for — Cut-off, U	kg/kWh	1,00E-05
Nickel, 99.5% {GLO}— market for — Cut-off, U	kg/kWh	1,43E-07
Reinforcing steel {GLO}— market for — Cut-off, U	kg/kWh	2,00E-04
Steel, chromium steel 18/8, hot rolled {GLO}— market for — Cut-off, U	kg/kWh	4,09E-05
Stone wool, packed {GLO}— market for stone wool, packed — Cut-off, U	kg/kWh	1,50E-05
Diesel, burned in building machine {GLO}— market for — Cut-off, U	MJ/kWh	3,36E-03
Electricity, medium voltage {RER}— market group for — Cut-off, U	kWh/kWh	6,86E-05
Heat, district or industrial, other than natural gas {RER}— market group for — Cut-off, U	MJ/kWh	3,20E-03

Table 14: Inventory for Natural gas power plant construction

EMISSIONS TO AIR		
Ecoinvent process	**Unit**	**Amount**
Carbon dioxide	g CO2/kWh	412.6
Nitrogen oxides	g NOx/kWh	0.122
Carbon monoxide	g CO/kWh	0.160

Table 15: Inventory for Natural gas power plant operation

Table 16: Mapping for Inventory of inputs for wind power plant to Ecoinvent

ENERGY RESOURCES	
Crude oil (resource)	Tall oil, crude {GLO}— market for tall oil, crude — Cut-off, U
Hard coal (resource)	Hard coal {Europe, without Russia and Turkey}— market for hard coal — Cut-off, U
Lignite (resource)	Lignite {RER}— market for — Cut-off, U
Natural gas (resource)	Natural gas, high pressure {GLO}— market group for — Cut-off, U
MATERIAL RESOURCES	
Chromium	Chromium {GLO}— market for — Cut-off, U
Copper	Copper {GLO}— market for — Cut-off, U
Iron	Cast iron {GLO}— market for — Cut-off, U
Lead	Lead {GLO}— market for — Cut-off, U
Magnesium	Magnesium {GLO}— market for — Cut-off, U
Silicon	Silicon, metallurgical grade {GLO}— market for — Cut-off, U
Zinc	Zinc {GLO}— market for — Cut-off, U
Bauxite	Bauxite {GLO}— market for bauxite — Cut-off, U
Clay	Clay {RoW}— market for clay — Cut-off, U
Colemanite ore	-
Copper - Gold - Silver - ore (1,0% cu; 0,4 g/tAu; 66 g/tAg)	Copper {GLO}— market for — Cut-off, U
Copper - Gold - Silver - ore (1,1% cu; 0,01 g/tAu; 2,86 g/tAg)	Copper {GLO}— market for — Cut-off, U
Copper - Gold - Silver - ore (1,16% cu; 0,002 g/tAu; 1,06 g/tAg)	Copper {GLO}— market for — Cut-off, U
Copper ore (sulphidic, 1,1%)	Copper {GLO}— market for — Cut-off, U
Copper ore (2,23%)	Copper {GLO}— market for — Cut-off, U
Dolomite	Dolomite {RER}— market for dolomite — Cut-off, U
Gypsum (natural gypsum)	Gypsum, mineral {RER}— market for gypsum, mineral — Cut-off, U
Inert rock	-
Iron ore (56,86%)	Iron ore, crude ore, 46% Fe {GLO}— iron mine operation, crude ore, 46% Fe — Cut-off, U
Limestone (calcium carbonate)	Limestone, crushed, washed {RoW}— market for limestone, crushed, washed — Cut-off, U
Potashsalt, crude (hard salt, 10% K20)	-
Natural Aggregate	Gravel, crushed {GLO}— market for — Cut-off, U
Quartz sand (silica sand; silicon dioxide)	Sand {GLO}— market for — Cut-off, U
Rare-earth ore	Rare earth concentrate, 70% REO, from bastnasite {GLO}— market for rare earth concentrate, 70% REO, from bastnasite — Cut-off, U
Sodium chloride (rock salt)	Sodium chloride, powder {RER}— production — Cut-off, U
Soil	-
Shale	Shale {GLO}— market for — Cut-off, U
Water	Water, unspecified natural origin/m3, agri, GLO
Air	Air
Carbon dioxide	Carbon dioxide, in air
Nitrogen	Nitrogen

