Hunting Hotspots

A Framework to Assess the Effectiveness of Using Environmentally Extended Input-Output Models as a Method to Identify CO2-eq Hotspots in the Upstream Supply Chain of a Company

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LUCSUS
Lund University Centre for Sustainability Studies

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Abstract

Industry's indirect upstream greenhouse gas (GHG) emissions contribute significantly to climate change. To identify and reduce them, some companies conduct a hotspot analysis using an environmentally extended input-output (EEIO) model (often utilizing EXIOBASE database). Despite the widespread use of EEIO models to identify hotspots in industry, their effectiveness in estimating GHG emissions has not yet been investigated. Therefore, this thesis explores what effectiveness constitutes in this context and compares the strengths and weaknesses of EEIO (and EXIOBASE) with alternative methods, such as using supplier-specific, average-data and hybrid methods (and other common EEIO databases: Eora, GTAP, WIOD). Using a mixed methods model of literature research, systematized literature review, and expert interviews, the results lead to an effectiveness framework with three dimensions and a precondition to determine its applicability. Finally, practical implications provide guidance for companies on how to apply it to positively contribute to carbon management and combating climate change.

Keywords: GHG emissions, Effectiveness, Hotspot analysis, EXIOBASE, Environmentally Extended Input-Output, Industrial climate action

Word Count: 11973

Deutschsprachige Zusammenfassung (German Abstract)

Die indirekten vorgelagerten Treibhausgasemissionen der Industrie tragen erheblich zum Klimawandel bei. Um diese zu ermitteln und zu reduzieren, führen einige Unternehmen eine Hotspot-Analyse unter Verwendung eines umweltbezogenen erweiterten Input-Output-Modells (EEIO) durch (häufig unter Verwendung der Datenbank EXIOBASE). Obwohl EEIO-Modelle zur Identifizierung von Hotspots in der Industrie weit verbreitet sind, wurde ihre Effektivität bei der Schätzung von Treibhausgasemissionen noch nicht untersucht. Daher wird in dieser Arbeit untersucht, was Effektivität in diesem Zusammenhang bedeutet, und es werden die Stärken und Schwächen von EEIO (und EXIOBASE) mit alternativen Methoden verglichen, wie z. B. der Verwendung von anbieterspezifischen, durchschnittlichen Daten und hybriden Methoden (und andere gängige EEIO-Datenbanken: Eora, GTAP, WIOD). Unter Verwendung eines gemischten Methodenmodells aus Literaturrecherche, systematischem Literaturüberblick und Experteninterviews führen die Ergebnisse zu einem Effektivitätsrahmen mit drei Dimensionen und einer Voraussetzung zur Bestimmung seiner Anwendbarkeit. Schließlich bieten praktische Implikationen eine Gebrauchsanweisung für Unternehmen, wie sie ihn anwenden können, um einen positiven Beitrag zum Kohlenstoffmanagement und zur Bekämpfung des Klimawandels zu leisten.

Acknowledgements

Completing this master's thesis has been a journey with ups and downs, but I could not have done it without the support and encouragement of some incredible people. Allow me to express my deepest gratitude and appreciation to all those who have been significant in making this thesis possible.

Let me begin by acknowledging and expressing my sincere gratitude to my interview partners. They generously shared their experiences and knowledge about EXIOBASE, providing me with valuable insights for this research. Their contribution was significant, and I am deeply grateful for their willingness to help. A special thanks to David from the climate team at Tetra Pak, who was my first interviewee and provided me with valuable feedback for the following interviews.

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I am also indebted to Tetra Pak and all the fantastic people who supported me during this research. My supervisors from the Climate team, Oliver, and Karin, provided me with a company perspective, structured my thoughts, and gave me valuable feedback, for which I am incredibly grateful. In addition, I want to thank my current team in supplier management for their support in my master's thesis. They listened to me talk about my thesis in countless meetings and gave me valuable feedback. Special thanks to Harry, Martin, Advait, and Alice.

Last but not least, my family and friends have been an enormous support system during this writing process. Thank you for listening to my endless ramblings about my thesis, motivating me, and providing me with feedback. And thank you for organizing a painting evening to take my mind off things - I still have the painting hanging on my wall!

In conclusion, I would like to say that this thesis would not have been possible without the help of these wonderful individuals. They have played an essential role in my academic and personal development, and for that, I am forever grateful. The journey may have been challenging, but with the help of these amazing people, I managed to reach the finish line while keeping my sanity.

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List of Abbreviations

CF	Carbon Footprint
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide Equivalent
GHG	Greenhouse Gas
GTAP	Global Trade Analysis Project
EEIO	Environmentally extended input-output
IE	Industrial Ecology
IO	Input-output
IOA	Input-output analysis
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Analysis
MRIO	Multi-regional Input-Output
ROSES	RepOrting standards for Systematic Evidence Syntheses
SBTi	Science Based Target initiative
WIOD	World Input-Output Database
WoS	Web of Science

1 Introduction

According to the Intergovernmental Panel on Climate Change (IPCC) the average global temperature has risen by approximately 1.09°C in 2011-2020 compared to the preindustrial period (IPCC, 2021) and will continue to increase with severe risks for humanity if we continue with business as usual (IPCC, 2022b). The scientific consensus is unambiguous (Cook et al., 2016) that humanity is contributing to this change by emitting greenhouse gases (GHG) through their activities (IPCC, 2021). Going forward, projections suggest that global surface temperature will rise at least until 2050, irrespective of emissions pathways, and that all GHG emissions must be sharply reduced to keep global warming within 2°C or below (IPCC, 2021). Every release of GHG emissions contributes to global warming and thereby enhances the frequency and intensity of extreme weather events, so their reduction is vital (IPCC, 2021, 2022b). Everyone in society needs to do their part to address this sustainability challenge – governments, individuals, and companies (Babie, 2011; Falkner, 2016; Zhou, 2020).

Companies have a responsibility to decarbonize, as the production and use of their goods and services emit GHGs that add to global warming (Plank et al., 2021; Zhou, 2020). Therefore, several companies practice carbon management to make their contribution to climate action (Zhou, 2020). Carbon management involves the understanding and measurement of the carbon footprint (CF) of an organization with the aim of continuously reducing it in a sustainable and cost-efficient manner across the entire supply chain (Zhou, 2020). "Carbon Footprint is a parameter that measures the impact human activities have on the environment in terms of the amount of greenhouse gases produced, measured in unit of carbon dioxide equivalent [CO_2-eq]." (Zhou, 2020, p. 22) When quantifying a company's CF, the differentiation between the type, also referred to as scope, of emissions is essential (Zhou, 2020).

The Greenhouse Gas Protocol (2011), which is an organization that provides companies with guidance to successfully calculate their CF, categorizes the emissions of a company in three scopes (Figure 1). There are direct emissions, which are the emissions from the company itself (Scope 1); and indirect emissions, which are related to purchased energy used for production facilities (Scope 2) and supply chain emissions (also called value chain emissions in this thesis; Scope 3). Scope 3 emissions are additionally categorized as upstream (e.g., purchased goods and services) and downstream (e.g., use of sold products); the remaining categories of Scope 3 are depicted in Figure 1.

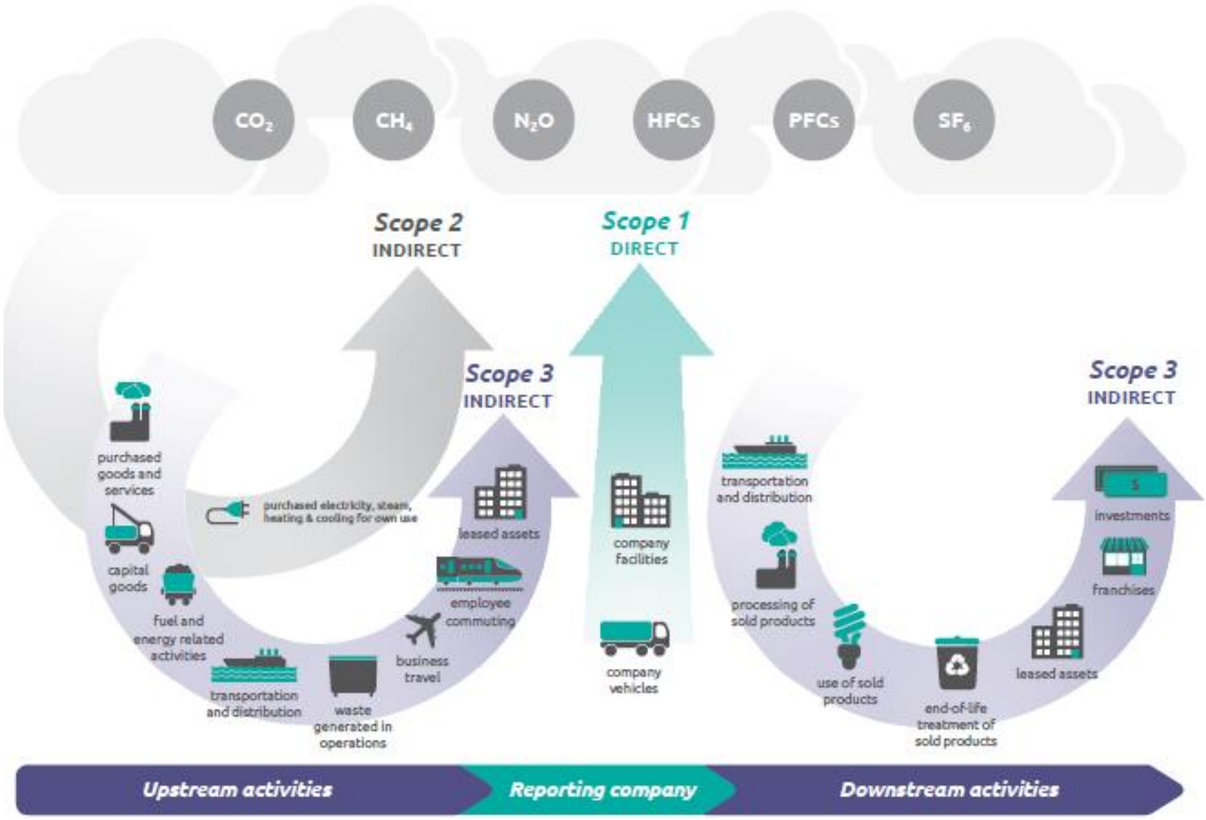


Figure 1. Scopes according to Greenhouse Gas Protocol (2011, p. 5)

Typically, the largest share of a company's emissions falls into the Scope 3 category, which is on average 11.4 times greater than the emissions of its own operations (CDP, 2023b). Thus, CDP[1] points out that it is key for a company to address emissions along their value chain. However, calculating a company's Scope 3 emissions is a major challenge, due to limited transparency, resources, and many other reasons (Erhard et al., 2019). Due to these barriers, only about 41% of the roughly 18600 reporting companies disclosed GHG emissions to CDP in 2022 for at least one Scope 3 category, and thereof only about one-third disclosed data on the goods and services they purchased (CDP, 2023b). Purchased goods and services are significant for most industries and contribute on average to the greatest share of a company's emissions, accounting for approximately 43% (CDP, 2023b).

A variety of methods are available for companies to illuminate their upstream supply chain emissions associated with the inputs they purchase (Erhard et al., 2019). Hotspot thinking is particularly useful in a business context where there are limited resources as it supports to prioritize and define targeted GHG reduction measures (Erhard et al., 2019; UNEP DTIE, 2014). Erhard et al. (2019) outline, that companies often apply a spend-based method to perform an initial screening, which is the hotspot

[1] Formerly known as the Carbon Disclosure Project. Now just *CDP*, as the not-for-profit charity has expanded their focus beyond the climate aspect to provide guideline to companies for environmental reporting, see CDP (2023a).

analysis. The spend-based approach estimates a company's GHG emissions by allocating emission factors based on their monetary data, which results in CO_2-eq per euro of purchasing volume (Erhard et al., 2019). Alternatively, companies can also calculate the emissions with average based data (e.g., weight of products), via data provided by the suppliers (supplier-specific) or by applying a mix of the supplier and e.g., the spend-based approach (hybrid method) (Erhard et al., 2019; Greenhouse Gas Protocol, 2013). However, Erhard et al. (2019) point out that the applicability of the methods largely depends on the data available in the company and the resources available to perform the analysis. Hence, many companies apply the spend-based approach, as they have only monetary data available and no physical or supplier-specific data (Erhard et al., 2019).

This thesis focuses on the spend-based approach because of its widespread application. A spend-based approach is using an environmentally extended input-output (EEIO) analysis, which provides an estimated CO_2-eq factor for each euro spent by a company in a certain supplier country, industry and product (Tukker et al., 2014). There are several different EEIO databases available, one of the most used EEIO databases in industry is EXIOBASE due to the open-license and the high coverage of industries and products compared to other databases (Deutsches Global Compact Netzwerk, 2019; Erhard et al., 2019). Therefore, EXIOBASE was chosen because the database is accessible and already extensively utilized.

While the use of EEIO databases (especially EXIOBASE) is prevalent in the industry when only monetary data or limited resources are available to perform hotspot analyses of upstream emissions (Erhard et al., 2019; Greenhouse Gas Protocol, 2011), there is no research that supports whether this method is appropriate - or one could say effective - for identifying emission hotspots in a company context because of the database's country focus (Wood et al., 2014). It is therefore necessary to find this out for companies, as it is valuable for them to know how suitable and useful this method is that they are already adopting. Understanding the potential limitations of such an approach is useful to identify how much reliance can be placed on its results. Furthermore, no clear understanding exists of what *effectiveness* would constitute in the context of the identification of CO_2-eq hotspots in an upstream supply chain of a company. Filling these knowledge gaps is essential for companies' carbon management to contribute to limiting global warming. This thesis aims to fill these gaps in line with sustainability research by "bringing together scholarship and practice […] and disciplines across the natural and social sciences [and engineering]" (Clark & Dickson, 2003, p. 8060).

Therefore, the objective of this thesis is to improve companies' carbon management by exploring whether EEIO (and EXIOBASE specifically) is an effective method for identifying emissions hotspots in the upstream supply chain of a company. While EEIO and EXIOBASE are considered the first step for hotspot analysis for most companies due to lack of data or limited resources (Erhard et al., 2019), this research will also compare it to other calculation methods and EEIO databases to provide a comprehensive answer on effectiveness. Thus, I derived the following research questions:

1) What are strengths and weaknesses of using EEIO (and EXIOBASE) to identify upstream CO_2-eq hotspots and how do they compare to:
    - other methods (supplier-specific, average-data and hybrid) to calculate and identify upstream CO_2-eq hotspots? and
    - other EEIO databases?
2) What is *effectiveness* and what constitutes *effectiveness* when assessing whether EEIO and EXIOBASE is an effective method for identifying upstream CO_2-eq hotspots?

The scope of this thesis focuses on the overall development of a framework for effectiveness and providing guidance to industry related to the application. In addition, the strengths and weaknesses of EEIO and EXIOBASE will complement this with a critical evaluation of hotspot calculation methods and databases, and corresponding decision trees for choosing between alternative methods.

This thesis is structured as follows. Chapter 2 introduces the theoretical approach of Industrial Ecology, a theoretical background on hotspot analyses and the EEIO-framework. Chapter 3 outlines the methodological approach of this thesis before presenting the results in Chapter 4. Among these are the strengths and weaknesses of EEIO (and EXIOBASE) compared to other methods and EEIO databases, and the definition of effectiveness and the framework. These findings will be discussed in the light of implications for practitioners and future research, as well as limitations of this thesis in Chapter 5. Chapter 6 concludes the thesis.

2 Theory and Background

As this thesis is closely connected to industry, I will firstly introduce Industrial Ecology (IE) as the theoretical approach. Secondly, I will go into the theoretical background of hotspots analysis and lastly outline the (EE)Input-Output-Analysis framework.

2.1 Industrial Ecology

IE aims to contribute towards a sustainable society by establishing sustainable production and consumption (Erkman, 1997; International Society for Industrial Ecology, 2023). There is no fixed definition of IE, but there is a semi-consensus on three components that are inherent in this viewpoint (Erkman, 2003). Robert White of the US National Academy of Engineering abridged these three components and described IE as "[1] the study of the flows of materials and energy in industrial and consumer activities, [2] of the effects of these flows on the environment, and [3] of the influences of economic, political, regulatory, and social factors on the flow, use, and transformation of resources. The objective of industrial ecology is to understand better how we can integrate environmental concerns into our economic activities." (White, 1994, p. V) IE studies focus on understanding the structure of industrial systems from the use of materials and energy to the conversion, use and disposal of resources (International Society for Industrial Ecology, 2023). Based on this, IE provides opportunities to improve resource efficiency and contribute to the reduction of human-induced environmental impacts by restructuring the current systems of production and consumption (Erkman, 1997; Suh & Kagawa, 2009).

Furthermore, through the focus on understanding the interaction of human society and the environment, IE offers an approach within sustainability science to capture nature-society connections (Hauff & Wilderer, 2008; Jerneck et al., 2011). IE unites several disciplines, most notably natural, social and engineering sciences, and encompasses a variety of approaches and methods (the majority quantitative) such as material flow analysis, industrial symbiosis, life cycle assessment or analysis (LCA), and, particularly relevant for this thesis, EEIO analysis (International Society for Industrial Ecology, 2023; Lifset, 2009). Many of these concepts and methods from industrial economics are an integral part of the now well-known circular economy approach (International Society for Industrial Ecology, 2023).

