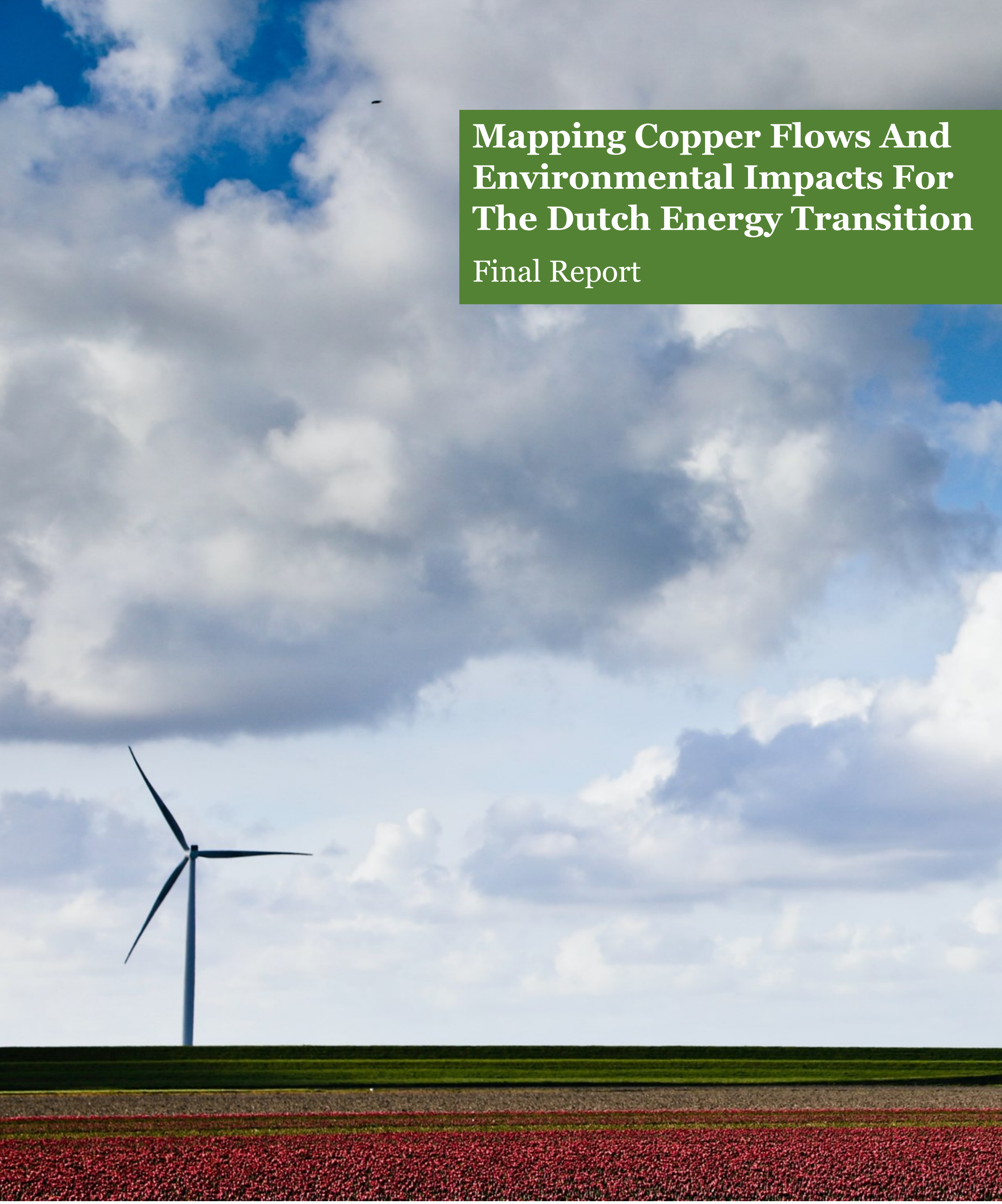

Mapping Copper Flows And Environmental Impacts For The Dutch Energy Transition

Final Report

Group 12
Sustainability Challenge
MSc Industrial Ecology
Leiden University & Delft University of Technology

Mapping copper flows for the Dutch energy transition

Final report

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Popular summary

As part of the Paris Agreement, the Netherlands must drastically reduce its greenhouse gas emissions. To achieve this goal, the Netherlands plans to increase its renewable share of electricity production from 39.6% in 2022 to 70% by 2030. This change will require a vast expansion of the Dutch renewable energy sector and increase demand significantly for specific metals such as copper. Copper is mostly mined and processed outside of the European Union, often in low- and middle-income countries. All these production stages come with considerable environmental impacts, which are not understood well.

To better understand the environmental impacts of the Dutch energy transition, we examine and visualise the upstream supply chain of copper and its corresponding impacts. Copper was chosen due to its large production volumes and relevance for renewables.

Throughout the research, it became apparent that there are large gaps and discrepancies in data on global copper production. Similar problems arose when researching the associated environmental impacts. These findings ultimately emphasise the complexity of the copper supply chain and the need for collaboration between relevant stakeholders to improve data. Doing so will improve how informed decision making on supply chain policy can be in order to reduce the environmental impacts of the energy transition.

Executive summary

The Netherlands targets an increase in renewable energy share of electricity production of 70% in 2030. As in 2022 the renewable energy share was 39.6%, a vast expansion of the Dutch renewable energy sector is evidently required. This transition will drive demand for specific metals, such as copper and rare earth metals, which are primarily mined and processed outside of the European Union. This rise in demand drives an urgent need to develop in depth knowledge on these supply chains and their corresponding global environmental impacts.

This project was commissioned by PBL to address the aforementioned gap in research through the main research question "What are the environmental impacts of the upstream copper supply chain for the Dutch energy transition?". A series of research steps were followed to address this question and related sub-questions to assess the primary production of copper for the stages of mining, smelting, and refining. First, a Material Flow Analysis was used to visualise the upstream supply chain of primary copper in the Dutch energy sector and was illustrated with a Sankey diagram. Then, the corresponding environmental impacts were quantified using two approaches of Life Cycle Assessment and Environmentally Extended Input-Output Analysis, with further visualisation through Sankey diagrams. Finally, data gaps to assist future research efforts were identified and clearly reported upon.

As a general theme, the results illustrated the stark variations between different datasets. The lack of harmonised data across copper production stages and databases ultimately makes evaluation of impacts a complex task. However, both impact assessment methods did concur that low- and middle-income countries do bear direct environmental impacts from copper production for the renewable energy transition in the Netherlands. These findings aim to call attention to the lack of transparency in copper data and highlight the need for improving documentation of material trade.

These findings underscore the complexities of the copper supply chain and emphasise the importance of improving transparency. Government stakeholders and researchers should increase collaboration to advocate for enhanced and centralised data collection from the mining industry more broadly.

The Team

To deliver the best possible, focus on cooperation was given vital importance throughout the project. Ownership over the project as a whole by each team member was considered as a key factor, as it entailed that each member felt equally responsible for the final product, which transcends the boundaries of responsibility for each one's "individual" task. We did this to ensure that we were all involved through every step and stage of the project, supporting our commitment to support each other in tasks unrelated to our own when needed. This also required team members to take a proactive stance in seeking to help others rather than leaving it for others to ask for help when it was needed.

Next to this, there was always a steady open line of communication between all of the team members, which created an environment in which we all felt comfortable sharing our thoughts and concerns. Due to the length of the project, and our keenness to deliver an excellent result, we experienced this project to be rewarding, but strenuous. Therefore, we ensured that the team spirits were running high by partaking in enjoyable activities unrelated to the project, creating a stronger sense of partnership and an open environment. By adhering to this, as well as our vision, we ensured motivation and success in our goals for this project.

The entire team, their background and assigned formal roles can be found in Table 1.

Table 1: Team members.

Name	Nationality	Student number	Background	Responsibility
Christina Drotenko	Canada	3608050	BSc Finance & Economics	Team Member
Kevin Heideman	Netherlands	2001292	BSc Economics & Governance	Team Member
Alessia Linares Capurro	Peru	2123681	BSc Global Sustainability Science	Communication
Aaron Paris	Germany	3422747	BSc & MSc Industrial Engineering	Editor
Adrien Perello-Y-Bestard	France	3629112	MSc Cognitive engineering	Chair

List of Abbreviations

BZ	Ministry of Foreign Affairs
Comtrade	United Nations Commodity Trade Statistics Database
CO_2e	CO_2-equivalent
DRC	Democratic Republic of Congo
EEIOA	Environmentally Extended Input-Output Analysis
EF	Environmental footprint
GHGE	Greenhouse gas emissions
GW	Gigawatt
GWP	Global Warming Potential
HCLA	Hybrid Life Cycle Assessment
IOA	Input-Output Analysis
LCA	Life Cycle Assessment
LCI	Life cycle inventories
LMICs	Low- and middle-income countries
M	Million
MFA	Material Flow Analysis
MRIO	Multiregional Input-Output
PBL	PBL Netherlands Environmental Assessment Agency
PIOT	Physical Input-Output Tables
RoW	Rest of the World
USA	United States of America
USGS	United States Geographical Survey Mineral Yearbook

1 Background and context

As part of their commitments under the Paris Agreement, the Netherlands wants to reduce their greenhouse gas emissions (GHGE) by 49% by 2030 and 95% by 2050 compared to 1990 levels (Government of the Netherlands, 2023b). An essential measure to achieve these goals is the transition from fossil to renewable energy. The Dutch government wants to achieve a renewable share of 70% of the electricity production and 32% of total energy use by 2030 (Government of the Netherlands, 2023d). In 2022, 39.6% of the electricity produced in the Netherlands came from renewables (Statline, 2023b) and they made up for only 15% of the gross final consumption of energy (Statline, 2023a).

Achieving the Dutch goals will require a vast expansion of renewable energy production as well as decarbonisation of building and transport sectors. While the total amount of mining might be reduced due to a reduced demand for fossil fuels (Nijnens et al., 2023), the transition will cause a significant increase in the demand for specific materials, especially metals like copper, nickel, lithium and rare earth elements (IEA, 2022b). These are all mined and processed outside of the Netherlands, often in low- and middle-income countries (LMICs) outside of Europe (IEA, 2022b). Apart from potential supply risks for the Dutch energy transition, the mining and processing also cause significant environmental and social impacts in the respective countries (IEA, 2022b).

As part of the European Critical Raw Material Act and the Dutch National Raw Materials Strategy, the Netherlands aims to reduce the environmental impact of materials needed for the energy transition (European Commission, 2023; Government of the Netherlands, 2023c). Moreover, the Netherlands' strategy to achieve full circularity by 2050 encompasses the objective of sourcing any remaining virgin materials through sustainable means (Government of the Netherlands, 2023a). Dutch companies are often the last element in supply chains and thus have a responsibility and leverage to limit impacts (van Exter et al., 2021). However, supply chains and connected environmental impacts are poorly understood due to their complexity, length and lack of transparency (van Exter et al., 2021). Linking Dutch demand to upstream and downstream environmental impacts remains a challenge.

2 Problem statement and research objectives

The Ministry of Foreign Affairs has asked the PBL Netherlands Environmental Assessment Agency (PBL, Dutch for Planbureau voor de Leefomgeving) to examine how supply chains of metals with high relevance for the energy transition could be made more sustainable. The focus is especially on environmental impacts in LMICs as other Ministries focus on different issues like supply risks or domestic policies.

PBL is one of the three national research institutes for strategic policy analysis in the Netherlands and is responsible for policies concerning the environment and spatial planning (PBL, 2010). PBL formally belongs to the Ministry of Infrastructure and Water Management but also conducts unsolicited research and research on behalf of other government departments.

We were commissioned by PBL to support their research for the Ministry of Foreign Affairs. The main objective of this project was to understand and visualise the environmental impacts of the supply chain of one or two metals with special relevance to the Dutch energy transition. This involved examining production volume, reserves, resources, and environmental impacts throughout the upstream supply chain as well as identifying hot spots along it. Ultimately, the aim is to help informing the political discussion and policymaking to increase sustainability of international supply chains, which is the 4th area of action defined in the Dutch raw materials strategy.

We decided to focus on only copper for 3 reasons: (a) data availability, (b) reducing complexity to fit the scope of a student project and (c) volume. Even with other energy transition minerals increasing their demand substantially, the total copper demand and thus mining, smelting and refining, will continue to be much larger and thus absolutely more relevant in terms of impacts (IEA, 2022a; Nijnens et al., 2023).

Considering the commissioner's specific interest in the initial stages of the supply chain, our analysis centres on the primary production of copper before any pre-fabrication. This scope entails the major processes of mining, smelting, and refining of copper. Copper processing begins with mining of primarily copper oxide and copper sulfide ores (ICSG, 2024). Subsequently, there are two main types of processing, namely pyrometallurgy and hydrometallurgy (Superfund Research Centre, 2020). The smelting stage takes place through only pyrometallurgy, as heat is applied to extract and purify copper from sulfide ores (Superfund Research Centre, 2020). In contrast, hydrometallurgy does not require smelting as ordinary temperatures are used for extraction from copper oxide ores with water-based solutions (Superfund Research Centre, 2020). Refining involves a process of electrolysis for pyrometallurgy and electrowinning for hydrometallurgy, resulting in the production of copper cathodes (Superfund Research Centre, 2020). However, due to lack of transparency across data sources and documentation, this distinguishment across pyrometallurgy and hydrometallurgy was deemed outside of the scope of this research.

Our **main research question** is: What are the environmental impacts of the upstream copper supply chain for the Dutch energy transition?

It was divided into **5 sub questions**:

1. What is the current status of the global primary copper production in terms of production scale, extraction and processing pathways as well as trade flows?
2. From mining to refining, what are the environmental impacts associated with copper production on a per country basis?
3. For how much of global refined copper demand and associated environmental impacts is the expansion of renewable energy in the Netherlands responsible?

4. What are the leverage points to mitigate environmental impacts?
5. What are the main data constraints for assessing the supply chain of metals and their environmental impacts?

The remainder of the report is structured as follows: In chapter 3, the applied methods and used data are explained. Chapter 4 shows the results for the supply chain mapping and the associated environmental impacts, followed by a discussion of implications, limitations and future research needs in chapter 5. In the end, a conclusion is drawn in chapter 6.

3 Data and Methods

To address the main research question and sub-research questions, the research strategy comprises of two main steps. First, a Material Flow Analysis (MFA) is used to visualise the upstream supply chain of primary copper in the Dutch energy sector, which is shown using a Sankey diagram. Second, Sankey diagrams are used again to illustrate the quantified impacts and the differences between the two applied approaches, namely Life Cycle Assessment (LCA) and Environmentally Extended Input-Output Analysis (EEIOA). Throughout the process, data requirements and corresponding gaps were reported on to enable future replication and understanding of limitations.

3.1 Supply chain mapping: Material Flow Analysis

MFA is a method used to quantify the stocks and flows of materials within a system defined in space and time while accounting for mass conservation (Brunner & Rechberger, 2004; Mehta et al., 2022). In this research, a MFA is conducted from cradle-to-gate, focusing on the mining and production phases from which the copper is used in renewable energy products. The analysis does not include full mapping of the supply chain, but only represents the global chain from mining, smelting, and refining. Thereafter, the share of primary copper consumption globally is scaled to the Netherlands based on a factor of refining demand and allocated to the renewable energy sector.

3.1.1 Data

The following section details the two main data sources used, namely the United States Geographical Survey Mineral Yearbook (USGS) for production data and the BACI database from CEPII for trade data. The calculation used for the Dutch renewable energy sector copper consumption is also outlined. Large discrepancies exist between the USGS and BACI datasets which required reconciliation for the completion of the MFA. See sections 3.1.2 and 5.3 for more details on the reconciliation process.

USGS: Data on the global copper primary production of countries was required to create the MFA visualisation. The United States Geographical Survey Mineral Yearbook has been used as a primary source to collect the data on domestic copper production across the three investigated stages (USGS, 2023a). USGS collected the data through annual surveys and personal contact on a per country basis. Missing data in the Mineral Yearbook is estimated on the basis of historical trends by USGS country specialists (USGS, 2023c).

