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Social and Environmental Assessment of Urban Energy Systems

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Abstract

Climate change is a global challenge that requires immediate and significant actions to reduce greenhouse gas emissions and limit global warming. The European Union (EU) has set an ambitious target for 2050: achieving carbon neutrality, which means reducing net carbon dioxide emissions to zero (European Comission, 2018). This goal entails a complete transformation of energy systems, gradually phasing out the use of fossil fuels and adopting renewable and sustainable energy sources. To achieve this transition, it is crucial to consider various sustainable energy sources such as photovoltaic, wind, nuclear, and biomass and which one is more favorable for the environment and minimizes societal impact. In this research study, our aim is to provide a global and holistic perspective on the analysis of urban energy systems, by focusing on the case study of the energy system at the Technical University of Munich (TUM) as an example. By considering the environmental and social impacts that may arise from different energy solutions, we seek to offer valuable insights for more effective energy planning. This comprehensive approach will enable informed decision-making and will promote the development of urban energy systems that are beneficial for both the environment and society at large.

Key Words: Climate Change, Urban Energy Systems, Sustainable Energy Sources, Life Cycle Assessment.

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Introduction

To achieve the transition towards more environmentally friendly energy sources, careful planning and design of urban and broader energy systems are required. To achieve this, the Chair of Energy Systems of the Technical University of Munich (TUM) conducted a research under the title “Clean-Tech-Campus Garching” that consists on the development of holistically optimized, sustainable and transferable energy concepts for complex mixed use areas using the example of the TUM Campus Garching (“CleanTechCampus,” 2020).

The study provides valuable insights into the optimization, simulation, and scenarios related to urban energy systems. One of the approaches explored by this research team is the concept of "sector coupling," which involves integrating different energy sectors such as electricity, heating, and transportation to achieve greater efficiency and synergies. This entails the use of renewable electricity in heating and transportation systems, reducing dependence on fossil fuels and promoting decarbonization.

The purpose of this thesis is to complement the existing research conducted by TUM researchers by investigating the selection of renewable energy sources that power those integrated urban energy systems. This choice (photovoltaic, wind, nuclear, and biomass energy sources) can have different impacts, not only economic and efficiency-related but also environmental and social. These two last aspects are the ones that we aim to analyze in-depth throughout this study to determine which type of energy sources is more environmentally and socially friendly.

The concern for achieving an energy transition with minimal social and environmental impact is not a novel concept. Researchers such as Jessica Wilkinson and Nels Johnson from The Nature Conservancy (The Nature Conservancy, 2023) have expressed their concerns regarding the goal of achieving zero emissions by 2050. While wind and photovoltaic energy may seem like obvious solutions, crucial questions arise regarding land availability, the potential industrialization of environmentally and culturally sensitive areas, and the ability to achieve a rapid and wide-ranging transition without compromising natural resources and species. Additionally, recognizing the importance of finding an appropriate mix of technologies that minimizes environmental impact is vital.

Partially inspired by The Nature Conservancy's "Power of Place" project, our research also aims to assess the social and environmental impacts arising from different urban energy systems and modifications to their parameters. Specifically, we have chosen to focus on the energy systems of the Technical University of Munich (TUM) campus for several reasons.

- Firstly, with the support of the Chair of Energy Systems, we have privileged access to campus energy facility information, enabling a thorough analysis of the social and environmental impacts of renewable energy integration.
- Secondly, the current research of the chair focuses on urban areas systems, such as cities or metropolitan areas and TUM campus represents an ideal case study for examining the effects of renewable energy sources on an urban energy system.
- Furthermore, our focus on the TUM campus contributes to sustainability efforts and provides valuable insights to enhance the sustainability of campus energy systems, serving as a model for other institutions and communities striving for a greener future.

While the "Power of Place" project primarily focuses on the impact of wind and photovoltaic energy systems on land use, we seek to broaden the scope of investigation. Although our subject of study is a relatively small system (a university campus) we aspire to examine and evaluate the primary energy sources employed (not only wind and PV) and their relationship with all the key impact categories (not only land use).

Our research will delve deeply into Life Cycle Assessment (LCA). LCA originated in the 1960s and has since experienced significant growth, evolving from a research methodology to a widely-used tool for assessing the environmental impact of products and systems. LCA is defined as “compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle” (ISO 14040, 2006). The LCA method applied to a general product system (in the thesis, we will particularize the method to an energy system), consists of four distinct stages: Goal and scope definition, Inventory analysis, Impact assessment, and Interpretation. In the following paragraphs there is a brief description of each stage taken from the chapter “Introduction to LCA methodology” (Hauschild, 2018), from the book “Life Cycle Assessment: Theory and Practice”

Methodology

Our research will delve deeply into Life Cycle Assessment (LCA). LCA originated in the 1960s and has since experienced significant growth, evolving from a research methodology to a widely-used tool for assessing the environmental impact of products and systems. LCA is defined as “compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle” (ISO 14040, 2006). The LCA method applied to a general product system (in the thesis, we will particularize the method to an energy system), consists of four distinct stages: Goal and scope definition, Inventory analysis, Impact assessment, and Interpretation. In the following paragraphs there is a brief description of each stage taken from the chapter “Introduction to LCA methodology” (Hauschild, 2018), from the book “Life Cycle Assessment: Theory and Practice”.

The LCA method applied to a general product system (in the thesis, we will particularize the method to an energy system), consists of four distinct stages: Goal and scope definition, Inventory analysis, Impact assessment, and Interpretation. The *Goal and Scope Definition* plays a crucial role in interpreting the study's results and ensuring the validity of conclusions and recommendations. It defines the study's goals and scope, determining the purpose of the study, the questions it aims to answer, and the target audience. This sets the context for the assessment and helps frame the assessment parameters, such as the functional unit, product system boundaries, assessment parameters, geographical and temporal boundaries, and the perspective. All of them will be carefully defined in the thesis.

The next phase is the *Inventory Analysis*, where information on physical flows, including inputs, outputs, emissions, waste, and valuable products, is collected for the product system. This involves studying all the processes within the product system and scaling the flows based on the reference flow determined from the functional unit. Generic data from databases and environmentally extended input-output analysis are often used to support the collection of inventory data.

The third phase is the *Impact Assessment*, which translates the physical flows and interventions of the product system into environmental impacts. This phase involves selecting representative impact categories, classifying the flows according to their contribution to each category, and characterizing their impact using environmental models. The impact scores are aggregated into a profile that represents the overall impact of the product system. Normalization and weighting techniques may be applied to compare and rank the impacts across categories.

The *Interpretation of Results* considers both the inventory analysis and the impact assessment, considering the goal and scope definitions and applying sensitivity and uncertainty analyses to ensure robust conclusions.

Conducting a Life Cycle Assessment (LCA) in our case, an energy system, involves applying the principles and methodology of LCA to comprehensively assess the environmental impacts associated with the entire life cycle of the energy system. This includes the extraction of raw materials, the production and distribution of energy, its use by end-users, and the eventual disposal or retirement of energy infrastructure. The LCA analysis considers various environmental indicators such as greenhouse gas emissions, energy consumption, land use, water usage, and other relevant impact categories. Evaluating the environmental performance of an energy system through LCA, provides insights into the system's sustainability, identifies hotspots of environmental concern, and helps in identifying opportunities for improving its overall environmental performance.

The LCA method adheres to the principles and requirements established in ISO 14040-44, which are a set of international standards developed by the International Organization for Standardization (ISO) that outline the principles and requirements for conducting LCA. It is also important to mention the International Reference Life Cycle Data System (ILCD), which is an international reference system providing guidelines and tools for life cycle inventory data exchange and life cycle analysis. It is designed to promote coherence and comparability of LCA results by standardizing the structure and format of data. ILCD offers technical guidelines and a common database for LCA.

Collectively, ILCD, ISO 14040-44, and the LCA method form a comprehensive framework for conducting consistent and comparable life cycle analyses. These tools and scientific sources are extensively covered on the previously mentioned book "Life Cycle Assessment: Theory and Practice" (Hauschild et al., 2018). For this reason, we have chosen this book as our main guide for our research methodology. By drawing on these current methodologies and tools, we aim to enhance our understanding of the challenges and opportunities associated with implementing more sustainable and socially responsible energy systems.

While the above-mentioned book provides the foundation for our LCA analysis, additional technological tools and software are necessary for data extraction and manipulation. In our research, we will utilize the open-source software for LCA, Activity Browser and the Ecoinvent database. Although popular tools such as SimaPro and GaBi exist, our research will utilize the Activity Browser as a free and intuitive interface for exploring inventories and performing LCA calculations. Activity Browser is an open-source tool that builds on Brithway2 (“Activity Browser,” 2023) and enables the creation and management of life cycle inventory databases and the conduct of simplified life cycle analyses.

Lastly, it is important to reference the database that will be used and incorporated into the Activity Browser. We will use Ecoinvent (“ecoinvent Database - ecoinvent,” 2020) one of the most renowned and widely-used databases, as it provides life cycle inventories for a broad range of processes and products, allowing for more accurate and reliable assessments.

We will also use various scientific papers to support our research by referring to previous studies related to our topic. Some of these papers include:

- “Energy systems modeling for twenty-first-century energy challenges” (Pfenninger et al., 2014): this study is similar to the one conducted by TUM researchers in the project CleanTechCampus, and it aims to optimize the design of urban-scale systems. The main objective is to achieve an optimal balance between energy supply and demand, maximizing efficiency, sustainability, and profitability.
- “A review on recent sizing methodologies of hybrid renewable energy systems" (Lian et al., 2019): This review focuses on planning energy systems and analyzes indicators such as reliability, economic, environmental, and social aspects. We will specifically examine the last two types of indicators and compare this analysis with LCA analysis to determine which approach is more accurate.
- "Sustainability assessment of energy systems: Integrating environmental, economic, and social aspects" (Santoyo-Castelazo and Azapagic, 2014): Although it does not strictly follow the official LCA process, it is interesting to compare their approach to evaluating the social and environmental impact on an energy system with the one proposed by the LCA method.

- "The Activity Browser—An open-source LCA software building on top of the brightway framework" (Steubing et al., 2020): This study will serve as a guide to familiarize ourselves with the platform and understand the different options and tools of the software to maximize its potential.
- "Life cycle assessment of power generation alternatives for a stand-alone mobile house" (Sevencan and Çiftcioğlu, 2013) and "Comparative Life Cycle Assessment of a Thai Island's diesel/PV/wind hybrid microgrid" (Smith et al., 2015): In Chapter 26, "LCA of Energy Systems," the authors classify the LCA research into two categories: global-scale and meso-scale. Studies belonging to the meso-scale category attempt to analyze policies or decisions that should be made at an urban scale, like our case study of the Munich campus. The size of our study resembles that of these two scientific papers that are mentioned on the book, which compare different energy sources in a Thai island microgrid and examine nine energy generation alternatives for a mobile house in Turkey. We believe these papers will be relevant as we may encounter similar data acquisition challenges that the researchers of these papers likely faced.
- "Life Cycle Assessment of solar energy systems: Comparison of photovoltaic and water thermal heater at the domestic scale" (Carnevale et al., 2014): This paper provides an example of LCA at a more domestic scale, following the format of an LCA report more strictly.
- "Introduction to evaluating energy justice across the life cycle: A social life cycle assessment approach" (Fortier et al., 2019): We also consider it necessary to study scientific papers specialized in analyzing social impacts, as it is the least studied impact category thus far and one that we anticipate will have limited analysis within the LCA method.

Finally, it's important to note that the methodology of Life Cycle Assessment (LCA) is complex and comprehensive, making it challenging to fully explain within the confines of this research section. Therefore, we have chosen to present a simplified case study to facilitate comprehension of the methodology. As we progress through this work, we'll gain valuable insights into the challenges of conducting a comprehensive LCA. We'll also become aware of the limitations we face due to data constraints. However, this journey will provide us with a deep understanding of the LCA methodology, its complexities, and the critical aspects involved in future studies.

By exploring the university campus as a case study, we aim to convey the essence of LCA and how it can be applied in real-world scenarios. While a full-fledged LCA can be daunting due to its data-intensive nature, our study will serve as a steppingstone for a more profound understanding of LCA's significance and potential in guiding sustainable and environmentally responsible decision-making processes.

Case Study

In this case study, we focus on a university campus to see how the energy it uses affects the planet. This university is known for its research and efforts to protect the environment. Each year, it uses around 70 megawatt-hours of electricity, mainly from the German electrical grid. As a forward-thinking pioneer in research endeavors that promote environmental responsibility, the university has undertaken initiatives to explore alternative energy sources beyond reliance on the national electrical grid. These alternative sources introduce a spectrum of energy choices, each potentially associated with distinct environmental and social impacts.

We want to use the Life Cycle Assessment (LCA) tool to understand how different energy sources impact a relatively compact system—our university campus. With this small system, we hope that we get a holistic view of the LCA method and that we get qualitative and quantitative result on the environmental impacts of different electricity solutions.

Our intention is to conduct a comprehensive analysis of the environmental impacts generated by the following six different types of energy sources.

- Electricity from the German grid.
- Electricity from a combined heat and power generation in a combined cycle.
- Electricity generated from biogas.
- Electricity generated from photovoltaic energy.
- Electricity generated from nuclear energy.
- Electricity generated from wind energy.

Initially, we aimed to explore more realistic scenarios (with a mix of the different energy sources). For instance, we considered scenarios where 90% of the energy comes from the electrical grid, with an additional 10% generated through on-campus solar panels. However, as we modeled these scenarios using the corresponding software, we encountered significant challenges in obtaining visually meaningful results.

Given that this study adopts a holistic approach to LCA analysis to facilitate methodology understanding and generating meaningful results, we have opted for extreme scenarios. Consequently, we will analyze seven scenarios (we will analyze two types of photovoltaic panels, along with the six above), where 100% of the electrical energy is exclusively sourced from a specific energy type, with this energy source changing from one scenario to the next. This approach ensures a clear and distinct analysis of the environmental impacts associated with each energy source, contributing to a more comprehensive understanding of the LCA for our study.

It's essential to clarify that our role is not to design these energy processes or their components from scratch (we have no data for this). Instead, we build upon existing databases that encapsulate the components and impacts of various electricity production activities.

In the context of a Life Cycle Assessment (LCA), an "activity" refers to a specific process or action within the system being analyzed. Each activity represents a particular stage or component of a product or process's life cycle, and it encapsulates the various inputs, outputs, and environmental impacts associated with that stage. These activities are essential building blocks in an LCA as they help model and evaluate the entire life cycle of a product, system, or process.

"EcoInvent" is a comprehensive database of such activities that cover a wide range of industrial and environmental processes. Each activity in the EcoInvent database is a standardized representation of a real-world process, providing data on the resources used, emissions generated, and other environmental factors associated with that process. These activities are meticulously documented and peer-reviewed, making them valuable resources for conducting LCAs.

The creation of this activities is a great part in most LCA studies, that ours will not cover. Instead, our work involves selecting and using pre-existing activities from the EcoInvent database. This approach is practical and efficient, as it allows us to leverage the extensive data and research already available, ensuring that our study is based on established and validated information. Our primary task will be to choose the most appropriate activities from EcoInvent to represent those scenarios relevant to our case study.

In Table 1, you will find the various activities we have carefully selected to represent our desired scenarios. These activities have provided us with the essential data we used to calculate environmental impacts and conduct the rest of the Life Cycle Assessment (LCA).

As it can be analysed from the Table 1, we used general filtering guidelines for selecting EcoInvent unit activities across all scenarios. First, we specifically filtered activities by location, focusing on those situated in Germany. This choice aligns with the geographical context of our university campus, ensuring that our analysis remains relevant to our regional setting. Secondly, Consistency in unit measurement was a crucial consideration. We selected activities that presented data in terms of 1 unit of electricity, equivalent to kilowatt-hours (kWh). This choice matched the format of the university's energy consumption data, which is specified as 70 MWh. Finally, although we tried to select activities with low-voltage electricity as their product whenever possible, we encountered situations in some scenarios where the only activity meeting our criteria and aligning best with our study had high-voltage electricity as its product. This high-voltage electricity would likely require transformation to low voltage for use on a university campus. Consequently, it becomes essential to consider the environmental impacts associated with the transformation from high voltage to low voltage, a step that may be necessary in the real-life scenario of a university campus.

Next, we will provide a brief analysis of why we selected each EcoInvent activity and offer a concise description of the chosen activity.

Electricity from the German grid. For this scenario, we selected the "market for electricity, low voltage" activity. We chose this activity because it conveniently falls under the category of "Market" activities in EcoInvent. Market activities are designed to represent the consumption mix of a product within a specific geographical area, connecting suppliers and consumers in the same location. Given that our university campus is in Germany, this choice aligns well with our study's geographical context and objective.

Electricity from a combined heat and power generation in a combined cycle. We opted for the "heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical" activity. This activity accurately represents the production of high voltage electricity and heat in a combined cycle natural gas power plant with combined heat and power (CHP) in Germany in 2012. It is well-suited for scenarios where both electricity and heat are generated simultaneously using natural gas, which is known for its efficiency and sustainability.