IE is commonly applied to the determination of GHG emissions, particularly in politics, e.g., via the determination of country footprints and related reduction measures (Bourg, 2003), but also in industry, where the methods of IE contribute to the determination of the ecological footprint of the company and offer a navigation tool for sustainable development (Erkman, 1997; Greenhouse Gas

Protocol, 2011). This calculation of the company's CF is part of the carbon management strategy (Zhou, 2020), and a company's Scope 3 indirect emissions have a key role to play because they account for a significant proportion of a company's total emissions (CDP, 2023b). Therefore, companies should have a basic understanding of their Scope 3 emissions by applying a screening method and based on this define a reduction strategy to support addressing climate change (Farsan et al., 2018).

2.2 Hotspot Analysis

A main difficulty for companies, but also in politics and science, is selecting which activities should be implemented where—given limited resources—to achieve the greatest possible impact and contribute to carbon management (Katris, 2015; UNEP DTIE, 2014). To support decision-making, there are a number of priority-setting methods, also known as *hotspot analyses*, which are designed to help break down large amounts of data into the essential *hotspots* on the basis of reliable and scientifically sound information, which can then be validated and addressed, for example, by the company or in politics (UNEP DTIE, 2014). While I do not conduct a formal hotspot analysis in this thesis, it will be theoretically described as I want to outline the effectiveness of using EEIO (and EXIOBASE) in hotspot analyses.

Hotspot analyses are particularly suitable in case of limited resources for prioritizing activities or targeted measures in the supply chain with the aim of reducing GHG emissions by identifying for example the *high emitting suppliers* (Erhard et al., 2019; UNEP DTIE, 2014). The hotspot analysis, therefore, provides an overview of the composition and drivers of emissions in terms of countries and industries which enables the identification of hotspots (Katris, 2015; Wiebe, 2018), in line with the IE research field mentioned earlier. Katris (2015) defines a hotspot as a sector or product that emits significantly higher GHG emissions relative to the total amount of emissions than a level that is considered acceptable. For countries or even companies, such an *acceptable* level may depend, for example, on the climate targets that have been set.

Despite the usefulness of hotspot analyses, there is no globally standard approach or method (UNEP DTIE, 2014). There are several ways to perform a hotspot analysis for upstream emissions, using either primary data, secondary data or a mix of both, e.g., supplier-specific, spend-based, average-data or the hybrid method (see Table 1 for overview and description of methods) (Greenhouse Gas Protocol, 2013). The emission factors used in the average-data method can be obtained through life cycle inventory data by using process-based LCA databases, such as ecoinvent (Greenhouse Gas Protocol, 2013; Steubing et al., 2022). In a hybrid approach multiple approaches can be combined, such as EEIO data with physical flows (see hybrid version of EXIOBASE 3 (Merciai, 2020)) or with primary, supplier-specific data. Understanding and comparing these methods is critical to assessing the effectiveness of using the spend-based method for hotspot analysis.

Table 1. Overview of different calculation methods for upstream GHG emissions based on Greenhouse Gas Protocol (2013, p. 21)

Primary data	**Secondary data**		**Primary and Secondary**
Supplier-specific	Spend-based	Average-data	Hybrid
"[T]he calculation of emissions is at the product level (cradle-to-gate) of goods or service providers/suppliers."[a)]	"[E]stimates emissions for goods and services by collecting data on the economic value of goods and services purchased and multiplying it by relevant secondary (e.g., industry average) emission factors (e.g., average emissions per monetary value of goods)."[a)]	"[E]stimates emissions for goods and services by collecting data on the mass (e.g., kilograms or pounds), or other relevant units of goods or services purchased and multiplying by the relevant secondary (e.g., industry average) emission factors (e.g., average emissions per unit of good or service)."[a)]	"[U]ses a combination of supplier-specific activity data (where available) and secondary data to fill the gaps."[a)]

Note. Source: **a)** Greenhouse Gas Protocol (2013, p.21). Additional Information: Primary data relates to "specific activities within a company's value chain [while secondary data] is not from specific activities within a company's value chain" (Greenhouse Gas Protocol, 2013, p. 15). See Greenhouse Gas Protocol (2013) for calculation examples.

Hereinafter, EEIO, which belongs to the spend-based approach, is described in detail, given that this is often the only way for companies to shed light on their emissions due to lack of data and limited resources (Erhard et al., 2019).

2.3 (EE)Input-Output Analysis Framework

In recent years Input-Output analyses (IOA), especially EEIO analyses, have become a focal point in IE research, enabling the quantification of the ecological footprint (Suh & Kagawa, 2009; Yale University, 2023) and thereby the identification of hotspots (Katris, 2015). The IOA framework is a modelling framework that depicts trade and commodity at the global, regional, local and intersectoral levels utilizing monitored economic indicators of these geographic locations (Miller & Blair, 2022).

"In its most basic form, an input–output (IO) model consists of a system of linear equations, each one of which describes the distribution of an industry's product throughout the economy." (Miller & Blair, 2022, p. 1) For better understanding, an exemplary basic IO table can be found in Appendix A. I also refer to chapter 2 of Miller and Blair (2022) for an extensive explanation including the mathematical logic behind IOA. Multi-Regional Input-Output (MRIO) models (also referred to as tables)[2] are constructed in a top-down approach by harmonizing many data sets, including national IO tables, and show the economic structure or trade between multiple sectors and countries (i.e. the global supply chains) (Miller & Blair, 2022; Osei-Owusu et al., 2021).

IO and MRIO models can be extended with environmental factors (e.g., water, GHG emissions) and social aspects (e.g., gender, employment) by combining data from various other sources (Bjelle et al., 2020; Moran et al., 2017; Stadler et al., 2018; Wood et al., 2014). This offers the advantage of allocating all emissions and resources used by the economic structures consistently to the sectors and products, and showing the related environmental and social impacts (Castellani et al., 2019). Environmentally-extended MRIO (thereafter referred to as EEIO) analyses are mainly applied to understand and quantify how the economic structures cause environmental destruction on country or household level including a consumption based approach, aiming towards policy development to reduce such impacts (Ivanova & Wood, 2020; Miller & Blair, 2022). Furthermore, this in-depth analysis of demand and supply enables the quantification of global spillover effects (Moran et al., 2017), revealing carbon leakage in the context of GHG emissions and facilitating a consumption-based approach to determining emissions (Usubiaga & Acosta-Fernández, 2015). Currently, several EEIO databases are available (Rocco et al., 2020), but they vary in sector, product and region coverage as well as in other factors such as license costs and time span available for the EEIO (Castellani et al., 2019; Deutsches Global Compact Netzwerk, 2019).

EXIOBASE is one of the most used EEIOs in industries. It was developed as part of an EU-funded project (Wood et al., 2014) and is open source (EXIOBASE Consortium, 2015), which makes it accessible for any company and thus increases the reach of potential improvements to carbon management. "EXIOBASE […] provides a consistent framework for tracking emissions, resource use, and other environmental pressures along global supply chains and thus linking consumption patterns to production processes elsewhere" (Stadler et al., 2018, p. 11) and can be applied for identifying environmental hotspots and developing targeted policies to address these (Stadler et al., 2018). EXIOBASE, like any EEIO, is based on a top-down approach and harmonizes the contained data (e.g., multiple national IO tables) by creating uniform sectors, which in EXIOBASE's case follow the so-called NACE classification (Stadler et al., 2018)—i.e., the Statistical classification of economic activities in the European Community (Eurostat, 1996). There are three versions of EXIOBASE, with EXIOBASE 3 being the most recent version (EXIOBASE Consortium, 2015). EXIOBASE 3 is available as a monetary version, where only monetary values are used to derive emissions and hybrid versions, where products are

[2] The term model and table in context of IO/MRIO/EEIO will be used when specifically referring to tables and equations used, while analysis will be used when generally referring to the IO/MRIO/EEIO method.

expressed in physical units and services in monetary terms (Steubing et al., 2022). While the research questions focus on the monetary (spend-based) version of EXIOBASE, the hybrid version will be considered in the comparison. Applying EXIOBASE (monetary) enables an overview of how much resources have been used or how much emissions have been emitted per euro spent in a specific sector and country (Tukker et al., 2014). Other prevalent EEIOs are Eora (Lenzen et al., 2012; Lenzen et al., 2013), the World Input-Output Database (WIOD) (Timmer et al., 2015) and the Global Trade Analysis Project (GTAP) (Aguiar et al., 2022). These databases are relevant because they will be compared with EXIOBASE later to draw better conclusions about the effectiveness of EXIOBASE for hotspot analyses.

3 Methodological Approach

This section describes the methods used to answer the research questions. I used a mixed methods approach (Döring & Bortz, 2016), which included several steps (Figure 2). For the first research question, the results of a systematized literature review and expert interviews have been compiled into one answer, while the second research question followed more of an iterative process between methods until the framework was finalized. Following the chronological order of the research, I will first explain the initial literature search for *effectiveness* definitions and existing frameworks. This determined the way the systematized literature review on *EXIOBASE and GHG or carbon dioxide (CO_2) emissions* was conducted, which will be explained in a second step including how the review was analyzed for both research questions. Lastly, I will explain the expert interviews and respective analysis techniques. Noteworthy, the focus of the expert interviews was to verify the framework based on the literature review to develop the effectiveness framework in a final outcome.

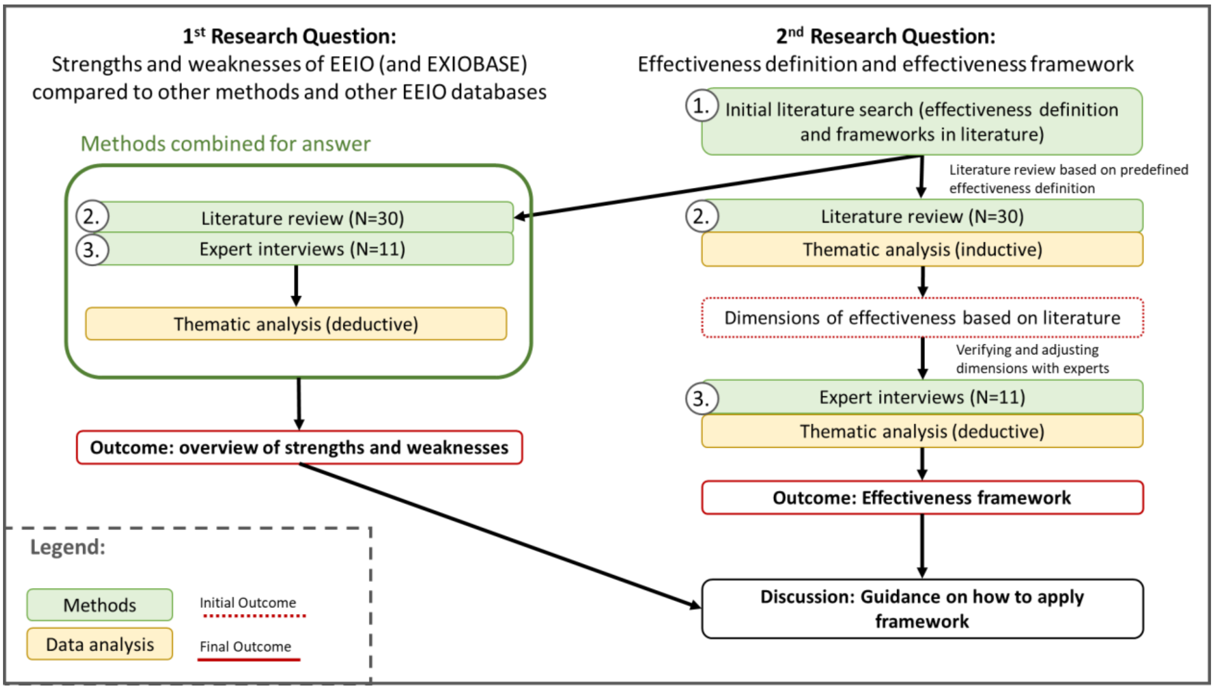


Figure 2. Methodological approach of thesis (own creation). The numbers indicate the chronological order in which the research has been conducted.

3.1 Step 1: Effectiveness Definition and Frameworks in Literature

Before developing an effectiveness framework, it is necessary to understand what *effectiveness* means in the context of using EEIO (and EXIOBASE) for the identification of GHG hotspots. The initial search was conducted on various platforms such as Scopus, Google Scholar, Google with the aim to find a definition of effectiveness. While there are various definitions that explain effectiveness for different purposes (Cambridge University Press & Assessment, n.d.), none has been found that relates to the topic of GHG hotspots in particular. Therefore, among the definitions found, a suitable definition was selected to be adopted in the context of this thesis. The Australian Productivity Commission (2013) has published a definition on effectiveness in one of its papers, which will serve as the basis for this thesis.

> *"In general, effectiveness [is] the extent to which stated objectives are met […]." (Productivity Commission, 2013, p. 6) "Effectiveness (of a program or service) [is a] measure of how well the outputs of a program or service achieve the stated objectives (desired outcomes) of that program or service." (Productivity Commission, 2013, p. 13)*

For better alignment, this definition has been adjusted by replacing *program or service* with *method*, as the objective of this thesis is to identify the effectiveness of a method (EEIO and EXIOBASE) to reach the desired outcome (identification of GHG emissions hotspots). Additionally, the *method* was contextualized within this research by specifying *method for identification of upstream greenhouse gas emission hotspots*. This refined definition was the starting point for developing the framework, which is comprised of dimensions that must be considered to assess the effectiveness of a particular method for hotspot analysis in this context.

The Australian Council for International Development, ACFID (2015), has released a guideline on how to develop an effectiveness framework related to development. They point out that it is essential to define the scope and approach of the framework and agree on dimensions that the framework should entail (the content). When this is set, it is recommended to do research if there is already a framework available that covers the approach and content. If not, an initial outline of the framework should be developed based on perceived relevant dimensions and afterwards verified with relevant stakeholders.

Aligned with this guideline, I researched different platforms to gather information regarding whether there already exist effectiveness framework(s), which was not the case. Given the absence of effectiveness frameworks, the effectiveness definition and other frameworks served as inspiration (Mandl et al., 2008; Pastor, 2009; Productivity Commission, 2013). Especially Pastor's (2009) framework in the context of finance was helpful because it provided some inspiration on what dimensions constitute effectiveness, such as the "Prerequisite of Quality, Methodological soundness, Accuracy [and] Reliability [as well as] Accessibility" (Pastor, 2009, p. 16). These exemplary frameworks and dimensions will be used to help guide the thematic analysis of the literature review and finally the development of the framework. Additionally, a verification of the framework and dimensions was undertaken with relevant stakeholders through expert interviews.

3.2 Step 2: Systematized Literature Review and Thematic Analysis

3.2.1 Systematized Literature Review

A systematized literature review (Grant & Booth, 2009) was used to conduct a screening of relevant literature to support answering both research questions. "Systematized reviews attempt to include one or more elements of the systematic review process while stopping short of claiming that the resultant output is a systematic review." (Grant & Booth, 2009, p. 102) While the search and screening of the literature review has been conducted in a systematic manner, a rather flexible review approach to answer the research questions (e.g., find strengths, weaknesses and patterns that relate to effectiveness framework) was applied.

The objective of the systematized literature review is to screen all papers that are related to EXIOBASE and GHG or CO_2 emissions, as EXIOBASE includes other environmental factors that are not relevant for this thesis. The aim of the review is to outline strengths and weaknesses of EXIOBASE related to the research question and to support the development of an effectiveness framework by finding patterns in the literature, e.g., different dimensions of effectiveness. Additionally, this review will serve as a foundation for expert interviews to have an in-depth understanding of the topic in academia and industry. While the way the review was performed is identical for both questions, the techniques to analyze the papers and the results were twofold. Thus, I will first describe the process of conducting the review and then focus on describing the analysis procedures.

To conduct the systematized review, I followed and adapted the method of *RepOrting standards for Systematic Evidence Syntheses* (ROSES) for systematic literature reviews, as they are suitable for environmental topics (Haddaway et al., 2020; Haddaway et al., 2018). The ROSES strategy was chosen as it provides guidance for the initial process for searching, screening and the critical appraisal, while being flexible when it comes to synthesizing the review (Haddaway et al., 2018). Figure 3 depicts the systematized literature review based on ROSES flow chart Version 1 (Haddaway et al., 2017) and each of the three steps in the figure will be described in the following.