BACI: Trade data is required to map the flows between each of the stages, which was sourced from the BACI database from CEPII (CEPII, 2023). CEPII created the BACI database using the United Nations Commodity Trade Statistics Database (Comtrade; United Nations, 2024). The Comtrade database contains the imports and exports reported by statistical authorities from the designated countries or areas. The BACI database provides bilateral trade flows at a product level, which are produced by means of harmonisation of the Comtrade database trade flows (Gaulier & Zignago, 2010). BACI contains flows in monetary and physical units (mass), however, does not disclose the content of copper per traded commodity. For that, values for the selected Comtrade HS codes were drawn from the Supplementary Information of Liu et al. (2023).

3.1.2 Framework

The MFA maps the supply chain of primary production of copper globally. The year 2019 was selected for the analysis. To show the mining, smelting and refining of copper and the trade flows, the USGS and BACI data had to be reconciled.

In this reconciliation process of the two data sources, black boxes of unknown flows became prominent. **Figure 1**, **Table 2** below show this gap more clearly. For example, the given USGS mining process data (PF_1) with exports (E_1) subtracted and imports (I_1) added for that particular process should equal the given USGS smelting process data (PF_2), leading to the equation $PF_1 + I_1 - E_1$ which should equal PF_2. This should be repeated for smelting to refining, illustrated by the equation $PF_2 + I_2 - E_2$ which should equal PF_3 and the same for PF_4. However, in all cases the left side of the equation would not equal the corresponding right side which flows into the next process due to imbalances in data. These values were allocated by country imports or exports as percentages of what the correct imports or exports are. However, a remaining gap remains which is an unknown volume of copper flows and is not part of process data (PF), not imported (I), and not exported (E). In the Sankey, this has been illustrated transparently with black boxes to call attention to data gaps when reconciling the two sources.

Table 2: Variables used in **Figure 1**.

Variables	Descriptions	Data source
MP, SP, RP	Mining production, smelting production, refining production	USGS
PF_1, PF_2, PF_3, PF_4	Production flows calculated with formulas	Calculated
I_1, I_2, I_3	Imports (Mining, Smelting, Refining)	BACI
E_1, E_2, E_3	Exports (Mining, Smelting, Refining)	BACI

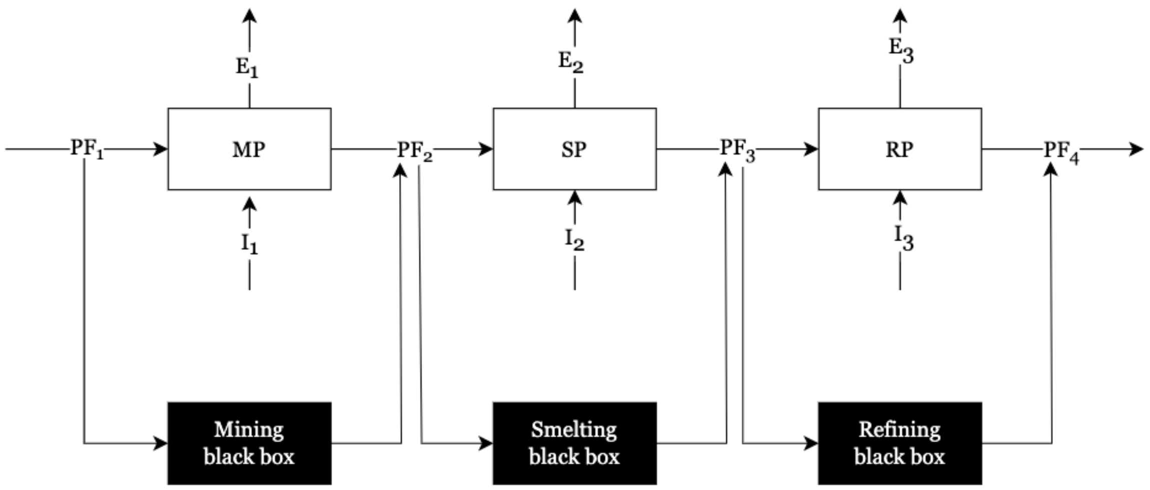

Figure 1: Illustration of the USGS and BACI data reconciliation issue. The figure excludes the 'Use' stage as that was not part of the reconciliation issue between the two datasets.

Detailed documentation of the steps used in the code after the initial datasets are imported and cleaned is shown in Appendix 1 for the MFA portion. The overall process involves importing and cleaning the required datasets, cleaning the data, and calculating the equations in **Table 2** to assess for misalignment. Thereafter, these missing balancing items are distributed as shares of imports and exports to each stage and country.

There are then four cases that could occur based on the diagram in **Figure 1**:

1. More imports of mining are necessary because there is not enough in smelting (there is a positive value).
2. More imports of smelting are necessary because there is not enough in refining (there is a positive value).

3. More exports of mining are necessary because there is too much in smelting (there is a negative value).
4. More exports of smelting are necessary because there is too much in refining (there is a negative value).

According to the corresponding case above for each country flow and stage, the correct import and export allocations are calculated based on if imports or exports are missing. Then, the imports and exports are allocated based on the corrected aforementioned values. The next step is to calculate the volume of flows which must end up in black boxes because these are not part of the process data, not imported, and not exported. Some special cases are also analysed for countries with stages that must be allocated, but which have no trade data. This resulted in the global production and trade flows of copper.

In order to scale this to the Netherlands, the global trade flows of copper were traced to the Netherlands through the BACI data. This was done by assessing the amount of copper products that entered the Netherland through assessing net copper imports, since the Netherlands does not mine its own copper. The quantity of copper products imported by the Netherlands from each individual country was calculated by aggregating the total mass of products containing copper, which were identified by use of HS codes, which are internationally used by customs services to classify products (CEPII, 2023). The total copper quantity imported by the Netherlands was calculated through multiplying the total mass of the copper product imports, with the estimated amount of copper per HS classified product category for each individual HS code as described above. This resulted in a comprehensive overview of trade flows copper entering the Netherlands per country of origin, that was then aggregated to acquire the Netherlands copper demand share.

Then, to estimate the copper consumption of the Dutch renewable energy sector, the following methodology has been followed. For the Netherlands, the amount of renewable energy generating capacity per year has been recorded since the year 2000 (Brandenburg et al., 2023). From this the amount of installed capacity per renewable over the years from 2019 to 2020 was assessed. From literature, the copper consumption per Gigawatt (GW) installed per renewable energy source was used and averaged (van Oorschot et al., 2022). Thereafter, the number of GW installed per renewable energy source in the Netherlands was multiplied by the average copper usage per GW for each individual renewable to create an average consumption for 2019 to 2020 in tonnes. This value was then expressed in a percentage of the Netherlands' total copper import from 2019. **Table 3** shows the calculated averages between the minimum and maximum values that were used for the MFA.

Table 3: Calculated share of copper use in absolute tonnes and as a percentage of the Dutch copper demand for 2019-2020.

MFA stage	Minimum	Maximum	Average
Total copper use in tonnes	2.49	75.13	38.81
Share of total copper imports	1.6%	48.5%	25.1%

Important to note is that the values for the calculated copper share of the Dutch renewable energy sector vary considerably due to the large discrepancies between estimated copper demands per individual renewable in the energy sector from literature. This can have considerable impact on our final results and will be further discussed within the limitations.

Finally, the share of copper used for the energy transition in the Netherlands was integrated and the Sankey is built.

3.2 Impact quantification

In this study, two approaches were applied to assess the impacts of mining and processing copper: LCA, often referred to as bottom-up, and IOA, often called top-down (Hertwich, 2005). LCA is based on the physical descriptions of processes in a product life cycle while IOA builds on links among sectors of the economy derived from national accounts and sector-average environmental impacts (Hertwich, 2005). Both typically account for impacts during production, distribution, use and disposal of products. However, they can also be applied to parts of the supply chain only, for example from mining to refining.

The rationale for incorporating a second assessment methodology arises from recognising the inherent limitations of the predominant approach, LCA. LCA often introduces inaccuracies, due to challenges in adequately encompassing the entire system. On the other hand, EEIOA suffers from limitations in aggregation (see discussion in section 5.2). Significant discrepancies in footprint calculations typically arise between these two approaches (Steubing et al., 2022). Consequently, our objective is to underscore the uncertainties associated with the environmental impacts of the upstream copper supply chain.

3.2.1 Impact quantification: Life Cycle Assessment

In this section, the data and framework for the LCA approach are described. LCA is defined as the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO, 2006). LCA consists of assembling data on all inputs from and outputs to the environment from all stages and corresponding processes of a products life cycle and calculating their impacts using different impact assessment methods (Guinée, 2002).

3.2.1.1 Data

For the LCA we used ecoinvent as database. Ecoinvent encompasses over 20,000 life cycle inventory datasets that undergo annual updates (ecoinvent, 2022). Life cycle inventories (LCI) show the total environmental interventions of processes, consisting of substance and environmental compartment they end up in (Guinée, 2002). In this study, ecoinvent version 3.9.1 was used, which states that the data is representative up to December 31st, 2022. However, this does not mean that the data is from any recent year but only that ecoinvent considers it representative for 2022. The limitations of the ecoinvent data are further discussed in section 5.3.

Each stage and country of the MFA was associated with a process from the database. A summary of the data is available in **Table 4**, whereas the complete information can be found in Appendix 2.

Table 4: Linking MFA stages with ecoinvent processes.

MFA stage	Process name	Available geographies
Mining	copper mine operation and beneficiation, sulfide ore	9 countries and RoW
Smelting	smelting of copper concentrate, sulfide ore	5 countries and RoW
Refining	electrorefining of copper, anode	global

For countries and stages without a corresponding ecoinvent process, averages from broader regions were used. The countries were allocated to regions using the World Bank's country classification (The World Bank Group, 2024). For regions without any process in ecoinvent, the Rest of the World (RoW) values were used. For the refining stage, there was only one process available, which represented hydrometallurgy with a single global value provided.

Table 5 shows the number of processes available in ecoinvent per world region and MFA stage. As can be seen, the representativity for most regions is low.

Table 5: Number of processes available in ecoinvent per world region and stage. The total of region representation column refers to the share of countries which a process was available in ecoinvent. In other words, of the total number of countries present in the region, which percentage of countries have data in ecoinvent.

Region	Mining	Smelting	Refining	Total	Total of region representation
Global	1	1	1	3	/
East Asia & Pacific	3	2	0	5	13%
Europe & Central Asia	2	1	0	5	5%
Latin America & Caribbean	1	1	0	2	5%
Middle East & North Africa	0	0	0	0	0%
North America	2	0	0	2	67%
South Asia	0	1	0	1	13%
Sub-Saharan Africa	1	0	0	1	2%
Grand total	**10**	**6**	**1**	**17**	**8%**

3.2.1.2 Framework

To not only include the direct impacts of the processes, but also those from all preceding processes, we apply an environmental footprint (EF) approach, attributing all impacts along the supply chain to the mining, smelting or refining stage.

For each stage and country, a small LCA was conducted. First, we calculated the impacts for one kg of refined, smelted and mined copper for all countries with available data. This includes all impacts along the supply chain up to the specific stage, including the production of capital goods and energy. Then, the impacts from smelted and mined copper were scaled according to the amount of smelted respectively mined copper needed to produce one kg of refined copper. To prevent double counting, the scaled impacts from the mining and smelting stage were then subtracted from the footprint of refined copper. The same was done for all available smelting processes. Looking at the illustration of the framework in **Figure 2** as an example, this ensured that “Activity A” and “Activity B” were only attributed to mining, “Activity C” and Activity D” only to smelting and “Activity E” and “Activity F” only to refining.

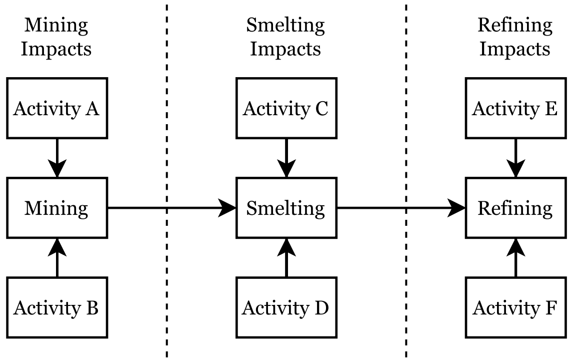

Figure 2: Framework for calculating the EF of the stages. The dashed lines represent the boundaries between the stages.

The impact assessment was done using the PEF 3.0 impact assessment family (European Commission, 2021b). It consists of 16 impact categories. In total, the LCAs yielded 16 impact indicator results, containing the value of an impact indicator per one kg of copper, for three stages in each country with available data. As the objective is to help informing political discussions in an easy-to-understand manner, we decided to focus on three impact categories: climate change, quantified using its Global Warming Potential (GWP) over a hundred years, water depletion in m^3 and natural land transformation in m^2.

The impact categories are defined as follows:

- **Climate change**: "Increase in the average global temperature resulting from greenhouse gas emissions." (European Commission, 2021a, p. 18)
- **Land use**: "Transformation and use of land for agriculture, roads, housing, mining or other purposes." (European Commission, 2021a, p. 18)
- **Water depletion**: "Depletion of available water depending on local water scarcity and water needs for human activities and ecosystem integrity." (European Commission, 2021a, p. 18)

Then, we scaled the impacts per kg of copper for each stage with the flows from the MFA to arrive at the total impacts of the supply chain.

3.2.2 Impact quantification: Input-Output Analysis

EEIOA is a method based on Multiregional Input-Output (MRIO) tables that capture the flow of goods and services between regions and sectors (Brand-Correa et al., 2022). These tables are compiled from all declared monetary transactions based on national accounts. Based on environmental data, coefficients are then assigned to these economic transactions to represent the environmental intensity of each sector's production and consumption (Brand-Correa et al., 2022). In the Figure 3, an overview of the basic structure of an EEIOA is given.

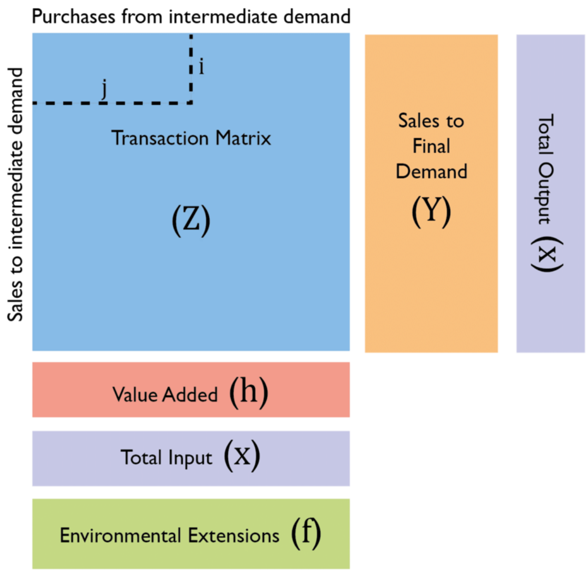

Figure 3: Basis structure of an EEIOA (Brand-Correa et al., 2022).

3.2.2.1 Data

The data used for the EEIOA is based on the MRIO database EXIOBASE3 (Stadler et al., 2021; Stadler et al., 2018). The database encompasses 163 industrial sectors across 44 countries (comprising 28 EU member states and 16 major economies) and five rest-of-the-world regions. Specifically, for the economic dimension, we utilized the calculated coefficient matrix A (which contains the multipliers for the inter-industry economic flows calculated from the transaction matrix Z) and the final demand matrix Y.

Concerning the economic dimension specifically, we utilised the coefficient matrix A and the final demand matrix Y. Matrix A is comprised of the inter-industry coefficients, calculated from the industry-to-industry transactions from matrix Z using formula below.

$$A = Z \times \hat{x}^{-1}$$

For the environmental dimension of the EEIOA, the selected environmental impacts are as follows. The GHGE intensities are obtained from EXIOBASE3 from satellite matrix F.