Table 1: Selected Activities of the EcoInvent database

Unit	**Product**	**Activity**	**Location**	**Database**
Kilowatt hour	Electricity, low voltage	Market for electricity, low voltage	Germany	apos391
Kilowatt hour	Electricity, high voltage	Heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical	Germany	apos391
Kilowatt hour	Electricity, high voltage	Heat and power co-generation, biogas, gas engine	Germany	apos391
Kilowatt hour	Electricity, low voltage	Electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted	Germany	apos391
Kilowatt hour	Electricity, low voltage	Electricity production, photovoltaic, 3kWp slanted roof installation, multi-Si, panel, mounted	Germany	apos391
Kilowatt hour	Electricity, high voltage	Electricity production, nuclear, pressure water reactor	Germany	apos391
Kilowatt hour	Electricity, high voltage	Electricity production, wind, >3MW turbine, onshore	Germany	apos391
Kilowatt hour	Electricity, high voltage	Electricity production, wind, 1-3MW turbine, offshore	Germany	apos391

Electricity generated from biogas. Our choice for electricity generated from biogas was the "heat and power co-generation, biogas, gas engine" activity. This dataset represents the production of electricity and heat from a biogas mix derived from different sources, such as biowaste and sewage sludge, when burned in a cogeneration unit with a gas engine. It accurately represents grid-connected electricity production using biogas. The primary product in this case is electricity at high voltage, with heat produced as a co-product.

Electricity generated from photovoltaic energy. For photovoltaic energy, we had three activities to choose from:

1. "electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted"
2. "electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted"
3. "electricity production, photovoltaic, 570kWp open ground installation, multi-Si"

First, we made the decision to exclude the third activity as it is meant for larger-scale open ground installations, typically around 570 kWp. This activity represents a larger system similar to what is found in central photovoltaic power stations. We assumed that if our university campus were to undertake a larger solar panel installation initiative, it would be more realistic to consider the first or second activity rather than a project as extensive as the third. This choice allows us to focus on scenarios that are more closely aligned with the campus's potential solar energy projects.

Second, the selection between the first and second activities hinges on the specific type of panels that would be employed on your campus. For instance, if an ample space is available and the aim is to maximize energy production and efficiency, monocrystalline panels may be the preferable choice. On the other hand, if budget constraints exist, and space is not a limiting factor, polycrystalline panels can offer cost-effective solutions for solar energy generation. Therefore, we deemed it interesting to analyze the different impacts of one activity compared to the other, as initially, we were uncertain about the type of panels the campus would choose to install. That is why two scenarios are considered within the photovoltaic one, one with the activity “electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted” and another with the “electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted”.We believe that these results could be valuable in informing future decisions if a photovoltaic project were to be undertaken on the campus.

Electricity generated from nuclear energy. In the case of nuclear energy, we chose the "electricity production, nuclear, pressure water reactor" activity. This choice aligns with the prevalent method of nuclear energy generation in Germany, specifically through Pressurized Water Reactors (PWR) rather than Boiling Water Reactors (BWR). PWRs are widely used globally and in Germany due to their higher efficiency and safety standards compared to BWRs. Additionally, PWRs typically have greater electricity generation capacity than BWRs, making them better suited to meet Germany's energy demands. It is essential to note that all nuclear power plants in Germany belong to the PWR type, further underscoring the relevance of this selection. This dataset accurately represents the production of high voltage electricity at a grid-connected nuclear pressure water reactor (PWR) in Germany in 2012.

Electricity generated from wind energy. For wind energy, we had four options to choose from, categorized as either onshore or offshore installations:

1. "electricity production, wind, 1-3MW turbine, onshore"

2. "electricity production, wind, >3MW turbine, onshore"
3. "electricity production, wind, 1-3MW turbine, offshore"
4. "electricity production, wind, <1MW turbine, onshore"

Initially, we were faced with the choice between onshore and offshore wind energy modalities. We could have opted for the onshore option, as it is more representative, with 8,3 megawatts (MW) of offshore turbines compared to 58,1 MW of onshore turbines (Deutsche Windguard GmbH). However, we considered it intriguing to create our own activity where we conduct an analysis of the real impact of wind technology in Germany, combining the contributions of onshore and offshore technologies.

Furthermore, when deciding on the size of onshore wind turbines, we referred to the 2021 study titled "Average Turbine Configuration of newly installed Wind Turbines in German Federal States". In this study we can see that all turbines installed in Germany had capacities exceeding 3 MW per turbine.

In summary, we selected activities two and three: "electricity production, wind, >3MW turbine, onshore" and "electricity production, wind, 1-3MW turbine, offshore." This decision is particularly interesting as it involves creating an activity that represents, on a per-kilowatt basis, the proportion of onshore and offshore wind energy in Germany. Essentially, we derived fractional unit values from these two activities to craft a new activity encompassing both. This simplified representation mirrors the process of creating custom activities, where data representing the presence of that activity, in fractional units, is obtained concerning the overall activity being developed.

In essence, unlike the photovoltaic scenario where we analyzed two activities separately as distinct scenarios, in the case of electricity generated through wind energy, we decided to establish a new activity that represents the blend of onshore and offshore wind electricity in Germany.

With this introduction to the campus case study, we can now delve into the complete LCA study. As already stated, the goal of our study does not include the creation of these activities. This is very important to clarify since most of LCA studies and available literature include this as a gid part of the study. However, we will keep the format of a complete LCA report, so that this work serves as a holistic view of what the complete methodology would look like.

In the following pages, you will find a breakdown of what a Life Cycle Assessment (LCA) report for a product might look like, as exemplified in our case study. While there will be many pages or sections that we cannot fully develop due to the nature of our study, we have included them to provide readers with a glimpse of what a comprehensive LCA study entails. As you will see, the report follows the structure of the LCA methodology itself, which is valuable for organizing the various phases and understanding the different tasks required at each stage.

1 Goal Definition

The goal definition in the methodology of Life Cycle Assessment (LCA) is crucial because it sets the foundation for the entire study and shapes its scope, focus, and purpose. By clearly defining the goals, the LCA process becomes more structured and meaningful. This part was developed following the guidelines and explanations in Chapter 7 of the book "Life Cycle Assessment: Theory and Practice" (Rosenbaum et al., 2018). From now on, to avoid unnecessary repetitions of the same reference, when referencing chapters or tables, the reference book remains consistently the same, unless otherwise specified.

As suggested in the book, we included and defined the following six aspects based on the ISO standard requirements: *intended application, method assumptions and impact limitations, reasons for carrying out the LCA study, target audience, comparative assertions to be disclosed to the public and commissioner of the LCA Study and other influential actors.*

1.1 Intended Applications

This study aims to compare how different energy supply systems might affect the environment and society in an urban place, such as the Garching Campus of the Technical University of Munich (TUM). We want to understand the impacts of various energy choices in a university setting.

1.2 Method Assumptions and Impact Limitations

Our study aims to comprehensively analyze the impacts of different energy systems. We do not intend to limit our investigation to a single life cycle phase of energy systems; rather, we will analyze all life cycle phases if the available data permits.

Furthermore, our goal is not to analyze a specific impact category (some studies chose to fouces on the climate change category, for example); rather, we seek to gain a holistic understanding of how these energy systems affect each of the environmental categories proposed by LCA. However, it is important to note that during the inventory analysis phase, we may need to establish certain assumptions due to a lack of specific data.

1.3 Reasons for Carrying Out the LCA Study and Decision

Since this study is purely descriptive in nature, we don't anticipate that any decisions regarding the energy systems at the University of Munich will be directly influenced by the outcomes of this LCA.

Moreover, we won't consider any interactions with other systems that are included in our model. Consequently, following the guidelines provided in Chapter 7/Box 7.1 of the referenced book (Bjørn et al., 2018a), the decision-making context aligns with Situation C2: accounting through allocation.

Hopefully, the study's findings, along with potential support from other studies validating the results of this environmental and social analysis, as well as economic and efficient outcomes, might encourage the university to make more environmentally and socially responsible decisions when managing the campus energy system. This approach underscores the university's commitment to setting an example in sustainable planning.

1.4 Target Audience

The study's findings are exclusively intended for communication within the "Lehrstuhl für Energiesysteme" at the University of Munich. It serves as a descriptive study that holds potential interest for ongoing or future research endeavors. Consequently, the study is presented in an academic manner, adhering to a suitable technical level of reporting.

1.5 Comparative Assertions to be Disclosed to the Public

While the LCA study incorporates comparative statements, its primary intention doesn't entail public disclosure. Rather, it is tailored for internal use within the Energy Systems department of TUM, as previously explained.

1.6 Commissioner of the LCA Study and Other Influential Actors

This study is the culmination of a university final thesis project, and as such, it is self-funded. Moreover, there are no external stakeholders exerting influence on the study's proceedings.

2 Scope Definition

The scope definition within the methodology of Life Cycle Assessment (LCA) establishes the boundaries and extent of the study's coverage. Much like the goal definition, clarifying the scope is essential for ensuring that the LCA study remains focused, comprehensive, and aligned with its intended purpose. This part was developed following the guidelines and explanations in Chapter 8 of the referenced book. As suggested in the book, we included and defined the following eight scope items: *deliverables; function, functional unit, and reference flows; LCI modelling framework; system boundaries and completeness requirements; representativeness of LCI data; basis for impact assessment; requirements for comparative studies and critical review needs.*

2.1 Deliverables

There are four main categories of deliverables, ranked from lower to higher complexity: LCI study and/or dataset, LCIA results, Comparative LCA study, Detailed LCI model of the analyzed system.

1. **LCI Study and/or Dataset (Lowest Complexity).** In this category, the focus is on the fundamental step of creating an LCI study and dataset. The primary objective is to collect and organize data that quantifies the environmental inputs and outputs associated with a product or system throughout its life cycle. This data encompasses details like raw materials, energy consumption, emissions, and other factors. However, this category primarily emphasizes data collection and organization, lacking in-depth analysis or interpretation. Its purpose is to serve as the foundational groundwork for more comprehensive LCA assessments.
2. **LCIA Results (Intermediate Complexity).** Moving up in complexity, the second category centers on LCIA results, which stands for Life Cycle Impact Assessment. Here, the shift is from data collection to the analysis of environmental impacts associated with a product or system. This phase involves the assessment of metrics such as carbon footprint, water usage, and toxicity. While more analytical than the first category, the main focus remains on presenting the results of the impact assessment, rather than delving into extensive alternative comparisons or complex decision-making processes.
3. **Comparative LCA Study (Moderate Complexity).** Transitioning further, the third category introduces the Comparative LCA Study, characterized by increased complexity. It entails a comprehensive and critical analysis, moving beyond mere data presentation. Rather than only presenting data or results, this type of LCA involves comparing different products, systems, or scenarios to determine which one has a lower environmental impact. Typically, it evaluates multiple alternatives, offering stakeholders valuable insights into the relative environmental performance of various options. Its main purpose is to facilitate informed decision-making by highlighting the environmental pros and cons of different alternatives.
4. **Detailed LCI Model of the Analyzed System (Highest Complexity).** Finally, the fourth category represents the highest level of complexity in LCA deliverables. This phase entails the creation of a detailed and intricate model of the analyzed product or system.

> This model encompasses all life cycle phases, incorporating detailed inputs and outputs. It empowers in-depth analysis and scenario testing, making it a powerful tool for understanding the intricate nuances of environmental impacts associated with a specific product or system. Researchers and decision-makers find this level of detail particularly valuable for exploring environmental performance intricacies and identifying areas for improvement.

Given the nature of this study (a university project), we need to be realistic about the complexity we can handle. In classifying our LCA study of the university campus energy supply, it's essential to understand that it doesn't fall into any single predefined category due to its unique characteristics and data constraints.

First, we have no specific data about the energy supply activities. Notably, it doesn't align with the first category, which involves gathering data about the composition of units and the formation of 1 kW of energy consumption. Our study doesn't focus on dissecting the detailed makeup of energy units, nor does it delve into the specific constituents of 1 kW of energy consumption.

This category would be more applicable if we had direct access to comprehensive data from the university regarding the origin, transportation, recycling processes, and other specific details of energy sourcing within the campus. However, the current energy supply for the university comes from the German grid, and the campus lacks comprehensive information on the particularities of this energy supply chain. Consequently, we've chosen to rely on existing data available in established databases and sources to inform our analysis.

To illustrate, a typical Life Cycle Inventory (LCI) study for the university might entail collecting precise data on energy sources, distribution methods, consumption patterns, and waste management practices specific to the campus. However, due to the external nature of our data sources and the absence of detailed, university-specific information, our study takes a different approach.

Moreover, our study doesn't neatly fit into the subsequent categories (LCIA results, Comparative LCA study, or Detailed LCI model) because all three categories involve a preliminary phase related to the first category, which we've established isn't the primary focus of our study. Thus, our study doesn't aim to create unit processes or data sets. Instead, it centers around evaluating the environmental impact results of pre-existing unit processes (such as those in the EcoInvent database) when scaled by the campus's energy consumption in kilowatts. These unit processes will represent various energy sources (wind, biomass, nuclear, solar, etc.), thereby incorporating elements of a Comparative Study as well.

In summary, our LCA study of the university campus doesn't fit precisely into any single category due to the nature of the data sources and our unique approach. It combines elements from different categories, focusing on the assessment of existing unit processes in relation to energy consumption patterns at the campus, allowing for a holistic understanding of its environmental impacts.

2.2 Function, Functional Unit and Reference Flows

In this part, we delve into the heart of our study – understanding what we are examining, what we are measuring, and how we are measuring the impact. This helps us build a strong foundation for our LCA study.

Function. What is the purpose? Every energy system has specific jobs it needs to do – some are necessary (obligatory) while others help it stand out (positioning). In our case, some obligatory properties are: continuous energy supply to the university campus, meeting the energy demand of the campus, compliance with environmental regulations and standards and feasible maintenance and management of the energy system. Some positioning properties could be: energy efficiency in operation or integration with energy storage systems.

Functional Unit. What are we measuring? The functional unit sets the reference point for evaluating environmental impacts and allows for meaningful comparisons between different scenarios or systems. It defines the scope and boundaries of the assessment by answering quantitative and qualitative questions like "What?" (the system or process being studied), "How much?" (the quantity or scale), "For how long/how many times?" (the time frame or frequency), "Where?" (the location or context), and "How well?" (the desired performance or quality). In our case, our answers to these questions are:

- What? Supply of electricity (here is where we decide to focus merely on the electricity supply, and leave the heat or cooling energy for future studies)
- How much? 70 megawatt-hours (MWh) (taken from TUM's electricity supply data)
- For how long/how many times? One year
- Where? Garching University Campus in Munich
- How well? Meeting the energy demand.

So, our complete functional unit would be: <u>Continuous supply of 70 megawatt-hours (MWh) of electricity to operate the university campus for one year, meeting the total energy demand.</u>

Reference Flows. What is needed to make it happen? To accomplish our established Functional Unit, a tangible supply of energy is requisite. This energy provision will be done by 70 MWh of grid electricity, 70 MWh of solar electricity (with two different PV panels), 70 MWh of electricity through biomass, 70 MWh of nuclear electricity, 70 MWh of wind electricity or 70 MWh of electricity through heat and power co-generation. These will are the 7 scenarios that we analyze in the LCA.

2.3 LCA Modelling Framework

In developing the LCI modeling framework for our study on the university's energy systems, we have taken a pragmatic approach that aligns with our goal of providing actionable insights while maintaining clarity and simplicity. Our decision context falls under category C2, focusing on micro-level, product or process-related decision support studies. Given this context, we have chosen to adopt the attributional principle as our LCI modeling framework.

The attributional principle, also known as "attributional LCA," is based on the idea of attributing environmental impacts to the processes or activities directly responsible for them. In other words, it focuses on assessing the environmental consequences of a specific product or system without considering the potential changes in the broader system because of its existence. This approach is often used for analyzing existing products, processes, or systems and is typically static in nature.

Our aim is to assess the primary environmental impacts associated with the energy supply systems on our campus. As such, we have decided to focus exclusively on the main function of these systems, which is the generation and distribution of energy. By doing so, we aim to avoid introducing unnecessary complexity related to secondary functions or co-products, such as those arising from cogeneration, waste heat utilization or grid stabilization.

While the cogeneration system on our campus is an integral part of our energy infrastructure, we believe that focusing on its primary function aligns with our study goals and simplifies our analysis. This approach allows us to provide valuable insights into the environmental performance of our energy systems without delving into complex allocation or crediting procedures.

In conclusion, our chosen LCI modeling framework, based on the attributional principle, provides a practical and clear path to assess the environmental impacts of our university's energy systems. By omitting the complexities of allocation and crediting for secondary functions, we ensure that our findings are both actionable and comprehensible for a diverse audience. Given our decision not to create inventories or develop unit processes, complexity beyond this framework is unnecessary.

2.4 System Boundaries and Completeness Requirements

Understanding and defining the system boundaries in a Life Cycle Assessment (LCA) is of paramount importance as it directly impacts the comprehensiveness and accuracy of the study. In our pursuit of being as inclusive and holistic as possible in our assessment, we aim to encompass the entire life cycle of the energy systems on our university campus, from material extraction to recycling after the end of their operational life.

Nevertheless, we have encountered a challenge related to the use of preexisting units from databases like EcoInvent. While these units come with descriptions, understanding the precise processes included or omitted can be challenging, especially for someone who did not create them.