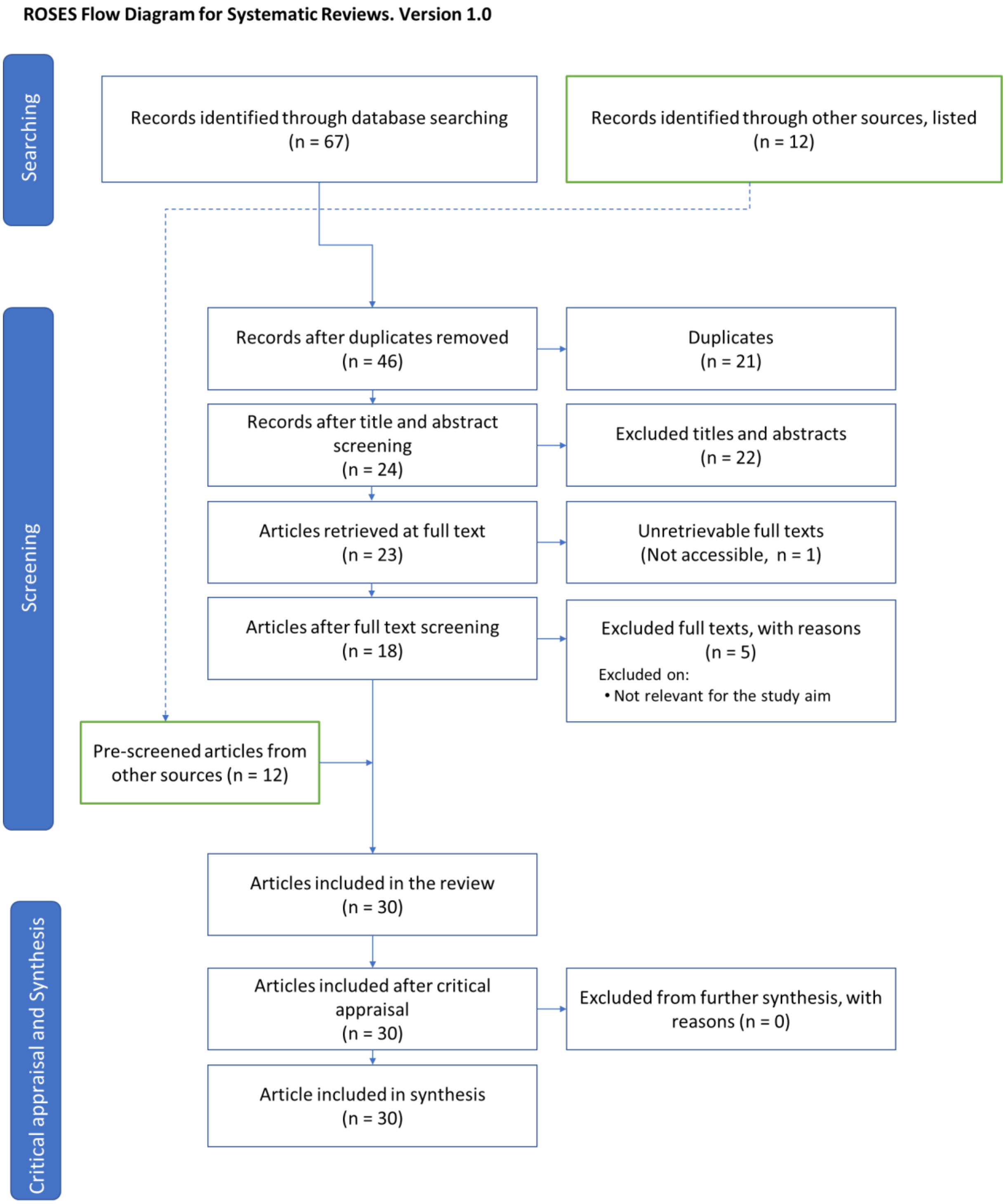


Figure 3. Systematized literature review for thesis based on ROSES Version 1.0 (Haddaway et al., 2017)

For the search strategy, I used Scopus and Web of Science (WoS) to obtain academic literature for my review and selected English and German as languages. I screened the article for title, abstract and keywords with the following search string "EXIOBASE AND (GHG OR CO2)" leading to 26 results in SCOPUS and 41 results in WoS. After removing the duplicates 46 articles have been added to the screening. Additionally, to ensure a close link to industry and avoid academic publication bias (Haddaway et al., 2020), organizational websites (e.g., the GHG Protocol, Science Based Target initiative (SBTi), CDP, and the EXIOBASE consortium) and the usage of web-based search engines (Ecosia and Google) have been screened using similar keyword search, resulting in including 12 pre-screened industry-related articles. The 46 academic articles were screened first based on title and abstract and then on full text, resulting in 28 articles being excluded because they either did not appear relevant to achieving the objective of the review (e.g., old EXIOBASE version, strong policy, or country focus) or were not accessible. This accounts for 18 academic articles in the final review plus the 12 pre-screened industry-related sources, making a total of 30 articles included in the final synthesis. Finally, the critical appraisal of the articles has been conducted by verifying if the articles have been peer-reviewed and as for the 12 additional added sources if the institutions are internationally recognized. No article has been excluded in this last step, leading to 30 articles that are included in the final synthesis.

3.2.2 Thematic Analysis

For the analysis of the literature review, I chose thematic analysis, which stems from content analysis and according to Mayring and Fenzl (2019) is a common qualitative method to analyze texts that have been obtained for example through gathering documents or conducting interviews and the respective transcripts. They specify that content analysis in its original form can also include categorization, also called coding of texts, or even statistical analysis of e.g., frequencies of words/phrases. However as the analysis aims more towards the identification patterns/themes (e.g., the dimensions of the effectiveness framework or strengths and weaknesses of EXIOBASE) and not so much on a statistical analysis, thematic analysis is more suitable in this case (Braun & Clarke, 2006; Galletta, 2013). Therefore, in line with the objective of this thesis, a thematic analysis was chosen.

For the first research question, the literature has been screened in a deductive way (Braun & Clarke, 2006). The strengths and weaknesses of EEIO approach compared to the supplier-specific, average-data and hybrid methods have been qualitatively analyzed based on the literature and summarized. As for EXIOBASE (Stadler et al., 2018) the strong and weak features were analyzed compared to three of the most common EEIO databases mentioned by literature and expert interviews: Eora (Lenzen et al., 2012; Lenzen et al., 2013), WIOD (Timmer et al., 2015) and GTAP (Aguiar et al., 2022). This analysis was more structured, as common features such as coverage, base year, costs and usability have been analyzed in the literature. The findings of the literature review have been extended by searching the website of Eora, GTAP and WIOD to ensure that the data of the databases is up to date. For a better understanding of the level of comparison of strengths and weaknesses in the first research question see Figure 4.

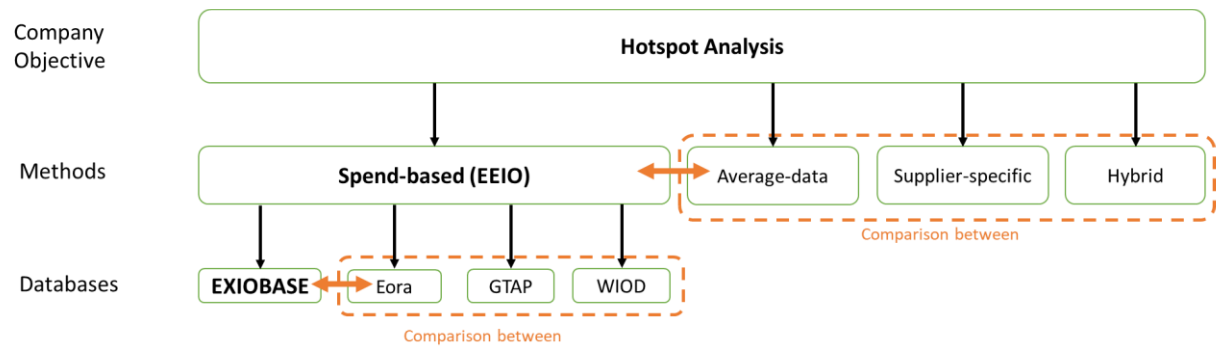


Figure 4. Level of comparison for strengths and weaknesses (first research question) (own creation)

For the second research question, thematic analysis was used more inductively (Braun & Clarke, 2006), with the goal of finding dimensions that could explain the construct of effectiveness. The refined effectiveness definition and the exemplary frameworks survey as inspiration for these dimensions (as described above) but have been supplemented and adjusted based on the literature review findings. Based on the literature, effectiveness constitutes the four overarching dimension of *Transparency and Prerequisite Data Quality, Methodological Soundness, Accuracy and Reliability* and *Cost/Benefit Comparison*, which will be described further in the results.

3.3 Step 3: Semi-structured Interviews and Thematic Analysis

3.3.1 Semi-structured Interviews

As my thesis concentrates on the industry, I need to align the knowledge (initial dimensions) obtained in literature to industry, which is why I decided to interview industry experts and IE academics. Furthermore, as my research questions have a more explanatory nature (especially related to the effectiveness framework) a qualitative approach using semi-structured interviews was chosen (Döring & Bortz, 2016). This approach was selected to allow the interviewer to adjust the order of questions and include spontaneous follow-up questions while still following a rough structure, often thematically sorted open-ended questions (Döring & Bortz, 2016). The interviews consisted of 4-5 thematic blocks; 1) Introduction, 2) general questions about EXIOBASE, 3) the effectiveness framework, 4) follow-up questions (if time allows), and 5) concluding questions (see Appendix B for interview guide). The interview questions were ranked according to their importance to ensure to not exceed the time frame (Adams, 2015).

To obtain the desired knowledge about EXIOBASE and EEIO, in-depths interviews were conducted with experts (Helfferich; Johnson, 2001) who have personal experience with EXIOBASE (developing, researching, applying the database). To enable a broad sample of different experts from academia and industry, potential experts were identified through the LinkedIn search function (keyword: EXIOBASE), authors of academic papers, Google searches, and recommendations from initially contacted individuals. Of the approximately 100 search results, 31 experts were contacted via email or LinkedIn, and the final sample size of 11 experts was determined by participants' positive responses. The ethical guidelines of the Swedish Research Council (2017) and Lund University were respected and attached in a document to the interview request to safeguard privacy and consent of the respondents and to follow the tenets of honesty and transparency (Moriña, 2021).

Prior to conducting the interviews, the interview guide was peer reviewed and pre-tested with two industry climate experts and adjusted based on this. The interviews were conducted individually from Feb. 28 to Mar. 23, 2023 (see Appendix C for interview logbooks with participants) to gain insights of each expert opinion (Döring & Bortz, 2016). Due to the different locations of the experts worldwide, an online interview mode via Microsoft Teams was chosen. The interviews were mainly conducted in English (10), while one was conducted in German, as it is beneficial to conduct the interview in the participant's native language if possible and desired (Mann, 2016). Each interview lasted between 45-60 minutes and a PowerPoint presentation was shown during the interview that included the agenda, the definition of effectiveness, and the literature-based dimensions of the effectiveness framework. The participants provided consent to use the data either in writing or verbally (if the written version was not pre-filled, which is recommended by Warren (2001)) (see Appendix D). All interviews were recorded and transcribed in an editorial style (focus on content and relevant information to answer the research question or related) with participant consent (Hussy et al., 2013) and anonymized if requested.

3.3.2 Thematic Analysis

After data collection, transcription, and initial familiarization with the data (refers to the 11 interviews) for inspiration of data analysis (Mann, 2016), a strategy for analyzing the data must be determined (Galletta, 2013). There are several ways to conduct an analysis of qualitative semi-structured interviews (Döring & Bortz, 2016; Mann, 2016). Among the most common is content analysis, and again, I chose thematic analysis with a deductive approach (Braun & Clarke, 2006; Mayring & Fenzl, 2019) as I aimed to find information to shape the initial dimensions of the framework and add strengths and weaknesses to the literature review findings. For coding the transcripts, NVivo software (QSR International Pty Ltd., 2020) was used as it provides a way to structure, organize and summarize findings across various datasets. Firstly, I went through each transcript inductively, considering the findings from the literature and attempting to make connections whenever possible and coded text passages by either naming them similar to the original (literature) patterns or outlining new categories (thematic codes) if they were not already included. In a second step, I went through these codes, merged similar codes and grouped codes (divided according to research questions, i.e., structured into dimensions of the effectiveness framework and strengths and weaknesses).

As mentioned above, the expert interviews focused on verifying the effectiveness framework developed based on literature (second research question), as suggested by the guideline to develop an effectiveness framework (ACFID, 2015). Using the interviews, the literature-based framework with four dimensions was modified, which resulted in an effectiveness framework that is aligned with relevant stakeholders from industry and academia. However, the expert interviews also provided insights into the strengths and weaknesses (first research question), especially concerning EXIOBASE and the interviewees' personal experiences with the database. These findings complemented the results of the literature review and contributed to the final overview of strengths and weaknesses.

4 Results

In this chapter, I will first outline the strengths and weaknesses of the EEIO approach and EXIOBASE to provide a thorough understanding for the effectiveness framework. Afterwards, I will go into the effectiveness framework based on the literature review and summarize the results of verifying the framework with experts.

4.1 Strengths and Weaknesses of EEIO Approach and EXIOBASE in Comparison

In this section, the strengths and weaknesses of the EEIO spend-based approach (EXIOBASE) will be discussed and compared to average-data, supplier-specific and the hybrid approach (Eora, GTAP and WIOD).

4.1.1 Strengths and Weaknesses of EEIO Compared to Other Methods

The systematized literature review and expert interviews revealed several advantages and disadvantages of spend-based EEIO approaches that are depicted in Table 2 and divided into general and company-specific. Generally (i.e., independent of any specific company), the strengths of EEIO are the full coverage of the global economy including international spillover effects as it is a consumption-based approach, the clustering of impacts based on diverse categories such as sectors, products, or regions. The weaknesses are primarily in the time dimension, as the data is quite old and includes a time-consuming data harmonization and aggregation process that varies amongst different EEIO databases leading to trade-offs.

For any specific company, EEIO provides quick estimations of their GHG emissions with comparably low effort. These quick estimations are not focused on supply chain data of the respective company but on data from the EEIO database. Thus, EEIO is not feasible for steering and monitoring suppliers, as specific reductions cannot be tracked. All interviewees agreed that EEIO is suitable for an initial hotspot analysis, but the results need verification and complementation with other methods.

Table 2. Strengths and Weaknesses of EEIO in general and for any specific company. Literature sources from each strength and weakness are given as superscripts, with the citations below the table.

Strengths of EEIO approach	Weakness of EEIO approach
In general	**In general**
• Macroeconomic top-down approach leading to a full coverage of global economy (and supply chain) [h)i)n)] • Consumption based approach: Capturing of all direct and indirect (environmental) impacts associated with consumption of goods and services in one year, regardless of place of production including international spillover effects [a)e)g)l)] • Clustering of results (including several economic, social and environmental impacts) by sectors, product, material group and end-use category as well as by regional or country differentiations with level of detail depending on the type of EEIO database [f)h)n)] • The different EEIO databases are quite robust. Despite partially different aggregation methods, still similar qualitatively results [d)]	• Offers only one data point per reference year and relatively old data (2-9 years back) due it being data-intensive (dependence on data such as IO-tables of national countries, data availability issues) and time-consuming (harmonization/aggregation process of data). [e)i)j)k)] • No standardized harmonization and aggregation process for data across current EEIO databases leads to trade-off of resolution level of sector and country making comparison difficult. [i)m)] • Monetarily modelled linkages of economy can lead to distortions if overlaps between sectors and commodity groups are small, especially since there is a lack of product granularity [a)h)] • The assumption of a homogeneous product for an industry can lead to distortions, especially if the mass-related prices of different products within a sector are large [h)] • Limited accuracy and robustness of results; just a rough overview, not company-specific, see below [b)c)]
Company-specific	**Company-specific**
• Simple way to provide initial screening with little effort [c)] • EEIO is a suitable method to obtain GHG emission estimations that consider regional differences by using purchasing volume [b)n)]	• Results provide only rough representation of supply chain [b)c)] as not company-specific (usage of IO-data, partially possibility to adjust if skills available[n)]) and price effects may result in distorted results [b)c)n)] • Not feasible as steering/monitoring tool for suppliers, as specific reduction cannot be tracked [n)]

Note. Own creation based on literature review. Sources: **a)** Castellani et al. (2019) **b)** Erhard et al. (2019) **c)** Deutsches Global Compact Netzwerk (2019) **d)** Moran and Wood (2014) **e)** Osei-Owusu et al. (2022) **f)** Osei-Owusu et al. (2021) **g)** Schmidt et al. (2019) **h)** Scholz et al. (2020) **i)** Stadler et al. (2018) **j)** Steubing et al. (2022) **k)** Wiebe et al. (2018) **l)** Wood et al. (2020) **m)** Wood et al. (2015) **n)** Interviews

The literature review and interviews revealed that there is always a trade-off of advantages and disadvantages between the choice of different methods for hotspot analysis. The supplier-specific method potentially has the highest accuracy amongst all the methods and provides a good basis for steering, as it is possible to track emission reductions in the supply chain (Erhard et al., 2019). However, this is associated with a high effort in data collection (depending on the number of suppliers) and the availability as well as quality of the primary data is not guaranteed (Deutsches Global Compact Netzwerk, 2019; Erhard et al., 2019). Additionally, data quality depends on the maturity level of the suppliers, as many do not have the corresponding know-how and first need to be coached (Greenhouse Gas Protocol, 2011).

The average-data method involves little effort (if mass-based sectoral averages are used), but if general average data are used, it also has lower accuracy and cannot sufficiently differentiate between regions, and is of limited use as a steering tool (Deutsches Global Compact Netzwerk, 2019; Osei-Owusu et al., 2022). Nevertheless, this approach is relatively resource-intensive in the context of money and know-how (Erhard et al., 2019) and labor-intensive according to the interviewees, while the results show an estimate of the real emissions (Erhard et al., 2019). Compared to EEIO, which covers the entire economy, LCAs choose system boundaries (cut-offs) for products, which vary greatly depending on the LCA-practitioner (Osei-Owusu et al., 2021; Steubing et al., 2022). Therefore, CFs of EEIO are often higher than those of LCA according to Steubing et al. (2022). Additionally, they state that in LCAs, emissions are determined over the entire life cycle and are not limited to a base year. Steubing et al. (2022) point out the benefits of product-level granularity, as LCAs provide detailed emission sources for multiple products, while EEIOs do not have the same level of product resolution. However, EEIOs offer a more detailed sector and region/country resolution than LCAs (Steubing et al., 2022). Interviewees additionally mentioned that most LCA software includes a license fee.