The water depletion intensity was obtained by multiplying the total blue water consumption intensity, originating from the satellite matrix F, with the characterisation factors from the Available WAter Remaining (Boulay et al., 2018; WULCA, 2023) project. This follows the recommendation of UNEP (UNEP, 2016) and the Product Environmental Footprint Category Rules (European Commission, 2018). This is also consistent with the LCA approach which made use of the latter, and hence allows for a more direct comparison between the two methods. The water depletion intensity as calculated reflects the demand on water resources by both humans and ecosystems, considering the availability within the watershed over time. The intensities are further scaled to global average of water consumption to facilitate comparison among regions that are impacted differently.

Regarding land-use area associated with mining, the environmental intensity is sourced from Cabernard and Pfister (2022), who addressed the poor data quality of EXIOBASE3 concerning mining and metal processing. However, due to methodological constraints, integration with the satellite matrix F is not straightforward (see the data gaps section below for a discussion). Consequently, the land-use indicator does not comprehensively capture all instances of land transformation within the Copper value-chain, but only those related to actual mines.

3.2.2.2 Framework

Standard MRIO analysis presents an inaccurate picture of the environmental footprint of intermediary products (Cabernard & Pfister, 2022; Cabernard et al., 2019, 2022; Hertwich, 2021; Rasul & Hertwich, 2023). This discrepancy arises because, on the one hand, production-based accounting overlooks the upstream consequences of material use. This is a result of attributing impacts to the upstream industry where they originate. On the other hand, traditional consumption-based accounting allocates the impacts of intermediary products to the end-use sector rather than to the sector processing these materials themselves. These mask their impact leading to an underestimation of the associated environmental impacts when decomposing the value-chain.

Additionally, when applying scope 3 accounting to a specific sector rather than the global economy, there is a pronounced risk of double counting for metal production (Cabernard, Pfister, & Hellweg, 2022; Dente et al., 2018; Hertwich, 2021). This complicates the accurate assessment of the environmental impact of the copper value chain, and it would hinder a meaningful comparison with the LCA approach. To tackle this issue, several methods have recently emerged to differentiate between the upstream and downstream effects of materials and prevent instances of double counting (Cabernard et al., 2019; Dente et al., 2019; Nakamura, 2023a, 2023b).

In this study, we follow the approach proposed by Cabernard et al. (2019), Cabernard and Pfister (2022), Cabernard, Pfister, and Hellweg (2022) and Cabernard, Pfister, Oberschelp, and Hellweg (2022). This approach allows multiple representations of the upstream and direct impact of the copper value chain (the share linked to the Dutch consumption). It also shows the copper-induced footprint embodied in trade. We redirect the reader to the GitHub repository for the actual implementation (see Code and data availability).

4 Results

In this chapter the results for the supply chain mapping with MFA as well as impacts quantification using EEIOA and LCA are shown.

4.1 Supply chain mapping: Material Flow Analysis

Figure 4 the mapped supply chain as Sankey diagram. The classification of countries to income groups in the Sankey is based on the World Bank classification (The World Bank Group, 2024). Certain countries emerge as prominent contributors to the supply chain across the various phases. For high-income economies this includes Chile, Canada, Australia, Japan, and the United States of America (USA). China and Peru are the most prominent within upper-middle income economies, Zambia is for lower-middle income economies, and Democratic Republic of Congo (DRC) within low-income economies. Another insight is that in many countries all three processing steps take place. Furthermore, the supply is very dependent on China with regard to the processing stages of smelting and refining.

Important to consider when interpreting the following Sankey diagrams is that the vertical sizes of the stages do not represent the production in each but the total size of the flows from the side with a larger total. Decisive for the volume of production in the stages is the total size of the flows, not the nodes. While it looks, for example, like approximately equal volumes of copper were mined and smelted globally, the USGS data actually shows significantly more smelting. These might be due to data gaps from USGS or stock-building, for example if mined copper was stored in 2018 and smelted in 2019, which is the year shown in the diagram.

The black box for smelting, so balancing flows that could not be fully allocated, is the largest. Large volumes of flows relating to the black boxes are prevalent in certain cases. For example, data gaps are notable in Chile's supply chain as a significant portion of the country's mining volumes flow into the smelting black box. Thereafter, a large portion of the imports into refining in Chile are sourced from an unknown location. Another example of a country with notable data gaps is China. This is evident in the large flow from the mining black box that moves into copper smelting in China. Overall, the results highlight the need to improve copper primary production data reconciliation with trade data and emphasise the countries and stages where to prioritise improvements.

4.1.1 Resources and reserves

The MFA results offer a static perspective for the year 2019. A dynamic evaluation is beyond the scope of this report. However, to give an indication for potential future changes in the supply chain and thus impacts, we included estimates for copper reserves and resources from USGS. Resources are defined as "concentrations or occurrences of material of economic interest in or on the Earth's crust in such form, quality, and quantity that there are reasonable prospects for eventual economic extraction" (Hammarstrom et al., 2019). Reserves refers to the economically mineable part of a resource. Important to keep in mind is that estimates for both reserves and resources develop over time due to technological and economic circumstances, for example innovation in technology to discover or extract metal deposits as well as changes in prices (Hammarstrom et al., 2019).

Table 6 shows the estimated global copper reserves and the sum of world-class deposits, i.e. deposits containing at very large amounts of copper (Hammarstrom et al., 2019) for a few chosen countries. As can be seen some countries like Chile and Peru will likely continue to provide a large share of the world's copper mining. Particularly Chile has a large share of reserves and an even larger one of the world-class deposits. China does not have significant reserves and will thus likely continue to focus on smelting and refining.

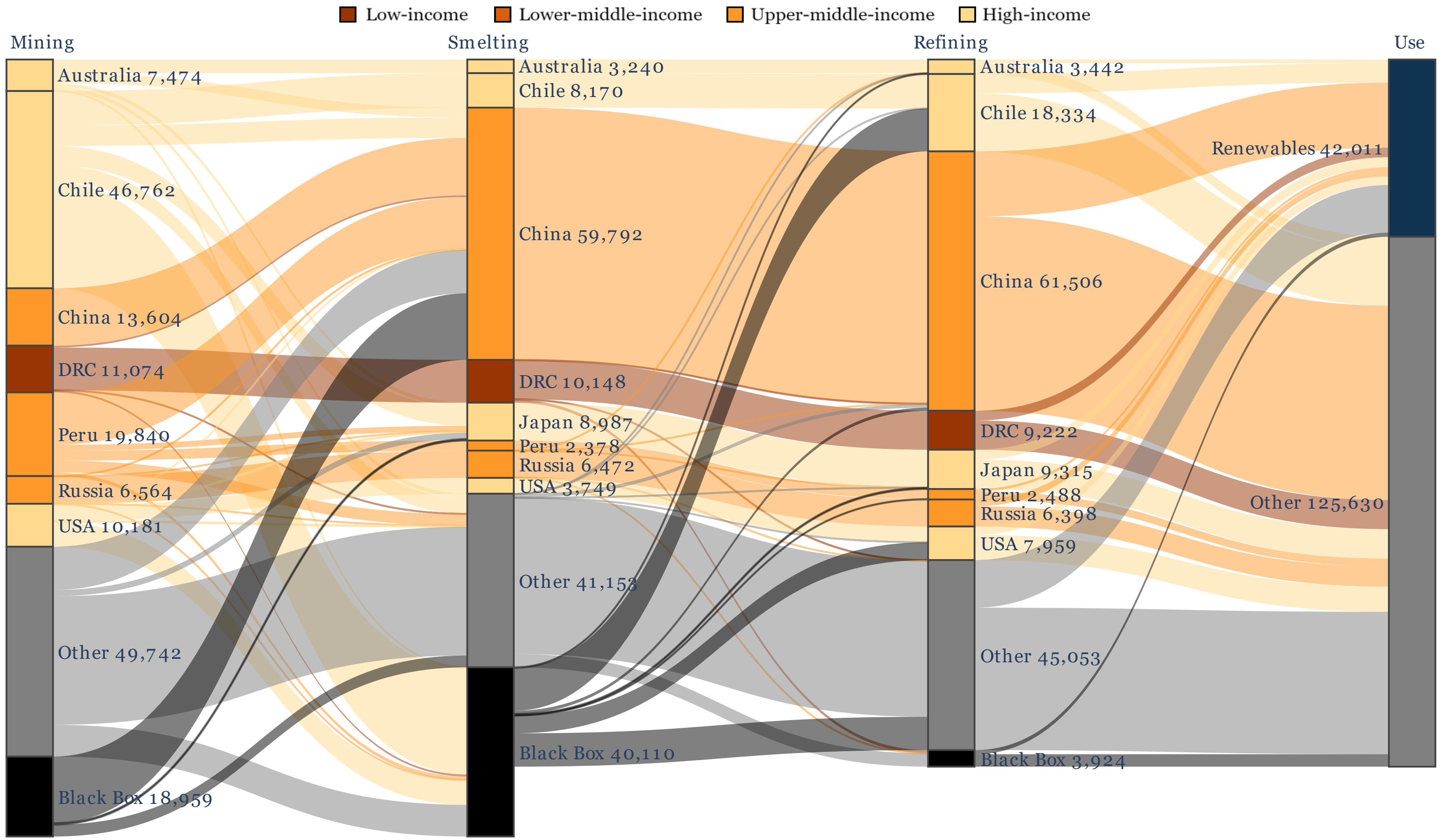

Figure 4: Sankey diagram for copper content in the Dutch primary production copper supply chain in 2019. All values are in tonnes of pure copper. The nodes represent the total production in each of the phases. The flows show the volumes traded between countries. The "Renewables" stage in "Use" represents the copper used for expanding renewable energy capacities in 2019. "Other" in mining, smelting and refining includes countries with less than 2.5% contribution to all stages. Due to overlaps, not all labels are shown.

Table 6: Estimates of global copper reserves (USGS, 2023b) and world-class deposits (Hammarstrom et al., 2019, Table A4 & A5).

Country	Reserves (kt)	Reserves (%)	World-class deposits (kt)	World-class deposits (%)
Australia	97,000	10.9%	10,000	0.5%
Canada	7,600	0.9%	43,800	2.3%
Chile	190,000	21.3%	687,500	35.5%
China	27,000	3.0%	53,700	2.8%
DRC	31,000	3.5%	48,000	2.5%
Indonesia	24,000	2.7%	35,300	1.8%
Kazakhstan	20,000	2.2%	41,200	2.1%
Mexico	53,000	6.0%	53,600	2.8%
Peru	81,000	9.1%	114,900	5.9%
Poland	30,000	3.4%	72,000	3.7%
Russia	62,000	7.0%	48,400	2.5%
USA	44,000	4.9%	321,400	16.6%
Zambia	19,000	2.1%	78,600	4.1%
Other countries	200,000	22.5%	328,500	17.0%
World total	**890,000**	**100%**	**1,936,900**	**100%**

Table 7 shows the estimated identified and undiscovered global copper resources, inferred from various methods (Hammarstrom et al., 2019). Again, South America makes up for the largest share of identified and undiscovered resources. This indicates that a large shift in the supply chain is unlikely. However, North Amerika shows the second largest resources and will likely play a more important role in copper mining in the future, if economically viable methods to exploit the resources are developed or the copper price rises accordingly.

Table 7: Estimates of identified and undiscovered global copper resources (Hammarstrom et al., 2019, Table A3).

Region	Identified copper resources (kt)	Identified copper resources (%)	Undiscovered in-place copper resources, mean estimate (kt)	Undiscovered in-place copper resources, mean estimate (%)
Africa	160,000	8%	170,000	5%
Central Amerika & Caribbean	43,000	2%	170,000	5%
Central and Eastern Asia	187,000	9%	505,000	14%
Eastern Australia	15,000	1%	21,000	1%
Southeast Asia Archipelagos	130,000	6%	270,000	8%
Middle East	68,900	3%	213,000	6%
North America	484,000	23%	455,000	13%
Northeast Asia	8,800	0%	260,000	7%
South America	800,390	38%	750,000	21%
Southeast Asia	60,500	3%	420,000	12%
Europe	130,000	6%	300,000	8%
World total	**2,087,590**	**100%**	**3,534,000**	**100%**

4.2 Impact quantification

To facilitate the comparison of LCA and EEIOA, the results of both approaches are presented here by impact category. Notably, the due to the above-described differences in methodology, the two approaches cannot be compared directly. The LCA builds on the MFA and thus is divided into the same stages while the MFA uses a different classification. Important to keep in mind is that both the LCA and EEIOA results only show the upstream supply chain of primary copper as defined in the scope definition. We also provide the reader with a correspondence diagram between the LCA and EEIOA Sankey in Appendix 4.

4.2.1 Climate change

Figure 5 shows the Sankey for the impact category climate change from the LCA approach. The flows represented the accumulated impacts caused by the Dutch demand. So for mining the flows represent only the impacts from the mining itself, for smelting both of mining and smelting and for refining the impacts of all three stages. As can be seen from the Sankey and Figure 14 in Appendix 3, the mining stage contributes the most to GHGE while smelting and refining have a similar share. When examining the overall environmental impacts by country, Chile emerges as the predominant emitter of greenhouse gases during the mining stage, while China leads in smelting and refining. This matches the MFA results, which indicates that is mostly due to the volume of copper production. The total GHGE are almost 1,4 MtCO_2e (50% mining, 22% smelting and 28% refining).

This is supported by the regional average impact factors, that can be seen in **Figure 11** in Appendix 2. As can be seen, all regions show relatively similar emission intensities. The three regions in Asia demonstrate the largest, while Latin America and Sub-Saharan Africa have the lowest values. The differences might be due to local conditions, but also choices of modelling. For electricity, for example, ecoinvent assumes a 40% energy consumption from the local grid mix that is likely very different between the countries. For details on the modelling we refer the reader to Classen et al. (2009).

Figure 6 shows the results for the EEIOA approach. It reveals that the total carbon footprint of the Dutch copper supply chain amounts to almost 1.7 MtCO_2e. The direct emissions from copper mining and processing only account for 23% and significant contributions stem from electricity generation (15%) and fossil fuel extraction (9%). Emissions predominantly occur in Europe (22%), China (13%), and the Middle East (8%). Yet this does not align with the locations of final product manufacturing since European copper products account for nearly 35% of the total carbon footprint, followed by Chinese products (15%). Infrastructure emerges as the primary driver of Dutch copper consumption. Despite China's substantial role in the copper supply chain, its influence is less pronounced than suggested by the LCA approach. Regarding the other low- and middle-income countries, 11% of emission occurs in Asian countries, over 8% in Latin America and 5% in African countries.