Therefore, the completeness and accuracy of the preexisting units in databases like EcoInvent play a critical role in the reliability of our LCA. If these units do not fully encompass the entire life cycle of energy production and distribution, our analysis may not be as complete as desired.

2.5 Representativeness of LCI Data

In our LCA study, this section holds limited relevance due to the nature of our research. Unlike studies where data selection and creation of inventory activities are integral to the research process, our study relies on pre-existing activities sourced from the EcoInvent database. However, it is still worth noting some aspects related to the representativeness of the data for a comprehensive understanding.

Geographical representativeness. The activities available in our EcoInvent database are assumed to be geographically representative, specifically tailored to the context of Germany, aligning with the geographic scope of our study. This ensures that the data utilized corresponds to the regional context where our university campus is situated.

Temporal representativeness. For our study's objectives, it is essential to acknowledge the temporal representativeness of the data. In most cases, the descriptions of the activities within the EcoInvent database indicate that the data used for their creation dates back to 2012. This temporal representation is deemed sufficient for our study's purposes, as it offers a baseline understanding of the environmental impacts associated with the selected activities during that time frame.

Technological representativeness. For more detailed insights into the technical, temporal, or geographic representativeness of the data, we recommend referring to the descriptions of the individual activities as provided by their creators. These descriptions can be found in the Annex, offering a comprehensive source of information regarding the specifics of each activity's representativeness.

In summary, while the "Representativeness of LCI Data" section may hold limited relevance in our case due to our use of pre-existing activities, we have ensured that the selected data is geographically and temporally representative for our study's objectives. Detailed technical and geographical information about the data sources can be found in the activity descriptions provided in the annex.

2.6 Basis for Impact Assessment

The Basis for Impact Assessment section outlines the methodology for selecting impact categories and corresponding Life Cycle Impact Assessment (LCIA) methods, aligning them with the goals and scope of our study on the university's energy systems.

The choice of a Life Cycle Impact Assessment (LCIA) method can be a complex task in academic research due to the multitude of available methods that are continually evolving to better reflect our understanding of environmental and social impacts. Staying up-to-date with these ever-evolving methodologies can be overwhelming, making it challenging to make clear-cut decisions.

On the one hand, modelling impacts at midpoint is considered sufficient for one goal of our study: understanding the LCA in general terms. For this, we have used the CML method. CML stands for "Center of Environmental Science, Leiden University" (Centrum voor Milieuwetenschappen Leiden). The categories analyzed include acidification (unit: kg SO2 eq.), climate change (kg CO2 eq.), freshwater ecotoxicity (kg 1,4 DCB eq.), marine ecotoxicity (kg 1,4-DCB eq.), terrestial ecotoxicity (kg 1,4-DCB eq.), energy resources ADP (megajoule), eutrophication (kg PO4 eq.), human toxicity (kg 1,4 DCB eq.), material resources ADP (kg Sb eq.), ozone depletion (kg CFC 11 eq.) and photoquemical oxidant formation (kg ethylene eq.)

One primary reason for choosing the CML method over others, such as ReCiPe, is its simplicity and widespread use in academic programs aimed at introducing students to life cycle assessment (LCA) and environmental impact evaluation. The CML method offers a straightforward and comprehensible framework, making it suitable for educational purposes and for providing a clear understanding of LCA principles. While ReCiPe is renowned for its comprehensive analysis capabilities, we determined that it may go into more detail than necessary for the specific focus of this study. For instance, within the ReCiPe framework, various types of eutrophication impacts, such as freshwater and marine eutrophication, are distinguished. However, given the nature and objectives of this research, we deemed it more appropriate to maintain a simpler approach. This allows us to maintain clarity in our impact assessment, making it easier to communicate and understand the results.

On the other hand, the other part of our goal study is to analyze the effectiveness of the LCA method on asserting social impacts. For that, we also considered necessary to analyze some endpoint categories, that offer a broader perspective by considering the potential consequences of these midpoint impacts on larger environmental and societal factors. This analysis though, is done in a shorter version with more of a qualitive approach, and the results and interpretation will only be commented in the *Discussion: Social Approach* section of this thesis. The results can be found in the *Appendix*. We used the IMPACT 2002+ method for analyzing four midpoint impact categories: climate change, ecosystem quality, human health, and resources. This method keeps the endpoint categories to four and uses the same unit (score) for all impact categories, providing a convenient means to summarize and compare the overall environmental performance of different scenarios.

Also, a more deepen analysis will be done for the "land occupation" subcategory (also in the *Discussion: Social Approach* section of the thesis), since we consider they more directly address the social impact that we are trying to assess.

2.7 Requirements for Comparative Studies

The requirements for a comparative study, such as those regarding quality, exclusion of identical processes, and interpretation considering stakeholders, are typically applicable to reports at level 3 (i.e., comparative studies intended for public disclosure). Our case study is as defined in section 1.5 not meant for public disclosure. However, one of our goals is to compare different energy systems, and for ensuring a robust and transparent evaluation, we have maintained functional equivalence by employing a consistent "1 GWh of supplied energy" functional unit for fair energy system comparisons. Additionally, data quality has been ensured through uniform reliance on the Ecoinvent database. Our study is committed to methodological rigor and transparency, bolstering the validity of our comparative assessment of the university's energy systems.

2.8 Critical Review Needs

This is a comparative study but since it is not intended for disclosure to the public, there is no obligation for a critical review by a third-party panel.

3 Inventory Analysis

The inventory analysis phase, typically the most time-intensive component of a conventional Life Cycle Assessment (LCA), assumes a pivotal role in assembling the requisite data for the study. This phase involves collecting and organizing data on elementary flows from all processes within the studied product system, drawing upon various sources. The resulting inventory of elementary flows serves as the foundation for the next life cycle impact assessment phase. It is worth noting that, in our specific case, as outlined in Section 2.1 on *Deliverables*, we will not be generating a comprehensive inventory. Nonetheless, our objective remains to comprehensively examine each section, providing insights into the detailed inventory compilation process that would be undertaken in a full-fledged LCA. Thus, while we won't execute the complete inventory, our analysis will shed light on the intricacies involved.

This part was developed following the guidelines and explanations in Chapter 9 of the referenced book (Bjørn et al., 2018b). As suggested in the book, we included and defined the following five steps of an LCI analysis: *LCI model at system level, data collection, system modelling per life cycle stage, basis for sensitivity and uncertainty analyses and calculated LCI results.*

3.1 LCI Model at System Level

In the assessment of the energy supply for our university campus, the creation of a comprehensive Life Cycle Inventory (LCI) model at the system level presents specific challenges and considerations. As we utilize activities directly available in the Ecoinvent database, it is essential to recognize that the system boundaries are inherently defined by the activities designed within that database. This implies that we are constrained by the system boundaries pre-established by the activity designers, limiting our ability to customize the boundaries for our specific analysis.

Each activity within the Ecoinvent database represents a predefined process or system with its inherent inputs and outputs. The details of recycling or other post-energy supply processes may not always be explicitly considered in these activities. Consequently, our analysis is confined to the boundaries and environmental impacts that are integrated into these predefined activities.

In an LCAI report, it is crucial to distinguish between foreground processes and background processes. Foreground processes represent the specific activities that have been chosen to investigate and include in the LCI model. On the other hand, background processes typically encompass the upstream and downstream processes associated with the foreground processes but are not individually analyzed due to their complexity or their lack of direct influence on our decision-making.

In the campus scenario, the university's decision to install and maintain solar power installation on campus, for example, would represent the foreground system. The university can directly control and make specific decisions about the installation, including the type and capacity of solar panels, maintenance schedules, and any potential expansion of the solar infrastructure. This foreground process is within the university's direct influence, and they can tailor it to their sustainability goals and energy needs.

On the other hand, the electricity supplied by the national grid serves as the background system. While the university can choose to purchase electricity from the grid, they have limited control over how that electricity is generated or the specific sources used by the grid. The background system includes various power generation methods (e.g., fossil fuels, nuclear, renewables) and grid management processes that are beyond the direct control of the university. The efficiency and environmental impact of the grid's electricity generation are important factors but are not individually manipulated by the university in this context.

However, it is important to note that, in our case, differentiating between foreground and background processes is not particularly relevant or meaningful. Our analysis is focused on assessing the environmental impacts generated by individual activities within the context of various energy supply scenarios. The decisions we can make in our foreground system involve selecting one energy source over another for powering our campus. These choices, though significant, do not directly influence the environmental impact generated once the activity has been determined. In essence, we are evaluating the consequences of selecting specific energy sources within the predetermined system boundaries of each activity, rather than defining complex foreground and background processes.

Therefore, our approach to the LCI model at the system level primarily involves the assessment of individual activities under extreme scenarios, rather than attempting to modify system boundaries or delve into intricate foreground-background distinctions. Our focus remains on quantifying the environmental impact associated with our campus's energy supply choices, considering the inherent boundaries and assumptions encapsulated within each selected activity.

3.2 Data Collection

In the process of developing a Life Cycle Assessment (LCA) model, data collection is a fundamental step that underpins the accuracy and reliability of our analysis. However, it is important to emphasize that in our case, the has barely been any data collection since our study relies extensively on activities readily available within the Ecoinvent database, and the data included in our assessment are inherent to these predefined activities.

As an example, consider the activity representing the supply of 1 kWh of electricity from the German market for electricity from the grid. The data used in this activity, including information about the German electricity provision, are collected, and curated by the activity creator. This includes details such as grid characteristics, energy mix, and emissions factors for electricity production, which are essential for our LCA.

However, we can provide a simplified overview of how the data collection process for an LCI study looks like, using the example of creating a unit activity for electricity generated from both onshore and offshore wind turbines, which we custom-made using the Activity Browser.

In this case, we needed to collect data on the percentage of onshore and offshore wind turbines in Germany and assume that this percentage corresponds to the electricity generated by onshore and offshore turbines. Then, we converted that data into a proportion, allowing us to create a unit activity in EcoInvent that represents the quantity of kilowatt-hours of electricity generated from onshore and offshore sources per kilowatt-hour of total wind-generated electricity.

Finally, the last piece of data that we used in the modelling of our scenarios is the annual electricity consumption of the campus. This critical metric has been directly obtained from authoritative sources within the Technical University of Munich. Presently, the campus consumes a total of 70 GWh of electricity annually.

3.3 System Modelling per Life Cycle Stage

In this section of the LCA report, it's important to acknowledge that we cannot provide a comprehensive description of the System Modeling per Life Cycle Stage. This limitation arises from the fact that we were not the creators of the data used in this study. To gain insight into the processes included in each scenario, we rely on the descriptions provided by the creators of the EcoInvent activities. However, it's essential to note that these descriptions do not consistently specify which life cycle stages were considered in the analysis or which stages may have been omitted due to data limitations.

Referring to the "Process contribution" graphs included in the Annex can be helpful to read some processes involved in each scenario. In the legend, there are named a few processes that can be classified into one of the first three stages of a life cycle: raw materials processing, assembly, and installation; transport and operation.

However, we haven´t found any mention to processes related to the recycling of electrical components within each scenario, which makes us think that the creators of the activities might not have taken into consideration the last stage of life cycle: end-of-life waste management.

3.4 Basis for Sensitivity and Uncertainty Analyses

The "Basis for Sensitivity and Uncertainty Analyses" section is pivotal in a Life Cycle Assessment (LCA) because it provides critical insights into the reliability and robustness of the study's findings. By conducting sensitivity and uncertainty analyses, researchers can identify the key parameters and data inputs that have the most significant influence on LCA results, pointing out potential sources of variability and inaccuracy. This understanding is crucial for stakeholders and decision-makers as it helps them assess the confidence and validity of the LCA outcomes, ultimately guiding more informed and well-founded environmental decision-making. Therefore, this section plays a vital role in enhancing the transparency, credibility, and overall utility of the LCA study.

In our specific case, we have chosen not to conduct sensitivity and uncertainty analyses for practical reasons. While these analyses can offer valuable insights, they can also be resource-intensive and time-consuming, requiring extensive data collection and manipulation. Additionally, since we have utilized existing activities from EcoInvent for our study, the sensitivity and uncertainty coefficients are already embedded in these activities, offering a certain level of inherent robustness. Furthermore, advanced techniques such as Monte Carlo simulations could potentially be employed to explore sensitivity and uncertainty, considering the inherent variability within these activities. However, given the limitations in resources and time constraints, we have opted to avoid this detailed analysis, as it is not essential for achieving the primary objectives of our study.

3.5 Calculated LCI Results

In this section of a Life Cycle Assessment (LCA), the results of the Life Cycle Inventory (LCI) analysis are typically presented. This phase of an LCA is where the inputs and outputs associated with the various processes within a product system are calculated.

Due to the specific nature of our study, we want to emphasize that we have not conducted the inventory of the activities we analyzed ourselves. Instead, we have utilized pre-existing activities from the Ecoinvent database.

The activity representing the mix of electricity generated by onshore and offshore wind turbines is an exception of this. There is no activity in the database strictly representing this, which is why we created it ourselves. This creation can be seen as a very simplified unit processes and life cycle inventory creation. As you can see in the following chart, the unit process only consists of two other activities as inputs.

Table 3.5: Inventory of the unit process “Mix of onshore and offshore wind energy in Germany 2023” corresponding to our Scenario 7 of study.

Activity	**Scenario 7**	**Unit**	**Source/note**
Output (main product or function)			
Production of 1 kWh of mix onshore and offshore wind energy in Germany 2023	1	kWh	process output
Output (waste to treatment)			
Disposal of turbines	0		not considered
Inputs (materials, energy, resources)			
Electricity production, wind, >3MW turbine, onshore	0,875*	kWh	ecoinvent
Electricity production, wind, 1-3MW turbine, offshore	0,125*	kWh	ecoinvent

*in our analysis, we derived the proportion of 87.5% onshore wind electricity and 12.5% offshore wind electricity based on data obtained from Deutsche WindGuard GmbH. According to their reports, Germany had an installed offshore wind capacity of 8,3 megawatts (MW) in the first half of 2023, while the total installed capacity of onshore wind energy stood at 58,1 MW. These figures allowed us to estimate the contribution of each source to the electricity blend accurately.

4 Impact Assessment

The Life Cycle Impact Assessment (LCIA) marks the fourth phase in an LCA study, where the information collected during the life cycle inventory phase, specifically the elementary flows, is transformed into environmental impact scores. LCIA is often automated by LCA software and in our case, we used the Activity Browser tool.

In the Life Cycle Impact Assessment (LCIA) phase, as explained in Chapter 10 of the referenced book (Rosenbaum et al., 2018), several **mandatory steps** play a pivotal role in the translation of life cycle inventory data into meaningful environmental impact scores. First, the *selection of impact categories, category indicators, and characterisation models* is a crucial process that delineates which specific impacts will be assessed. In our case, we've already made this selection by opting for the CML method, which inherently includes predefined impact categories.

Secondly, the *classification* step assigns the results from the life cycle inventory to relevant impact categories based on their known potential effects. Fortunately, this classification process has been automated for us, thanks to the pre-existing activities in the EcoInvent database and the utilization of the Activity Browser software, which collectively aid in associating each LCI result with its corresponding impact category.

Lastly, the *characterisation* step quantifies the contributions of inventory flows to different impact categories, providing insights into the extent of their influence. It's noteworthy that this facet of the process was already embedded within the Ecoinvent software, streamlining the calculation of how much each LCI result contributes to the selected impact categories. The characterized results, represent the environmental impacts of a product or system across various impact categories. These impacts are expressed in quantitative terms, and they involve the translation of the inventory data collected during the LCA into impact scores, allowing stakeholders to understand the specific environmental consequences associated with the analyzed product or system. These scores help identify areas of concern and prioritize improvement efforts, making it a crucial part of the LCA process. The characterized impacts for each electricity supply scenario can be found in the Appendix in Table A.1. Figure 4.1 is more useful to visualize the results.