Lastly, as a middle ground, the hybrid method offers a good control basis (for the primary data e.g., of most important suppliers) and progress tracking through the combination of primary and secondary as stressed during the interviews. However, this is associated with a high level of effort in data collection (Deutsches Global Compact Netzwerk, 2019; Erhard et al., 2019). According to Scholz et al. (2020) a hybrid method that uses e.g., IOA data with coefficients from LCA studies can use the advantages of both approaches (complete coverage of supply chains and higher resolution by individual products). However, they point out that mixing different approaches (and thus different process and system definitions) should be done with caution, which has been stressed by several experts as it can lead to inconsistencies. Moreover, reproducibility is difficult due to very specific, sometimes unpublished data and the lack of consistent data for material intensity coefficients for hybrid approaches (Scholz et al., 2020).

4.1.2 Strengths and Weaknesses of EXIOBASE Compared to Other EEIO Databases

The most common EEIO databases (EXIOBASE, Eora, GTAP and WIOD) were compared in term of their features (Table 3) such as geographic and sectoral coverage, covered years, costs and usability and additional factors (Deutsches Global Compact Netzwerk, 2019; Walmsley et al., 2014). Generally, there is not one database that is best for all purposes; it depends on each project's specific goal. Besides, trade-offs between strong and weak features of databases are potentially inevitable due to data availability and computational complexity. However, improvements are being made.

Table 3. Summary of the feature comparison among the most common EEIO databases. Literature sources are given as superscripts, with the citations below the table.

	EXIOBASE 3 (Stadler et al., 2018)	**Eora** (Lenzen et al., 2012; Lenzen et al., 2013)	**GTAP** (Aguiar et al., 2022)	**WIOD** (Timmer et al., 2015)
Version of database	Version 3.8.2 [h)] (Version 3xr available) [a)]	Eora26/FullEora (v199.82) [d)]	GTAP 11 Data Base [f)]	WIOD 2016 [j)]
Coverage (Geographical, Sectors, etc.)	Monetary version [b) i)]: - 44 countries* (27EU & 17 major economies) and 5 rest of the world countries (Europe, Africa, Asia, America and Middle East) - 200 products, 163 industries, 417 emission categories, 663 raw materials *paper available that extends EXIOBASE to 214 countries (Bjelle et al., 2020) [a)]	Full EORA version [d)] - 190 countries - 26 harmonized sectors across all countries available, up to 16000 country-specific sectors available - 2720 environmental indicators	- 19 aggregated regions - 141 countries - 65 sectors [f)]	- 43 countries and one rest of world model - 56 sectors - Environmental data for 27EU countries and 16 additional big countries [j)]
Covered Years	1995-2011*[i)] *available on Zenodo up to 2022 (however partially with limited updated data) [h)]	1990-2021 [d)]	2004,2007,2011,2014,2017 [f)]	2000-2014 [j)]
Costs	Free available on Zenodo [k) h)]	License costs range depending on type of institution and scope of product from ~4.000€ to ~35.000€ [e)]	License costs range depending on institution (type, size) from 370$ to 6240$ [g)]	Free available [j)]
Usability/User -friendliness	Difficult for EEIO-beginners [c)], Software solutions provided by companies for more user friendliness, pre-existing codes available, fast to use for experts [k)]	Difficult for EEIO-beginners Only accessible via MS Access (MATLAB Workspace Variable Data files) [c)]	Difficult for EEIO-beginners Special Software required for usage [c)]	Difficult for EEIO-beginners [c)]

Note. The structure of the table is based on Deutsches Global Compact Netzwerk (2019, p. 6). The content has been updated and expanded based on the findings of the literature review and the official websites of the databases. *Sources*: **a)** Bjelle et al. (2019) **b)** EXIOBASE Consortium (2015) **c)** Deutsches Global Compact Netzwerk (2019) **d)** KGM & Associates Pty. Ltd. (2023b) **e)** KGM & Associates Pty. Ltd. (2023e) **f)** Purdue University (2023a) **g)** Purdue University (2023b) **h)** Stadler et al. (2021a) **i)** Stadler et al. (2018) **j)** University of Groningen (2023) **k)** Expert interviews

In terms of sectoral and geographic *coverage*, there is a trade-off among existing EEIO databases (Bjelle et al., 2020), between sectoral detail and country coverage. However, although EXIOBASE lacks country resolution, it is very suitable especially for European-centered companies with their main trading partners being similar to the ones from EU (such as China, America, India, etc.) (Ivanova & Wood, 2020). Additionally, it offers high product and industry resolution (Stadler et al., 2021b), which is valuable for mapping it to any particular company. By considering emissions through capital goods, EXIOBASE is one of the most detailed EEIOs (Hertwich, 2020; Södersten et al., 2018); a literature review finding that was also mentioned in interviews. In summary, for companies, EXIOBASE and WIOD are quite comparable in terms of country resolution (quite low) and time frame. EXIOBASE offers more than 160 sectors/industries, compared to between 26 and 65 for the other databases analyzed (Table 3). If high country resolution is desired, GTAP and Eora offer a good alternative with 141 and 190 countries, respectively. However, GTAP and Eora offer less harmonized sectors in the region compared to the other two databases.

Regarding the *covered years*, Eora offers the most extensive time series from 1990-2021, while EXIOBASE has published data available from 1995-2011 (but additional uploaded versions on Zenodo until 2022). By contrast, WIOD offers the time series from 2000-2014 and GTAP only offers 5 years in the time span of 2004-2017. Eora and GTAP both have high country resolution, but Eora is available for a time series of over 30 years while GTAP is only available for five individual years, Eora should be preferred over GTAP if good country and time series coverage is desired.

Regarding the *costs*, EXIOBASE and WIOD have a strong advantage as they are available for free, while Eora and GTAP include license costs.

In terms of *usability*, it can be stated that all of these are difficult to use for beginners (Deutsches Global Compact Netzwerk, 2019). However, special software is required to access GTAP and Eora, which adds another level of difficulty. EXIOBASE and WIOD on the other hand can be downloaded in different formats. An additional aspect mentioned in the interviews is that EXIOBASE does not provide any uncertainty indications or standard deviation data, which has been also mentioned in literature (Castellani et al., 2019; Zhang et al., 2019), while Eora indicates the standard deviation (KGM & Associates Pty. Ltd., 2023c). Having said that, according to the interviews, a single emissions indicator is more feasible for a company, as it can more easily communicate the results to the relevant stakeholders.

While based on the comparison EXIOBASE is preferable to WIOD and Eora is preferable to GTAP, the choice between EXIOBASE and Eora depends on the desired level of resolution of countries and industries/sectors. Notably, according to the interviews, EXIOBASE is one of the most widely used analytics software and EXIOBASE is working on a successor version with a planned country expansion and possibly more products, which will make EXIOBASE even more advantageous.

4.2 Effectiveness Framework

The effectiveness framework is based on the following refined definition that emerged from the initial literature research (Productivity Commission, 2013) and relates to the effectiveness of a method (here EEIO and EXIOBASE) in identifying GHG hotspots:

> In general, effectiveness is the extent to which stated objectives are met. Effectiveness of a method for identifying upstream GHG emission hotspots is a measure of how well the outputs of the method achieve the stated objectives (desired outcomes) of that method.

This definition was shared with the experts during the interview prior to discussing the literature-based framework and was viewed as reasonable. Additionally, the expert interviews revealed that effectiveness depends on the person who is applying the EEIO, as a company for example would understand effectiveness more related in the context of efficiency of applying a method.

4.2.1 Effectiveness Framework Based on Theory and Literature Review

Based on the findings of the systematized literature review, effectiveness includes four overarching dimensions (Table 4), which will be explained in depth below.

Table 4. Framework for determining the effectiveness of methods to identify GHG emission hotspots based on the systematized literature review. Literature sources are given as superscripts, with the citations below the table.

Transparency and Prerequisite Data Quality	**Methodological Soundness**	**Accuracy and Reliability**	**Cost/Benefit Comparison**
• Source [b)], type [b)g)] and relevance [v)α)β)] of data • Data availability [n)s)w)y)] and age [e)g)l)m)u)w)β)]	• Scope [a)b)g)o)v)], system boundaries/ completeness [c)f)h)j)l)m)o)s)u)α)β)] • Classification/Sectorization of data [a)b)f)g)h)i)j)k)l)m)o) p)q)r)t)u)x)y)z] • Consensus on approach [b)j)v)] • Reproducibility/Replicability [j)v)y)]	• In general: assessment and validation of data (including sensitivity analysis) [j)] • Input: financial & environmental data accuracy [v)], consistency of data [α)β)] (across time [t)], countries [t)], pricing layers [c)g)h)l)w)y)z)]) [p)t)y)], technological development [a)h)p)l)t)u)v)w)y)β)] • Output: Relative ranking of categories [j)y)] (magnitude)[k)], absolute/relative (un)certainty of results [a)b)f)h)l)n)o)q)u)δ)], robustness of results [i)j)v)y)]	• Cost effectiveness/ technical efficiency: Resources needed (time, money, ...) [c)e)g)w)] and limitations/weaknesses vs. strengths [d)] • Usefulness of results: Meta(data) accessibility [e)]; appropriateness and implication of results [c)]

Note. Own creation based on literature review. Sources: **a)** Bjelle et al. (2020) **b)** Castellani et al. (2019) **c)** Erhard et al. (2019) **d)** Farsan et al. (2018) **e)** Deutsches Global Compact Netzwerk (2019) **f)** Harris et al. (2020) **g)** He and Hertwich (2019) **h)** Hertwich (2020) **i)** Ivanova and Wood (2020) **j)** Moran and Wood (2014) **k)** Moran et al. (2017) **l)** Osei-Owusu et al. (2022) **m)** Osei-Owusu et al. (2021) **n)** Owen et al. (2016) **o)** Sato and Narita (2022) **p)** Scherer et al. (2019) **q)** Schmidt et al. (2019) **r)** Scholz et al. (2020) **s)** Södersten et al. (2018) **t)** Stadler et al. (2018) **u)** Steubing et al. (2022) **v)** Usubiaga and Acosta-Fernández (2015) **w)** Wiebe et al. (2018) **x)** Wood et al. (2014) **y)** Wood et al. (2020) **z)** Wood et al. (2015) **α)** Greenhouse Gas Protocol (2004) **β)** Greenhouse Gas Protocol (2011) **δ)** Zhang et al. (2019)

The first dimension is *Transparency and prerequisite data quality*, which is divided into two subcategories. Transparency (Greenhouse Gas Protocol, 2004, 2011) is related to the source and type of data, i.e. the origin of the data (Castellani et al., 2019), for example the environmental extension of the database (He & Hertwich, 2019). Additionally, another criterion is the relevance of data (Greenhouse Gas Protocol, 2004, 2011); that is, whether the included data in the EEIO covers the relevant information for identifying GHG hotspots in the upstream supply chain of a company. Furthermore, prerequisite data quality refers to the data age (Osei-Owusu et al., 2022; Steubing et al., 2022), what time series are available for the EEIO and the respective time lag (He & Hertwich, 2019). Collecting and analyzing all national IOA data requires time, hence not all data are always available in a timely manner (Wiebe et al., 2018).

The second dimension is *methodological soundness,* which consists of four parts. First, the scope of the analysis, i.e. the completeness of the analysis (Greenhouse Gas Protocol, 2004, 2011; Steubing et al., 2022). Noteworthy are the system boundaries or cut-offs, meaning which emissions are included in the analysis and whether there are any spillover effects or carbon leakage (Harris et al., 2020; Moran et al., 2017; Steubing et al., 2022). Second, classification or sectorization of the database, more specifically the sector/industry, product and geographical (region/country) detail (Schmidt et al., 2019; Stadler et al., 2018; Wood et al., 2020). This includes the way the aggregation/disaggregation of the classification is conducted, as aggregated models account for bigger errors (Bjelle et al., 2020; Stadler et al., 2018; Wood et al., 2014). Thirdly, if the approach is internationally accepted, is there consensus on the methodology (Moran & Wood, 2014), data concepts, definitions and uncertainties (Castellani et al., 2019; Usubiaga & Acosta-Fernández, 2015). Fourthly, whether the method is reproducible and hence the results are replicable (Moran & Wood, 2014; Wood et al., 2020).

The third dimension is *accuracy* (Bjelle et al., 2020; Greenhouse Gas Protocol, 2004, 2011; Osei-Owusu et al., 2021) *and reliability* (Greenhouse Gas Protocol, 2004, 2011) and comprises three subcategories. First, a general assessment and validation of the data by conducting a sensitivity analysis to examine the different parameters included with respect to their influence (Moran & Wood, 2014). Second, related to the input variables of the results it is crucial that the user verifies the financial accuracy of their own data, e.g., the monetary data provided by the company that wants to conduct the analysis (Farsan et al., 2018). Furthermore, the accuracy of the environmental extensions is also important (Usubiaga & Acosta-Fernández, 2015). Considering potential changes in technological development or economic structures when using older EEIO data to calculate current emissions are vital, as this might lead to distortion of GHG hotspots and needs to be reflected upon (Scherer et al., 2019; Wiebe et al., 2018; Wood et al., 2020). Therefore, the data should be analyzed with respect to the consistency (Greenhouse Gas Protocol, 2004, 2011) across time, countries, structure and size (Stadler et al., 2018).

This also includes the consistency of the data on price effects (Hertwich, 2020), such as taxes or inflation and growth rates (He & Hertwich, 2019; Wood et al., 2020). Lastly, with respect to the output, there are a few criteria that need to be considered in the accuracy and reliability dimension of the framework. This includes the reliability of the relative ranking of the categories of interest (i.e. have the real hotspots been identified, is the sensitivity small enough that it covers the real difference between categories (e.g., by conducting a Monte Carlo analysis), what is the confidence level of the analysis?) (Moran & Wood, 2014; Wood et al., 2020). Referring to this, the absolute and relative (un)certainty of the results is of interest (Bjelle et al., 2020, Castellani et al., 2019), also compared to other EEIOs or calculation methods (Hertwich, 2020; Steubing et al., 2022). According to Steubing et al. (2022) when comparing the uncertainty and magnitude of the results with other methods the relative deviation should be analyzed or a spearman's rank order correlation can be conducted. Additionally, the robustness of results is an important criterion, which refers to how variable the results are (also compared to other databases calculation methods) (Ivanova & Wood, 2020; Wood et al., 2020). The sensitivity analysis and uncertainty assessment are closely connected to this, as based on this conclusions about the robustness are possible (Wood et al., 2020).

The last dimension is called *Cost/Benefit comparison* and aims to bring in the company perspective that employs EXIOBASE to identify their CO_2-eq hotspots in the upstream supply chain. The first of two subcategories is the assessment of the cost effectiveness or also technical efficiency (Productivity Commission, 2013). This includes the resources needed to conduct the analysis (time, money, computing space necessary since EEIO involves a lot of data, etc.), also in comparison to other potential calculation methods that the company could apply (Deutsches Global Compact Netzwerk, 2019; Erhard et al., 2019; He & Hertwich, 2019; Wiebe et al., 2018). With respect to this, the limitations, blind spots and weaknesses of the analysis should be compared to the strengths and expected benefits (Farsan et al., 2018) and for this the part about the strengths and weaknesses of EXIOBASE can be a helpful guidance. Second, the usefulness of the results should be assessed based on the accessibility of the data and metadata (Deutsches Global Compact Netzwerk, 2019), i.e. the comprehensibility and clarity of the information about the hotspots. Linked to this, the appropriateness (usefulness) of the results should be addressed and the potential implications of the results. As mentioned before, EEIO and EXIOBASE depict trade flows of countries or regions, thus it needs to be investigated how close this country EEIO analysis is to the real supply chain of the respective company (Erhard et al., 2019).

4.2.2 Verifying the Effectiveness Framework Based on Expert Interviews

The general attitude towards the framework was very positive and the number of dimensions was considered appropriate for building a framework. Additionally, one expert stressed that the framework applies to CO_2-eq emission in general (not only CO_2) as EXIOBASE provides all relevant emission factors.

One of the experts mentioned that it is a good generic framework and emphasized the importance of these expert interviews for adapting the framework with relevant stakeholders. The interviewees suggested structural changes, renamed dimensions, but also added factors they felt were missing. Nothing from the current framework was excluded. Following the interviews, the four themes found in the literature were adjusted by merging and restructuring and including a prerequisite category that defines whether the particular EEIO method and effectiveness framework is even applicable for the company. The adjusted framework is depicted in Figure 5 and will be explained in detail in the following.