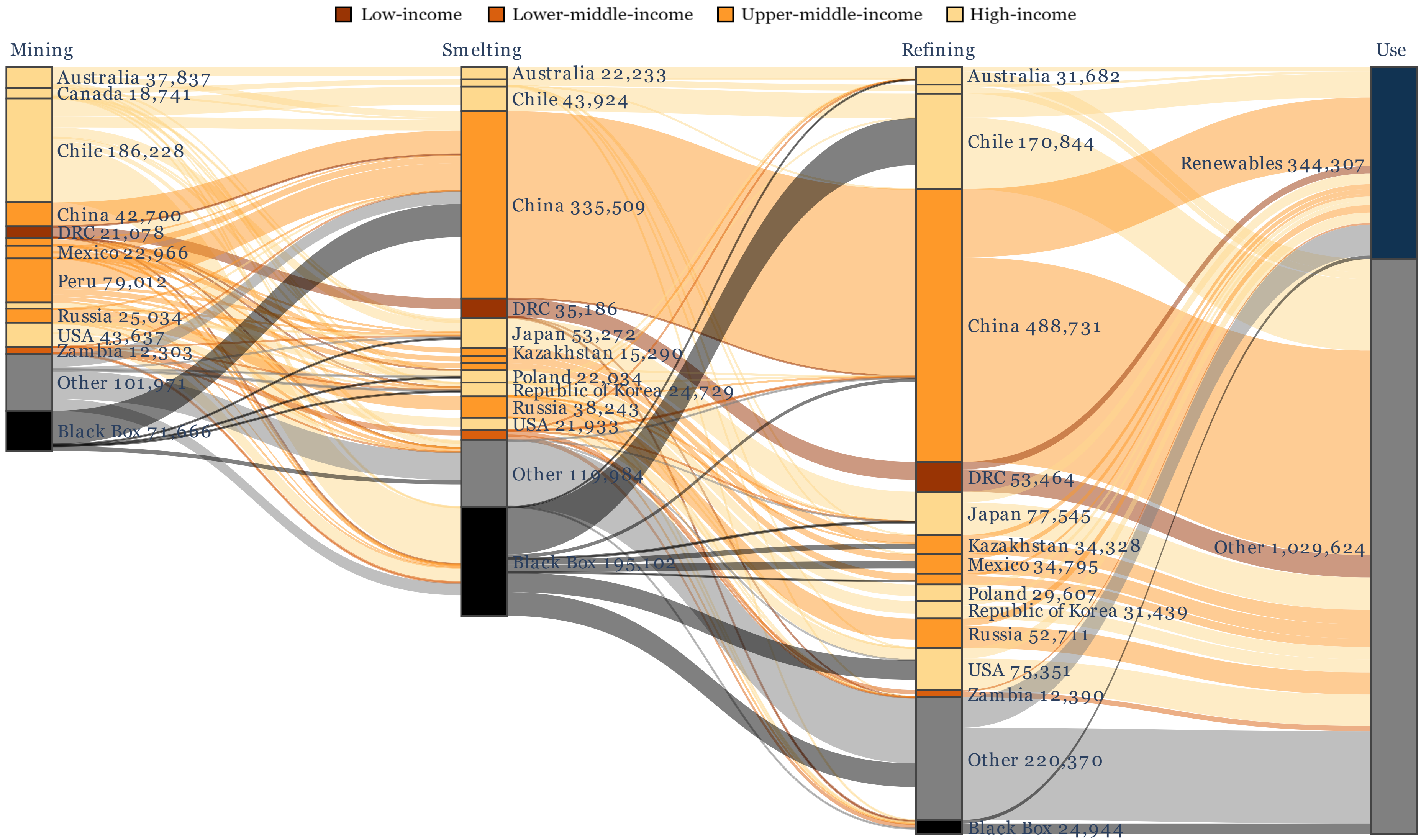

Figure 5: LCA-based Sankey diagram for GHGE allocated to the Dutch consumption of copper in 2019, in tCO_2e. The flows the cumulative impacts along the supply chain. The "Renewables" stage represents the copper use for expanding renewable energy capacities in 2019. "Other" flows include countries with less than 2.5% contribution to all stages with respect to copper production. Due to overlaps, not all labels are shown.

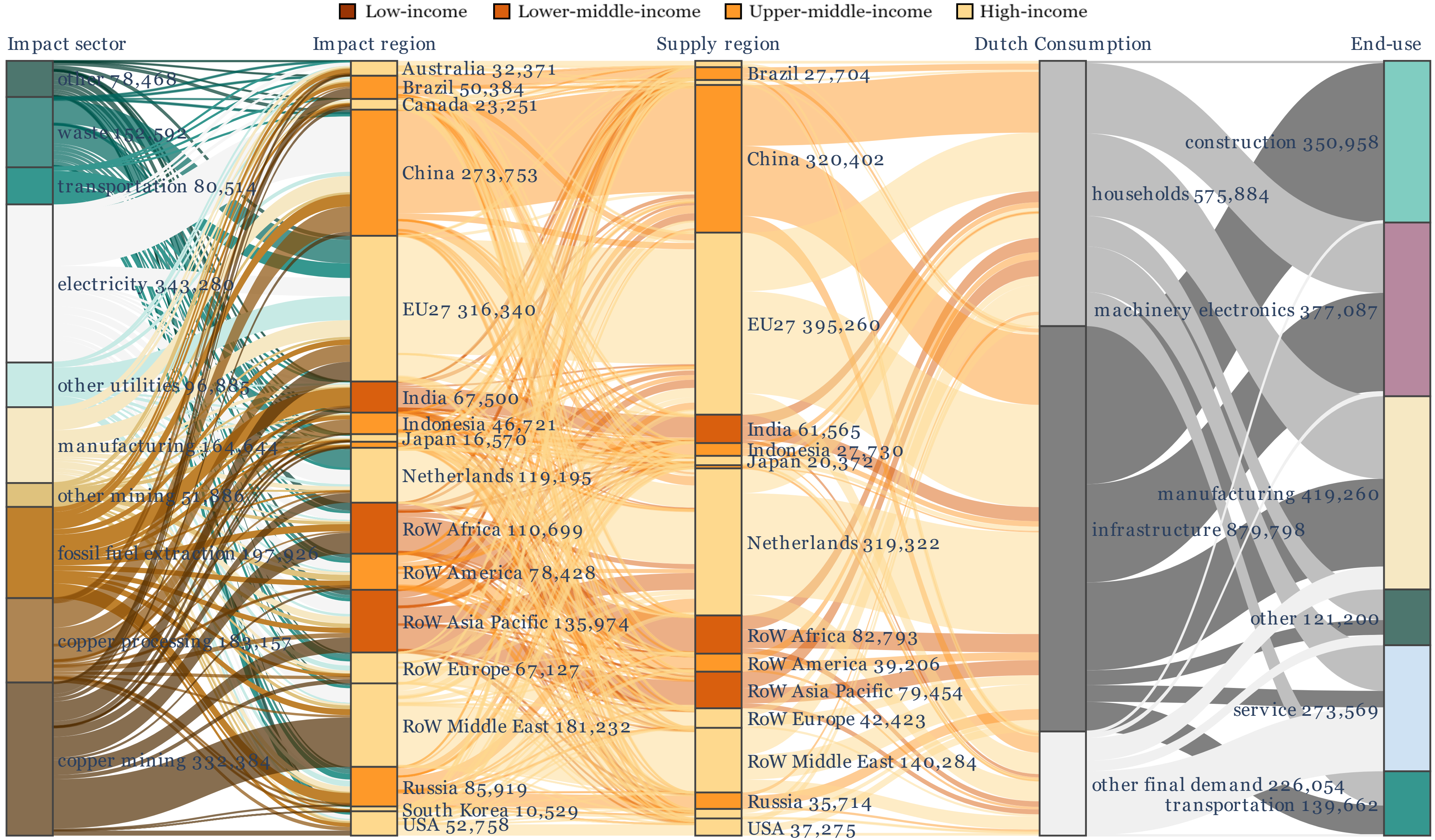

Figure 6: EEIOA-based Sankey diagram for greenhouse gas emissions allocated the Dutch consumption of copper in 2019, in tCO_2e. Impact sector and region show where and when emissions occur. The production perspective indicates where the processed copper is manufactured before being consumed in the Netherlands. The final two perspectives disclose where the demand for copper comes from and the specific purposes for which they are used.

4.2.2 Water depletion

Regarding the results for water depletion from the LCA approach (see **Figure 7**), Chile emerges once again as having the largest total impact during mining operations, while China dominates the smelting stage. However, the fractured supply chain is also represented here with many countries contributing to overall impacts. Notably, smelting and refining show much smaller impacts than mining, which can be seen from the only slight change in volume between the stages (see also Figure 15 in Appendix 3). The total impact of the supply chain according to the LCA approach is 32 Mm^3 (91% mining, 3% smelting and 6% refining).

With regard to the water depletion intensities, all regions show again relatively similar value with only North America standing out (see **Figure 12** in Appendix 2). All intensities are dominated by the mining stage.

The top-down approach depicts a different picture of the embodied water footprint (see **Figure 8**). African and Asian nations seem much more impacted by water depletion, mainly due to copper processing (for Africa) and the upstream requirement in manufacturing (for Asia). While electricity generation does impact Asian countries, its influence is less pronounced than in Latin American nations. In contrast, copper mining directly contributes to less than 1% of the total 1.5 Mm^3 of water requirements. Interestingly, China faces minimal impact from water depletion, even though more than 8% of the embodied water passes through its borders. Finally, inequalities between western countries and the global south are more prevalent when looking at environmental impact associated with water than compared to GHGE.

The LCA and EEIOA approaches yield very different results. The large differences might be partly explained by water depletion being overestimated in the LCA modelling due to the diverse forms of setting system boundaries, especially in mines connected to large quantities of waterbodies (Classen et al., 2009).

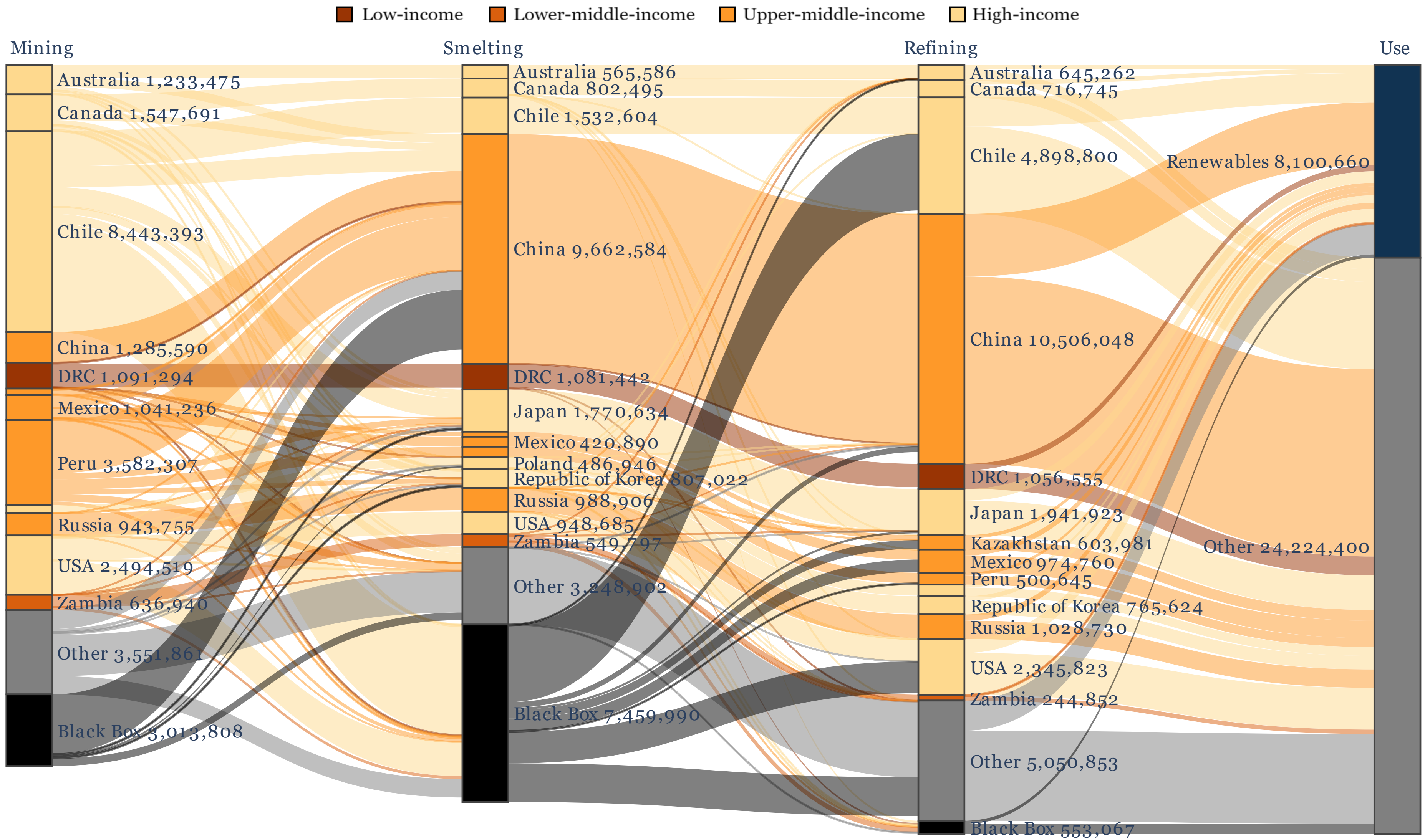

Figure 7: LCA-based Sankey diagram for water depletion allocated to the Dutch consumption of copper in 2019, in m³ of water. The flows the cumulative impacts along the supply chain. The "Renewables" stage represents the copper use for expanding renewable energy capacities in 2019. "Other" flows include countries with less than 2.5% contribution to all stages with respect to copper production. Due to overlaps, not all labels are shown.

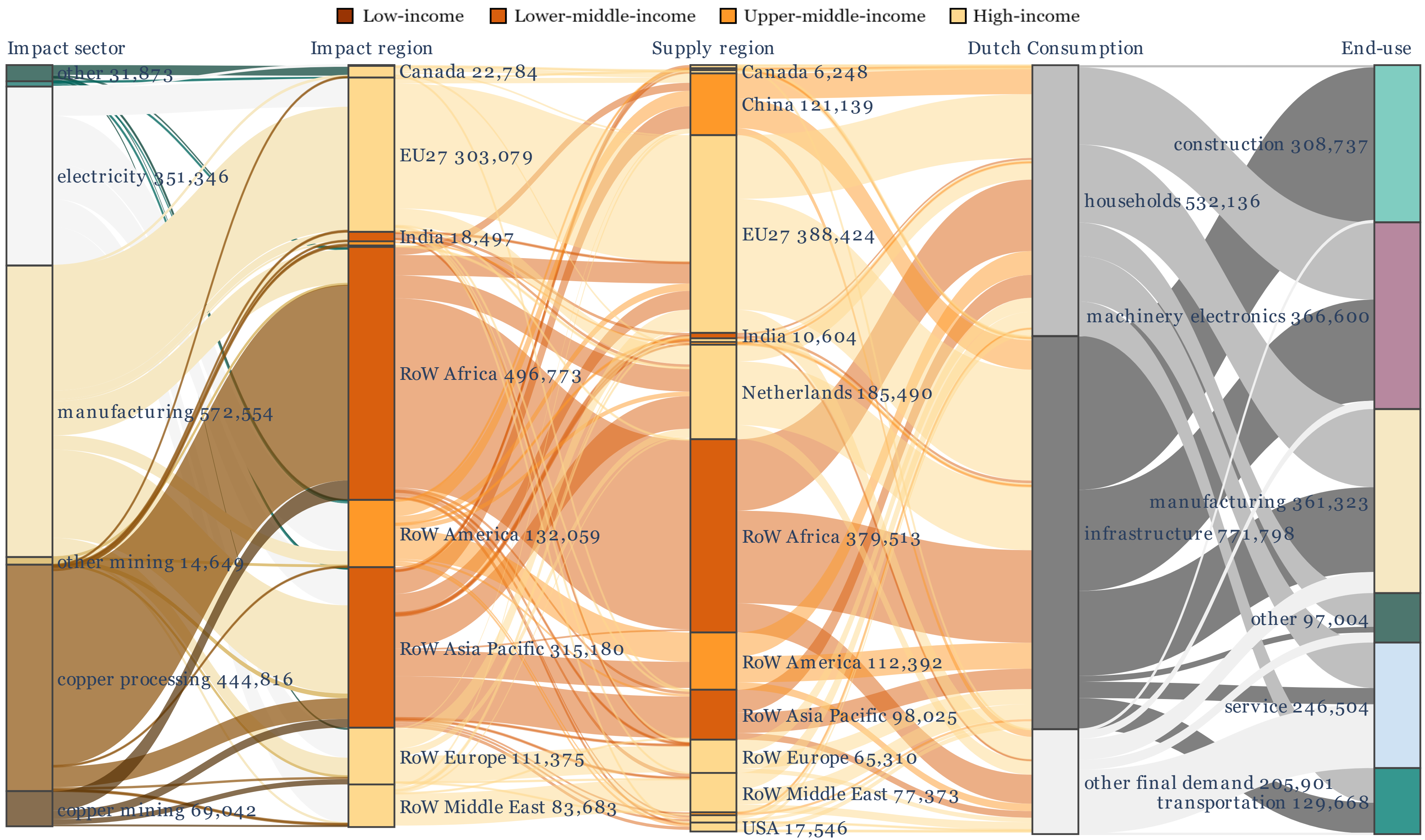

Figure 8: EEIOA-based Sankey diagram for water depletion allocated to the Dutch consumption of copper in 2019, in m³ of water. Impact sector and region show where and when depletion occur. The production perspective indicates where the processed copper is manufactured before being consumed in the Netherlands. The final two perspectives disclose where the demand for copper comes from and the specific purposes for which they are used.