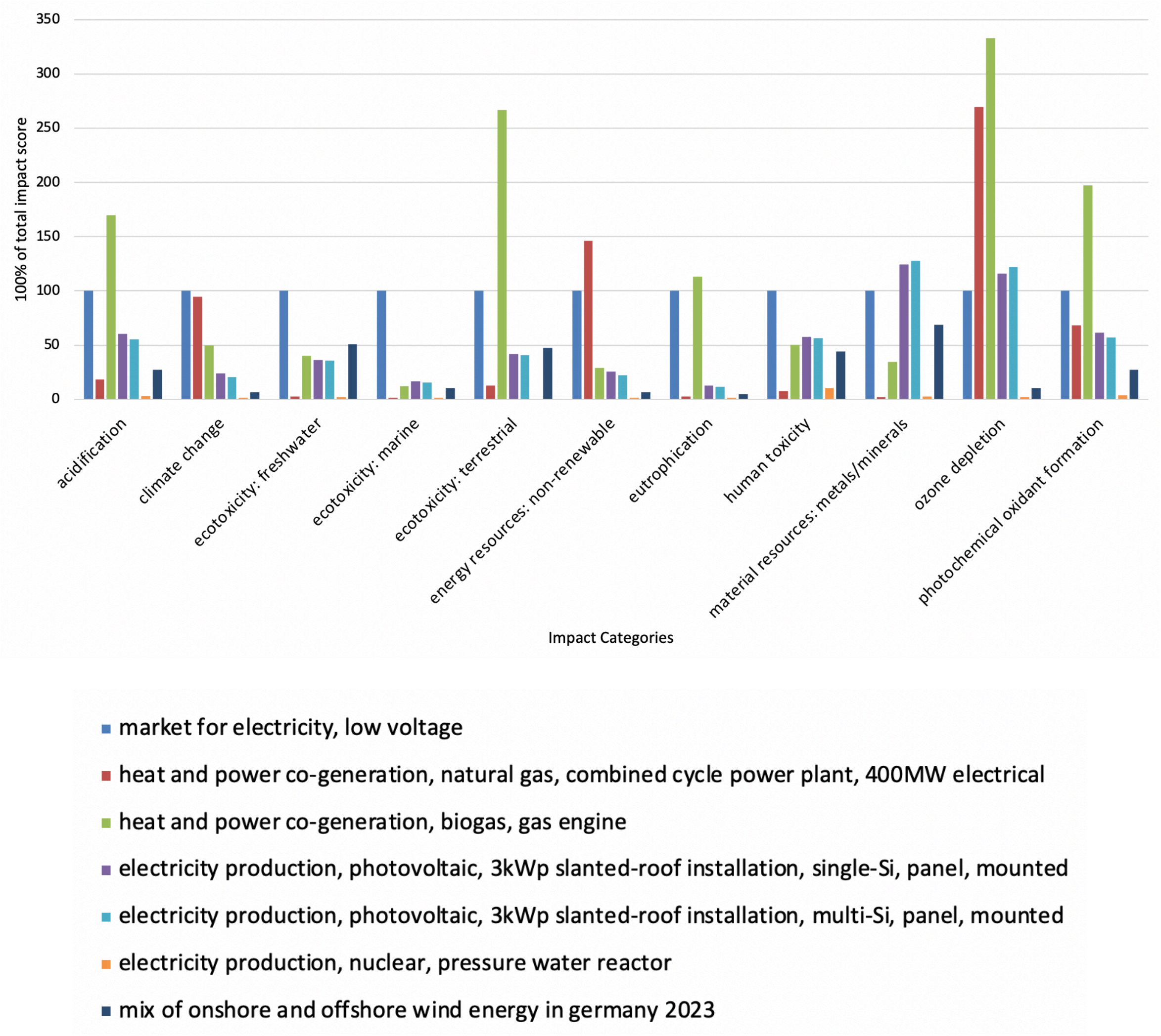

Figure 4.1: Characterized impacts for each electricity supply scenario with impact scores scaled to those of the electricity from the German grid scenario. This scenario (“market for electricity, low voltage) is the current scenario happening in the campus, equal to 100% of total impact.

Within the Life Cycle Impact Assessment (LCIA) phase, there are **optional steps** that provide further depth and context to the assessment process. One such step is *normalization*, where LCIA results are expressed in relation to those of a reference system. This allows us to understand how the impacts of various energy scenarios compare to a standard reference system, providing insights into their relative significance. In our case study, we've chosen to perform normalization to assess the significance of environmental impacts in the broader context of the chosen reference system. The normalization factors that we used can be found in Table 4.3 and the normalized impact scores for each electricity supply scenario can be found in Figure 4.4.

Additionally, there's the optional step of *weighting*, which involves prioritizing or assigning weights to each impact category based on specific criteria. We avoided this step, since it requires subjective decisions about the relative importance of different impact categories, which may vary depending on the study's objectives and perspectives.

Furthermore, there's the *grouping* step, where several impact indicator results are aggregated into a group. This step can simplify the interpretation of results by combining similar impacts into broader categories. However, in our case study, we have not implemented the grouping step, as our focus has primarily been on normalization and understanding the impacts at the individual category level.

Table 4.3: Normalization factors for each impact category

Impact Category	Unit	CML Normalization Factors
acidification	kg SO2 eq./yr	2,39E+11
climate change	kg CO2 eq./yr	4,18E+13
ecotoxicity: freshwater	kg 1,4 DCB eq./yr	3,48E+12
ecotoxicity: marine	No normalization factor founded	
ecotoxicity: terrestrial	kg 1,4-DCB eq./yr	1,09E+11
energy resources: non-renewable	Megajoule eq/yr	4,50E+14*
eutrophication	kg PO4 eq./yr	1,58E+11
human toxicity	kg 1,4 DCB eq./yr	3,82E+13
material resources: metals/minerals	kg Sb eq./yr	4,39E+08*
ozone depletion	kg CFC 11 eq./yr	2,30E+08
photochemical oxidant formation	kg ethylene eq./yr	5,44E+10

Source: World 2000 and *European Commission (these lasts, are based on EF 2017 method, not CML and there might be some inconveniences with that).

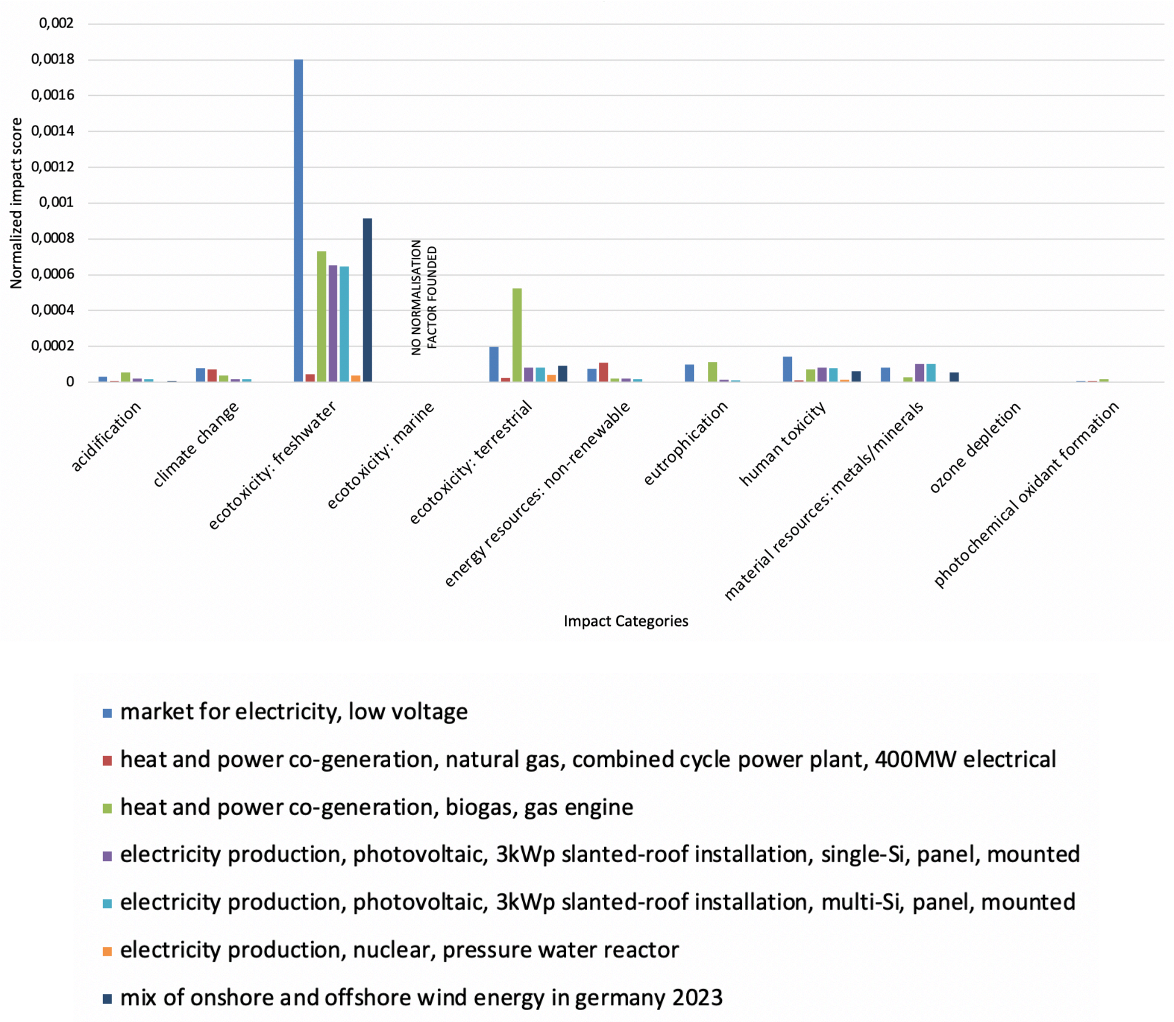

Figure 4.4: Normalized impact scores for each electricity supply scenario.

Now, we will delve into the detailed outcomes of the characterized impact results, represented in Figure 4.2 and Figure 4.3. Our primary focus will be to analyze the variations in impact categories from one scenario to another, emphasizing the relative improvements or deteriorations observed.

Electricity from the grid is the primary contributor to several environmental impacts, including global warming, ecotoxicity in freshwater, ecotoxicity in marine water, and human toxicity. It ranks second in all cases, except for material resources, where it is third, following the two photovoltaic energy sources studied. One noteworthy aspect is that it has a lower contribution to ozone depletion compared to other energy sources (only nuclear and wind energy have less contribution).

The heat and power co-generation with natural gas in a combined cycle, has the highest impact on non-renewable energy resource depletion. The use of natural gas in this process significantly contributes to depleting non-renewable energy resources, as natural gas itself is a non-renewable resource.

Heat-power cogeneration with biogas is a significant contributor to acidification, terrestrial ecotoxicity, eutrophication, ozone depletion, and photochemical oxidant formation. It ranks within the top four energy types in terms of impact contribution in these categories. However, as we expected, it reduces CO2 emissions by nearly half compared to grid electricity or a combined cycle of natural gas with heat and power co-generation. A reason for this, is that biogas is a low-carbon and renewable energy source, primarily derived from organic materials like agricultural waste and manure. By using biogas instead of fossil fuels or natural gas, emissions are significantly reduced, contributing to climate change mitigation. Additionally, it is the third least impactful option concerning the depletion of raw materials.

Photovoltaic electricity scenarios generally exhibit lower environmental impacts compared to grid electricity, with two exceptions: material resources and ozone depletion. Photovoltaic panels, especially multi-Si panels, have a significant impact on material resources due to the various materials involved in their production, including silicon, metals, glass, and polymers. The extraction, processing, and transportation of these materials contribute to material resource impact. In terms of ozone depletion, multi-Si panels are the most significant contributors, followed by single-Si panels.

One objective of the study was to compare the environmental impacts of multi-Si and single-Si photovoltaic panels. We have seen that multi-Si panels have a higher impact on material resources and ozone depletion, but single-Si panels perform slightly better in the rest of categories.

Moreover, it is intriguing to observe that *nuclear energy* has significantly lower overall environmental impacts compared to other alternatives in nearly all scenarios. This is likely related to its high energy efficiency and low greenhouse gas emissions during production. Lastly, *wind energy*, along with nuclear energy, stands out as the only alternative that improves environmental impacts in all categories compared to grid electricity.

These conclusions are derived from an analysis of the characterized results of impact categories. To further enrich our understanding, we will now delve into the normalized results, which provide an intriguing perspective. Normalization allows for a comparative assessment, highlighting the relative performance of each energy source in specific impact categories. Figure 4.5 shows the normalized results. The common unit for indicator scores is equivalents per year (eq/yr) representing their environmental performance on an annual basis. This helps in understanding which source has a lower or higher impact on specific environmental categories when considering the same timeframe.

In nearly all categories, our results indicate that the environmental impacts associated with the different scenarios are consistently below 0.0002% of the global impact per year. Notably, in the category of ecotoxicity in freshwater, the campus's current electricity supply, relying on 70 MWh from the German grid, appears to contribute significantly more. According to these findings, our current electricity consumption pattern contributes approximately 0.0018% to the annual global impact on freshwater ecotoxicity.

5 Interpretation

The interpretation phase in a Life Cycle Assessment (LCA) is the culmination of the entire study, where the results obtained in the preceding phases are thoroughly examined and analyzed. This analysis is conducted while considering the uncertainties associated with the data used and the assumptions made and documented throughout the study.

Regarding Chapter 12 of the referenced book, there are three elements in this phase: identification of significant issues, evaluation (the evaluation involves completeness check, sensitivity analysis in combination with uncertainty analysis and consistency check) and conclusions, limitations, and recommendations.

We have decided to provide a simplified interpretation of the obtained results, as we believe that the data and graphs presented in the previous section are sufficient for the purpose of this study (we do not intend to make decisions regarding the campus's electrical supply, for which a more careful interpretation involving sensitivity analysis, uncertainty assessment, or consistency checks would be necessary). However, in line with the idea of demonstrating what a complete report would entail, we will briefly outline the steps required for a proper interpretation. For instance, if we were to follow the typical LCA report template, this section should be subdivided into three parts:

1. Significant Issues: In this section, we would need to analyze the Process Contribution and Substance Contribution, to gain further insights into the causes of environmental impacts. These analyses are conducted based on graphs generated from the LCA software (Activity Browser in our case), which separately illustrate the contribution of each process and substance within an activity to each impact category. The graphs of our case study can be found in the Annex of the paper. For example, looking at Figure 5.1, we could investigate why energy consumption through the German electrical grid has a significant impact on freshwater ecotoxicity. We might discover that processes like the treatment of spoil from lignite mining in surface landfills, along with the treatment of municipal solid waste, are the sub-processes that contribute most to this category.
2. Sensitivity and Uncertainty Check: This step would be necessary if we had modeled the energy processes ourselves, as assumptions and choices made during system modeling can influence study conclusions. Here, we would assess how impacts generated by the system change when we alter parameters, such as the quantity of materials required for the creation of 1 kWh, for example. However, in our case, we have utilized pre-existing activities and, therefore, do not need to assess their sensitivity or uncertainty.
3. Completeness and Consistency Checks: Completeness checks involve a comprehensive review of all stages in the product life cycle, ensuring that each stage has been considered in the analysis. This also includes verifying the inclusion of all relevant environmental impact categories. Consistency checks, on the other hand, entail reviewing data sources, assumptions, and models to confirm their alignment with the study's goals and scope. This encompasses checking that the chosen functional unit, system boundaries, and allocation methods are consistent with the study's overall objectives. Once again, it's important to note that this analysis is not within the scope of our study's objectives.

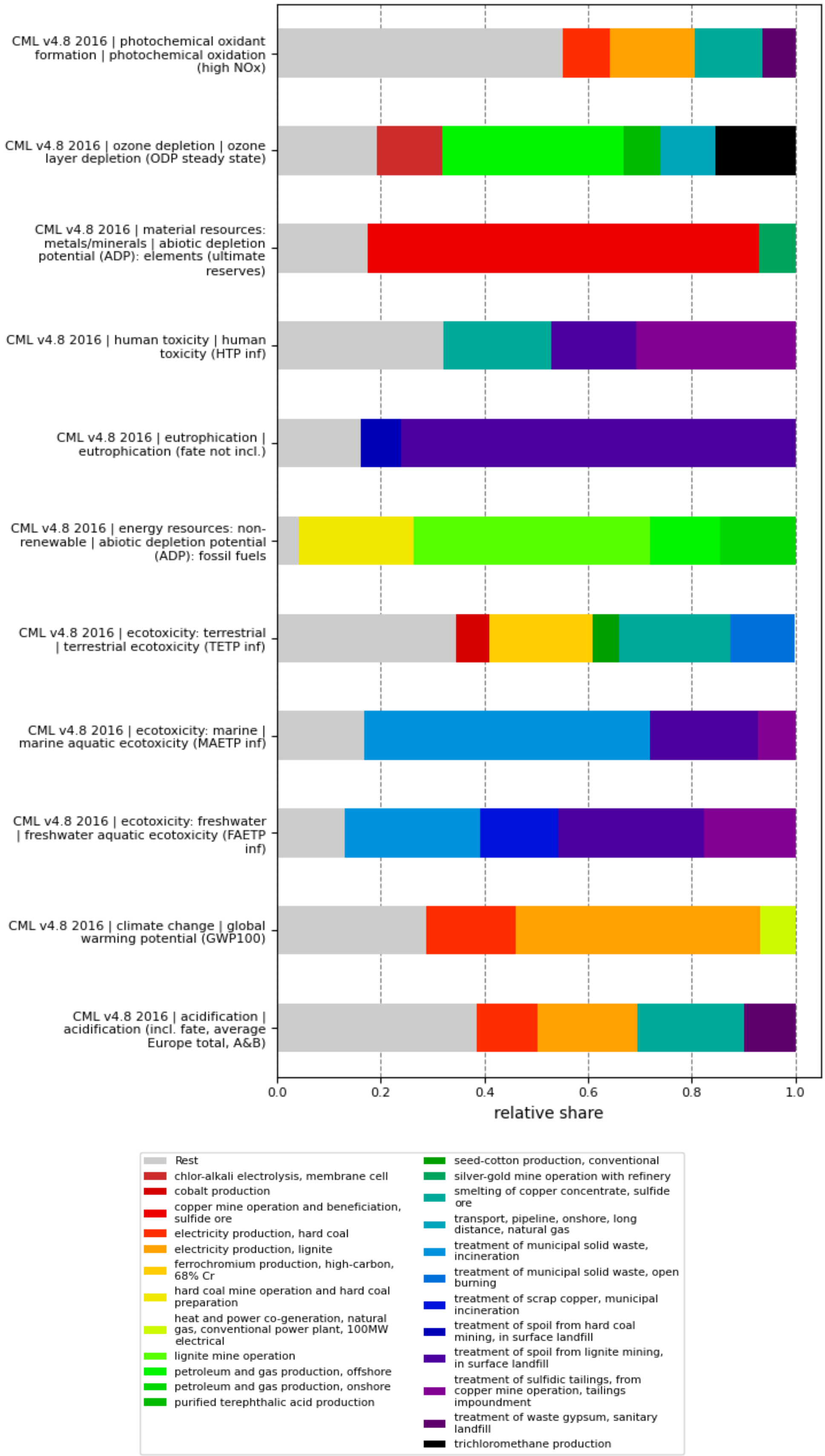

Figure 5.1: Process contribution to each impact category of the CML method in the scenario where the campus electricity supply is entirely done through the German electricity grid.