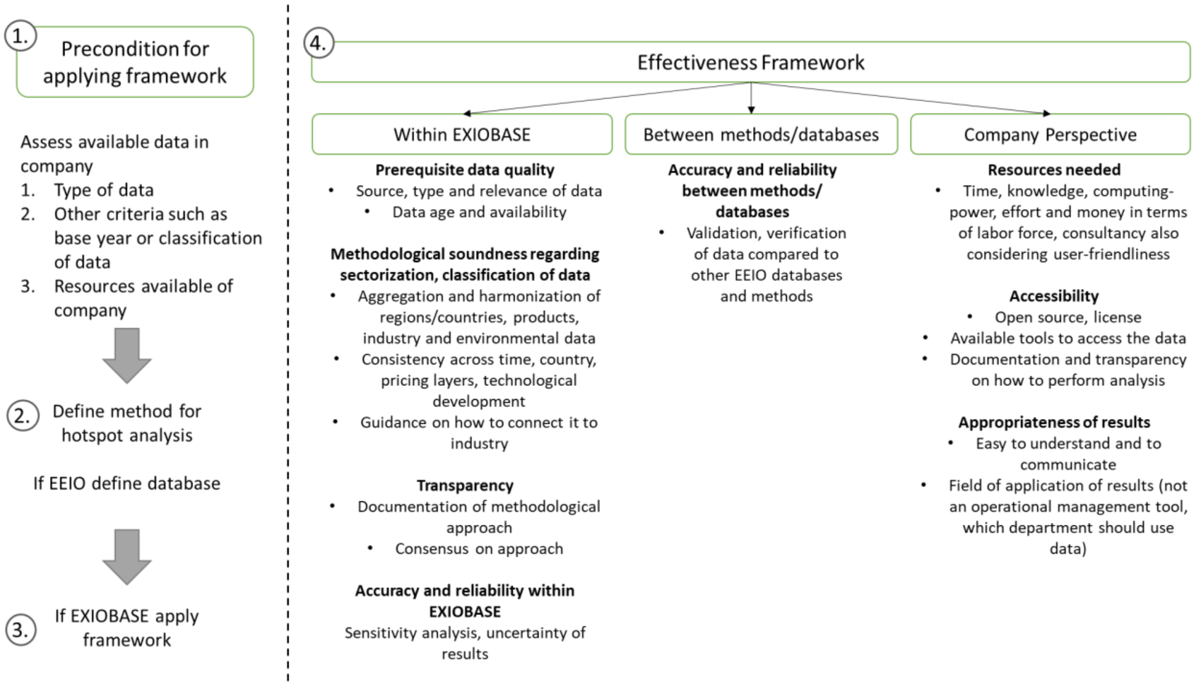


Figure 5. Effectiveness Framework for identifying CO_2-eq hotspots in the upstream supply chain (own creation)

The expert interviews revealed that there needs to be a *precondition* dimension that precedes the actual framework. This should serve as a decision-making tool to determine whether EEIO is the right method for companies in the first place, because if they have physical data, EEIO may not be the most effective method for identifying hotspots. Therefore, as a first step, a company needs to assess its available data in terms of the type and classification of the data, the base year, and finally the available resources. Based on the assessment of these available data of a company, an appropriate calculation method (see Table 1) and, if EEIO, the preferred EEIO database is selected. Guidelines for this precondition dimension, including two decision trees, are provided in the discussion chapter below. If a company draws the conclusion after going through the precondition dimension, that EEIO and EXIOBASE is the best option for them, the framework is applicable.

The revised framework was then divided into three parts (similar to Figure 4): *within EXIOBASE* (as database perspective), *between methods and databases* and *company perspective*.

The dimension of *within EXIOBASE* encompasses four subcategories that are closely related to the three original literature-based dimensions but were restructured and reorganized. First, the *prerequisite data quality* is identical to the original first dimension of the literature framework, except that transparency was removed from the title. Second, *methodological soundness regarding sectorization, classification of data* is another subcategory, which is similar to dimension two in the literature (methodological soundness). However, the experts added that guidance on mapping the EXIOBASE factors to the enterprise factors would be helpful and subsumed the consistency aspect from the accuracy and reliability dimension of the literature review. Third, *Transparency* is now a subcategory on its own, comprising documentation of methodological approach and consensus aiming towards replicability. Fourth, *accuracy and reliability within EXIOBASE* refer to sensitivity analysis and uncertainty results (only from EXIOBASE, not compared to other methods as originally stated in the literature). In this context, some experts discussed the advantage of greater accuracy from a range of emission estimates versus the disadvantage of greater complexity.

The second dimension *between methods and databases* includes the remaining part of the initial accuracy and reliability category, i.e., the validation and verification of the data compared to other EEIO databases and methods. This is essential, as the real figure of GHG emissions is unknown and therefore, the verification can only be between databases and methods by focusing on the uncertainty assessment, reliability of the relative ranking and robustness of results (i.e., whether results are approximately correct), as stated in the literature findings.

Finally, the *company perspective* is similar in content to the cost/benefit comparison, however the subcategories have been restructured and expanded. Generally, there are three subcategories. First, the resources required are time, money, computing power, knowledge and connected to this the work and consulting effort (also user-friendliness). Second, the accessibility of EXIOBASE as an open-source database (no licensing costs), the tools to access the database, and the transparency or documentation to perform the analysis. Thirdly, the appropriateness and implication of the results in relation to the area of application of the results, e.g., in the purchasing department. The results of the analysis (identified hotspots) need to be easy to understand and communicate and additionally pointed out that it is not an operational management tool as it does not capture supplier-specific reductions.

When going through the steps of the precondition dimension and then applying the framework, it will be possible to provide company specific insights into the effectiveness of applying EXIOBASE and EEIO to identify the GHG hotspots in the upstream supply chain.

5 Discussion

In the following, I will first discuss the findings and elaborate on the practical implications of the study by providing guidance on how to apply the framework. I will then touch on companies and sustainability before concluding the discussion with limitations and suggestions for future research.

5.1 Summary and Discussion of Results in the Context of Carbon Management

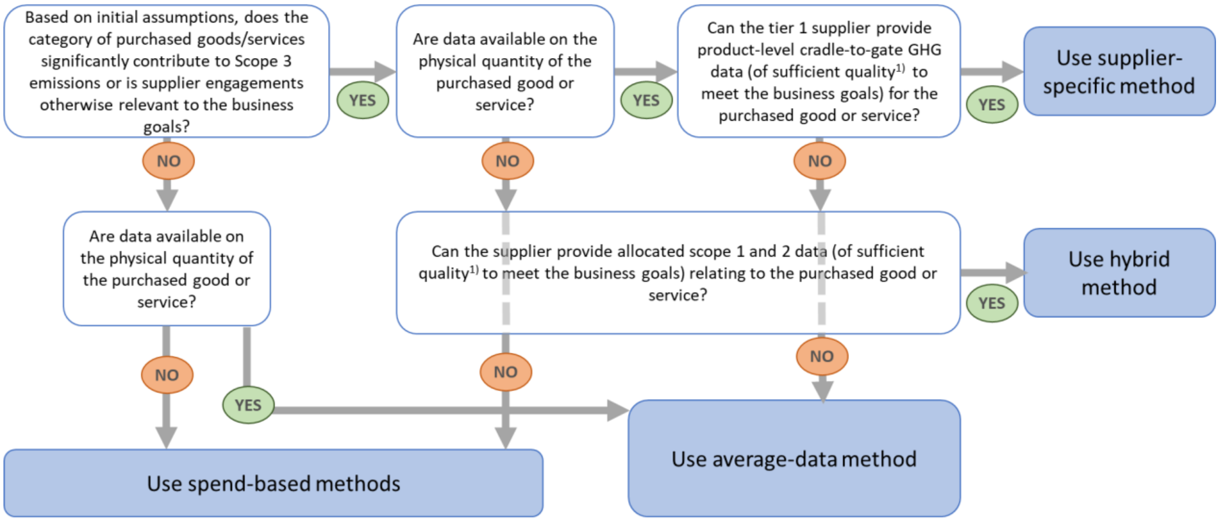
Companies need an understanding of their emissions to have a thriving carbon management strategy (Greenhouse Gas Protocol, 2011) and EEIO and EXIOBASE are commonly used by companies to initially estimate their upstream GHG emissions to serve as hotspots analysis (UNEP DTIE, 2014). The objective of this thesis was to provide insights into the effectiveness of EEIO (and EXIOBASE) to identify hotspots and thereby contributing to carbon management and addressing climate change. The previous chapter provides findings that support the enhancement of carbon management, and here I will outline how.

Results from the first research question identified strengths and weaknesses of EEIO compared to supplier-specific, average-data and hybrid methods, as well EXIOBASE as compared to other EEIO databases (Eora, GTAP and WIOD) and their implications for corporate carbon management. EEIO's strengths lie in its complete coverage of the economy and all direct and indirect emissions associated with the consumption of goods and services and the simplicity and low effort of performing the analysis. In prevailing EEIOs, there is a trade-off between different EEIO databases in terms of high country/region resolution and high product/sector resolution. Despite many weaknesses from the EEIO approach, several experts emphasized it is still the best method available considering that some companies do not have data other than monetary data. It provides an initial starting point and allows companies to begin their carbon management strategy. Among current EEIOs available, EXIOBASE is the most advanced by offering companies an open-source database (free license) with high product/industry resolution, broad coverage of environmental factors, and a good ability to perform hotspot analysis. The current limitation of EXIOBASE's comparatively low country resolution is planned to be addressed in EXIOBASE 4, according to expert interviews and literature (Stadler et al., 2018), which will further increase EXIOBASE's dominance. However, in the future, companies should seek to collect necessary data for extending their analysis beyond the spend-based approach (EEIO) and apply the average-data method and collect supplier-specific data. Using a hybrid method is appropriate in the transition period but the differences in the approaches should be considered when interpreting results and drawing conclusions.

Findings from the second research question led to a definition of effectiveness and a corresponding effectiveness framework related to the use of EEIO and EXIOBASE to identify GHG hotspots. This thesis provides a company with the means to evaluate the effectiveness of using EEIO (and EXIOBASE) for a hotspot analysis. This enables companies to gain insight into the effectiveness regarding their company and industry after applying the framework. However, the question of the effectiveness of a method is not straightforward because it is very subjective and depends on circumstances such as the user and the type of company. For some companies EXIOBASE might be more suitable, e.g., if their categories used in spend reporting are very close to those of EXIOBASE. The framework only provides insights into the indication of effectiveness, but not a definitive answer, primarily because the actual value of emissions is not known, and it is ultimately only an estimate. Therefore, the framework is more aimed at whether the method is effective, in the spirit of the famous quote by George E. P. Box that two of the interviewees mentioned, “Essentially, all models are wrong, but some are useful” (Box & Draper, 1987, p. 424). While the experts outlined the effectiveness of EEIO for a company’s hotspot analysis as a first step, they emphasized the necessity of verification and follow-up steps to successfully contribute to carbon management. Nevertheless, the framework allows a company to critically evaluate their hotspot analysis and draw assumptions about the indication of effectiveness in their specific case and the next part provides practical guidance.

5.2 Practical Implications of This Study

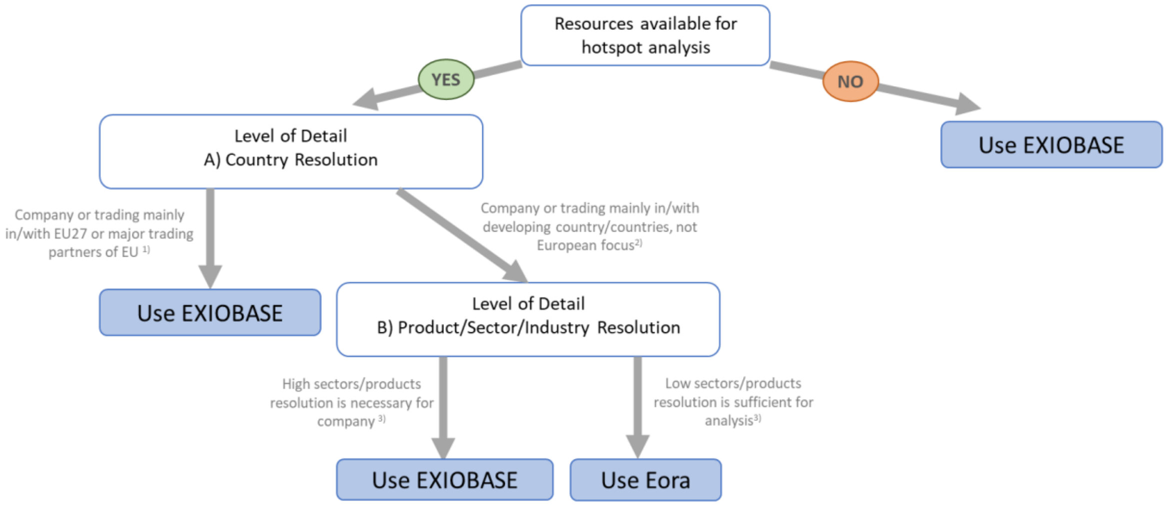
Recognizing that companies need appropriate guidance on how to use the framework in practice and for their specific company, practical implications follow. The precondition of the framework determines the applicability by selecting upfront the best calculation method (and if EEIO, the best database) for the company. To uncover this, there are two decision trees; Figure 6 depicts the first decision tree that provides guidance based on the Greenhouse Gas Protocol (2013) on which of the four methods introduced in Chapter 2 is most suitable by assessing the available data in a company. The decision tree includes aspects such as the relevance for the business goal, importance of purchased goods or services to the overall Scope 3 emissions, as well as the availability and quality of data. Data quality is a critical issue, as supplier-specific data provide company-specific emission factors, but depending on how the supplier acquired the data, the average-based method could provide more accurate data, e.g., if the supplier uses the spend-based data itself (Greenhouse Gas Protocol, 2013).



Notes
1) Quality needs to be assessed on different aspects (the GHG protocol provides guidance for this)

Figure 6. Decision tree for selecting calculation method for upstream CO_2-eq emissions of a companies purchased goods and services; adapted from Greenhouse Gas Protocol (2013, p. 23)

If, after applying the decision tree, the company concludes that EEIO is currently the best method for identifying hotspots, the choice must be made between different EEIO databases. As outlined in the results, EXIOBASE should be preferred over WIOD and Eora over GTAP. When it comes to determining whether to use Eora or EXIOBASE the decision is more complex, hence some of the potential decisions for a company are depicted below in another decision tree (Figure 7), which is based on the strengths and weaknesses in Chapter 4.1.2. A company's available resources such as costs in terms of license of the database, labor and time are important factors, along with the desired level of country resolution and industry/sector/product resolution factors, in deciding which EEIO database to choose (see Appendix E for EXIOBASE and Appendix F for Eora).



Notes
1) EXIOBASE data bases covers EU27 countries, 16 major trading partners of the EU (Brazil, Canada, China, India, Indonesia, Japan, Mexico, Norway, Russia, South Africa, South Korea, Switzerland, Turkey, Taiwan, United States of America, UK) and 5 Rest of the World categories (Europe, Middle East, America, Asia and Pacific, Africa)
2) Eora covers 190 countries (see Appendix for list)
3) Eora offers only 26 harmonized sectors across the 190 countries, while EXIOBASE covers 163 industries and 200 products across 44 countries and 5 RoW regions. See Appendix E and F for overview to see if necessary sectors are included.

Figure 7. Decision tree for selecting the EEIO database (own creation)

If, after following the precondition instructions, the decision is made to use EEIO and EXIOBASE, a company can apply the effectiveness framework (Figure 5) to its specific use case. The framework presents dimensions that should be considered when looking at the effectiveness of EXIOBASE to identify GHG hotspots in the upstream supply chain.

For assessing the first category of the framework, *within EXIOBASE*, the comparison of strengths and weaknesses as well as the literature overview provides a good guide. Most important for the company is probably how well the regions/countries/industries/products fit with the one from EXIOBASE and from what base year their data and the data of EXIOBASE is (inflation, price, technology aspects) and for this transparency is needed. This will be comparably straightforward to answer as this information was already necessary for the precondition. Furthermore, companies can conduct a sensitivity analysis by employing a Monte Carlo analysis to make initial statements about the uncertainty of results.

The second category, *between methods/database*, is relevant to assess the accuracy and reliability outside of EXIOBASE, by comparing with other EEIO databases and other calculation methods with the help of Chapter 2 and 4.1. If required, companies should collect necessary data, e.g., by contacting suppliers. This category is very closely related to resources available, as doing this takes time and costs money and the extent to which a company conducts this comparison is highly dependent upon available resources.

The last dimension, *company perspective*, offers an even stronger focus on the resources of the company but is linked to the EXIOBASE analysis. The evaluation of the resources needed is very company-subjective, as time, knowledge, computing-power, effort, and money in terms of labor force, consultancy and user-friendliness will differ between companies. The accessibility relates to the open source of EXIOBASE and if there are available tools on how to access the data (e.g., someone available with Python skills, software solution) and if the necessary documentation on how to perform the analysis is transparent enough. Finally, the appropriateness of the results points to the ease of understanding and communicating the results and to the field of application, for example as baseline for a short-term carbon management strategy. Though this is very subjective, the following section provides some insights in this regard.

While this framework offers a very generic approach, it opens the necessary discussion regarding effective methods for companies to enhance their carbon management and encourages a closer dialogue between academia and industry. This practical guidance assists companies in deciding which method and database to choose and, if EXIOBASE, provides an indication of the effectiveness (high/low). If other methods or databases are chosen this framework offers a first anchor point of potential aspects that should be considered, especially the dimensions that are not related to EXIOBASE.