4.2.3 Land use

Similar to water depletion, natural land transformation from the LCA approach is dominated by the mining stage with Chile showing the largest share while China dominates the subsequent stages (see Figure 9). Refining continues to make the smallest contribution to the overall impact of 1.4 km² (91% mining, 5% smelting and 4% refining). See also Figure 16 in Appendix 3 for the contribution of the stages.

Once again, the environmental impact per kilogram of copper production (see **Figure 13** in Appendix 2) illustrates that North America has the highest overall impact, mainly due to the scale of mining activities. Latin America follows, with the three Asian regions and Sub-Saharan Africa showing relatively lower impacts.

It is important to note that the top-down approach solely consider land use associated with mining. Therefore, the comparison should be limited to the mining stage of the LCA approach. With this in mind, a significant disparity can be noted. The LCA indicates a natural land transformation of 1.4 km² for the Dutch copper supply chain, contrasting with 28.5 km² in the EEIOA approach. However, the distribution of relative impact across countries aligns more closely between EEIOA and LCA when compared to previous indicators. Latin American nations bear the highest impact, accounting for almost a third of the total surface required for mining-related activities. In line with the water indicator, 12% of the embodied mining surface transits through the Chinese border, while only 1% of the land use occurs in China. Interestingly, a substantial portion of land use takes place in European countries. This seems contradictory to LCA results, but it should be remembered that LCA does not account for trade transactions beyond the refinery stage, and instead assume that the copper consumed by the Netherlands is supplied in relative proportion to the production of refining countries.

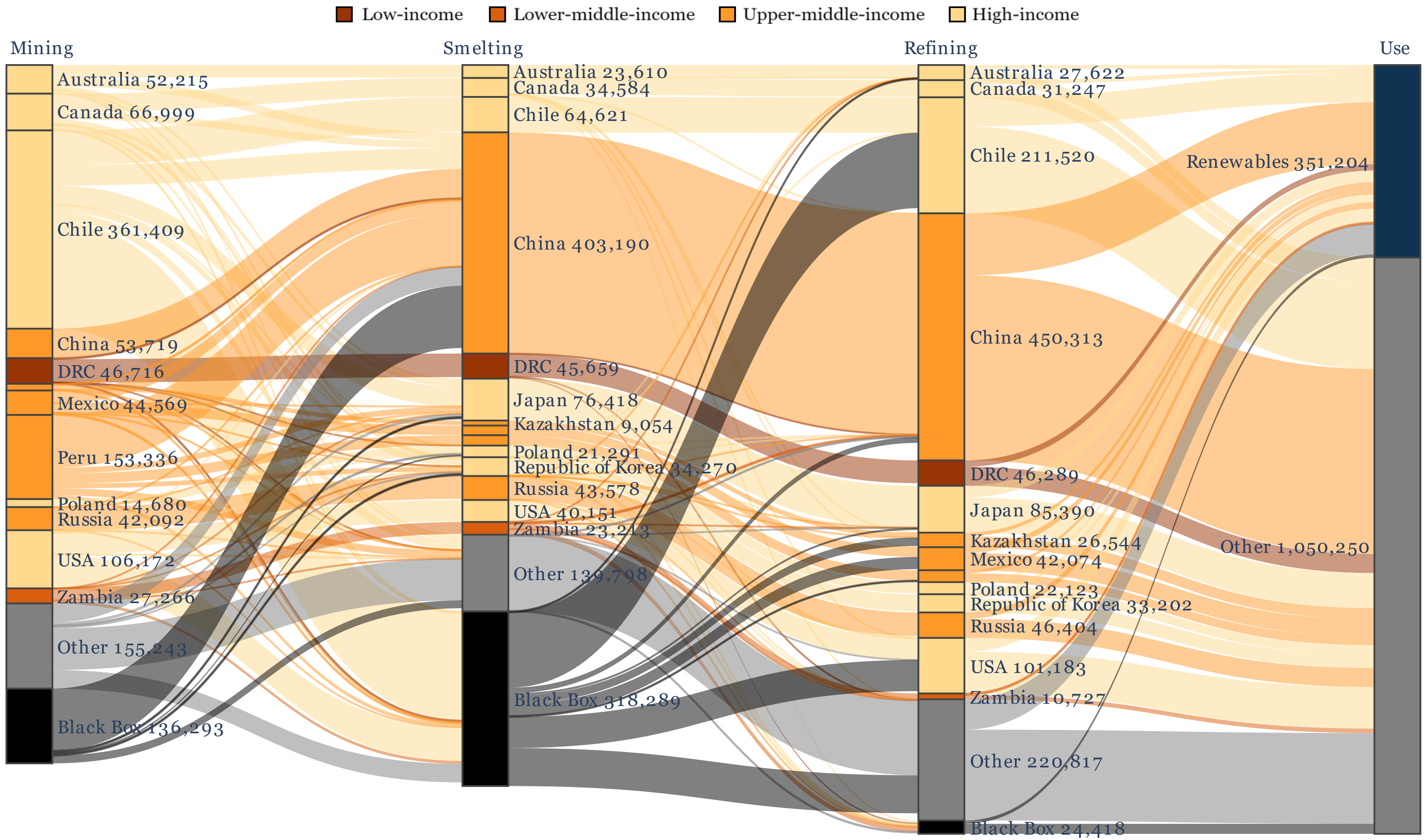

Figure 9: LCA-based Sankey diagram for natural land transformation allocated to the Dutch consumption of copper in 2019, in m² of land. The flows the cumulative impacts along the supply chain. The "Renewables" stage represents the copper use for expanding renewable energy capacities in 2019. "Other" flows include countries with less than 2.5% contribution to all stages with respect to copper production. Due to overlaps, not all labels are shown.

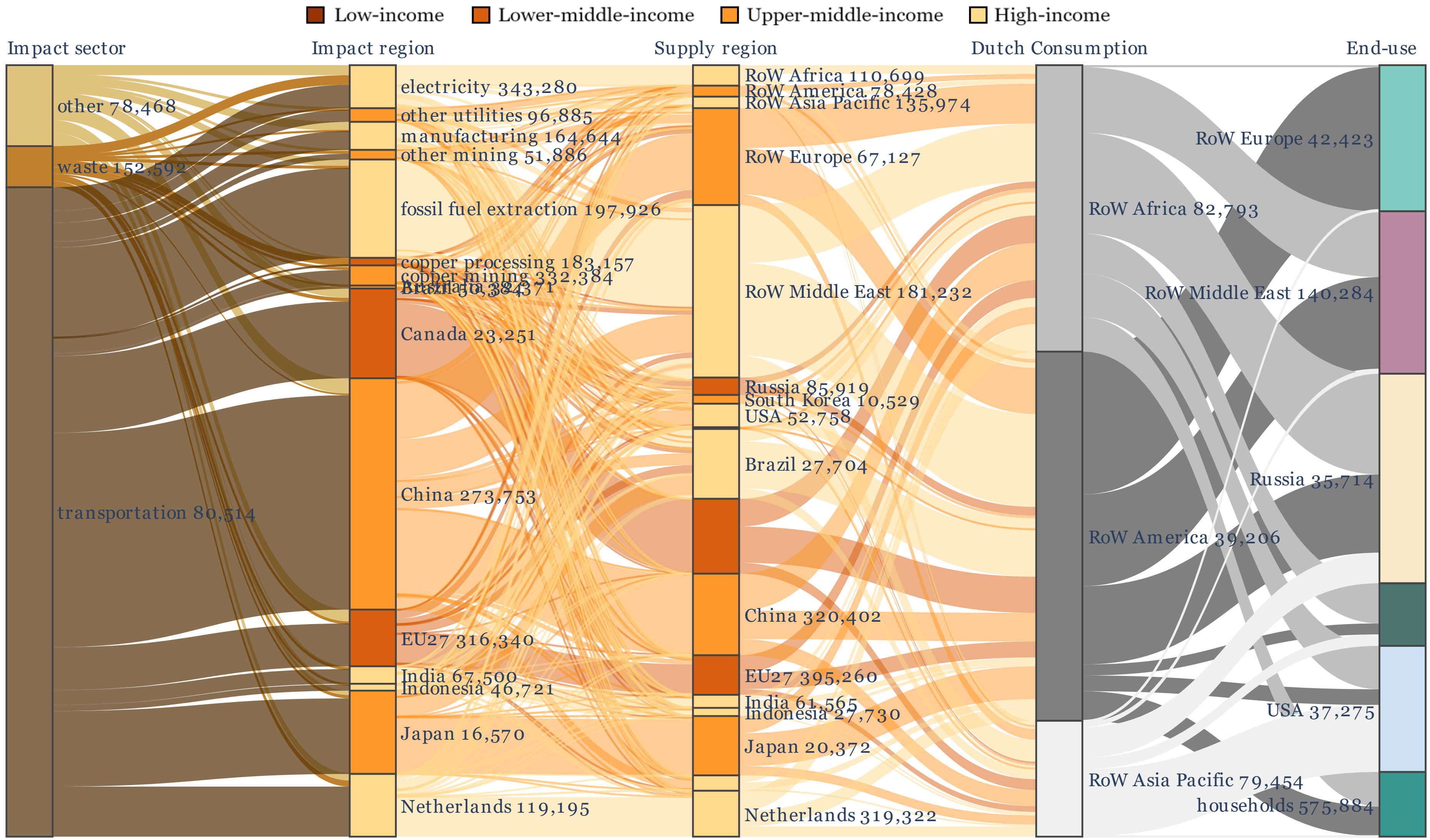

Figure 10: EEIOA-based Sankey diagram for land-use area of mining allocated to the Dutch copper supply chain in 2019, in m² of land. Impact sector and region show where and when pressure on land-use occur. The production perspective indicates where the processed copper is manufactured before being consumed in the Netherlands. The final two perspectives disclose where the demand for copper comes from and the specific purposes for which they are used.

5 Discussion

In this chapter, first the research questions are answered, followed by a discussion of methodological and data limitations. In the end, recommendations to the Dutch government and the scientific community are given.

5.1 Answering the research questions

Section 4.1 addressed our first research question by examining the global primary copper production landscape. We now shift our focus towards the insights that can be gained from both LCA and EEIOA approaches to the remaining research questions.

RQ2: From mining to refining, what are the environmental impacts associated with copper on a per country basis, particularly for low- and middle-income countries?

Our results reveal several discrepancies between these approaches. The disparities are already evident in terms of total footprint, with the LCA indicating a total carbon footprint of 1,4 $MtCO_2e$ compared to 1.7 $MtCo_2e$ for the EEIOA approach. An even larger contrast appears with the water depletion with 32 Mm^3 for the LCA and 1.5 Mm^3 for the EEIOA, despite their reliance on similar environmental intensities. A similar difference is observed for land-use although only the mining stage can be compared and reveal the use of 1.3 km^2 and 28.5 km^2 for LCA and EEIOA respectively.

However, this outcome is not surprising and aligns with Steubing et al.'s findings (Steubing et al., 2022). Their research revealed twofold variations between EEIOA and LCA across numerous sectors, especially for mining. The research specifically focused on carbon footprint and given that this is one of the most extensively researched environmental impact, it is reasonable to assume that less studied impacts, such as water consumption, would show even greater variations.

There are significant disparities not only in the actual numbers but also in the distribution of impact shares at a country level. For instance, it is evident that countries under water stress are more impacted by water depletion. But this is insufficiently reflected in the LCA diagram, and it highlights a major limitation of this approach. With no data available for North Africa, global averages were used, leading to potential misinterpretation. The results from the IOA demonstrate that African nations represent a larger proportion of water depletion impacts. And the data limitation can explain the discrepancy between the two methods.

Additionally, it should be noted that the assessment was carried at a country or region level, yet mining impacts are site-specific and have differentiated effects on local communities. For example, research has shown that within high-income unequal societies, smaller poorer communities may be more affected by mining activities without benefiting from them equally (Al Rawashdeh et al., 2016). Finally, and irrespectively of the scale of environmental impacts found by both assessments, the two methodologies converge in highlighting a stark reality: LMICs bear an unequal burden from mining activities when compared to the local economic benefits they receive. Much of the added value in the supply chain is captured in regions distinct from where the environmental impacts occur. Therefore, prioritising sustainable mining practices alongside addressing social inequalities arising from mining operations becomes imperative.

RQ3: For how much of global refined copper demand and associated environmental impacts is the expansion of renewable energy in the Netherlands responsible?

Copper plays a crucial role in various technologies driving the energy transition (IEA, 2022a). It serves as a primary material for motor in electric vehicles and wind turbines. Additionally, it is a key component in batteries used for energy storage. When it comes to energy infrastructure, copper is not only extensively employed in electrical wiring and power cables, but also in many critical equipment, including transformers, inverters, switchgear, and busbars. Beyond its electrical properties, copper is also an excellent thermal conductor, meaning that is widely used for piping and heat exchangers in heat pump installations and solar-water heaters.

Consequently, evaluating the environmental repercussions linked to the expansion of renewable energy poses another challenge: to determine the adequate scope. This is far from straightforward. For instance, to which extent the installation of a heat pump should be attributed to the energy transition? Similarly, as the integration of renewable sources expand, the upgrading of grid infrastructure becomes imperative (Netbeheer Nederland, 2021; pwc, 2024). This not only entails adding new power cables to support a decentralised grid structure, but also adapting components like converters and transformers. Yet, these components would have eventually required replacement. Therefore, this calls for establishing an adequate temporal boundary to distribute the impacts of physical infrastructure over time. Without that, strong biases can appear since most of the impacts happen when capital assets are created, in years preceding their utilisation.

Due to time constraints, and the effort involved in harmonising data for the MFA, the aforementioned points could only be addressed superficially. First, under the LCA approach, simplifications were implemented by confining the analysis to the 2019 installed photovoltaic and wind turbines, as detailed in chapter 3.1. But the considerable uncertainty range prevents definitive interpretations, even without factoring in the variation caused by the change in grid infrastructure. Second, the additional methodological steps required to disaggregate the supply and demand of capital stock in EEIOA (also known as capital endogenisation) remains an activate field of research and could not be satisfactorily integrated in this work. This issue is further discussed in the methodological limitations section. As such, the EEIOA approach should be understood as a means of providing context to the footprint derived from the LCA in two ways: i) by exposing the strong assumption of a proportional connection between the sourcing of copper for Dutch consumption and the production capacity of the primary global suppliers, and ii) by providing insights into inherent uncertainties. Finally, it should be underscored that a single reference year cannot capture the broader landscape of renewable energy expansion in the Netherlands. Therefore, the next logical step involves constructing time series to gain a deeper understanding of the evolving trends in copper demand. Although this avenue was not pursued due to time limitations, it is now greatly facilitated by the tools developed as part of this project.

Having discussed the challenges in attributing environmental impacts to the renewable energy sectors, it remains necessary to contextualise the transition, even when delving into a particular value chain. While it is certain that the energy transition will lead to an increasing demand for some metals, several authors have emphasised that overall mining would decrease due to the phasing out of fossil fuels, especially coal (Nijnens et al., 2023; Watari et al., 2019). This reduction stems from the stock building nature of renewable energy infrastructure, which allows for subsequent recycling. In contrast, the infrastructure associated with fossil fuels demands a continuous flow of feedstock. Although the impact of fossil fuels is not the primary source of indirect impacts in the copper supply chain, it remains significant, as can be seen with the EEIOA Sankey for GHGE.