Discussion: Social Approach

So far, the results of a Life Cycle Assessment (LCA) using the CML method can be sufficient to assess the environmental impact of a product or process quite comprehensively. We have observed that this method focuses on identifying and quantifying the most significant environmental impacts, providing an overview of how a system affects the natural environment. However, when it comes to assessing the social impact, the results of LCA with CML may fall short. The main reason is that CML tends to focus on direct environmental impacts, overlooking more complex and subjective social aspects. For a comprehensive social assessment, additional approaches are necessary, such as Social Life Cycle Assessment (S-LCA) or considering specific social impact indicators and metrics. These can include factors such as employment, healthcare aspects, poverty alleviation, quality of life, and other social aspects not fully reflected in CML.

The limited availability of literature on specific social impact indicators and metrics poses a significant challenge when attempting to thoroughly evaluate social aspects in a Life Cycle Assessment (LCA). Given this limitation, our research aims to explore whether simply using a different LCA method, while keeping other factors such as methodology, software, and scenarios constant, could yield different results. If so, it may shed light on whether there is a more socially oriented approach underlying that method.

Therefore, we chose to conduct a second LCA using a different method, the IMPACT 2002+ Endpoint method, instead of CML. Analyzing endpoint impact categories in the study of the social impact of an energy system is highly relevant for several fundamental reasons. Firstly, these categories provide a clearer and more accessible understanding of the final outcomes of the system, facilitating communication of findings to a diverse audience, including decision-makers and society at large. Moreover, by focusing on key categories such as human health, air quality, biodiversity, and other social and environmental aspects, the areas where the energy system directly impacts people's lives, and the environment can be more effectively identified. This, in turn, enables more informed decision-making and the implementation of concrete measures to mitigate negative impacts and promote a more sustainable energy system for society.

The "IMPACT 2002+ Endpoint" method stands out in the field of Life Cycle Assessment (LCA) for its focus on the final outcomes of environmental impacts. Widely recognized and used, this method covers four impact categories: climate change, ecosystem quality, human health, and resources. We selected this method because it was available in the Activity Browser, and it evaluates each category in points. This suggests a subjective assessment of the importance of each category, sparking our curiosity about which energy system it might recommend based on its scoring.

The results of this LCA can be found in Appendix B. As you can see, in Figure 6.1, the results of this LCA show that the scenario with the most points in a category is nuclear electricity, which always had the best scores (across all categories) in the CML method. This raises questions about the construction of each method and how, with the same activities, scenarios, and kWh amounts, they yield such different results. We assume that differences in assumptions and data used in each method can vary considerably, influencing how environmental and social impacts are quantified. Furthermore, the choice of specific impact categories and their relevance in each method plays a significant role. For example, CML might focus on categories where nuclear energy has notable advantages, such as low greenhouse gas emissions, while the IMPACT 2002+ Endpoint method may consider a broader set of impacts, including radioactive waste management and safety, which have always been significant challenges for nuclear energy.

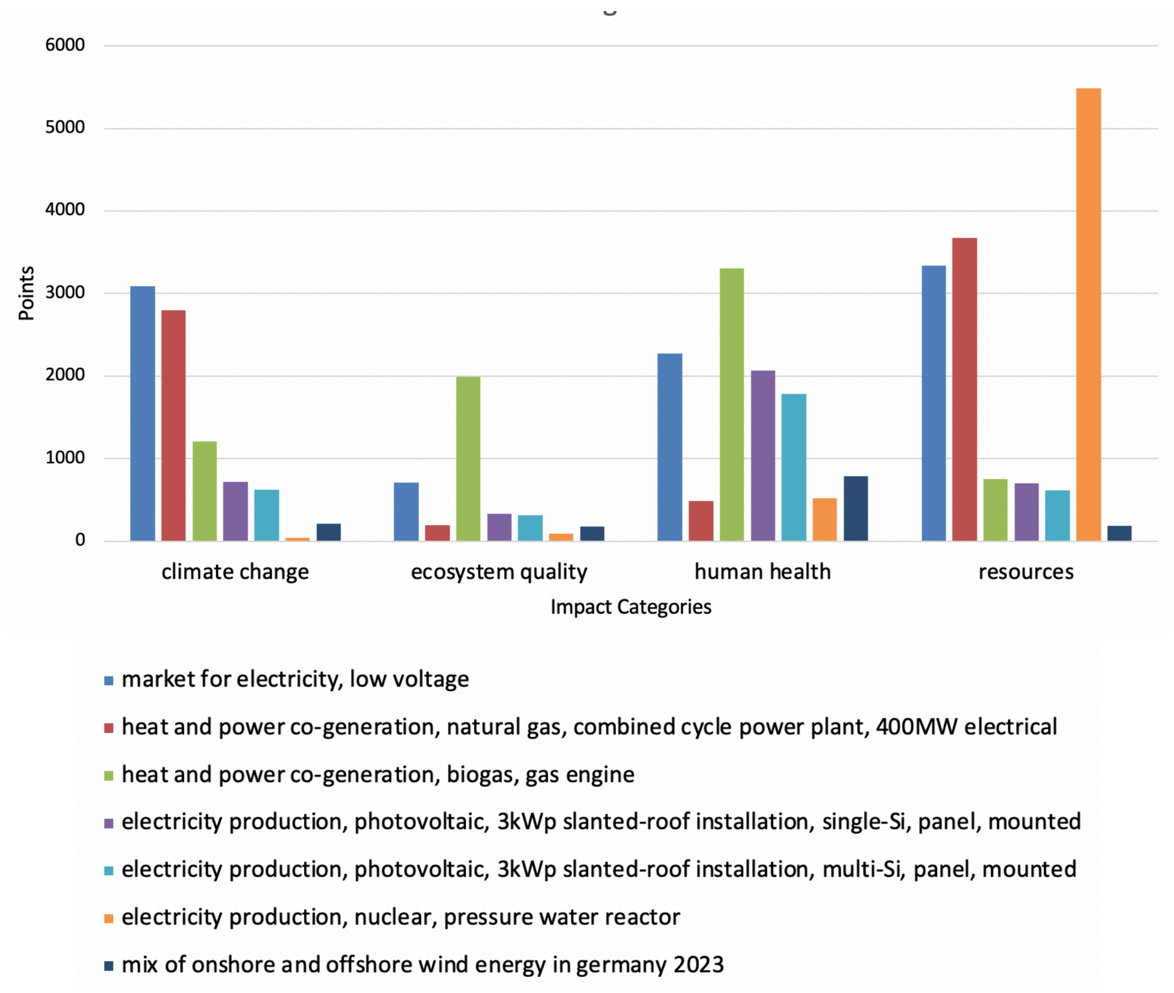

Figure 6.1: Characterized impacts for each electricity supply scenario with “IMPACT 2000+ Endpoint” method.

Finally, we would like to relate all these findings to what served as the source of inspiration for this work. In David Roberts' interview with Jessica Wilkinson and Nels Johnson of The Nature Conservancy, the scientists explain their fundamental concern regarding land occupation and its social effects in the context of the transition to clean energy sources. Jessica and Nels highlight the growing local opposition and concerns about land use and the environment as we move towards a massive implementation of renewable energy.

The central issue revolves around the conflict between the need to expand renewable energy to combat climate change and land occupation, some of which is environmentally sensitive. It is discussed how this conflict can generate resistance in local communities and how land use planning decisions can affect both nature and people.

Therefore, we have also wanted to specifically study the impact that our seven scenarios have on the "land occupation" category. As we have observed, this category is not found in the CML method, nor in the final categories of the IMPACT 2000+ Endpoint method. In the latter, it is found as a subcategory when analyzing the impact in the "ecosystem quality" category. The subcategories of this category are aquatic ecotoxicity (with 650 points), land occupation (30 points), terrestrial acidification and nutrification (19 points), and terrestrial ecotoxicity (636 points). Therefore, we wanted to visualize the results graphically only for the "land occupation" subcategory to assess which scenario would be the most detrimental based on the concerns of The Nature Conservancy. The results can be seen in Figure 6.2.

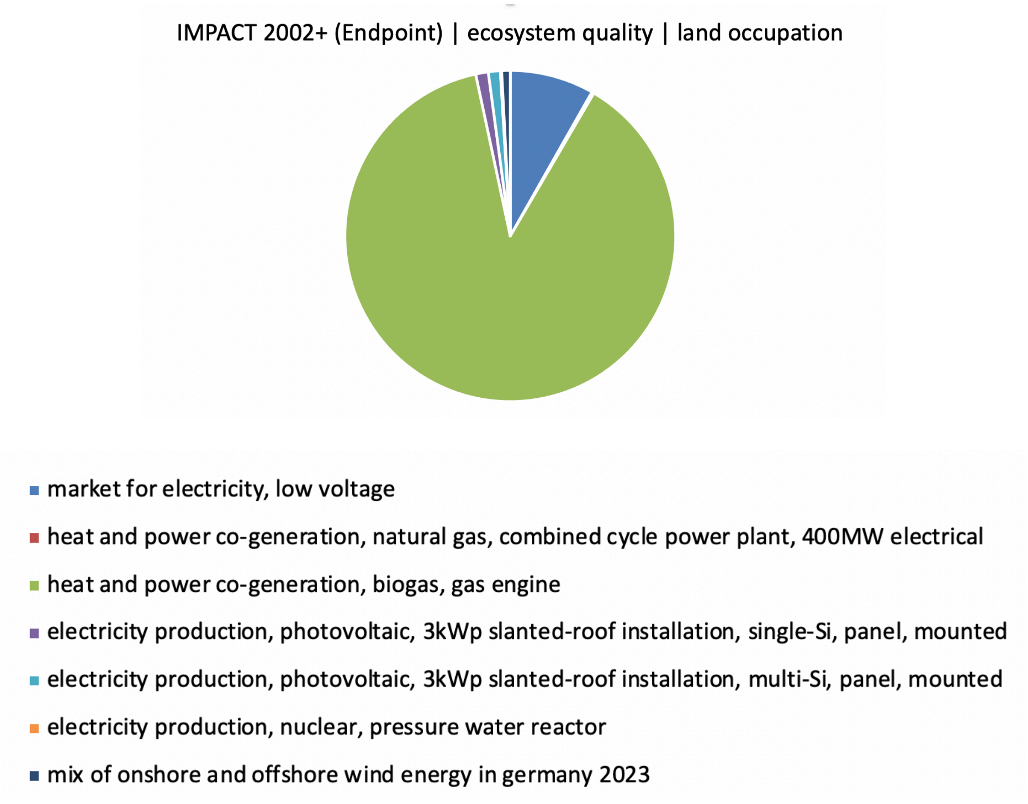

Figure 6.2: Characterized impacts for each electricity supply scenario to the land occupation category of the "IMPACT 2000+ Endpoint" method.

As we can see in the results, the scenario of electricity production through biogas has the most significant impacts on land use. Although this category is only considered by the method with 30 points in the ecosystem quality category, we can see in Figure 6.1 that this scenario also contributes the most to it, which leads us to assume that it will also be the most significant contributor in the rest of the subcategories.

Finally, to use and demonstrate another functionality of the LCA software in this work, if we wonder, for example, what exactly is the reason why biogas contributes so much to land occupation, we can use the Sankey diagram.

A Sankey diagram in a Life Cycle Assessment is a visual representation that shows the flow of resources or energy throughout a process or system in a flowchart format. It is a useful tool to illustrate clearly and concisely how resources or energy are distributed in different stages of the life cycle of a product, process, or system, as well as to identify key inputs and outputs.

Observing Figure 6.3, we can see that the main reason why electricity generated from biogas contributes to land occupation is due to the use of manure, liquid waste, and cattle from milk production from cows. This process is closely related to the biogas market through the anaerobic digestion. Anaerobic digestion is a biological process in which microorganisms break down organic matter, such as manure and liquid waste, in the absence of oxygen. This process produces biogas, which is used as a renewable energy source.

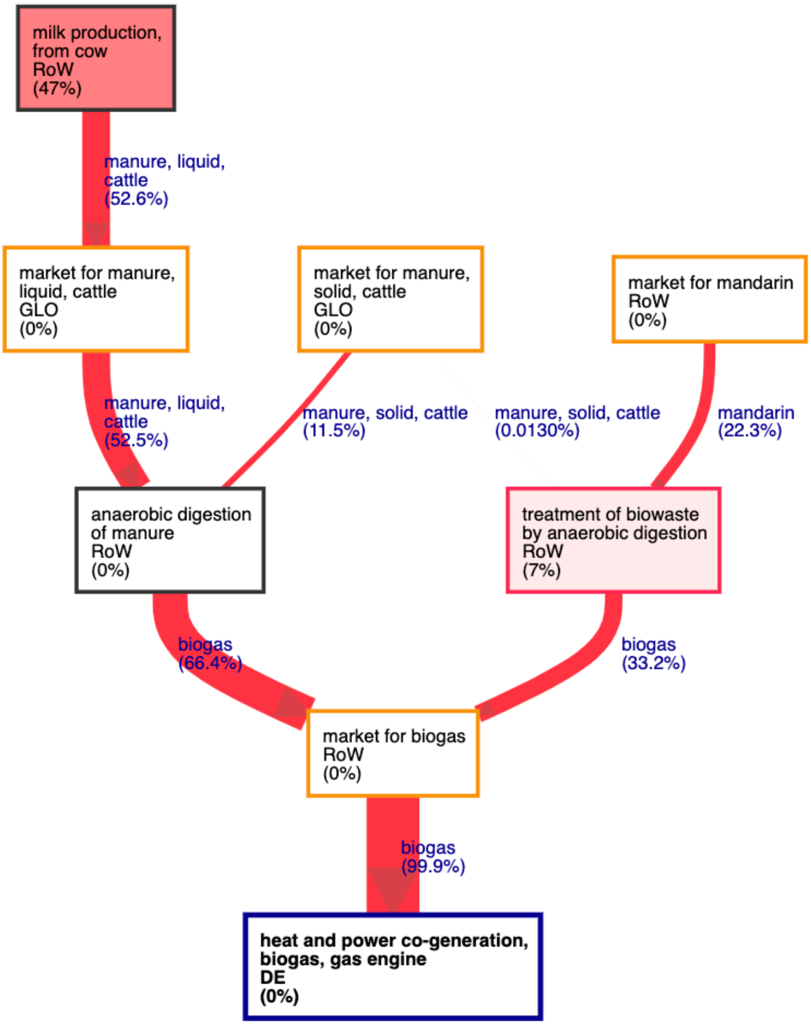

Figure 6.3: Sankey diagram with the scenario 3 (heat and power co-generation, biogas, gas engine) as reference flow and land occupation as impact indicator.

Conclusion

This study highlights the effectiveness and precision of the Life Cycle Assessment (LCA) methodology as a valuable tool for analyzing the environmental impacts of our university's energy systems. Despite having limited data, we were able to identify relevant activities in existing databases that closely approximated our study's objectives. Leveraging available software, we easily visualized the environmental impacts generated by different electricity alternatives. Through this investigation, we gained insights into the available electricity options and how each of them can contribute to improving environmental aspects.

The results of our study show that the current method of supplying electrical energy to our university campus through the national grid is the scenario with the highest impact on crucial categories such as climate change, ecotoxicity in freshwater, marine ecotoxicity, and human ecotoxicity. Furthermore, in the normalized results, we have observed that the campus's contribution to freshwater ecotoxicity is particularly relevant. If we aim to transition towards more sustainable energy sources, this impact category should be seriously considered in any future decision-making process.

Our findings have the potential to significantly influence decision-making within the university regarding its energy systems. Although the nuclear energy scenario, arises overall as the best scenario in the CML method, we acknowledge that the adoption of more nuclear energy is unrealistic for a university decision level. Therefore, if we were to give practical recommendations, we would seriously consider investment in photovoltaic panels or more wind energy. These approaches could reduce dependence on the conventional electrical grid, thereby positively influencing the environment. For example, a new scenario could be modelled, reflecting the decision that the university is planning to make. For example, and scenario where a 95% of electricity comes from the grid and 5% from photovoltaic panels. This would allow for precise quantification of how this decision would improve the environment. Additionally, the university could consider preparing a Life Cycle Assessment (LCA) report (following the guidelines provided in this reports) to officially demonstrate its commitment to taking sustainable energy actions.

It is essential to highlight two key limitations of this study. Firstly, the lack of sufficient data for a comprehensive inventory analysis was a significant constraint. Additionally, the scarcity of literature on the LCA method for evaluating exclusively social impacts was an additional limitation that warrants further research and development.