5.3 Companies and Sustainability

In this thesis I argue that conducting a hotspot analysis with EEIO is a good initial starting point for companies to take climate action, as it generates a list of emissions hotspots that can be helpful for prioritizing measures for carbon management (Greenhouse Gas Protocol, 2011). The hotspots, however, need to be verified with the help of other methods or databases. As a next step following a hotspot analysis, the CO_2-eq reduction or saving potential must be investigated, as some emissions may be inevitable for now (Wood et al., 2020). Afterwards, a company can develop a carbon reduction strategy and evaluate the effectiveness of various measures. It is noteworthy that the measures regarding the reduction of indirect emissions fall within different spheres of responsibility; it may be the company itself or the (sub-)supplier that need to implement reductions (Erhard et al., 2019). However, companies should go beyond hotspot thinking to fulfill their responsibility toward combating climate change. While hotspots are a good starting point—and for some companies just beginning to develop a carbon management strategy, the only option at this time—efforts must not end there. Especially when engaging suppliers, companies should be aware that while the EEIO can identify high-emitting suppliers based on the industry and country in which the suppliers operate, and purchasing volume, it does not represent supplier-specific emissions (Erhard et al. 2019). This means that it is not suitable for tracking supplier emission reductions, because to achieve a reduction in EEIO for the same supplier, it is also possible to just reduce the price while ordering the same number of products, which then does not represent an actual reduction (Erhard et al. 2019).

A profound carbon management strategy aiming for decarbonization of the upstream supply chain consists of short-term and long-term strategies (Farsan et al., 2018; Watson et al., 2023). A hotspot analysis is part of the short-term strategy to achieve quick-fixes and a considerably big impact with low effort, potentially focusing on the low hanging fruits first (Lewandowski, 2017). Based on the verified hotspot analysis, a company can even develop internal policies such as carbon pricing mechanism to address the emissions, similar to countries using EXIOBASE for policy development (Ivanova & Wood, 2020; Stadler et al., 2018). Aside from this short-term view, a long-term perspective needs to be followed to limit global warming to 1.5°C as global emissions need to peak before 2025 and further rapid reductions until by latest 2050 are required (IPCC, 2022a). Part of this is going beyond calculating the direct or indirect emissions of a company, but instead asking meta questions, e.g., if the business model in its current structure is compatible with the sustainability ambition or whether it needs to be changed, and if so, what kind of change is required (Bocken & Short, 2021). However, both short and long-term strategies are valuable and necessary, and the hotspot analysis offers a first immediate step for companies to start their journey. Additionally, it should be noted that a company's responsibility for sustainability goes beyond the climate aspect (Hauff & Wilderer, 2008). Companies need to take a comprehensive approach to sustainability and be careful "to limit potential trade-offs between climate change mitigation and socially desirable outcomes" (Ivanova & Wood, 2020, p. 10).

The framework developed in this thesis allows companies to gain a holistic understanding of the various dimensions of effectiveness as they relate to their company, and it opens the discussion of effectiveness by bridging academic and industry views. To this end, a problem-solving approach (Clark & Dickson, 2003; Kates et al., 2001) was followed by focusing on the problem of industries' upstream emissions and the lack of scientifically-evaluated methods to capture them, and engaging with relevant stakeholders to solve this (Clark & Dickson, 2003). As Jerneck et al. (2011) describe it, focus should not only be on optimizing a current system and making it more sustainable by conducting problem-solving research, but also employing critical research to "critically questioning conditions that created problems of un-sustainability in the first place" (Jerneck et al., 2011, p. 78). These two aspects directly connect to short-term (problem-solving) and long-term (critical) strategy. Therefore, there is a need to critically research the business model of each company and investigate what the problem of unsustainable production and consumption is and find ways on how to address it. One approach could be circular economy, which stems from IE as previously mentioned and provides an alternative economic model for industry (Desing, 2021).

5.4 Limitations and Future Research

The scope of this thesis was first, to explore strengths and weaknesses of EEIO (and specifically the EXIOBASE database) compared to other calculation methods and other EEIO databases; and second, to define effectiveness and its dimensions in the context of identifying CO_2-eq hotspots and thereby contribute to improved carbon management. In the following I will go through limitations of the study by reflecting upon methodological and other aspects.

The methodological reflections involve the research design and study itself. Regarding the interview process, there may have been some concern from (industry-related) interviewees about confidentiality due to the recording, which could lead them to withhold information for fear of revealing too many company details (Warren, 2001). However, this limitation was outweighed by the importance of a comprehensive transcript of the interview, as it was critical for verifying the results of the literature review. Although this thesis provides a framework for evaluating effectiveness and related guidance, the framework has not been applied, and no evaluation of the effectiveness has been performed. There are two reasons for this. First, effectiveness depends on the type of company, so applying the framework to a specific company only provides insights into the effectiveness of EXIOBASE for that specific company or the industry in which the company operates. Second, the scope of this thesis was limited, which is why the development of the effectiveness framework was pursued, as this is the prerequisite for any evaluation, regardless of the type of company. Nevertheless, based on the interviews, this framework can provide companies with an indication of effectiveness, which contributes to the objective of this research. As mentioned earlier, effectiveness can be subjective, but due to the methodological approach in this thesis and synthesizing the industrial and academic perspectives this thesis provides a holistic understanding of effectiveness and the respective framework. Therefore, the next step is to apply this framework to different types of companies in multiple industries producing different products to draw further conclusions about industry and company specific effectiveness of using EXIOBASE to identify hotspots in the upstream supply chain.

Lastly, sustainability goes beyond climate and incorporates other environmental and social aspects (Bocken & Short, 2021), which have been so far disregarded in the analysis. One expert pointed out the potential risk of burden shifting: If climate change is handled properly, hopefully, other dimensions will shift to the forefront that have been ignored or rather neglected so far. Notable is that EXIOBASE offers extensions that go beyond climate, such as land use change, waste, water, or social factors (Wood et al., 2015), and these should be explored in the future. In this context it can be investigated if the framework might also be applicable for identifying other sustainability hotspots that are available in EEIO databases (in this case EXIOBASE, but also for example for Eora the threatened species indicator as mentioned by an interviewee). Generally, there is also future research need in the applicability of the framework for other EEIO databases, as well as other calculation methods.

6 Conclusion

Industry's indirect upstream GHG emissions contribute significantly to climate change. To identify and reduce them, companies can conduct hotspot analyses using an EEIO model (often utilizing EXIOBASE database). Despite the widespread use of EEIO models to identify hotspots in industry, their effectiveness in estimating GHG emissions has not yet been investigated.

Thus, the guiding questions of what effectiveness is and what it constitutes in this context were pursued in this thesis. Additionally, the strengths and weaknesses of EEIO (spend-based method) were discussed and compared with the supplier-specific, average data, and hybrid methods. Similarly, the strong and weak features of EXIOBASE were explored and compared to Eora, GTAP, and WIOD. An initial literature search led to the definition of the term *effectiveness* and similar framework concepts, which served as inspiration for the mixed methods approach. The systematized literature review and expert interviews resulted in an overview of strengths and weaknesses and an effectiveness framework (Figure 5) aligned with academia and industry. The framework developed in this thesis consists of three dimensions: 1) within EXIOBASE, 2) between method/database, and 3) the company perspective; as well as a precondition to determine its applicability. Companies can use the decision trees in Figure 6 and 7 to determine the calculation method for their upstream GHG emissions and database. Furthermore, guidance is provided on how to apply the framework, if applicable for the company.

The framework opens the discussion and encourages academia and industry to take a joint approach and strive toward decarbonization of companies' GHG footprint beyond their own operation to improve their carbon management. The findings of this thesis support companies with developing a carbon management strategy for upstream GHG emissions or refining their existing strategy and aligning it with academia. If a company decides to use EEIO and EXIOBASE (or has already done the analysis), then this thesis offers guidance on how to gain insight into the effectiveness of this method for identifying hotspots specific to that company and industry. However, companies need to be aware that this EEIO hotspot analysis can only be a first step in a comprehensive carbon management strategy. There is a need to verify this short-term strategy and complement it with a long-term carbon management strategy. Having said that, both short- and long-term strategies are needed to successfully manage GHG emissions and limit global warming.

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Appendix

The Appendix incorporates supplements that provide readers with additional information if desired.

In addition, there are other resources available to follow the research process, but due to the size and non-essential nature, they are included in a separate Google Drive Folder, which comprises:

1. Interview material (PowerPoint in English and German)
2. Consent form draft (1 page)
3. Information sheet for expert interviews (1 page)
4. German interview guide (4 pages)
5. All transcript of the interview (136 pages in total)
6. Code book - NVivo Analysis (56 pages)

All of these resources can be accessed until May 25th 2023 under the following link:
https://drive.google.com/drive/folders/1qb8F72551XffPqmHDPN21xRx1ErNhYAM?usp=share_link

Afterwards they can be requested at bauereli785@gmail.com.

Appendix A. IOA Table in its Basic Form

Table 1.1 *Input–output transactions table*

		Industry Producers as Consumers								Final Demand for Goods and Services			
		Agric.	Mining	Const.	Manuf.	Trade	Transp.	Services	Other	Personal Consumption Expenditures	Gross Private Domestic Investment	Government Purchases of Goods & Services	Net Exports of Goods and Services
Industry Producers	Agriculture												
	Mining												
	Construction												
	Manufacturing												
	Trade												
	Transportation												
	Services												
	Other Industry												
Value Added	Employees	Employee Compensation											
	Business Owners and Capital	Profit-type income and capital consumptions allowances								Gross Domestic Product			
	Government	Indirect Business Taxes											

Note. Source: Miller and Blair (2022, p. 4).

Appendix B. Semi-structured Interview Guide

Part I: Introduction

Thank you very much for taking the time to talk to me.

- Quick Introduction of person

I have asked you for an interview as part of a master thesis at Lund University. As mentioned in the email, the objective of my thesis is to outline strengths and weaknesses of EXIOBASE and to develop a framework with the objective to assess the effectiveness of EXIOBASE to identify CO_2 Hot Spots in the upstream Supply chain.

I have a few questions that I would like to ask you. (Show Agenda slide)

I will first start with general questions about EXIOBASE related to your personal experience. Afterwards I'd like to go into how one could define a framework of "effectiveness". Lastly there are some follow-up questions if time allows, and some concluding questions.

Some technicalities: All information is confidential and will only be used for the purpose of this research project. For research purposes, I would like to record and transcribe this interview. As part of my university ethic's guidelines, I need your consent to record this interview. Do you agree with the recording? Then I would start the recording now.

Thank you for your permission to record. Before we start with the questions, I would like to point out that the interview is entirely voluntary, and you can discontinue it at any moment.

- If the consent form has not been filled out: Do you consent, that I can use your answers for my project? Do you want to stay anonymous?

Lastly, if you want me to explain a question further, please do let me know.

Do you have any questions before we start?

Part II: Main part

So, first I will give a bit of background to the main questions. In my thesis I will apply a spend-based method to estimate the CO_2 emissions of Tetra Pak's purchased goods and services. By using an EEIO (in my case EXIOBASE) I aim towards the identification of CO_2 Hot Spots in the upstream supply chain. Thus, I will primarily focus on EXIOBASE and EEIO.

EXIOBASE and EEIO

1. I have contacted you as an expert for this interview because you have experiences with EXIOBASE. Thus, I am interested in what your experiences/ lessons learnt with EXIOBASE are in particular related to CO_2 emissions?
   - If no experience with EXIOBASE, ask question 3 and 4 and adjust question 2 (based on other EEIO)
2. Strengths and weaknesses of EXIOBASE (database/ output/ other factors)?
3. Are you familiar with any other EEIO databases? If yes which?
4. Which database do you usually use (prefer) for your work and why?

Effectiveness framework

As I mentioned in the beginning, one goal of my thesis is to evaluate the effectiveness of using EEIO (EXIOBASE) to identify CO_2 Hot Spots in the upstream Supply Chain.

5. Firstly, I would like to know what would constitute *effectiveness* for you in this context?
6. What would be important dimensions/variables that you would include in an *effectiveness* framework?

Now, with your perspective of effectiveness in mind I would like to explain to you an initial version of an effectiveness framework that I developed with the help of literature and theory. Your insights will help to shape this framework.

Definition of effectiveness that I got from the Australian government and the productivity commission: (show slide)

"In general, *effectiveness* [is] the extent to which stated objectives are met." (Productivity Commission, 2013, p. 8) "Effectiveness of a [method]. A measure of how well the outputs of a method achieve the stated objectives (desired outcomes) of that [method]". (Productivity Commission, 2013, p. 13)

In my case: Objective is to identify CO_2 Hot Spots in the upstream supply chain. And with the framework I want to measure how well this is achieved. (Do I really have the Hot Spots, …)

7. ***Framework based on literature & Theory*** *(ACFID, 2015; Pastor, 2009; Productivity Commission, 2013)*

First, I will outline the dimensions/variables of effectiveness that I found based on literature and theory for the effectiveness framework and I would like to know your opinion (is something missing, should something be excluded, is it good?). Afterwards we will go through each variable and discuss it a bit more in-depth.

- **Transparency and prerequisite data quality**
  Source, Type and Relevance of data; Data availability and age

- **Methodological Soundness**
  Scope/ Completeness (System boundaries cut-offs; carbon leakage), Classification/ Sectorization of data (Industry, Product, Country (dis)aggregation), Consensus/ internationally accepted approach of data concepts and definitions; Reproducibility/ Replicability

- **Accuracy & Reliability**
  Assessment and Validation of data
  - Input: financial, environmental data accuracy; consistency across time, countries, pricing layers; technological development
  - Output: Relative Ranking of categories (magnitude); Absolute/ relative (un)certainty of results, Robustness of results
  - In general: Sensitivity analysis

- **Cost/Benefit comparison**
  Cost effectiveness/ technical efficiency
    - Resources needed (time, money,…) à also compared to other methods
    - Limitations/Blind spots/ weaknesses vs strengths

  Usefulness of result
    - Data and Metadata accessibility (information about Hot Spots is clear and understandable and easy to follow)
    - Appropriateness and Implications of results

➔ Maybe an industry specific framework? Ranking dimensions based on importance.

<u>Part III: Additional Questions (if time allows)</u>

Although I focus on EXIOBASE and EEIO, I am also interested in other/ *alternative methods to calculate upstream emissions of purchased goods and services* such as the average-data method (collecting data on quantity/weight/unit of products and using emission factors), supplier-specific method (primary supplier data) or hybrid method (combining the different approaches).

8. What alternatives do/did you use and why do you use them/ don't you use them?
9. Strengths and weaknesses compared to EEIO/spend-based approach (and alternative methods)

<u>Part IV: Conclusion</u>

10. In the beginning we talked about your experience with EXIOBASE (or other EEIO databases). How have you used the outcome of your EEIO analysis? (As a Hot Spot analysis? For other purposes (e.g., policy implications)?)
    - What have you done as the next step? How did you take the results further from the analysis?
    - What was the value of the analysis? Did you achieve your expected goal?
11. Do you have a general summary regarding the effectiveness of EEIO/EXIOBASE for identifying CO_2 Hot Spots in the upstream Supply Chain for a company?

12. Anything else you would like to mention?
13. Do you have any questions for me?

Thank you very much for your support!

Appendix C. Interview Logbooks

Number	Date	Time	Name	Institution/ if anonymous cluster (industry/ consultancy/ academia)
Interviewee 1	28.02.2023	9:30 – 10:35	David Cockburn	Tetra Pak AB (Director Climate Programmes)
Interviewee 2	06.03.2023	14:45-15:45	Konstantin Stadler	Norwegian University of Science and Technology (NTNU) (Manager and Lead Researcher of the Digital Laboratory, Industrial Ecology Programme)
Interviewee 3	06.03.2023	19:00-19:45	Gilang Hardadi	University of Freiburg (Research Associate)
Interviewee 4	07.03.2023	11:00-11:45	Jonas Eliassen	2.-0 LCA consultants (Life Cycle Engineer)
Interviewee 5	07.03.2023	13:00-13:45	ANONYMOUS	Consultancy/ PhD
Interviewee 6	08.03.2023	15:00-16:00	Glenn Aguilar Hernandez	Leiden University (Postdoc/ lecturer)
Interviewee 7	09.03.2023	15:30-16:15	Isabella Todaro	Climate Neutral (Director of Carbon Measurement)
Interviewee 8	10.03.2023	11:00-12:00	ANONYMOUS	Consultancy
Interviewee 9	13.03.2023	15:30-16:15	ANONYMOUS	Consultancy/ PhD
Interviewee 10	20.03.2023	09:00-09:45	ANONYMOUS	Consultancy
Interviewee 11	23.03.2023	11:00-11:50	ANONYMOUS	Industry/ PhD

Appendix D. Consent Documentation Interviewees

Interviewee	Institution	Consent given	Authorization for using the information/ responses	Respondent wants to stay anonymous
Interviewee 1: David Cockburn	Tetra Pak AB	Written	Yes	No
Interviewee 2: Konstantin Stadler	Norwegian University of Science and Technology (NTNU)	Orally Recording	Yes	No
Interviewee 3: Gilang Hardadi	University of Freiburg	Written	Yes	No
Interviewee 4: Jonas Lassen Eliassen	2.-0 LCA consultants	Written	Yes	No
Interviewee 5:	ANONYMOUS	Orally Recording	Yes	Yes
Interviewee 6: Glenn Aguilar Hernandez	Leiden University	Orally Recording	Yes	No
Interviewee 7: Isabella Todaro	Climate Neutral	Written	Yes	No
Interviewee 8:	ANONYMOUS	Orally Recording	Yes	Yes
Interviewee 9:	ANONYMOUS	Written	Yes	Yes
Interviewee 10:	ANONYMOUS	Orally Recording	Yes	Yes
Interviewee 11:	ANONYMOUS	Orally Recording	Yes	Yes

Appendix E. Level of Detail of EXIOBASE

Table E1. Country Resolution of EXIOBASE (Stadler et al., 2021b; Wood et al., 2013)

Number	Country/Region	Code	EU member
1	Austria	AT	EU
2	Belgium	BE	EU
3	Bulgaria	BG	EU
4	Croatia*	HR	EU
5	Cyprus	CY	EU
6	Czech Republic	CZ	EU
7	Germany	DE	EU
8	Denmark	DK	EU
9	Estonia	EE	EU
10	Spain	ES	EU
11	Finland	FI	EU
12	France	FR	EU
13	Greece	GR	EU
14	Hungary	HU	EU
15	Ireland	IE	EU
16	Italy	IT	EU
17	Lithuania	LT	EU
18	Luxembourg	LU	EU
19	Latvia	LV	EU
20	Malta	MT	EU
21	Netherlands	NL	EU
22	Poland	PL	EU
23	Portugal	PT	EU
24	Romania	RO	EU
25	Sweden	SE	EU
26	Slovenia	SI	EU
27	Slovakia	SK	EU
28	United Kingdom	GB	nonEU*
29	United States	US	nonEU

30	Japan	JP	nonEU
31	China	CN	nonEU
32	Canada	CA	nonEU
33	South Korea	KR	nonEU
34	Brazil	BR	nonEU
35	India	IN	nonEU
36	Mexico	MX	nonEU
37	Russia	RU	nonEU
38	Australia	AU	nonEU
39	Switzerland	CH	nonEU
40	Turkey	TR	nonEU
41	Taiwan	TW	nonEU
42	Norway	NO	nonEU
43	Indonesia	ID	nonEU
44	South Africa	ZA	nonEU
45	RoW Asia and Pacific	WA	nonEU
46	RoW America	WL	nonEU
47	RoW Europe	WE	nonEU
48	RoW Africa	WF	nonEU
49	RoW Middle East	WM	nonEU

Note. Based on Wood et al. (2013, p. 62) and updated according to Stadler et al. (2021b).
*Corrections: Croatia was added, and UK is no longer part of EU.