EMISSIONS TO AIR	
Carbon dioxide	Carbon dioxide
Carbon dioxide (biotic)	Carbon dioxide, biogenic
Carbon dioxide (land use change)	Carbon dioxide, land transformation
Carbon monoxide	Carbon monoxide
Nitrogen (atmospheric nitrogen)	Nitrogen, atmospheric
Nitrogen oxides	Nitrogen oxides
Oxygen	Oxygen
Sulphur dioxide	Sulfur dioxide
Water (evapotranspiration)	Water (evapotranspiration)
Water vapour	Water
Methane	Methane
Clean gas	Clean gas
Exhaust	Exhaust
Unused primary energy from solar energy	-
Used air	Used air
Particles to air	Particulates
EMISSIONS TO FRESH WATER	
Chemical oxygen demand	COD (Chemical Oxygen Demand)
Chloride	Chloride
Sodium (+1)	Sodium
Sodium chloride (rock salt)	Sodium chloride
Sodium sulphate	Sodium sulfate
Sulphate	Sulfate
Waste water	Waste water
Water (river water from technosphere, rain water)	Water, river
Soil loss by erosion into water	Soil loss by erosion into water
Solids (suspended)	Suspended solids, unspecified
Radium (Ra226)	Radium-226/kg
EMISSIONS TO SEA WATER	
Chloride	Chloride
Waste water	Waste water
Water (sea water from technosphere, cooling water)	Cooling water
Water (sea water from technosphere, waste water)	Cooling water

Table 17: Mapping of direct emissions for wind power plant to Ecoinvent

INPUTS FROM TECHNOSPHERE	
Product	**Ecoinvent product**
chromium steel 18/8, at plant	Steel, chromium steel 18/8 {GLO}— market for — Cut-off, U
diesel, burned in building machine	Diesel {GLO}— market group for — Cut-off, U
explosives, tovex, at plant	-
gravel, round, at mine	Gravel, round {GLO}— market for — Cut-off, U
cement, unspecified, at plant	Cement, unspecified {GLO}— market group for cement, unspecified — Cut-off, U
reinforcing steel, at plant	Reinforcing steel {GLO}— market for — Cut-off, U
steel, low-alloyed, at plant	Steel, low-alloyed {GLO}— market for — Cut-off, U
copper, at regional storage	Copper {GLO}— market for — Cut-off, U
tap water, at user	Tap water {RER}— market group for — Cut-off, U
electricity, medium voltage, at grid	Electricity, medium voltage {RER}— market group for — Cut-off, U
disposal, building, reinforced concrete, to recycling	-
disposal, building, concrete, not reinforced, to final disposal	-
disposal, building, reinforcement steel, to recycling	-
transport, lorry 20-28t, fleet average transport, freight, rail	Transport, freight, lorry 16-32 metric ton, euro3 {RER}— market for transport, freight, lorry 16-32 metric ton, EURO3 — Cut-off, U
transport, freight, rail	Transport, freight train {RER}— market group for transport, freight train — Cut-off, U
EMISSIONS	
Heat, waste	Heat, waste
Particulates, <2.5 um	Particulates, <2.5 um
Particulates, >10 um	Particulates, >10 um
Particulates, >2.5 um, and <10um	Particulates, >2.5 um, and <10um

Table 18: Mapping between Hydro LCA and Ecoinvent for construction of reservoir hydro power plant Inventory

INPUTS FROM TECHNOSPHERE	
Product	**Ecoinvent product**
sulphur hexafluoride, liquid, at plant	Sulfur hexafluoride, liquid {GLO}— market for — Cut-off, U
lubricating oil, at plant electricity, high voltage, at grid	Lubricating oil {RER}— market for lubricating oil — Cut-off, U
electricity, high voltage, at grid	Electricity, high voltage {RER}— market group for — Cut-off, U
INPUTS FROM NATURE, LAND	
Transformation, from unknown	Transformation, from unknown
Transformation, to water bodies, artificial	Transformation, to water bodies, artificial
Transformation, to industrial area, built up	Transformation, to industrial area
Occupation, water bodies, artificial	Occupation, water bodies, artificial
Occupation, industrial area, built up	Occupation, industrial area
INPUTS FROM NATURE, WATER	
Volume occupied, reservoir	Volume occupied, reservoir
Water, turbine use, unspecified natural origin	-
Energy, potential (in hydropower reservoir), converted	-
EMISSIONS TO AIR	
Dinitrogen monoxide	Dinitrogen monoxide
Methane, biogenic	Methane, biogenic
Carbon dioxide, land transformation	Carbon dioxide, land transformation
Sulfur hexafluoride	Sulfur hexafluoride
Heat, waste	Heat, waste
Water, CH	Water, Europe
EMISSIONS TO WATER AND SOIL	
Oils, unspecified	Oils, unspecified