Therefore, as future perspectives, we recommend on the one hand, conducting a new LCA that includes data collection and the creation of a comprehensive inventory analysis. For example, if the university is researching a new energy system and is interested in understanding the environmental impact of its lifecycle, it would be interesting to gather data on its components, origins, transportation, and recycling to create its activity dataset (unit process). This would allow for a deeper understanding of LCA and its practical application.

On the other hand, it would be intriguing to explore alternative LCA methods that better encapsulate social impacts, particularly by incorporating categories related to land use and assigning greater significance to categories with social ramifications. Our research demonstrates the potential of using alternative LCA methods, such as the IMPACT 2002+ Endpoint method, to explore different dimensions of impact, including social considerations. The finding or creation of a more social-orientated method would provide a more holistic view of the interplay between energy systems and societal well-being, enabling us to make more informed decisions regarding sustainable energy alternatives.

To conclude, while this study presents a preliminary exploration of the LCA methodology, it's essential to recognize the significance of LCA as a valuable tool in addressing the pressing environmental and social challenges of our time. In an era marked by a growing awareness of sustainability and environmental responsibility, LCA emerges as a critical methodology that aligns with the global goals of ecological transition. As we strive to achieve a more sustainable and environmentally conscious world, LCA offers a systematic approach to comprehensively assess the impact of energy systems, products, and processes on our environment and society. This methodology allows us to not only quantify and understand the environmental consequences of our actions but also to identify opportunities for improvement and innovation. By conducting LCAs, we can pinpoint the hotspots where interventions are most needed, guiding decision-makers toward more sustainable choices.

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Appendix

A) Main Appendix: LCA results with the CML method

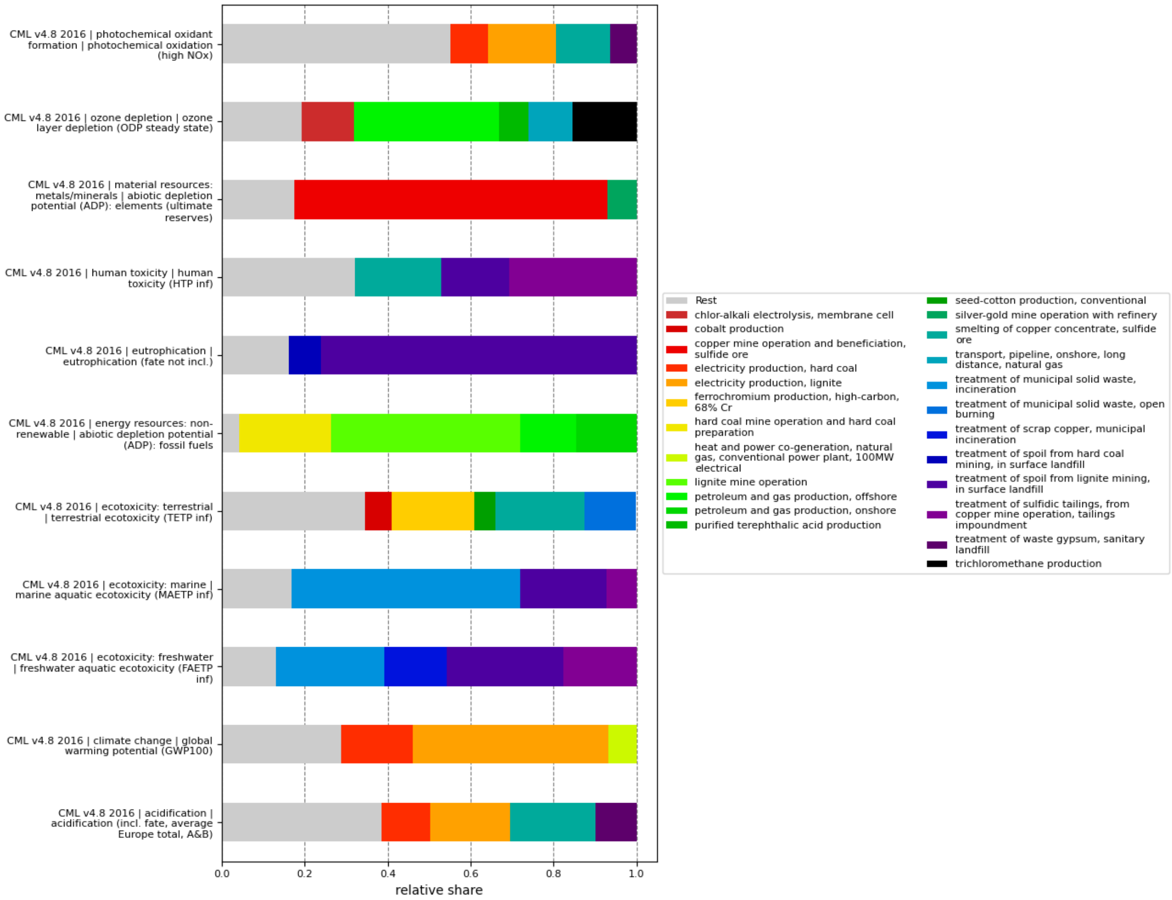

Figure A.1.1: Process contribution to each impact category of the CML method in the scenario where the campus electricity supply is entirely done through the German electricity grid.

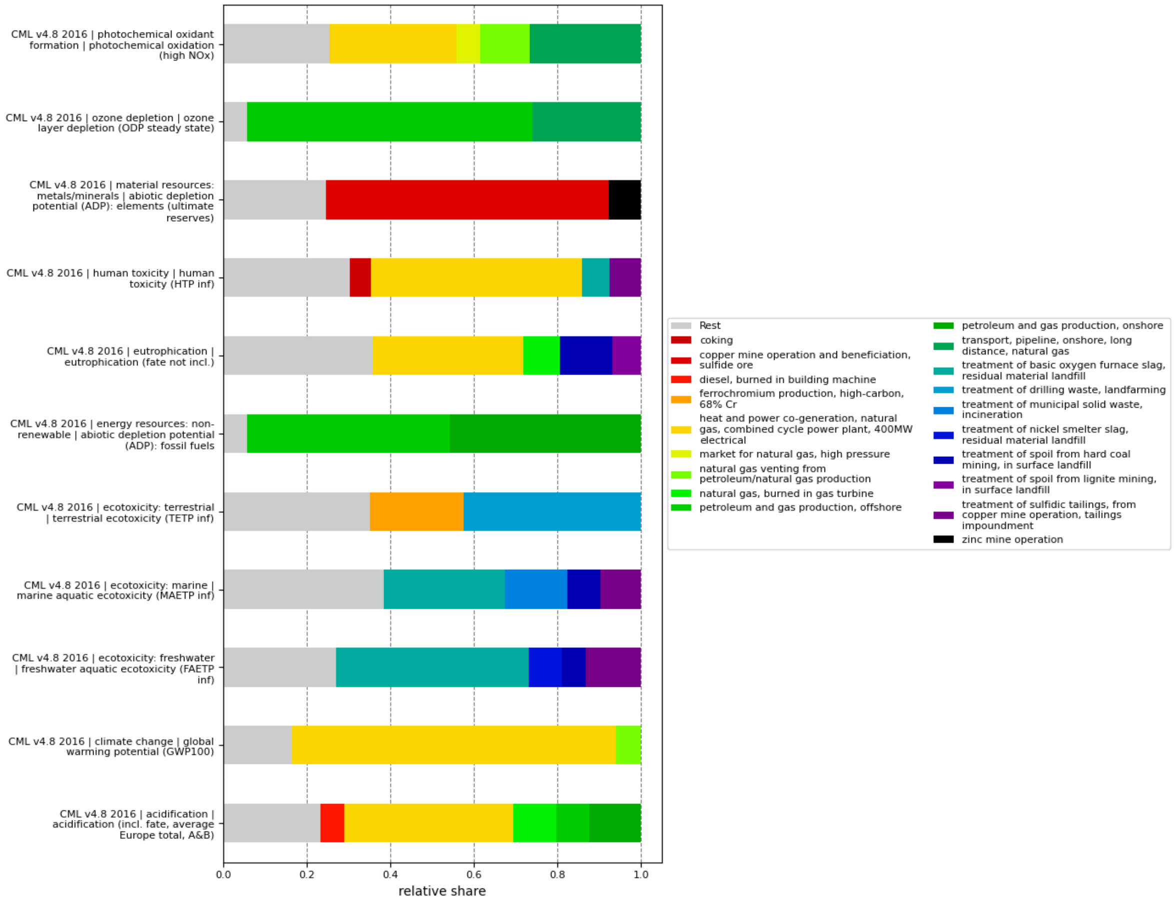

Figure A.1.2: Process contribution to each impact category of the CML method in the scenario where the campus electricity supply is entirely done through a combined heat and power co-generation cycle with natural gas.

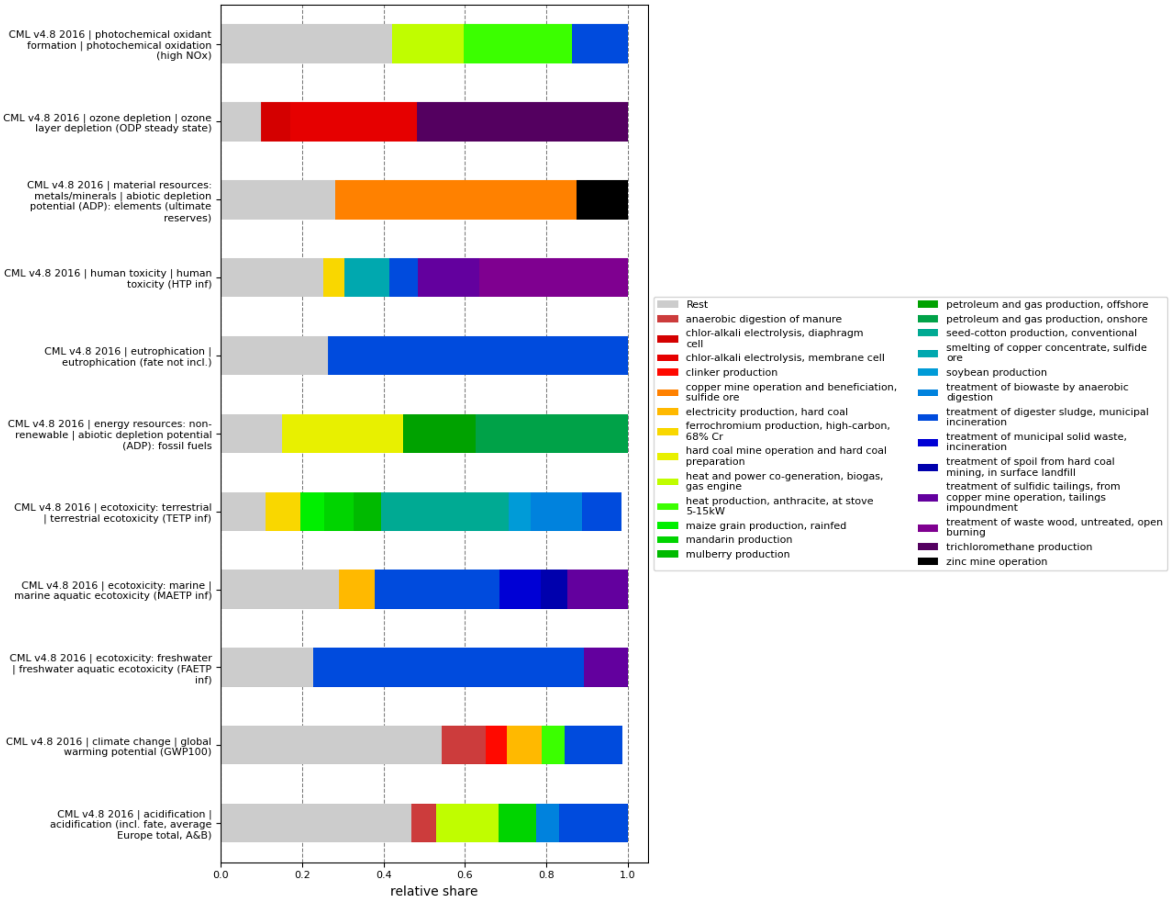

Figure A.1.3: Process contribution to each impact category of the CML method in the scenario where the campus electricity supply is entirely done through a heat and power co-generation cycle with biogas.

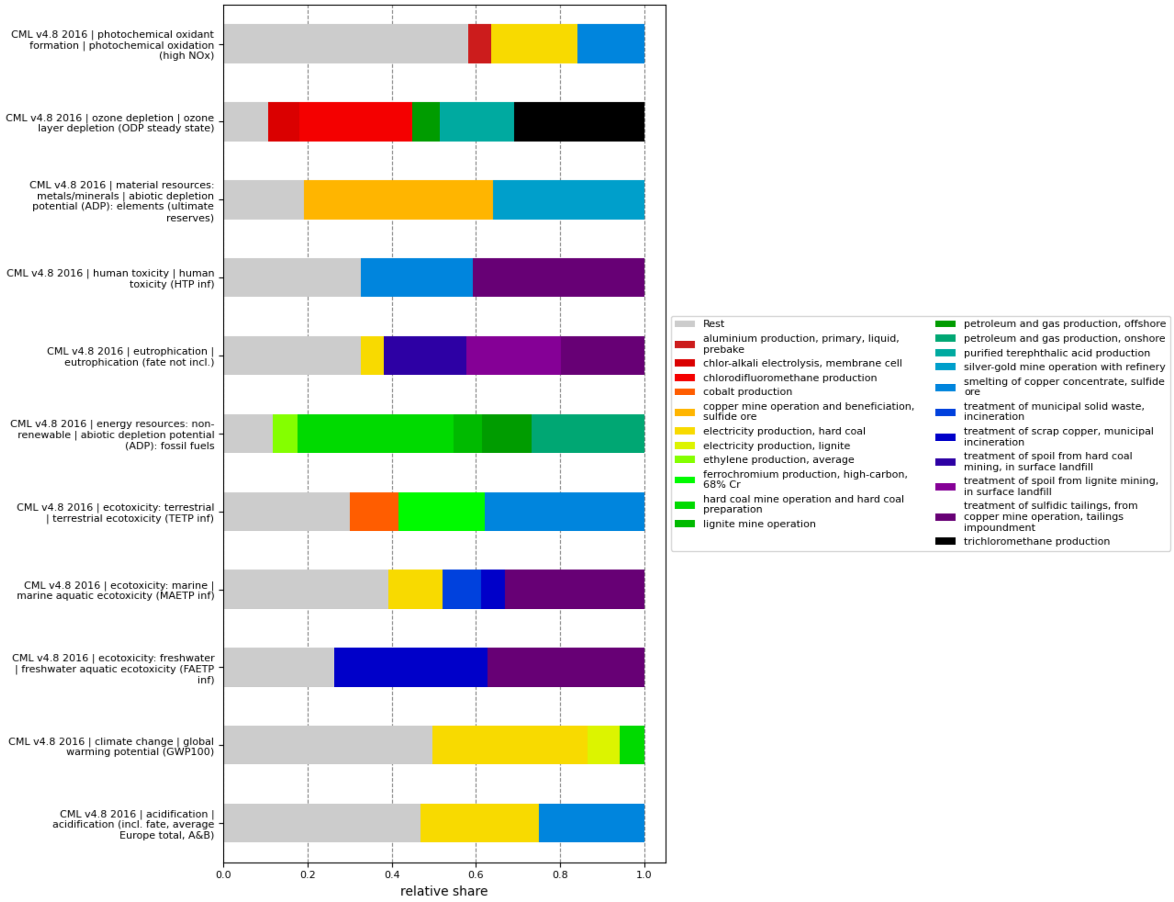

Figure A.1.4: Process contribution to each impact category of the CML method in the scenario where the campus electricity supply is entirely done through photovoltaic single-Si panels.