Table E2. Industry Resolution (Stadler et al., 2021b, Wood et al., 2013, pp. 58-61)

Number	**Name**	**CodeNr**	**CodeTxt**
1	Cultivation of paddy rice	i01.a	A_PARI
2	Cultivation of wheat	i01.b	A_WHEA
3	Cultivation of cereal grains nec	i01.c	A_OCER
4	Cultivation of vegetables, fruit, nuts	i01.d	A_FVEG
5	Cultivation of oil seeds	i01.e	A_OILS
6	Cultivation of sugar cane, sugar beet	i01.f	A_SUGB
7	Cultivation of plant-based fibers	i01.g	A_FIBR
8	Cultivation of crops nec	i01.h	A_OTCR
9	Cattle farming	i01.i	A_CATL

10	Pigs farming	i01.j	A_PIGS
11	Poultry farming	i01.k	A_PLTR
12	Meat animals nec	i01.l	A_OMEA
13	Animal products nec	i01.m	A_OANP
14	Raw milk	i01.n	A_MILK
15	Wool, silk-worm cocoons	i01.o	A_WOOL
16	Manure treatment (conventional), storage and land application	i01.w.1	A_MANC
17	Manure treatment (biogas), storage and land application	i01.w.2	A_MANB
18	Forestry, logging and related service activities (02)	i02	A_FORE
19	Fishing, operating of fish hatcheries and fish farms; service activities incidental to fishing (05)	i05	A_FISH
20	Mining of coal and lignite; extraction of peat (10)	i10	A_COAL
21	Extraction of crude petroleum and services related to crude oil extraction, excluding surveying	i11.a	A_COIL
22	Extraction of natural gas and services related to natural gas extraction, excluding surveying	i11.b	A_GASE
23	Extraction, liquefaction, and regasification of other petroleum and gaseous materials	i11.c	A_OGPL
24	Mining of uranium and thorium ores (12)	i12	A_ORAN
25	Mining of iron ores	i13.1	A_IRON
26	Mining of copper ores and concentrates	i13.20.11	A_COPO
27	Mining of nickel ores and concentrates	i13.20.12	A_NIKO
28	Mining of aluminium ores and concentrates	i13.20.13	A_ALUO
29	Mining of precious metal ores and concentrates	i13.20.14	A_PREO
30	Mining of lead, zinc and tin ores and concentrates	i13.20.15	A_LZTO
31	Mining of other non-ferrous metal ores and concentrates	i13.20.16	A_ONFO
32	Quarrying of stone	i14.1	A_STON
33	Quarrying of sand and clay	i14.2	A_SDCL
34	Mining of chemical and fertilizer minerals, production of salt, other mining and quarrying n.e.c.	i14.3	A_CHMF
35	Processing of meat cattle	i15.a	A_PCAT
36	Processing of meat pigs	i15.b	A_PPIG
37	Processing of meat poultry	i15.c	A_PPLT

38	Production of meat products nec	i15.d	A_POME
39	Processing vegetable oils and fats	i15.e	A_VOIL
40	Processing of dairy products	i15.f	A_DAIR
41	Processed rice	i15.g	A_RICE
42	Sugar refining	i15.h	A_SUGR
43	Processing of Food products nec	i15.i	A_OFOD
44	Manufacture of beverages	i15.j	A_BEVR
45	Manufacture of fish products	i15.k	A_FSHP
46	Manufacture of tobacco products (16)	i16	A_TOBC
47	Manufacture of textiles (17)	i17	A_TEXT
48	Manufacture of wearing apparel; dressing and dyeing of fur (18)	i18	A_GARM
49	Tanning and dressing of leather; manufacture of luggage, handbags, saddlery, harness and footwear (19)	i19	A_LETH
50	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials (20)	i20	A_WOOD
51	Re-processing of secondary wood material into new wood material	i20.w	A_WOOW
52	Pulp	i21.1	A_PULP
53	Re-processing of secondary paper into new pulp	i21.w.1	A_PAPR
54	Paper	i21.2	A_PAPE
55	Publishing, printing and reproduction of recorded media (22)	i22	A_MDIA
56	Manufacture of coke oven products	i23.1	A_COKE
57	Petroleum Refinery	i23.2	A_REFN
58	Processing of nuclear fuel	i23.3	A_NUCF
59	Plastics, basic	i24.a	A_PLAS
60	Re-processing of secondary plastic into new plastic	i24.a.w	A_PLAW
61	N-fertiliser	i24.b	A_NFER
62	P- and other fertiliser	i24.c	A_PFER
63	Chemicals nec	i24.d	A_CHEM
64	Manufacture of rubber and plastic products (25)	i25	A_RUBP
65	Manufacture of glass and glass products	i26.a	A_GLAS
66	Re-processing of secondary glass into new glass	i26.a.w	A_GLAW

67	Manufacture of ceramic goods	i26.b	A_CRMC
68	Manufacture of bricks, tiles and construction products, in baked clay	i26.c	A_BRIK
69	Manufacture of cement, lime and plaster	i26.d	A_CMNT
70	Re-processing of ash into clinker	i26.d.w	A_ASHW
71	Manufacture of other non-metallic mineral products n.e.c.	i26.e	A_ONMM
72	Manufacture of basic iron and steel and of ferro-alloys and first products thereof	i27.a	A_STEL
73	Re-processing of secondary steel into new steel	i27.a.w	A_STEW
74	Precious metals production	i27.41	A_PREM
75	Re-processing of secondary preciuos metals into new preciuos metals	i27.41.w	A_PREW
76	Aluminium production	i27.42	A_ALUM
77	Re-processing of secondary aluminium into new aluminium	i27.42.w	A_ALUW
78	Lead, zinc and tin production	i27.43	A_LZTP
79	Re-processing of secondary lead into new lead, zinc and tin	i27.43.w	A_LZTW
80	Copper production	i27.44	A_COPP
81	Re-processing of secondary copper into new copper	i27.44.w	A_COPW
82	Other non-ferrous metal production	i27.45	A_ONFM
83	Re-processing of secondary other non-ferrous metals into new other non-ferrous metals	i27.45.w	A_ONFW
84	Casting of metals	i27.5	A_METC
85	Manufacture of fabricated metal products, except machinery and equipment (28)	i28	A_FABM
86	Manufacture of machinery and equipment n.e.c. (29)	i29	A_MACH
87	Manufacture of office machinery and computers (30)	i30	A_OFMA
88	Manufacture of electrical machinery and apparatus n.e.c. (31)	i31	A_ELMA
89	Manufacture of radio, television and communication equipment and apparatus (32)	i32	A_RATV
90	Manufacture of medical, precision and optical instruments, watches and clocks (33)	i33	A_MEIN
91	Manufacture of motor vehicles, trailers and semi-trailers (34)	i34	A_MOTO
92	Manufacture of other transport equipment (35)	i35	A_OTRE
93	Manufacture of furniture; manufacturing n.e.c. (36)	i36	A_FURN

94	Recycling of waste and scrap	i37	A_RYMS
95	Recycling of bottles by direct reuse	i37.w.1	A_BOTW
96	Production of electricity by coal	i40.11.a	A_POWC
97	Production of electricity by gas	i40.11.b	A_POWG
98	Production of electricity by nuclear	i40.11.c	A_POWN
99	Production of electricity by hydro	i40.11.d	A_POWH
100	Production of electricity by wind	i40.11.e	A_POWW
101	Production of electricity by petroleum and other oil derivatives	i40.11.f	A_POWP
102	Production of electricity by biomass and waste	i40.11.g	A_POWB
103	Production of electricity by solar photovoltaic	i40.11.h	A_POWS
104	Production of electricity by solar thermal	i40.11.i	A_POWE
105	Production of electricity by tide, wave, ocean	i40.11.j	A_POWO
106	Production of electricity by Geothermal	i40.11.k	A_POWM
107	Production of electricity nec	i40.11.l	A_POWZ
108	Transmission of electricity	i40.12	A_POWT
109	Distribution and trade of electricity	i40.13	A_POWD
110	Manufacture of gas; distribution of gaseous fuels through mains	i40.2	A_GASD
111	Steam and hot water supply	i40.3	A_HWAT
112	Collection, purification and distribution of water (41)	i41	A_WATR
113	Construction (45)	i45	A_CONS
114	Re-processing of secondary construction material into aggregates	i45.w	A_CONW
115	Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motor cycles parts and accessoiries	i50.a	A_TDMO
116	Retail sale of automotive fuel	i50.b	A_TDFU
117	Wholesale trade and commission trade, except of motor vehicles and motorcycles (51)	i51	A_TDWH
118	Retail trade, except of motor vehicles and motorcycles; repair of personal and household goods (52)	i52	A_TDRT
119	Hotels and restaurants (55)	i55	A_HORE
120	Transport via railways	i60.1	A_TRAI
121	Other land transport	i60.2	A_TLND

122	Transport via pipelines	i60.3	A_TPIP
123	Sea and coastal water transport	i61.1	A_TWAS
124	Inland water transport	i61.2	A_TWAI
125	Air transport (62)	i62	A_TAIR
126	Supporting and auxiliary transport activities; activities of travel agencies (63)	i63	A_TAUX
127	Post and telecommunications (64)	i64	A_PTEL
128	Financial intermediation, except insurance and pension funding (65)	i65	A_FINT
129	Insurance and pension funding, except compulsory social security (66)	i66	A_FINS
130	Activities auxiliary to financial intermediation (67)	i67	A_FAUX
131	Real estate activities (70)	i70	A_REAL
132	Renting of machinery and equipment without operator and of personal and household goods (71)	i71	A_MARE
133	Computer and related activities (72)	i72	A_COMP
134	Research and development (73)	i73	A_RESD
135	Other business activities (74)	i74	A_OBUS
136	Public administration and defence; compulsory social security (75)	i75	A_PADF
137	Education (80)	i80	A_EDUC
138	Health and social work (85)	i85	A_HEAL
139	Incineration of waste: Food	i90.1.a	A_INCF
140	Incineration of waste: Paper	i90.1.b	A_INCP
141	Incineration of waste: Plastic	i90.1.c	A_INCL
142	Incineration of waste: Metals and Inert materials	i90.1.d	A_INCM
143	Incineration of waste: Textiles	i90.1.e	A_INCT
144	Incineration of waste: Wood	i90.1.f	A_INCW
145	Incineration of waste: Oil/Hazardous waste	i90.1.g	A_INCO
146	Biogasification of food waste, incl. land application	i90.2.a	A_BIOF
147	Biogasification of paper, incl. land application	i90.2.b	A_BIOP
148	Biogasification of sewage slugde, incl. land application	i90.2.c	A_BIOS
149	Composting of food waste, incl. land application	i90.3.a	A_COMF
150	Composting of paper and wood, incl. land application	i90.3.b	A_COMW

151	Waste water treatment, food	i90.4.a	A_WASF
152	Waste water treatment, other	i90.4.b	A_WASO
153	Landfill of waste: Food	i90.5.a	A_LANF
154	Landfill of waste: Paper	i90.5.b	A_LANP
155	Landfill of waste: Plastic	i90.5.c	A_LANL
156	Landfill of waste: Inert/metal/hazardous	i90.5.d	A_LANI
157	Landfill of waste: Textiles	i90.5.e	A_LANT
158	Landfill of waste: Wood	i90.5.f	A_LANW
159	Activities of membership organisation n.e.c. (91)	i91	A_ORGA
160	Recreational, cultural and sporting activities (92)	i92	A_RECR
161	Other service activities (93)	i93	A_OSER
162	Private households with employed persons (95)	i95	A_PRHH
163	Extra-territorial organizations and bodies	i99	A_EXTO

Table E3. Product Resolution (Stadler et al., 2021b, Wood et al., 2013, pp. 53-57)

Number	**Name**	**CodeNr**	**CodeTxt**
1	Paddy rice	p01.a	C_PARI
2	Wheat	p01.b	C_WHEA
3	Cereal grains nec	p01.c	C_OCER
4	Vegetables, fruit, nuts	p01.d	C_FVEG
5	Oil seeds	p01.e	C_OILS
6	Sugar cane, sugar beet	p01.f	C_SUGB
7	Plant-based fibers	p01.g	C_FIBR
8	Crops nec	p01.h	C_OTCR
9	Cattle	p01.i	C_CATL
10	Pigs	p01.j	C_PIGS
11	Poultry	p01.k	C_PLTR
12	Meat animals nec	p01.l	C_OMEA
13	Animal products nec	p01.m	C_OANP
14	Raw milk	p01.n	C_MILK
15	Wool, silk-worm cocoons	p01.o	C_WOOL
16	Manure (conventional treatment)	p01.w.1	C_MANC
17	Manure (biogas treatment)	p01.w.2	C_MANB

18	Products of forestry, logging and related services (02)	p02	C_FORE
19	Fish and other fishing products; services incidental of fishing (05)	p05	C_FISH
20	Anthracite	p10.a	C_ANTH
21	Coking Coal	p10.b	C_COKC
22	Other Bituminous Coal	p10.c	C_OTBC
23	Sub-Bituminous Coal	p10.d	C_SUBC
24	Patent Fuel	p10.e	C_PATF
25	Lignite/Brown Coal	p10.f	C_LIBC
26	BKB/Peat Briquettes	p10.g	C_BKBP
27	Peat	p10.h	C_PEAT
28	Crude petroleum and services related to crude oil extraction, excluding surveying	p11.a	C_COIL
29	Natural gas and services related to natural gas extraction, excluding surveying	p11.b	C_GASE
30	Natural Gas Liquids	p11.b.1	C_GASL
31	Other Hydrocarbons	p11.c	C_OGPL
32	Uranium and thorium ores (12)	p12	C_ORAN
33	Iron ores	p13.1	C_IRON
34	Copper ores and concentrates	p13.20.11	C_COPO
35	Nickel ores and concentrates	p13.20.12	C_NIKO
36	Aluminium ores and concentrates	p13.20.13	C_ALUO
37	Precious metal ores and concentrates	p13.20.14	C_PREO
38	Lead, zinc and tin ores and concentrates	p13.20.15	C_LZTO
39	Other non-ferrous metal ores and concentrates	p13.20.16	C_ONFO
40	Stone	p14.1	C_STON
41	Sand and clay	p14.2	C_SDCL
42	Chemical and fertilizer minerals, salt and other mining and quarrying products n.e.c.	p14.3	C_CHMF
43	Products of meat cattle	p15.a	C_PCAT
44	Products of meat pigs	p15.b	C_PPIG
45	Products of meat poultry	p15.c	C_PPLT
46	Meat products nec	p15.d	C_POME
47	products of Vegetable oils and fats	p15.e	C_VOIL