RQ4: What are the leverage points to mitigate environmental impacts, particularly in low- and middle-income countries?

The findings from this study align with those presented in Maus and Werner (2024). The fragmented and incomplete understanding of mine production, resource consumption, and pollution hinders thorough assessment. Consequently, decision-makers lack the necessary information to effectively implement environmental strategies. One of the most impactful intervention points involves enhancing the differentiation and dissemination of mining data while promoting data transparency in scientific reports. This also entails strengthening the statistical capacity of LMICs. However, limitations extend beyond data alone. Accounting methodologies, such as LCA and EEIOA, also encounter constraints. The subsequent sections delve into limitations associated with both methodologies and data acquisition.

Additionally, the closure of coal mines and oil and gas fields, driven in part by the expansion of copper mining operations, provides a chance for rehabilitating the land and undertaking ecological restoration efforts (Sonter et al., 2023). Reflecting recent discussions at COP28 on the Loss and Damage Fund, it is essential to acknowledge that certain vulnerable countries may endure the negative effects of deteriorated land without the financial means to address them. As such an important leverage also consist in supporting local communities in the slow and costly process of land restoration.

RQ5: What are the main data constraints for assessing the supply chain of metals and their environmental impacts?

This question is addressed below in the discussion of the limitations (mainly in section 5.3).

5.2 Methodological limitations

In EEIOA, achieving comprehensive coverage of the entire economy necessitates a trade-off with maintaining product resolution. The compromise is reflected in the aggregation of each industry's production into a singular output. This leads to a homogeneous price assumption with a proportional relationship between monetary and physical flows within the same sector. However, in reality, various products within a sector may exhibit different environmental intensities and physical quantities are not uniformly priced for all consumers (Wieland et al., 2022). For instance, the cost disparity between copper processed through hydrometallurgy and pyrometallurgy may not accurately capture the differences in environmental impacts associated with these distinct pathways (Yang et al., 2022). Consequently, the homogeneous price assumption may oversimplify the complexity of environmental analyses.

Another aspect of aggregation in EEIOA pertains to capital formation, where investment in long-lived assets like infrastructure or machinery is documented in a country's final demand. This is due to their lifespan surpassing one year, the typical duration of an accounting period in national accounts. This practice results in the loss of valuable information (Font Vivanco, 2020; Södersten & Lenzen, 2020). For example, investment in electrical equipment containing copper (e.g. motor) would appear in the final demand category. But from then, it is not possible to know which sector utilizes this capital, making it unclear whether it ends up contributing to the renewable energy sector or another industry.

On the other hand, the process resolution provided by bottom-up approaches like LCA introduces inaccuracies (Nakamura, 2023a). This arises from the difficulty of ensuring comprehensive coverage of the entire system and result in the exclusion of specific aspects (also known as truncation error). The data collection effort at the process level also limits the number of data points available for each process, as discussed in the subsequent section.

Several contemporary research trends are exploring avenues for enhancing the identified trade-offs. Physical Input-Output Tables (PIOT) aspire to synergize the strengths of Material Flow Analysis (MFA) and Input-Output Analysis (IOA) modelling by incorporating detailed records of mass and energy flows within inter-industry transactions (Merciai & Schmidt, 2018). Conversely, Hybrid Life Cycle Assessment (HLCA) seeks to leverage the respective strengths of both EEIOA and LCA achieve comprehensive coverage while providing nuanced insights into specific processes (Nakamura, 2023a). Finally capital endogenization methods aim to account for the role of capital assets in environmental footprints (Miller et al., 2019; Södersten & Lenzen, 2020). These developments represent the forefront of current industrial ecology methodologies and have the potential to advance our comprehension of societal metabolism, particularly shedding light on the environmental impacts linked to material footprints.

5.3 Data limitations

5.3.1 Supply chain mapping: Material Flow Analysis

As described in the methods section, the data used in the MFA consists of both the BACI and USGS datasets. When comparing these BACI and USGS datasets, discrepancies between the copper flows for mined, smelted, and refined copper range between 5% to approximately 35% for some countries across the categories. While differences are to be expected across databases, the discrepancies between the datasets are far too frequent and large to ignore. This provides further uncertainty concerning the size of the copper flows and in extend the total environmental impacts.

The differrences can be due to many reasons. For instance, BACI is already harmonised with HS codes, which are transformed to actual copper content by multiplication of estimated copper content (from Liu et al. (2023)). BACI is based on countries' self-reported imports and exports, for which exports are known to be imperfect and further harmonisation is needed.

Concerning USGS, this database relies on survey data from countries themselves, which creates the same problem. In addition, historical trends for estimation in the case of non-response or missing data with unclear reporting on their specific data estimation or collection methods. Another notable limitation of USGS is that primary and secondary production are not fully differentiated for all countries, leaving further room for inconsistency within copper allocations.

While there is large scale data available on the Dutch copper demand on an annual basis, specific data concerning copper use per industrial sector is very limited. This leads to the need for the estimation based on gigawatts installed. As seen in **Table 3**, the minimum and maximum values based on the gigawatts of capacity installed vary considerably causing the average to vary considerably from both the minimum and maximum estimations. This high amount of variability diminishes the reliability of the estimated copper consumption of the Dutch renewable energy sector and calls for more accurate documentation and data to improve upon these estimates in the future.

A general limitation is due to lack of funding, meaning that not all databases, such as the International Copper Study Group and SNL databases, with potentially more robust production and trade data could be accessed. Due to the fact that both databases are very widely used in MFA and a wide array of other scientific disciplines, we stress that an improvement of data collection methods and improved documentation on collection methods could significantly improve the quality of these databases.

5.3.2 Impact quantification: Life cycle Assessment

In general, the LCA showed a low data quality specially in terms of representation of regions as well as differences within the regions. As described, certain regions to not even have one data point and for refining only one process was available. Environmental impacts from mining are generally underexplored (Maus & Werner, 2024). LCA data is often only based on a few cases deemed representative (Classen et al., 2009). However, mining impacts are complex and very dependent on local conditions, regulation and management. Furthermore, the technological representation was very low with no values being available for hydrometallurgy and some of the ecoinvent processes come from data acquired more than 15 years ago. This is critical because mining impacts are dynamic. For copper, for example, the ore average grade decreases substantially, increasing environmental impacts per unit of output (S. Northey et al., 2014; Priester et al., 2019).

Mining has the most countries represented per region, indicating comparably reliable results. When considering representation in ecoinvent, East Asia and Pacific had the largest number of countries included, but North America stood out with a higher proportion of country presence with two out of three countries having available data (**Table 5**). However, it is essential to recognise that our limited geographical knowledge constrains drawing conclusions about factors contributing to differing environmental impacts across regions and countries. In simpler terms, insufficient data hampers determining whether, for example, North America's larger environmental impact arises from technology use, energy sources, or regional characteristics.

5.3.3 Impact quantification: EEIOA

Data limitations regarding EEIOA relates to two aspects: the industry-to-industry monetary transactions (i.e., the matrix Z) and the environmental extension (i.e., the satellite matrix F). The two aspects should be considered simultaneously, and currently no dataset covers both monetary and environmental dimensions sufficiently for the purpose of this study (Giljum et al., 2019).

For instance, the Global Trade Analysis Project (GTAP; Center for Global Trade Analysis, 2023), and the OECD-led Inter-Country Input-Output (ICIO; OECD, 2023) encompass more countries (141 and 75, respectively) but fewer industries (65 and 45). But unfortunately, the environmental coverage remains a notable gap. The Global Resource Input-Output Assessment (GLORIA; M. Lenzen et al., 2023), despite addressing a significant number of countries (160) and industries (120), also falls short in environmental coverage. On the other hand, Exiobase is known for its environmental data, albeit at the expense of aggregating multiple countries. Efforts to integrate diverse Input-Output Tables (IOT) with complementary strengths have been made and present an interesting avenue for future research (Cabernard & Pfister, 2021). More promising even, these limitations have been acknowledged by the statistics department of the International Monetary Fund (MARIO; Guilhoto et al., 2023). Given the authority and resource of this organization, a new emerging IO table under their direction offers a much welcome prospect.

In considering environmental impact factors, two noteworthy aspects merit attention. First, despite the current endorsement by the UNEP, the water intensity coefficients derived from the Aware project exhibit limitations when applied to the analysis of mining and metal processing. These coefficients, designed for quantifying depletion potential based on current blue water consumption, are well-suited for the agricultural sector due to the specification of diverse crop products. However, for all other industries, they are aggregated into a single impact factor. This limitation could be mitigated, in part, through the involvement of relevant stakeholders. For instance, comprehensive corporate reporting could enable the weighting of characterization factors based on actual production and water consumption (S. A. Northey et al., 2019). Nevertheless, significant progress remains impeded without watershed-specific impact assessment (S. A. Northey et al., 2018).

Second, the EEIOA approach only considered land use specific to mining, resulting in clear underestimations. Attempts to reconcile this with Exiobase's other impacts on land transformation led to double counting. The effort to harmonise both sets of data demanded more resources than could be allocated within the span of the project. Additionally, the current assessment makes use of the environmental extension developed by Cabernard and colleagues (Cabernard & Pfister, 2022) that is based on Maus' satellite dataset (Maus et al., 2020). To develop this extension, the authors established a correspondence between site-specific land-use surface and the primary commodity mined based on the SNL dataset. However Maus's dataset has been improved since then (Tang & Werner, 2023).

This new dataset not only broadens coverage but also delivers quantitative insights into the influences of mining activities. For example, it shed light into violation of protected areas. The current trend toward employing artificial intelligence techniques provide the tools for global impact assessment that do not compromise on granularity (Maus & Werner, 2024). But it also underscores the need for automated methods to convert findings into readily usable formats for decision-making. As such, developing routines to translate spatial datasets into environmental extensions for Input-Output analysis becomes a critical avenue of research.

5.4 Recommendations and future research

There are two targeted recipients of this research, namely government stakeholders and the scientific community. Recommendations and relevant areas for future research which would target each of these recipient groups is outlined below.

5.4.1 Government stakeholders

The Sankey diagrams are a starting point for government stakeholders to use for informing future plans for diplomatic relations. For example, an agency responsible for addressing water-related environmental issues can use the impact results for water as a preliminary assessment on which countries that are traded with contribute most. However, due to large disparities across the databases, governments should focus near-term efforts on promoting transparent reporting to improve the quality of insights that can be extracted from these Sankey diagrams and other similar research. The level of how informed governmental decisions can be hinges on the quality of the underlying data.

Therefore, governments should promote transparent reporting within mining companies on not only production levels, but also the corresponding impacts on the environment. Currently, annual sustainability reports are not produced by all mining companies, and those which do publish these primarily provide aggregated corporate level data and do not provide site-level data (Christmann, 2021). To improve usability and transparency of these mining reports, governments should advocate for centralised public data repositories which are simple for companies to upload information onto and for the public to access (Maus & Werner, 2024). Focused advocacy should be conducted on underrepresented regions, beginning with over half of the global mining areas visible from satellite images which have no production information listed in a global database (Maus & Werner, 2024). Collaborating with established organisation such as the International Sustainability Standards Board and the Global

Reporting Initiative which already have protocols aimed at enhancing transparency in the mining sector, can contribute to advancing ongoing efforts (Maus & Werner, 2024).

But only enforcing transparency will likely not be enough. Strengthening the statistical capacity of countries along the supply chain, especially in LMICs, might be equally important.

Additionally, future collaboration between government stakeholders and the scientific community is critical to ensure this research is used in practice. Governments can assist researchers by advocating for better documentation of material production and trade data, while researchers can help define the most essential data that should be disclosed by the mining sector.

5.4.2 Scientific community

Overall, there is a significant gap in data availability that can and should be addressed by the scientific community. First, as previously mentioned, databases such as ecoinvent generally only present a few case studies per process, which tend to represent only one mine and are then generalised for the entire country. Therefore, further mine-specific case studies should be conducted not only to expand existing datasets but also to ensure representative and relevant data usage.

Second, we recommend expanding this study by utilising additional databases such as Fineprint (Jasansky et al., 2022) and Climate Trace (Climate Trace, 2024). Despite being beyond the scope of our research, these databases offer interesting and innovative methods for extending our research. This particular study focused on copper, however, the code can apply to any metal if Comtrade HS codes and USGS production datasets are available. Future work could combine our approach with above databases to explore localised impacts on countries based on their geographic variations for multiple metals.

Third, the footprints of water depletion and natural land transformation, although interesting and insightful, do not portray the whole picture of the environmental impacts. It is important to note that some of the highest-producing copper mines in the world are in deserts where water scarcity already exists. Therefore, water depletion plays an important role while land use does not affect biodiversity as intensely. On the other hand, mines are located in tropical areas do not suffer from water scarcity as strongly but have a significant impact on biodiversity when transforming land into mines.

Forth, we recommend continuing the improvement of Industrial Ecology Methods, especially with respect to dealing with data gaps and uncertainties.

Finally, our results show the importance of reporting data gaps, uncertainties and inconsistencies. Moreover, making methods, codes, and results accessible will assist other researchers.

6 Conclusion

This report provides an in-depth analysis of the global copper supply chain supporting the Dutch renewable energy transition. To accomplish this, a combination of three Industrial Ecology tools – Material Flow Analysis, Life Cycle Assessment, and Environmentally Extended Input-Output Analysis – was used to address five sub-research question, each tool with its own benefits and limitations.

The first question was answered by mapping the supply chain was using a static MFA from 2019, to highlighted production and processing quantities per country. This revealed key contributors to the supply chain across the multiple country income levels, but also showcases difficulties tracing the supply chain due to lack of harmonised data throughout stages and databases. For the second question, LCA and EEIOA were utilised to calculate environmental impacts such as climate change, water depletion, and natural land transformation in each country involved in the supply chain. However, evaluating these impacts proved complex due to the disparities between methods leading to diverging results for total impacts.

Yet, and responding to the third sub-research question, both tools concurred on the fact that LMICs bear direct environmental impacts from copper production for the renewable energy transition in the Netherlands. Addressing mitigation strategies, especially in LMICs, requires a multi-faceted approach of leverage points, as asked in sub-research question four. This includes strengthening the data available, promoting transparency, and supporting rehabilitation efforts in regions affected by mining. Lastly, for the fifth sub-research question, it is acknowledged that project constraints primarily stemmed from data limitations, made evident by the discrepancy between datasets, and environmental impact assessments. This highlighted the lack of transparency by the mining and industry sectors, for which we recommend improving documentation of material trade and advocating for enhanced data collection methods.

We recommend that informed decision-making and strategic interventions are considered to ensure that the renewable energy transition is done with environmental preservation at the forefront. The findings underscore the complexities of the copper supply chain and the necessity for improving the available data. Furthermore, they emphasise the importance of collaborative efforts between stakeholders and researchers to address environmental challenges and promote sustainable practices in the mining industry.

Code and data availability

Code written for this analysis will be made available along with the USGS datasets here: https://github.com/AaronParis/MFA_global_metal_flows. The BACI trade data is too large to be shared. It is publicly accessible via http://www.cepii.fr/CEPII/en/bdd_modele/bdd_modele_item.asp?id=37. Sharing the Ecoinvent data is not possible as it is licensed.