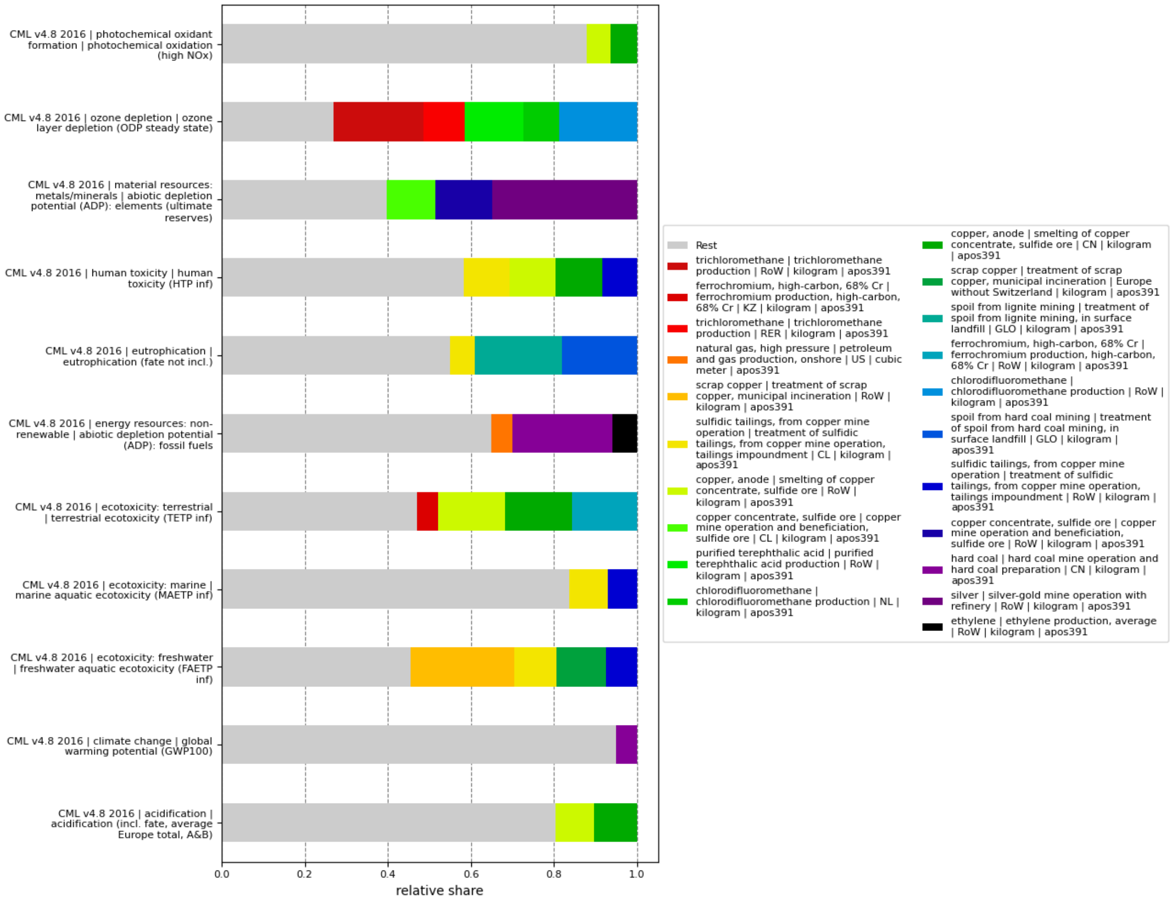

Figure A.1.5: Process contribution to each impact category of the CML method in the scenario where the campus electricity supply is entirely done through photovoltaic multi-Si panels.

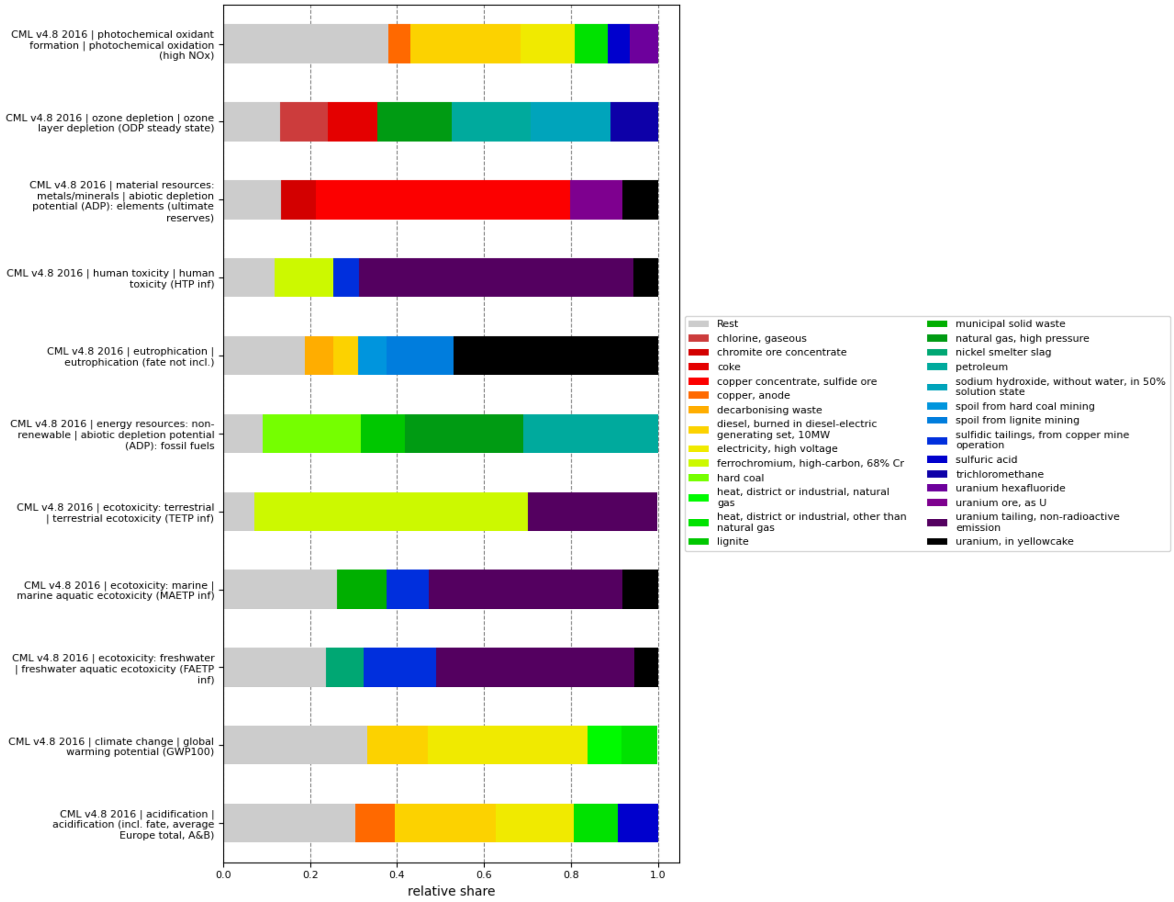

Figure A.1.6: Process contribution to each impact category of the CML method in the scenario where the campus electricity supply is entirely done through a nuclear PWR (Pressure Water Reactor).

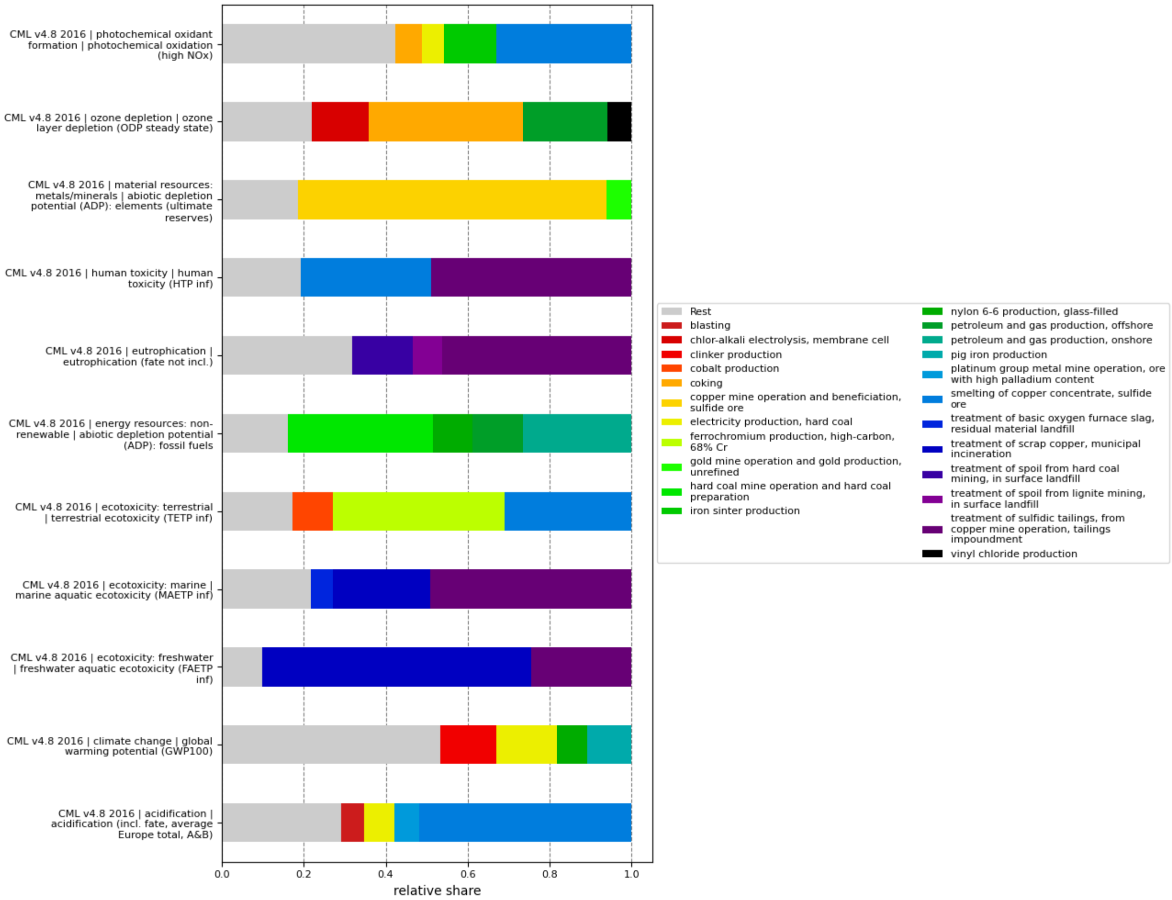

Figure A.1.7: Process contribution to each impact category of the CML method in the scenario where the campus electricity supply is entirely done through onshore and offshore wind turbines.

Table A.1: Characterized impacts for each electricity supply scenario with CML method.

acidification	kg SO2 eq.	7,82E+04	1,46E+04	1,33E+05	4,72E+04	4,34E+04	2,71E+03	2,12E+04
climate change	kg CO2 eq.	3,22E+07	3,04E+07	1,60E+07	7,69E+06	6,65E+06	4,47E+05	2,22E+06
ecotoxicity: freshwater	kg 1,4 DCB eq.	6,27E+07	1,52E+06	2,54E+07	2,27E+07	2,24E+07	1,37E+06	3,19E+07
ecotoxicity: marine	kg 1,4-DCB eq.	1,71E+11	2,34E+09	2,08E+10	2,86E+10	2,69E+10	2,63E+09	1,78E+10
ecotoxicity: terrestrial	kg 1,4-DCB eq.	2,14E+05	2,78E+04	5,71E+05	8,95E+04	8,77E+04	4,47E+04	1,02E+05
energy resources: non-renewable	megajoule	3,41E+08	4,99E+08	9,92E+07	8,69E+07	7,59E+07	5,11E+06	2,30E+07
eutrophication	kg PO4 eq.	1,57E+05	4,38E+03	1,79E+05	1,99E+04	1,81E+04	2,58E+03	7,85E+03
human toxicity	kg 1,4 DCB eq.	5,41E+07	4,07E+06	2,74E+07	3,11E+07	3,07E+07	5,80E+06	2,39E+07
material resources: metals/minerals	kg Sb eq.	3,58E+02	7,52E+00	1,23E+02	4,45E+02	4,57E+02	1,03E+01	2,47E+02
ozone depletion	kg CFC 11 eq.	4,23E-01	1,14E+00	1,41E+00	4,90E-01	5,15E-01	8,80E-03	4,39E-02
photochemical oxidant formation	kg ethylene eq.	4,88E+03	3,34E+03	9,62E+03	2,99E+03	2,80E+03	1,94E+02	1,34E+03
	Qty	70	70	70	70	70	70	70
	UNIT	MWh	MWh	MWh	MWh	MWh	MWh	MWh
	SCENARIO	**SCENARIO 1:** market for electricity, low voltage	**SCENARIO 2:** heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical	**SCENARIO 3:** heat and power co-generation, biogas, gas engine	**SCENARIO 4:** electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted	**SCENARIO 5:** electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	**SCENARIO 6:** electricity production, nuclear, pressure water reactor	**SCENARIO 7:** mix of onshore and offshore wind energy in Germany 2023

B) Second Appendix: LCA graph results with the “IMPACT 2000+ Endpoint” method

Table B.1: Characterized impacts for each electricity supply scenario with IMPACT 2000+ Endpoint method.

Climate Change	points		3,09E+03	2,80E+03	1,21E+03	7,20E+02	6,24E+02	4,20E+01	2,10E+02
Ecosystem Quality	points		7,10E+02	1,96E+02	1,99E+03	3,32E+02	3,10E+02	8,75E+01	1,79E+02
Human Health	points		2,27E+03	4,82E+02	3,31E+03	2,07E+03	1,78E+03	5,15E+02	7,90E+02
Resources	points		3,34E+03	3,67E+03	7,55E+02	7,02E+02	6,11E+02	5,49E+03	1,82E+02
		Qty	70	70	70	70	70	70	70
		UNIT	MWh	MWh	MWh	MWh	MWh	MWh	MWh
		SCENARIO	**SCENARIO 1:** market for electricity, low voltage	**SCENARIO 2:** heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical	**SCENARIO 3:** heat and power co-generation, biogas, gas engine	**SCENARIO 4:** electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted	**SCENARIO 5:** electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	**SCENARIO 6:** electricity production, nuclear, pressure water reactor	**SCENARIO 7:** mix of onshore and offshore wind energy in Germany 2023

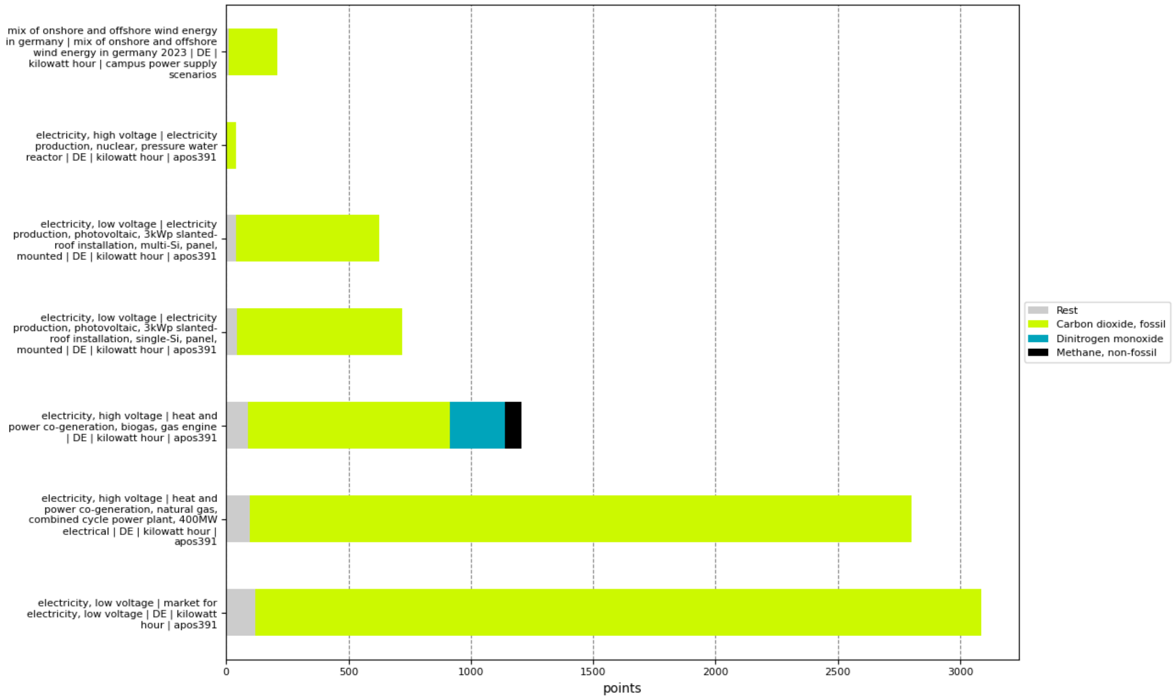

Figure B.1.1: Product contribution of each scenario to the “Climate Change” impact category of the IMPACT 2002+ Endpoint method.

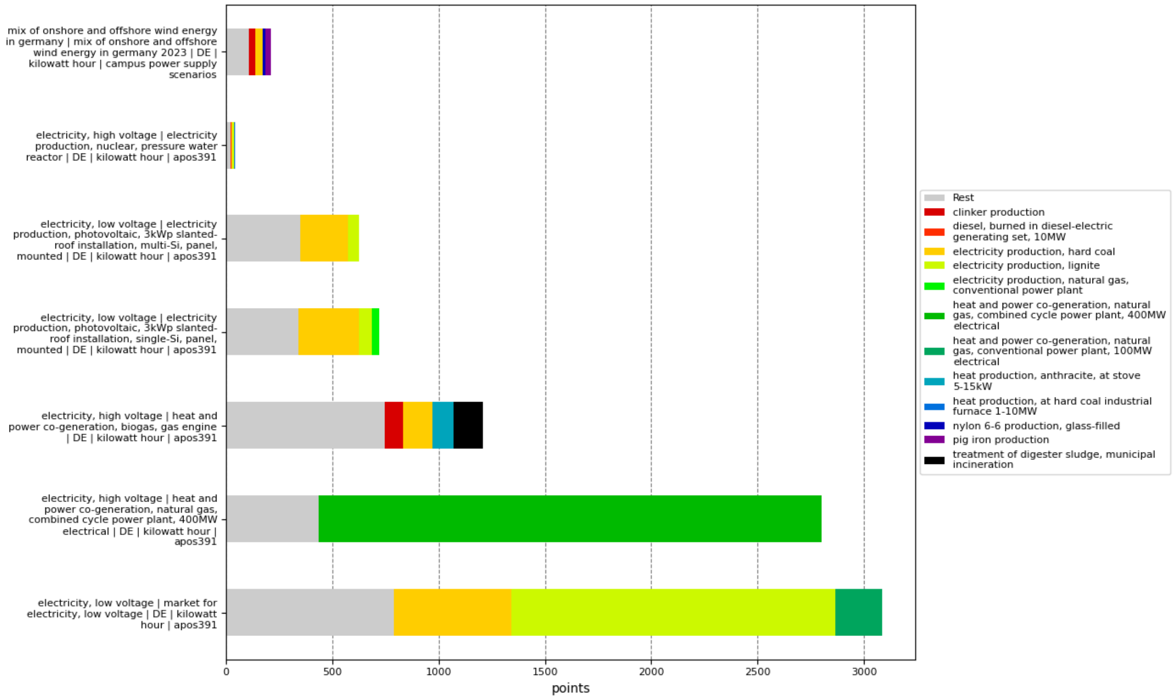

Figure B.1.2: Process contribution of each scenario to the “Climate Change” impact category of the IMPACT 2002+ Endpoint method.