Table 19: Mapping between Hydro LCA and Ecoinvent for operation of reservoir hydro power plant Inventory

CONSTRUCTION	
Input	**Ecoinvent Material**
Concrete	Concrete, normal {GLO}— market group for concrete, normal — Cut-off, U
Steel rebar	Steel, chromium steel 18/8 {GLO}— market for — Cut-off, U
Piping	Chromium steel pipe {GLO}— market for — Cut-off, U
Pipe welding	-
Electrical cables	Cable, unspecified {GLO}— market for — Cut-off, U
Electric motors	Electronic component, active, unspecified {GLO}— market for — Cut-off, U
Electric magnets	Permanent magnet, for electric motor {GLO}— market for permanent magnet, electric passenger car motor — Cut-off, U
Zirconium for rods	Zircon, 50% zirconium {GLO}— market for — Cut-off, U
Boron	Boron carbide {GLO}— market for — Cut-off, U
Silver	Silver {GLO}— market for — Cut-off, U
Indium	Indium {GLO}— market for — Cut-off, U
Cadmium	Cadmium {GLO}— market for — Cut-off, U
Enriched Uranium	Enriched uranium, 4.2% {GLO}— market for — Cut-off, U
Natural Uranium	-
Gadolinium	Samarium europium gadolinium concentrate, 94% rare earth oxide {GLO}— market for — Cut-off, U
OPERATION	
Input	Ecoinvent Material
Enriched Uranium (over 40y)	Enriched uranium, 4.2% {GLO}— market for — Cut-off, U
Natural Uranium (over 40y)	-
Op. En. Con. (over 40 years), - electric	Electricity high voltage {RER}— market group for — Cut-off, U market group for — Cut-off, U
Op. En. Con. (over 40 years) - thermal	Electricity, high voltage {GR}— electricity production, natural gas, conventional power plant — Cut-off, U

Table 20: Mapping of the Nuclear LCA inputs to Ecoinvent processes for construction and operation

INPUTS FROM NATURE	
Input process	**Simapro process**
Transformation, from sea and ocean	Transformation, from sea and ocean
Transformation, to sea and ocean	Transformation, to sea and ocean
Transformation, from industrial area, benthos	Transformation, from industrial area
Transformation, to industrial area, benthos	Transformation, to industrial area
Occupation, industrial area, benthos	Occupation, industrial area
INPUTS FROM TECHNOSPHERE	
diesel, burned in building machine	Diesel, burned in building machine {GLO}— market for — Cut-off, U
tap water, at user	Tap water {RER}— market group for — Cut-off, U
electricity, medium voltage, production UCTE, at grid	Electricity, medium voltage {RER}— market group for — Cut-off, U
steel, low-alloyed, at plant	Steel, low-alloyed {GLO}— market for — Cut-off, U
epoxy resin, liquid, at plant	Epoxy resin, liquid {RER}— market for epoxy resin, liquid — Cut-off, U
polyvinylchloride, bulk polymerised, at plant	Polyvinylchloride, bulk polymerised {RER}— polyvinylchloride production, bulk polymerisation — Cut-off, U
aluminium, production mix, at plant	Aluminium alloy, AlLi {GLO}— market for — Cut-off, U
cast iron, at plant	Cast iron {GLO}— market for — Cut-off, U
MG-silicon, at plant	Silicon, metallurgical grade {GLO}— market for — Cut-off, U
copper, at regional storage	Copper {GLO}— market for — Cut-off, U
zinc for coating, at regional storage	Zinc {GLO}— market for — Cut-off, U
concrete, normal, at plant	Concrete, normal {GLO}— market group for concrete, normal — Cut-off, U
transport, lorry 32t	Transport, freight, lorry >32 metric ton, euro3 {RER}— market for transport, freight, lorry >32 metric ton, EURO3 — Cut-off, U
transport, freight, rail	Transport, freight train {RER}— market group for transport, freight train — Cut-off, U
transport, transoceanic freight ship	Transport, freight, sea, container ship {GLO}— market for transport, freight, sea, container ship — Cut-off, U
Heat, waste	Heat, district or industrial, other than natural gas {GLO}— treatment of bagasse, from sweet sorghum, in heat and power co-generation unit, 6400kW thermal — Cut-off, U
EMISSIONS TO WATER	
Aluminum	Aluminium
Iron ion	Iron
Silicon	Silicon
Copper, ion	Copper
Zinc, ion	Zinc
Titanium, ion	Titanium

Table 21: Mapping of the Natural Gas LCA inputs to Ecoinvent processes for production and processing

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