References

Al Rawashdeh, R., Campbell, G., & Titi, A. (2016). The socio-economic impacts of mining on local communities: The case of Jordan. *The Extractive Industries and Society*, *3*(2), 494–507. https://doi.org/10.1016/j.exis.2016.02.001

Boulay, A.-M., Bare, J., Benini, L., Berger, M., Lathuillière, M. J., Manzardo, A., Margni, M., Motoshita, M., Núñez, M., Pastor, A. V., Ridoutt, B., Oki, T., Worbe, S., & Pfister, S. (2018). The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE). *The International Journal of Life Cycle Assessment*, *23*(2), 368–378. https://doi.org/10.1007/s11367-017-1333-8

Brand-Correa, L., Brook, A., Büchs, M., Meier, P., Naik, Y., & O'Neill, D. W. (2022). Economics for people and planet-moving beyond the neoclassical paradigm. *The Lancet. Planetary Health*, *6*(4), e371-e379. https://doi.org/10.1016/S2542-5196(22)00063-8

Brandenburg, K., Brummelkamp, S., Chan, H. S., Geurts, L., Linders, M. J., & Muller, Glenn, Segers, Reinoud (2023, October 12). Hernieuwbare energie in Nederland 2022. *Centraal Bureau Voor De Statistiek*. https://www.cbs.nl/nl-nl/longread/rapportages/2023/hernieuwbare-energie-in-nederland-2022

Brunner, P. H., & Rechberger, H. (2004). *Practical handbook of material flow analysis. Advanced methods in resource and waste management: Vol. 1*. CRC/Lewis.

Cabernard, L., & Pfister, S. (2021). A highly resolved MRIO database for analyzing environmental footprints and Green Economy Progress. *The Science of the Total Environment*, *755*(Pt 1), 142587. https://doi.org/10.1016/j.scitotenv.2020.142587

Cabernard, L., & Pfister, S. (2022). Hotspots of Mining-Related Biodiversity Loss in Global Supply Chains and the Potential for Reduction through Renewable Electricity. *Environmental Science & Technology*, *56*(22), 16357–16368. https://doi.org/10.1021/acs.est.2c04003

Cabernard, L., Pfister, S., & Hellweg, S. (2019). A new method for analyzing sustainability performance of global supply chains and its application to material resources. *The Science of the Total Environment*, *684*, 164–177. https://doi.org/10.1016/j.scitotenv.2019.04.434

Cabernard, L., Pfister, S., & Hellweg, S. (2022). Improved sustainability assessment of the G20's supply chains of materials, fuels, and food. *Environmental Research Letters*, *17*(3), 34027. https://doi.org/10.1088/1748-9326/ac52c7

Cabernard, L., Pfister, S., Oberschelp, C., & Hellweg, S. (2022). Growing environmental footprint of plastics driven by coal combustion. *Nature Sustainability*, *5*(2), 139–148. https://doi.org/10.1038/s41893-021-00807-2

Center for Global Trade Analysis (Ed.). (2023). *GTAP Data Bases: GTAP Data Base*. https://www.gtap.agecon.purdue.edu/databases/default.asp

CEPII. (2023, February 1). *BACI*. http://www.cepii.fr/CEPII/en/bdd_modele/bdd_modele_item.asp?id=37

Christmann, P. (2021). Mineral Resource Governance in the 21st Century and a sustainable European Union. *Mineral Economics*, *34*(2), 187–208. https://doi.org/10.1007/s13563-021-00265-4

Classen, M., Althaus, H.-J., Blaser, S., Scharnhorst, W., Tuchschmid, M., Jungbluth, N., & Emmenegger, M. F. (2009). *Life Cycle Inventories of Metals*. https://db.ecoinvent.org/reports/10_Metals_v2.1.pdf?area=463ee7e58cbf8

Climate Trace. (2024). *Independent Greenhouse Gas Emissions Tracking*. https://climatetrace.org/

Dente, S. M., Aoki-Suzuki, C., Tanaka, D., & Hashimoto, S. (2018). Revealing the life cycle greenhouse gas emissions of materials: The Japanese case. *Resources, Conservation and Recycling*, *133*, 395–403. https://doi.org/10.1016/j.resconrec.2017.12.011

Dente, S. M., Aoki-Suzuki, C., Tanaka, D., Kayo, C., Murakami, S., & Hashimoto, S. (2019). Effects of a new supply chain decomposition framework on the material life cycle greenhouse gas emissions—the Japanese case. *Resources, Conservation and Recycling*, *143*, 273–281. https://doi.org/10.1016/j.resconrec.2018.09.027

ecoinvent. (2022). *ecoinvent v3.9.1 - ecoinvent*. https://ecoinvent.org/the-ecoinvent-database/data-releases/ecoinvent-3-9-1/

European Commission (Ed.). (2018). *Product Environmental Footprint Category Rules Guidance: Version 6.3*. https://eplca.jrc.ec.europa.eu/permalink/PEFCR_guidance_v6.3-2.pdf

European Commission. (2021a). *Understanding Product Environmental Footprint and Organisation Environmental Footprint methods*. https://op.europa.eu/en/publication-detail/-/publication/c43b9684-4521-11ed-92ed-01aa75ed71a1/language-en

European Commission (Ed.). (2021b, December 30). *Commission Recommendation (EU) 2021/2279 of 15 December 2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations* (Official Journal of the European Union). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32021H2279

European Commission. (2023). *European Critical Raw Materials Act*. https://ec.europa.eu/commission/presscorner/detail/en/fs_23_1663 https://doi.org/10.2775/613159

Font Vivanco, D. (2020). The role of services and capital in footprint modelling. *The International Journal of Life Cycle Assessment*, *25*(2), 280–293. https://doi.org/10.1007/s11367-019-01687-7

Gaulier, G., & Zignago, S. (2010). *BACI: International Trade Database at the Product-level: The 1994-2007 Version*. http://www.cepii.fr/pdf_pub/wp/2010/wp2010-23.pdf

Giljum, S., Wieland, H., Lutter, S., Eisenmenger, N., Schandl, H., & Owen, A. (2019). The impacts of data deviations between MRIO models on material footprints: A comparison of EXIOBASE, Eora, and ICIO. *Journal of Industrial Ecology*, *23*(4), 946–958. https://doi.org/10.1111/jiec.12833

Government of the Netherlands. (2023a). *Circular Dutch economy by 2050*. https://www.government.nl/topics/circular-economy/circular-dutch-economy-by-2050

Government of the Netherlands. (2023b). *Climate policy*. https://www.government.nl/topics/climate-change/climate-policy

Government of the Netherlands. (2023c). *Resource Efficiency*. https://www.government.nl/topics/environment/resource-efficiency

Government of the Netherlands. (2023d). *Rijksoverheid stimuleert duurzame energie*. https://www.rijksoverheid.nl/onderwerpen/duurzame-energie/meer-duurzame-energie-in-de-toekomst

Guilhoto, J., Legoff, G., Pegoue, A., Borga, M., & Strassner, E. (2023). *IMF Multi-Analytical Regional Input-Output (IMF-MARIO) Database*. https://iioa.org/conferences/29th/papers/files/4743_IMF-MARIOPAPERIIOA2023.pdf

Guinée, J. B. (2002). *Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards. Eco-Efficiency in Industry and Science Ser: v.7*. Springer Netherlands. https://ebookcentral.proquest.com/lib/kxp/detail.action?docID=6350862

Hammarstrom, J. M., Zientek, M. L., Parks, H. L., & Dicken, C. L. (2019). *Scientific Investigations Report*. U.S. Geological Survey Global Copper Mineral Resource Assessment Team. https://doi.org/10.3133/sir20185160

Hertwich, E. G. (2005). Life cycle approaches to sustainable consumption: A critical review. *Environmental Science & Technology*, *39*(13), 4673–4684. https://doi.org/10.1021/es0497375

Hertwich, E. G. (2021). Increased carbon footprint of materials production driven by rise in investments. *Nature Geoscience*, *14*(3), 151–155. https://doi.org/10.1038/s41561-021-00690-8

ICSG. (2024). *The World Copper Factbook 2023*. https://icsg.org/copper-factbook/

IEA. (2022a). *The Role of Critical Minerals in Clean Energy Transitions* (World Energy Outlook Special Report). https://iea.blob.core.windows.net/assets/ffd2a83b-8c30-4e9d-980a-52b6d9a86fdc/TheRoleofCriticalMineralsinCleanEnergyTransitions.pdf

IEA. (2022b). *The Role of Critical Minerals in Clean Energy Transitions: Revised version, March 2022*. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

ISO (2006, July 1). *Environmental management — Life cycle assessment — Principles and framework* (International Standard ISO 14040).

Jasansky, S., Lieber, M., Giljum, S., & Maus, V. (2022). *Open database on global coal and metal mine production*. https://doi.org/10.5281/ZENODO.7369478

Liu, L., Zhang, L., Jiang, S., Yuan, Z., & Chen, J. (2023). Global copper cycles in the anthroposphere since the 1960s. *Resources, Conservation and Recycling*, *199*, 107294. https://doi.org/10.1016/j.resconrec.2023.107294

M. Lenzen, A. Geschke, J. West, J. Fry, A. Malik, S. Giljum, L.M.i. Canals, P. Piñero, S. Lutter, T. Wiedmann, M. Li, M. Sevenster, J. Potočnik, I. Teixeira, M.V. Voore, K. Nansai, & H. Schandl (2023). GLORIA MRIO. https://ielab.info/resources/gloria

Maus, V., Giljum, S., Gutschlhofer, J., Da Silva, D. M., Probst, M., Gass, S. L. B., Luckeneder, S., Lieber, M., & McCallum, I. (2020). A global-scale data set of mining areas. *Scientific Data*, *7*(1), 289. https://doi.org/10.1038/s41597-020-00624-w

Maus, V., & Werner, T. T. (2024). Impacts for half of the world's mining areas are undocumented. *Nature*, *625*(7993), 26–29. https://doi.org/10.1038/d41586-023-04090-3

Mehta, N., Cunningham, E., Doherty, M., Sainsbury, P., Bolaji, I., Firoozi-Nejad, B., & Smyth, B. M. (2022). Using regional material flow analysis and geospatial mapping to support the transition to a circular economy for plastics. *Resources, Conservation and Recycling*, *179*, 106085. https://doi.org/10.1016/j.resconrec.2021.106085

Merciai, S., & Schmidt, J. (2018). Methodology for the Construction of Global Multi-Regional Hybrid Supply and Use Tables for the EXIOBASE v3 Database. *Journal of Industrial Ecology*, *22*(3), 516–531. https://doi.org/10.1111/jiec.12713

Miller, T. R., Berrill, P., Wolfram, P., Wang, R., Kim, Y., Zheng, X., & Hertwich, E. G. (2019). Method for endogenizing capital in the United States Environmentally-Extended Input-Output model. *Journal of Industrial Ecology*, *23*(6), 1410–1424. https://doi.org/10.1111/jiec.12931

Nakamura, S. (2023a). Environmentally Extended Input-Output Analysis (EEIO) and Hybrid LCA. In S. Nakamura (Ed.), *A Practical Guide to Industrial Ecology by Input-Output Analysis* (pp. 145–232). Springer International Publishing. https://doi.org/10.1007/978-3-031-43684-0_5

Nakamura, S. (Ed.). (2023b). *A Practical Guide to Industrial Ecology by Input-Output Analysis*. Springer International Publishing. https://doi.org/10.1007/978-3-031-43684-0

Netbeheer Nederland. (2021). *Summary The Energy System of the Future 2030-2050 Integral Infrastructure Survey April 2021*. https://www.netbeheernederland.nlpublicaties-en-codes/publicaties

Nijnens, J., Behrens, P., Kraan, O., Sprecher, B., & Kleijn, R. (2023). Energy transition will require substantially less mining than the current fossil system. *Joule*. Advance online publication. https://doi.org/10.1016/j.joule.2023.10.005

Northey, S., Mohr, S., Mudd, G. M [G. M.], Weng, Z., & Giurco, D [D.] (2014). Modelling future copper ore grade decline based on a detailed assessment of copper resources and mining. *Resources, Conservation and Recycling*, *83*, 190–201. https://doi.org/10.1016/j.resconrec.2013.10.005

Northey, S. A., Madrid López, C., Haque, N., Mudd, G. M [Gavin M.], & Yellishetty, M. (2018). Production weighted water use impact characterisation factors for the global mining industry. *Journal of Cleaner Production*, *184*, 788–797. https://doi.org/10.1016/j.jclepro.2018.02.307

Northey, S. A., Mudd, G. M [Gavin M.], Werner, T. T., Haque, N., & Yellishetty, M. (2019). Sustainable water management and improved corporate reporting in mining. *Water Resources and Industry*, *21*, 100104. https://doi.org/10.1016/j.wri.2018.100104

OECD. (2023, November 27). *OECD Inter-Country Input-Output (ICIO) Tables - OECD*. https://www.oecd.org/industry/ind/inter-country-input-output-tables.htm

PBL. (2010). *About PBL*. https://www.pbl.nl/en/about-pbl

Priester, M., Ericsson, M., Dolega, P., & Löf, O. (2019). Mineral grades: an important indicator for environmental impact of mineral exploitation. *Mineral Economics*, *32*(1), 49–73. https://doi.org/10.1007/s13563-018-00168-x

pwc. (2024, February 1). *North Sea powerhouse: TenneT expands grid connectivity in Europe*. https://pwc.ft.com/article/tennet-expands-grid-connectivity-europe?moreFrom=true

Rasul, K., & Hertwich, E. G. (2023). Decomposition Analysis of the Carbon Footprint of Primary Metals. *Environmental Science & Technology*, *57*(19), 7391–7400. https://doi.org/10.1021/acs.est.2c05857

Södersten, C.-J. H., & Lenzen, M. (2020). A supply-use approach to capital endogenization in input–output analysis. *Economic Systems Research*, *32*(4), 451–475. https://doi.org/10.1080/09535314.2020.1784852

Sonter, L. J., Maron, M., Bull, J. W., Giljum, S., Luckeneder, S., Maus, V., McDonald-Madden, E., Northey, S. A., Sánchez, L. E., Valenta, R., Visconti, P., Werner, T. T., &

Watson, J. E. M. (2023). How to fuel an energy transition with ecologically responsible mining. *Proceedings of the National Academy of Sciences of the United States of America*, *120*(35), e2307006120. https://doi.org/10.1073/pnas.2307006120

Stadler, K., Wood, R., Bulavskaya, T., Södersten, C.-J., Simas, M., Schmidt, S., Usubiaga, A., Acosta-Fernández, J., Kuenen, J., Bruckner, M., Giljum, S., Lutter, S., Merciai, S., Schmidt, J. H., Theurl, M. C., Plutzar, C., Kastner, T., Eisenmenger, N., Erb, K.-H., . . . Tukker, A. (2021). *EXIOBASE 3*. https://doi.org/10.5281/ZENODO.5589597

Stadler, K., Wood, R., Bulavskaya, T., Södersten, C.-J., Simas, M., Schmidt, S., Usubiaga, A., Acosta-Fernández, J., Kuenen, J., Bruckner, M., Giljum, S., Lutter, S., Merciai, S., Schmidt, J. H., Theurl, M. C., Plutzar, C., Kastner, T., Eisenmenger, N., Erb, K.-H., . . . Tukker, A. (2018). EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables. *Journal of Industrial Ecology*, *22*(3), 502–515. https://doi.org/10.1111/jiec.12715

Statline. (2023a, June 2). *Renewable energy; consumption by energy source, technology and application*. https://opendata.cbs.nl/statline/#/CBS/en/dataset/84917ENG/table?dl=96D1E

Statline. (2023b, June 15). *Electricity and heat; production and input by energy commodity*. https://opendata.cbs.nl/statline/#/CBS/en/dataset/80030eng/table?dl=96D25

Steubing, B., Koning, A. de, Merciai, S., & Tukker, A. (2022). How do carbon footprints from LCA and EEIOA databases compare? A comparison of ecoinvent and EXIOBASE. *Journal of Industrial Ecology*, *26*(4), 1406–1422. https://doi.org/10.1111/jiec.13271

Superfund Research Centre. (2020). *Copper Mining and Processing: Processing Copper Ores*. https://superfund.arizona.edu/resources/learning-modules-english/copper-mining-and-processing/processing-copper-ores

Tang, L., & Werner, T. T. (2023). Global mining footprint mapped from high-resolution satellite imagery. *Communications Earth & Environment*, *4*(1). https://doi.org/10.1038/s43247-023-00805-6