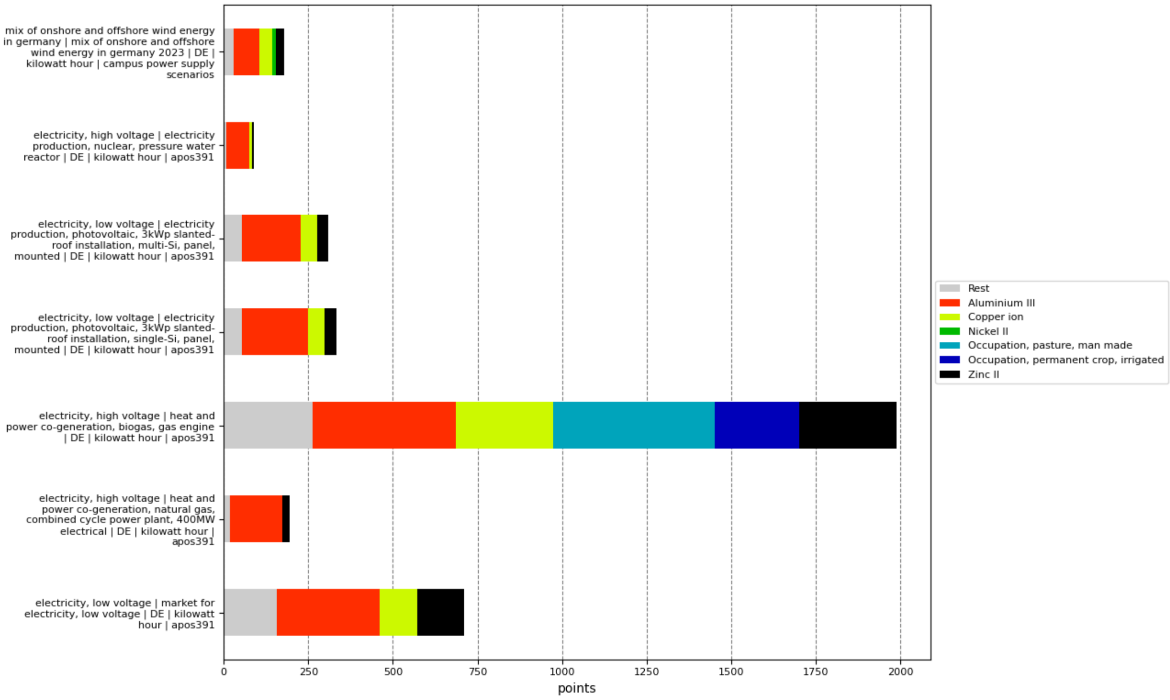

Figure B.2.1: Product contribution of each scenario to the “Ecosystem Quality” impact category of the IMPACT 2002+ Endpoint method.

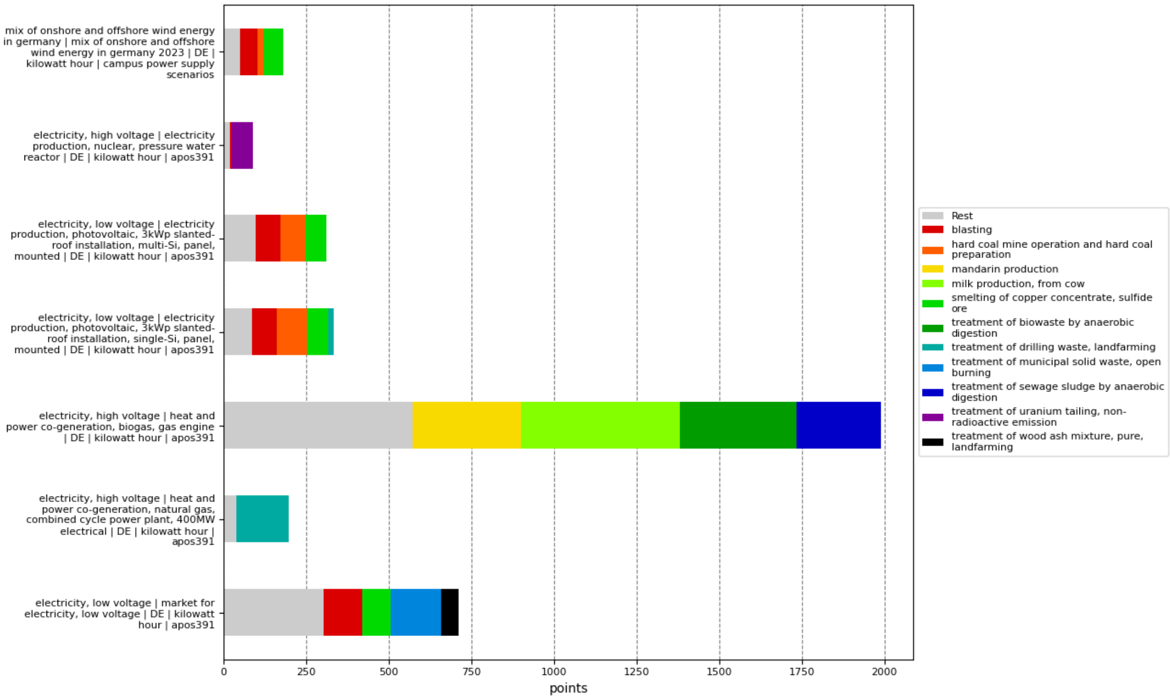

Figure B.2.2: Process contribution of each scenario to the “Ecosystem Quality” impact category of the IMPACT 2002+ Endpoint method.

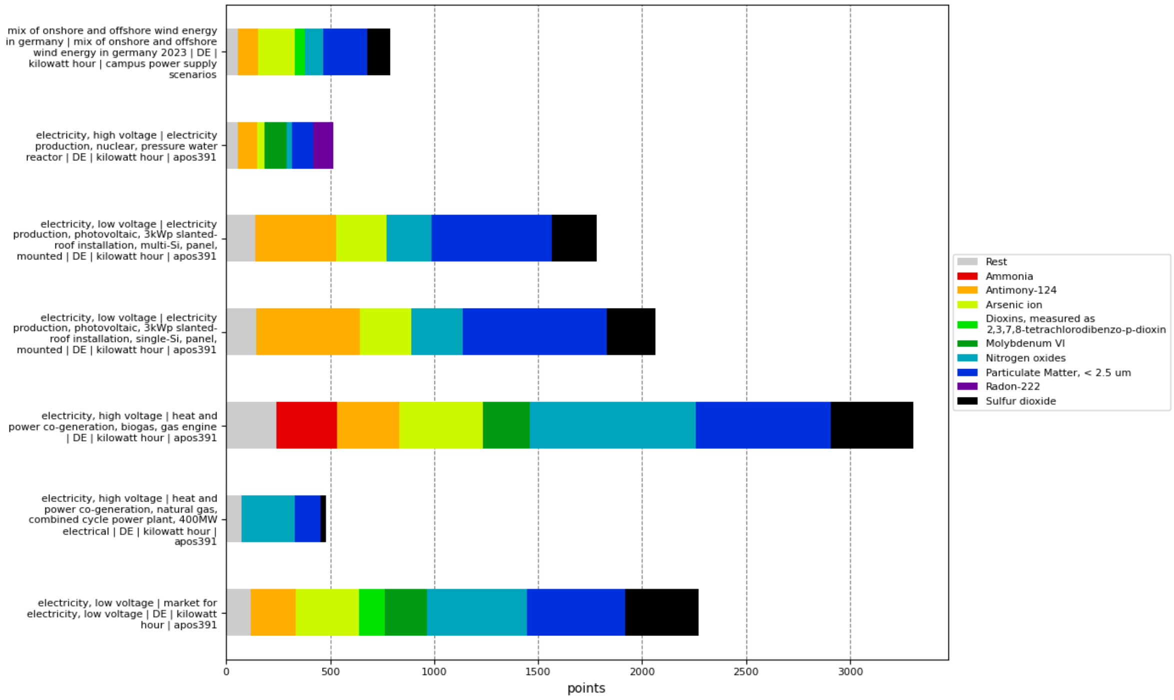

Figure B.3.1: Product contribution of each scenario to the “Human Health” impact category of the IMPACT 2002+ Endpoint method.

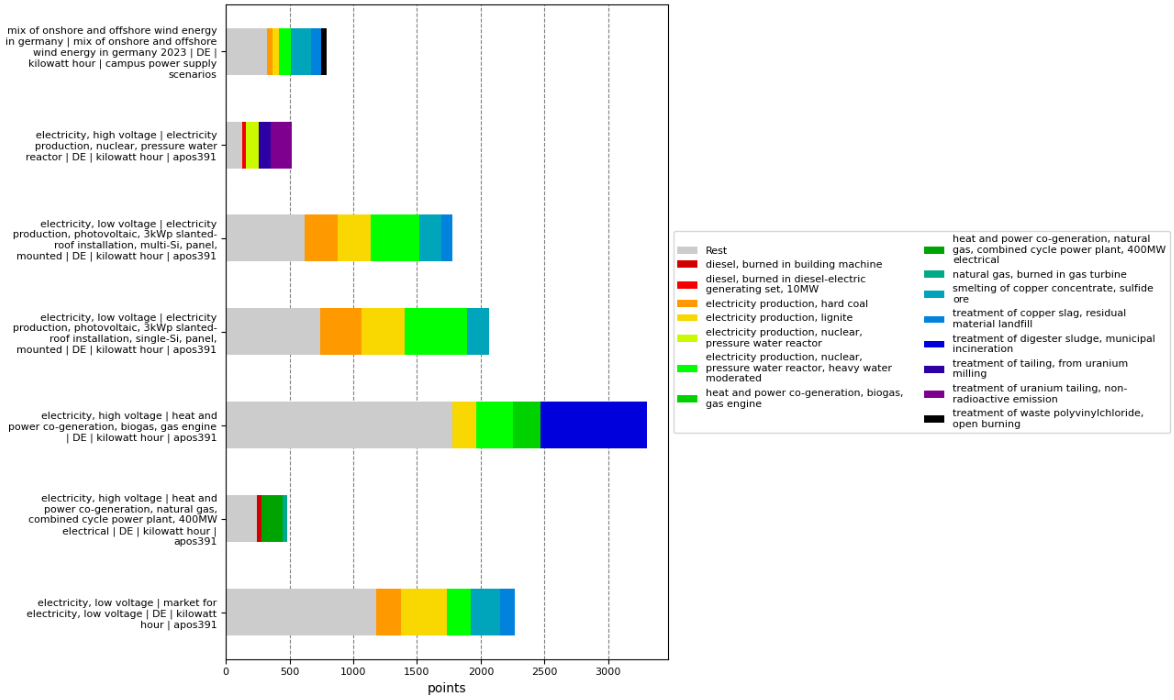

Figure B.3.2: Process contribution of each scenario to the “Human Health” impact category of the IMPACT 2002+ Endpoint method.

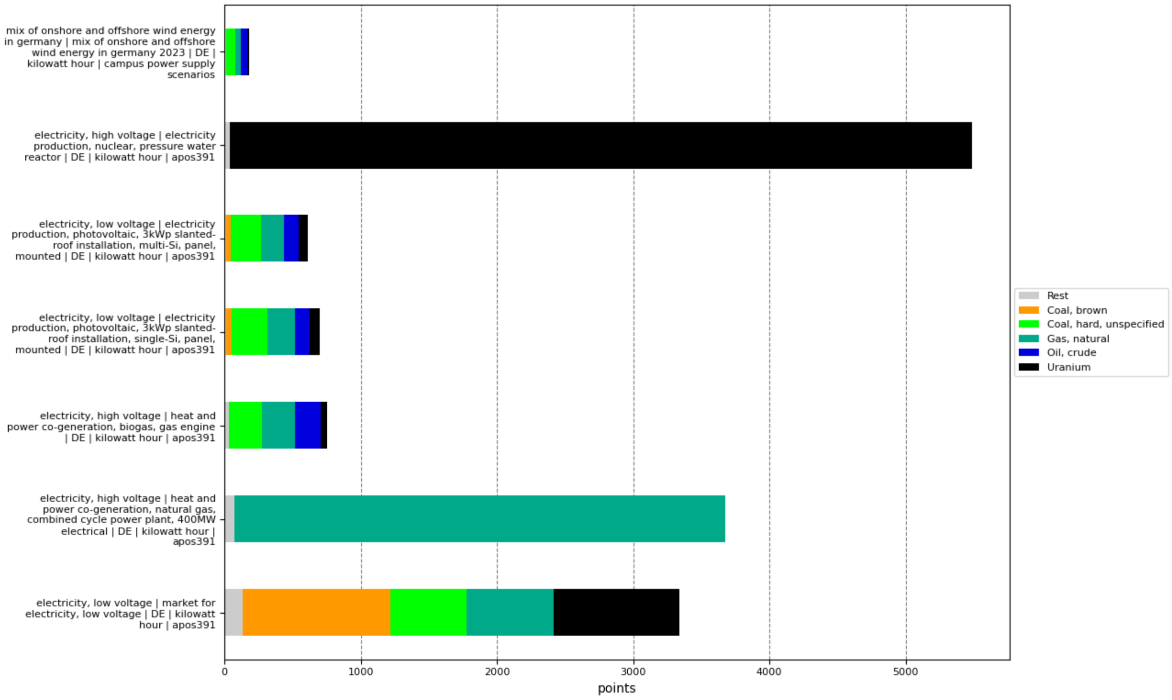

Figure B.4.1: Product contribution of each scenario to the “Resources” impact category of the IMPACT 2002+ Endpoint method.

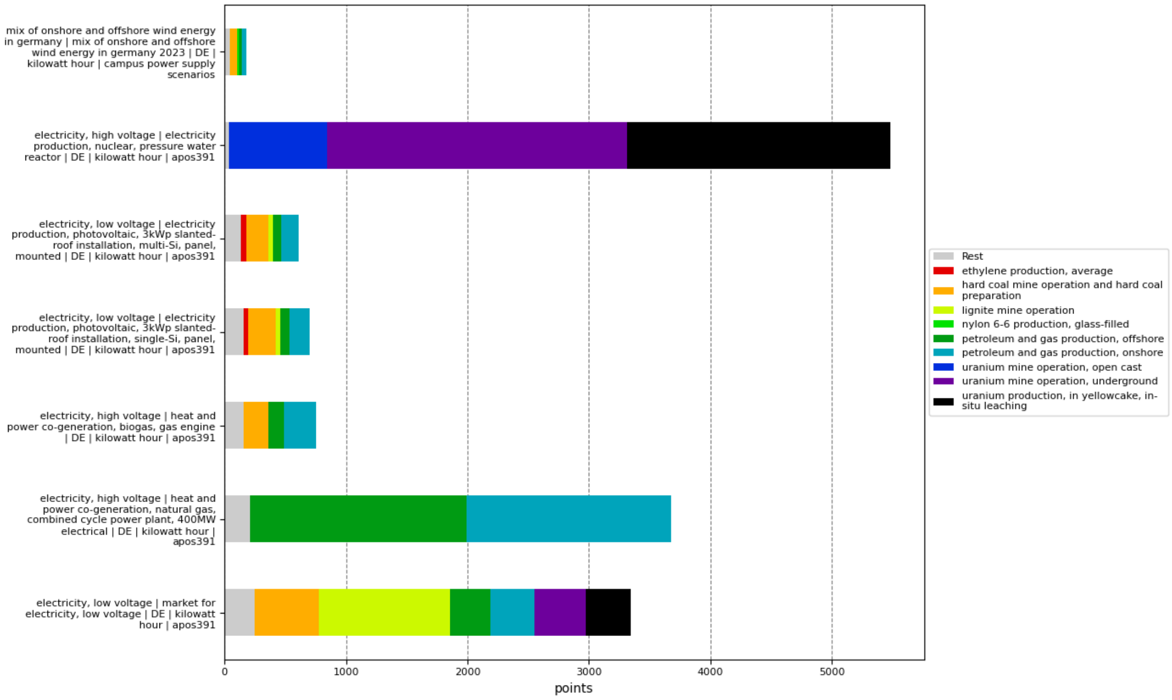

Figure B.4.2: Process contribution of each scenario to the “Resources” impact category of the IMPACT 2002+ Endpoint method.