48	Dairy products	p15.f	C_DAIR
49	Processed rice	p15.g	C_RICE
50	Sugar	p15.h	C_SUGR
51	Food products nec	p15.i	C_OFOD
52	Beverages	p15.j	C_BEVR
53	Fish products	p15.k	C_FSHP
54	Tobacco products (16)	p16	C_TOBC
55	Textiles (17)	p17	C_TEXT
56	Wearing apparel; furs (18)	p18	C_GARM
57	Leather and leather products (19)	p19	C_LETH
58	Wood and products of wood and cork (except furniture); articles of straw and plaiting materials (20)	p20	C_WOOD
59	Wood material for treatment, Re-processing of secondary wood material into new wood material	p20.w	C_WOOW
60	Pulp	p21.1	C_PULP
61	Secondary paper for treatment, Re-processing of secondary paper into new pulp	p21.w.1	C_PAPR
62	Paper and paper products	p21.2	C_PAPE
63	Printed matter and recorded media (22)	p22	C_MDIA
64	Coke Oven Coke	p23.1.a	C_COKE
65	Gas Coke	p23.1.b	C_GCOK
66	Coal Tar	p23.1.c	C_COTA
67	Motor Gasoline	p23.20.a	C_MGSL
68	Aviation Gasoline	p23.20.b	C_AGSL
69	Gasoline Type Jet Fuel	p23.20.c	C_GJET
70	Kerosene Type Jet Fuel	p23.20.d	C_KJET
71	Kerosene	p23.20.e	C_KERO
72	Gas/Diesel Oil	p23.20.f	C_DOIL
73	Heavy Fuel Oil	p23.20.g	C_FOIL
74	Refinery Gas	p23.20.h	C_RGAS
75	Liquefied Petroleum Gases (LPG)	p23.20.i	C_LPGA
76	Refinery Feedstocks	p23.20.j	C_REFF
77	Ethane	p23.20.k	C_ETHA
78	Naphtha	p23.20.l	C_NAPT

79	White Spirit & SBP	p23.20.m	C_WHSP
80	Lubricants	p23.20.n	C_LUBR
81	Bitumen	p23.20.o	C_BITU
82	Paraffin Waxes	p23.20.p	C_PARW
83	Petroleum Coke	p23.20.q	C_PETC
84	Non-specified Petroleum Products	p23.20.r	C_NSPP
85	Nuclear fuel	p23.3	C_NUCF
86	Plastics, basic	p24.a	C_PLAS
87	Secondary plastic for treatment, Re-processing of secondary plastic into new plastic	p24.a.w	C_PLAW
88	N-fertiliser	p24.b	C_NFER
89	P- and other fertiliser	p24.c	C_PFER
90	Chemicals nec	p24.d	C_CHEM
91	Charcoal	p24.e	C_CHAR
92	Additives/Blending Components	p24.f	C_ADDC
93	Biogasoline	p24.g	C_BIOG
94	Biodiesels	p24.h	C_BIOD
95	Other Liquid Biofuels	p24.i	C_OBIO
96	Rubber and plastic products (25)	p25	C_RUBP
97	Glass and glass products	p26.a	C_GLAS
98	Secondary glass for treatment, Re-processing of secondary glass into new glass	p26.a.w	C_GLAW
99	Ceramic goods	p26.b	C_CRMC
100	Bricks, tiles and construction products, in baked clay	p26.c	C_BRIK
101	Cement, lime and plaster	p26.d	C_CMNT
102	Ash for treatment, Re-processing of ash into clinker	p26.d.w	C_ASHW
103	Other non-metallic mineral products	p26.e	C_ONMM
104	Basic iron and steel and of ferro-alloys and first products thereof	p27.a	C_STEL
105	Secondary steel for treatment, Re-processing of secondary steel into new steel	p27.a.w	C_STEW
106	Precious metals	p27.41	C_PREM
107	Secondary preciuos metals for treatment, Re-processing of secondary preciuos metals into new preciuos metals	p27.41.w	C_PREW

108	Aluminium and aluminium products	p27.42	C_ALUM
109	Secondary aluminium for treatment, Re-processing of secondary aluminium into new aluminium	p27.42.w	C_ALUW
110	Lead, zinc and tin and products thereof	p27.43	C_LZTP
111	Secondary lead for treatment, Re-processing of secondary lead into new lead	p27.43.w	C_LZTW
112	Copper products	p27.44	C_COPP
113	Secondary copper for treatment, Re-processing of secondary copper into new copper	p27.44.w	C_COPW
114	Other non-ferrous metal products	p27.45	C_ONFM
115	Secondary other non-ferrous metals for treatment, Re-processing of secondary other non-ferrous metals into new other non-ferrous metals	p27.45.w	C_ONFW
116	Foundry work services	p27.5	C_METC
117	Fabricated metal products, except machinery and equipment (28)	p28	C_FABM
118	Machinery and equipment n.e.c. (29)	p29	C_MACH
119	Office machinery and computers (30)	p30	C_OFMA
120	Electrical machinery and apparatus n.e.c. (31)	p31	C_ELMA
121	Radio, television and communication equipment and apparatus (32)	p32	C_RATV
122	Medical, precision and optical instruments, watches and clocks (33)	p33	C_MEIN
123	Motor vehicles, trailers and semi-trailers (34)	p34	C_MOTO
124	Other transport equipment (35)	p35	C_OTRE
125	Furniture; other manufactured goods n.e.c. (36)	p36	C_FURN
126	Secondary raw materials	p37	C_RYMS
127	Bottles for treatment, Recycling of bottles by direct reuse	p37.w.1	C_BOTW
128	Electricity by coal	p40.11.a	C_POWC
129	Electricity by gas	p40.11.b	C_POWG
130	Electricity by nuclear	p40.11.c	C_POWN
131	Electricity by hydro	p40.11.d	C_POWH
132	Electricity by wind	p40.11.e	C_POWW
133	Electricity by petroleum and other oil derivatives	p40.11.f	C_POWP

134	Electricity by biomass and waste	p40.11.g	C_POWB
135	Electricity by solar photovoltaic	p40.11.h	C_POWS
136	Electricity by solar thermal	p40.11.i	C_POWE
137	Electricity by tide, wave, ocean	p40.11.j	C_POWO
138	Electricity by Geothermal	p40.11.k	C_POWM
139	Electricity nec	p40.11.l	C_POWZ
140	Transmission services of electricity	p40.12	C_POWT
141	Distribution and trade services of electricity	p40.13	C_POWD
142	Coke oven gas	p40.2.a	C_COOG
143	Blast Furnace Gas	p40.2.b	C_MBFG
144	Oxygen Steel Furnace Gas	p40.2.c	C_MOSG
145	Gas Works Gas	p40.2.d	C_MGWG
146	Biogas	p40.2.e	C_MBIO
147	Distribution services of gaseous fuels through mains	p40.2.1	C_GASD
148	Steam and hot water supply services	p40.3	C_HWAT
149	Collected and purified water, distribution services of water (41)	p41	C_WATR
150	Construction work (45)	p45	C_CONS
151	Secondary construction material for treatment, Re-processing of secondary construction material into aggregates	p45.w	C_CONW
152	Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motor cycles parts and accessoiries	p50.a	C_TDMO
153	Retail trade services of motor fuel	p50.b	C_TDFU
154	Wholesale trade and commission trade services, except of motor vehicles and motorcycles (51)	p51	C_TDWH
155	Retail trade services, except of motor vehicles and motorcycles; repair services of personal and household goods (52)	p52	C_TDRT
156	Hotel and restaurant services (55)	p55	C_HORE
157	Railway transportation services	p60.1	C_TRAI
158	Other land transportation services	p60.2	C_TLND
159	Transportation services via pipelines	p60.3	C_TPIP
160	Sea and coastal water transportation services	p61.1	C_TWAS
161	Inland water transportation services	p61.2	C_TWAI

162	Air transport services (62)	p62	C_TAIR
163	Supporting and auxiliary transport services; travel agency services (63)	p63	C_TAUX
164	Post and telecommunication services (64)	p64	C_PTEL
165	Financial intermediation services, except insurance and pension funding services (65)	p65	C_FINT
166	Insurance and pension funding services, except compulsory social security services (66)	p66	C_FINS
167	Services auxiliary to financial intermediation (67)	p67	C_FAUX
168	Real estate services (70)	p70	C_REAL
169	Renting services of machinery and equipment without operator and of personal and household goods (71)	p71	C_MARE
170	Computer and related services (72)	p72	C_COMP
171	Research and development services (73)	p73	C_RESD
172	Other business services (74)	p74	C_OBUS
173	Public administration and defence services; compulsory social security services (75)	p75	C_PADF
174	Education services (80)	p80	C_EDUC
175	Health and social work services (85)	p85	C_HEAL
176	Food waste for treatment: incineration	p90.1.a	C_INCF
177	Paper waste for treatment: incineration	p90.1.b	C_INCP
178	Plastic waste for treatment: incineration	p90.1.c	C_INCL
179	Intert/metal waste for treatment: incineration	p90.1.d	C_INCM
180	Textiles waste for treatment: incineration	p90.1.e	C_INCT
181	Wood waste for treatment: incineration	p90.1.f	C_INCW
182	Oil/hazardous waste for treatment: incineration	p90.1.g	C_INCO
183	Food waste for treatment: biogasification and land application	p90.2.a	C_BIOF
184	Paper waste for treatment: biogasification and land application	p90.2.b	C_BIOP
185	Sewage sludge for treatment: biogasification and land application	p90.2.c	C_BIOS
186	Food waste for treatment: composting and land application	p90.3.a	C_COMF

187	Paper and wood waste for treatment: composting and land application	p90.3.b	C_COMW
188	Food waste for treatment: waste water treatment	p90.4.a	C_WASF
189	Other waste for treatment: waste water treatment	p90.4.b	C_WASO
190	Food waste for treatment: landfill	p90.5.a	C_LANF
191	Paper for treatment: landfill	p90.5.b	C_LANP
192	Plastic waste for treatment: landfill	p90.5.c	C_LANL
193	Inert/metal/hazardous waste for treatment: landfill	p90.5.d	C_LANI
194	Textiles waste for treatment: landfill	p90.5.e	C_LANT
195	Wood waste for treatment: landfill	p90.5.f	C_LANW
196	Membership organisation services n.e.c. (91)	p91	C_ORGA
197	Recreational, cultural and sporting services (92)	p92	C_RECR
198	Other services (93)	p93	C_OSER
199	Private households with employed persons (95)	p95	C_PRHH
200	Extra-territorial organizations and bodies	p99	C_EXTO

Appendix F: Level of Detail of Eora

Table F1. Country Resolution (including number of available sectors). National economic sector classifications of Eora. (KGM & Associates Pty. Ltd., 2023a)

Acronym	Name	# Sectors	Classification
AFG	Afghanistan	26	Common
ALB	Albania	26	Common
DZA	Algeria	26	Common
AND	Andorra	26	Common
AGO	Angola	26	Common
ATG	Antigua	26	Common
ARG	Argentina	125/196	National
ARM	Armenia	26	Common
ABW	Aruba	26	Common
AUS	Australia	345/345	National
AUT	Austria	61/61	National
AZE	Azerbaijan	26	Common
BHS	Bahamas	26	Common
BHR	Bahrain	26	Common
BGD	Bangladesh	26	Common
BRB	Barbados	26	Common
BLR	Belarus	26	Common
BEL	Belgium	61/61	National
BLZ	Belize	26	Common
BEN	Benin	26	Common
BMU	Bermuda	26	Common
BTN	Bhutan	26	Common
BOL	Bolivia	37/37	National
BIH	Bosnia and Herzegovina	26	Common
BWA	Botswana	26	Common
BRA	Brazil	56/111	National
VGB	British Virgin Islands	26	Common
BRN	Brunei	26	Common
BGR	Bulgaria	26	Common

BFA	Burkina Faso	26	Common
BDI	Burundi	26	Common
KHM	Cambodia	26	Common
CMR	Cameroon	26	Common
CAN	Canada	49	National
CPV	Cape Verde	26	Common
CYM	Cayman Islands	26	Common
CAF	Central African Republic	26	Common
TCD	Chad	26	Common
CHL	Chile	75/75	National
CHN	China	123	National
COL	Colombia	60/60	National
COG	Congo	26	Common
CRI	Costa Rica	26	Common
HRV	Croatia	26	Common
CUB	Cuba	26	Common
CYP	Cyprus	26	Common
CZE	Czech Republic	61/61	National
CIV	Cote dIvoire	26	Common
PRK	North Korea	26	Common
COD	DR Congo	26	Common
DNK	Denmark	131	National
DJI	Djibouti	26	Common
DOM	Dominican Republic	26	Common
ECU	Ecuador	49/61	National
EGY	Egypt	26	Common
SLV	El Salvador	26	Common
ERI	Eritrea	26	Common
EST	Estonia	61/61	National
ETH	Ethiopia	26	Common
FJI	Fiji	26	Common
FIN	Finland	61/61	National

FRA	France	61/61	National
PYF	French Polynesia	26	Common
GAB	Gabon	26	Common
GMB	Gambia	26	Common
GEO	Georgia	47/68	National
DEU	Germany	72	National
GHA	Ghana	26	Common
GRC	Greece	61/61	National
GRL	Greenland	31	National
GTM	Guatemala	26	Common
GIN	Guinea	26	Common
GUY	Guyana	26	Common
HTI	Haiti	26	Common
HND	Honduras	26	Common
HKG	Hong Kong	38/38	National
HUN	Hungary	61/61	National
ISL	Iceland	26	Common
IND	India	116/116	National
IDN	Indonesia	77	National
IRN	Iran	100/148	National
IRQ	Iraq	26	Common
IRL	Ireland	61/61	National
ISR	Israel	163/163	National
ITA	Italy	61/61	National
JAM	Jamaica	26	Common
JPN	Japan	402	National
JOR	Jordan	26	Common
KAZ	Kazakhstan	121	National
KEN	Kenya	51/51	National
KWT	Kuwait	55	National
KGZ	Kyrgyzstan	89/87	National
LAO	Laos	26	Common
LVA	Latvia	61/61	National

LBN	Lebanon	26	Common
LSO	Lesotho	26	Common
LBR	Liberia	26	Common
LBY	Libya	26	Common
LIE	Liechtenstein	26	Common
LTU	Lithuania	61/61	National
LUX	Luxembourg	26	Common
MAC	Macao SAR	26	Common
MDG	Madagascar	26	Common
MWI	Malawi	26	Common
MYS	Malaysia	98	National
MDV	Maldives	26	Common
MLI	Mali	26	Common
MLT	Malta	61/61	National
MRT	Mauritania	26	Common
MUS	Mauritius	57/67	National
MEX	Mexico	80/80	National
MCO	Monaco	26	Common
MNG	Mongolia	26	Common
MNE	Montenegro	26	Common
MAR	Morocco	26	Common
MOZ	Mozambique	26	Common
MMR	Myanmar	26	Common
NAM	Namibia	26	Common
NPL	Nepal	26	Common
NLD	Netherlands	61/61	National
ANT	Netherlands Antilles	16/41	National
NCL	New Caledonia	26	Common
NZL	New Zealand	127/210	National
NIC	Nicaragua	26	Common
NER	Niger	26	Common

NGA	Nigeria	26	Common
NOR	Norway	61/61	National
PSE	Gaza Strip	26	Common
OMN	Oman	26	Common
PAK	Pakistan	26	Common
PAN	Panama	26	Common
PNG	Papua New Guinea	26	Common
PRY	Paraguay	34/47	National
PER	Peru	46/46	National
PHL	Philippines	77	National
POL	Poland	61/61	National
PRT	Portugal	61/61	National
QAT	Qatar	26	Common
KOR	South Korea	78	National
MDA	Moldova	26	Common
ROU	Romania	61/61	National
RUS	Russia	49	National
RWA	Rwanda	26	Common
WSM	Samoa	26	Common
SMR	San Marino	26	Common
STP	Sao Tome and Principe	26	Common
SAU	Saudi Arabia	26	Common
SEN	Senegal	26	Common
SRB	Serbia	26	Common
SYC	Seychelles	26	Common
SLE	Sierra Leone	26	Common
SGP	Singapore	154/154	National
SVK	Slovakia	61/61	National
SVN	Slovenia	61/61	National
SOM	Somalia	26	Common
ZAF	South Africa	95/96	National
SDS	South Sudan	26	Common

ESP	Spain	76/119	National
LKA	Sri Lanka	26	Common
SUD	Sudan	26	Common
SUR	Suriname	26	Common
SWZ	Swaziland	26	Common
SWE	Sweden	61/61	National
CHE	Switzerland	43/43	National
SYR	Syria	26	Common
TWN	Taiwan	163	National
TJK	Tajikistan	26	Common
THA	Thailand	180	National
MKD	TFYR Macedonia	61/61	National
TGO	Togo	26	Common
TTO	Trinidad and Tobago	26	Common
TUN	Tunisia	26	Common
TUR	Turkey	61/61	National
TKM	Turkmenistan	26	Common
USR	Former USSR	26	Common
UGA	Uganda	26	Common
UKR	Ukraine	121	National
ARE	UAE	26	Common
GBR	UK	511/511	National
TZA	Tanzania	26	Common
USA	USA	429/429	National
URY	Uruguay	84/103	National
UZB	Uzbekistan	123	National
VUT	Vanuatu	26	Common
VEN	Venezuela	122/122	National
VNM	Viet Nam	113	National
YEM	Yemen	26	Common
ZMB	Zambia	26	Common
ZWE	Zimbabwe	26	Common

Table F2. (Harmonized) Sector Resolution (KGM & Associates Pty. Ltd., 2023d)

Number	**Sector**
1	Agriculture
2	Fishing
3	Mining and Quarrying
4	Food & Beverages
5	Textiles and Wearing Apparel
6	Wood and Paper
7	Petroleum, Chemical and Non-Metallic Mineral Products
8	Metal Products
9	Electrical and Machinery
10	Transport Equipment
11	Other Manufacturing
12	Recycling
13	Electricity, Gas and Water
14	Construction
15	Maintenance and Repair
16	Wholesale Trade
17	Retail Trade
18	Hotels and Restraurants
19	Transport
20	Post and Telecommunications
21	Financial Intermediation and Business Activities
22	Public Administration
23	Education, Health and Other Services
24	Private Households
25	Others
26	Re-export & Re-import