UNEP. (2016). *Promoting global consensus on Life Cycle Impact Assessment Indicators*. https://www.lifecycleinitiative.org/activities/life-cycle-assessment-data-and-methods/global-guidance-for-life-cycle-impact-assessment-indicators-and-methods-glam/lcia-cf/

United Nations. (2024). *UN Comtrade*. https://comtradeplus.un.org/

USGS. (2023a). *Copper Statistics and Information*. https://www.usgs.gov/centers/national-minerals-information-center/copper-statistics-and-information

USGS. (2023b). *Mineral commodity summaries 2023*. https://pubs.usgs.gov/periodicals/mcs2023/mcs2023.pdf https://doi.org/10.3133/mcs2023

USGS. (2023c). *Survey Methods for Nonfuel Minerals 2016*. https://pubs.usgs.gov/myb/vol1/2016/myb1-2016-survey-methods.pdf

van Exter, P., Bouwens, J., Bosch, S., Favrin, S., Zeljlmans, S., Sprecher, B., van der Vlies, D., Wirtz, A., & van Oorschot, J. (2021). *Towards a circular energy transition: Exploring solutions to mitigate surging demand for critical metals in the energy transition*. https://www.metabolic.nl/publications/towards-a-circular-energy-transition/

van Oorschot, J., Sprecher, B., Roelofs, B., van der Horst, J., & van der Voet, E. (2022). Towards a low-carbon and circular economy: Scenarios for metal stocks and flows in the Dutch electricity system. *Resources, Conservation and Recycling*, *178*, 106105. https://doi.org/10.1016/j.resconrec.2021.106105

Watari, T., McLellan, B. C., Giurco, D [Damien], Dominish, E., Yamasue, E., & Nansai, K. (2019). Total material requirement for the global energy transition to 2050: A focus on transport and electricity. *Resources, Conservation and Recycling*, *148*, 91–103. https://doi.org/10.1016/j.resconrec.2019.05.015

Wieland, H., Lenzen, M., Geschke, A., Fry, J., Wiedenhofer, D., Eisenmenger, N., Schenk, J., & Giljum, S. (2022). The PIOLab: Building global physical input–output tables in a virtual laboratory. *Journal of Industrial Ecology*, *26*(3), 683–703. https://doi.org/10.1111/jiec.13215

The World Bank Group (Ed.). (2024). *World Bank Country and Lending Groups*. https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups

WULCA. (2023, August 24). *Download AWARE Factors - WULCA*. https://wulca-waterlca.org/aware/download-aware-factors/

Yang, Z [Zhaoyue], Yang, Z [Zhendong], Yang, S., Liu, Z [Ziliang], Liu, Z [Zhenghua], Liu, Y., Drewniak, L., Jiang, C., Li, Q., Li, W., & Yin, H. (2022). Life cycle assessment and cost analysis for copper hydrometallurgy industry in China. *Journal of Environmental Management*, *309*, 114689. https://doi.org/10.1016/j.jenvman.2022.114689

Appendices

Appendix 1: Documentation of MFA Coding Steps

The 'user input' at the top of the code allows for the user to adjust thresholds, the share of copper in the Netherlands used for renewables, which of the many Sankey diagrams to display, and in certain stylistic choices, such as grouping low- and middle-income countries.

1. **Filter USGS data:** In usgs_data pull the data from USGS and calculate the mining_share, which is the percentage that a country's mining makes up of the absolute total of the mining across all countries. Repeat this for smelting_share and refining_share. A threshold is applied to filter the data for relevance with countries below the threshold aggregated into 'Other', which is added to node_size.
2. **USGS domestic flows calculation:** Calculate the domestic flows (from a country to its own country, meaning this is the amount of tonnes which do not leave the country). Take the minimum in tonnes of USGS data for mining and smelting (for each country), and also for smelting and refining (for each country). Put these two columns into a dataframe called flows_domestic. The format of the dataframe is then adjusted to match the Plotly required format.
3. **USGS foreign flows calculation:** Find the necessary foreign flows (from a country to another country). The missing balancing items which cause differences between the USGS stages are calculated here. Mining from USGS is subtracted from smelting from USGS to find the required missing balance for mining to smelting. Smelting from USGS is subtracted from refining from USGS to find the required missing balance for smelting to refining.
4. **Filter BACI trade data:** Import the BACI data into trade_data which uses HS codes 2603 and 2620 for the mining stages, and 7401 and 7402 for the smelting stages. Further filter the trade dataset to only account for countries which are listed as both an importer and exporter, which covers most of total copper flow volume.
5. **Distribute the missing balancing items as shares of imports and exports to each stage and country:** Calculate the shares each country imports and exports from mining to smelting, and from smelting to refining. This portion of the code calculates the percentage share of total imports of each stage which each country interaction makes up, and also the percentage share of total exports of each stage which each country interaction makes up.
6. **Calculate the correct import and export allocations based on if imports or exports are missing:** Add flows to a dataframe called flows_foreign_pos which fulfil cases a or b below, and to flows_foreign_neg which fulfil cases c or d below. Add these correct allocation amounts to copper_trade_allocated.
    a. flows_foreign_pos: More imports of mining are necessary because there is not enough in smelting (there is a positive value).
    b. flows_foreign_pos: More imports of smelting are necessary because there is not enough in refining (there is a positive value).
    c. flows_foreign_neg: More exports of mining are necessary because there is too much in smelting (there is a negative value).
    d. flows_foreign_neg: More exports of smelting are necessary because there is too much in refining (there is a negative value).
7. **Allocate the imports and exports based on the corrected values:** Multiply the imports to allocate by the corrected share of imports for each stage and multiply the exports to allocate by the corrected share of exports for each stage.
8. **Allocate missing values to black boxes:** Calculate the volume of flows which must end up in black boxes because these are not part of the process data, not imported, and

not exported. Create dataframes for flows that do not need black boxes (copper_trade_no_black_boxes) and dataframes for flows that do need black boxes (copper_trade_black_boxes).

9. **Analyse special cases for some countries with stages that must be allocated, but which have no trade data:** Create a dataframe (countries_stages) where countries are missing specific stages. For example, there are certain USGS stages that must be allocated (e.g., refining) for a specific country (e.g., DRC), but for which there are no flows in the trade data. The remainder of flows calculated from USGS are allocated to another dataframe.
10. **Integrate the amount of copper used for the energy transition in the Netherlands:** See the 'Dutch renewable sector energy calculation' in the 'Data' section below for a detailed explanation of the sources of the values. These were applied to complete the 'Use' stage of the Sankey and scale to the Netherlands.
11. **Sankey:** Build the Sankey using plot.ly.

Appendix 2: Additional information for LCA impact quantification

Table 8 shows the ecoinvent processes used to calculate the footprint of the stages.

Table 8: Used ecoinvent processes.

Stage	ecoinvent process	Region	Functional flow
Mining	market for copper concentrate, sulfide ore	Global	1 kg copper concentrate, sulfide ore
Mining	copper mine operation and beneficiation, sulfide ore	Australia	1 kg copper concentrate, sulfide ore
Mining	copper mine operation and beneficiation, sulfide ore	Canada	1 kg copper concentrate, sulfide ore
Mining	copper mine operation and beneficiation, sulfide ore	Chile	1 kg copper concentrate, sulfide ore
Mining	copper mine operation and beneficiation, sulfide ore	China	1 kg copper concentrate, sulfide ore
Mining	copper mine operation and beneficiation, sulfide ore	Indonesia	1 kg copper concentrate, sulfide ore
Mining	copper mine operation and beneficiation, sulfide ore	Kazakhstan	1 kg copper concentrate, sulfide ore
Mining	copper mine operation and beneficiation, sulfide ore	RoW	1 kg copper concentrate, sulfide ore
Mining	copper mine operation and beneficiation, sulfide ore	Russia	1 kg copper concentrate, sulfide ore
Mining	copper mine operation and beneficiation, sulfide ore	USA	1 kg copper concentrate, sulfide ore
Mining	copper mine operation and beneficiation, sulfide ore	Zambia	1 kg copper concentrate, sulfide ore
Smelting	smelting of copper concentrate, sulfide ore	Global	1 kg copper, anode
Smelting	smelting of copper concentrate, sulfide ore	Chile	1 kg copper, anode
Smelting	smelting of copper concentrate, sulfide ore	China	1 kg copper, anode
Smelting	smelting of copper concentrate, sulfide ore	India	1 kg copper, anode
Smelting	smelting of copper concentrate, sulfide ore	Japan	1 kg copper, anode
Smelting	smelting of copper concentrate, sulfide ore	RoW	1 kg copper, anode
Smelting	smelting of copper concentrate, sulfide ore	Russia	1 kg copper, anode
Refining	electrorefining of copper, anode	Global	1 kg copper, cathode

Table 9 shows the stage-specific impacts per output of copper that were derived from the available ecoinvent processes. Important to keep in mind is that the impacts from previous stages were subtracted to isolate the footprint of the specific stage and that the impact category indicator results were scaled to one kg of pure copper to correspond to the MFA. Thus, they do not represent the cradle-to-gate results for the ecoinvent processes alone. According to the ecoinvent documentation of the processes, the copper content of the functional unit of mining processes is 29.63% and after smelting processes 99.75%, resulting in scaling factors of 3.375

and 1.003 respectively. The results for all previous processes that were subtracted cannot be shown here due to licensing reasons.

Table 9: Impacts per output of copper in each stage.

Stage	Region	Climate change ($kgCO_2e$ per kg copper)	Water depletion (m^3 per kg copper)	Natural land transformation (m^2 per kg copper)
Mining	Australia	5.06244	0.16504	0.00699
Mining	Canada	4.04995	0.33446	0.01448
Mining	Chile	3.98245	0.18056	0.00773
Mining	China	3.13871	0.09450	0.00395
Mining	Indonesia	5.50118	0.15660	0.00685
Mining	Kazakhstan	3.00034	0.06142	0.00270
Mining	RoW	3.77995	0.15896	0.00719
Mining	Russia	3.81370	0.14377	0.00641
Mining	USA	4.28620	0.24502	0.01043
Mining	Zambia	1.90348	0.09855	0.00422
Smelting	Chile	1.39348	0.00702	0.00018
Smelting	China	1.83459	0.01003	0.00017
Smelting	India	2.38596	0.01103	0.00017
Smelting	Japan	1.76441	0.00902	0.00043
Smelting	RoW	1.56391	0.00802	0.00028
Smelting	Russia	2.09524	0.00902	0.00032
Refining	Global	1.90348	0.09855	0.00422

Table 10 shows the regional averages of impacts per kg of copper output used for countries without a corresponding ecoinvent process. Important to keep in mind is that these values are only applied for countries without a specific corresponding process in ecoinvent. Furthermore, they are based on a low number of ecoinvent processes and can thus not be considered fully representative of the respective region.

Table 10: Regional averages for impacts per output of copper in each stage.

Region	Climate change (kgCO$_2$e per kg copper)			Water depletion (m^3 per kg copper)			Natural land transformation (m^2 per kg copper)		
	Mining	Smelting	Refining	Mining	Smelting	Refining	Mining	Smelting	Refining
Global	3.77995	1.56391	2.33000	0.15896	0.00802	0.00800	0.00719	0.00028	0.00052
East Asia & Pacific	4.56744	1.79950	2.33000	0.13871	0.00952	0.00800	0.00593	0.00030	0.00052
Europe & Central Asia	3.40702	2.09524	2.33000	0.10260	0.00902	0.00800	0.00455	0.00032	0.00052
Latin America & Caribbean	3.98245	1.39348	2.33000	0.18056	0.00702	0.00800	0.00773	0.00018	0.00052
Middle East & North Africa	3.77995	1.56391	2.33000	0.15896	0.00802	0.00800	0.00719	0.00028	0.00052
North America	4.16807	1.56391	2.33000	0.28974	0.00802	0.00800	0.01245	0.00028	0.00052
South Asia	3.77995	2.38596	2.33000	0.15896	0.01103	0.00800	0.00719	0.00017	0.00052
Sub-Saharan Africa	1.90348	1.56391	2.33000	0.09855	0.00802	0.00800	0.00422	0.00028	0.00052
Global	3.77995	1.56391	2.33000	0.15896	0.00802	0.00800	0.00719	0.00028	0.00052
East Asia & Pacific	4.56744	1.79950	2.33000	0.13871	0.00952	0.00800	0.00593	0.00030	0.00052
Europe & Central Asia	3.40702	2.09524	2.33000	0.10260	0.00902	0.00800	0.00455	0.00032	0.00052

The following figures illustrate the differences between the regional averages.

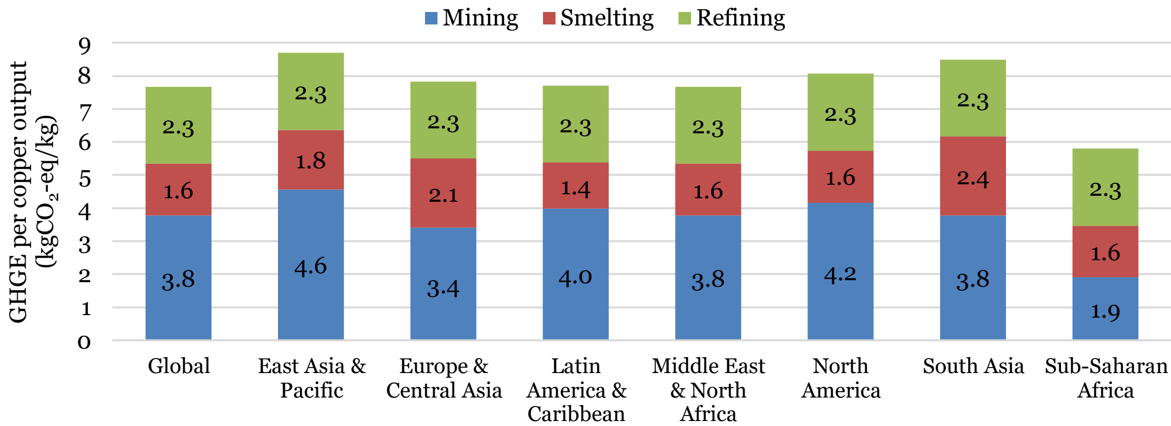

Figure 11: Regional averages for GHGE per output of copper in each stage.

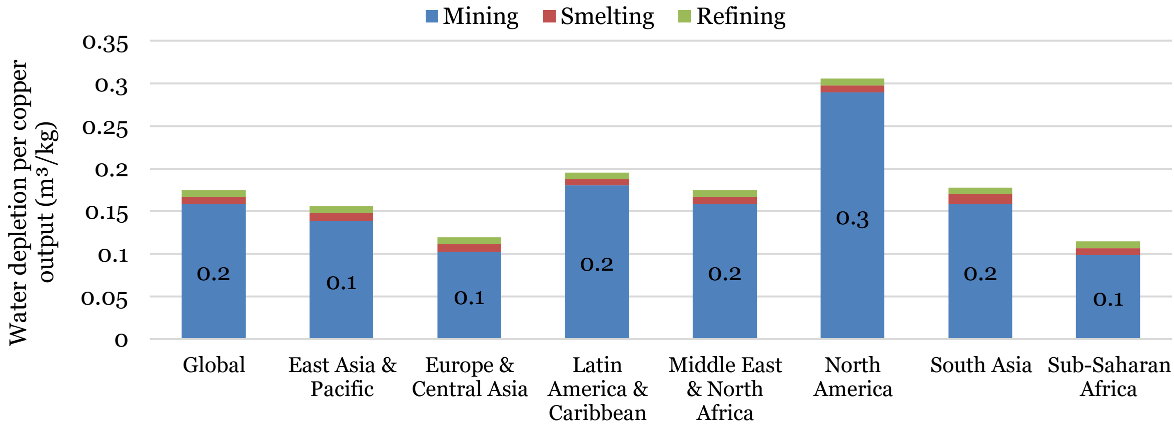

Figure 12: Regional averages for water depletion per output of copper in each stage.

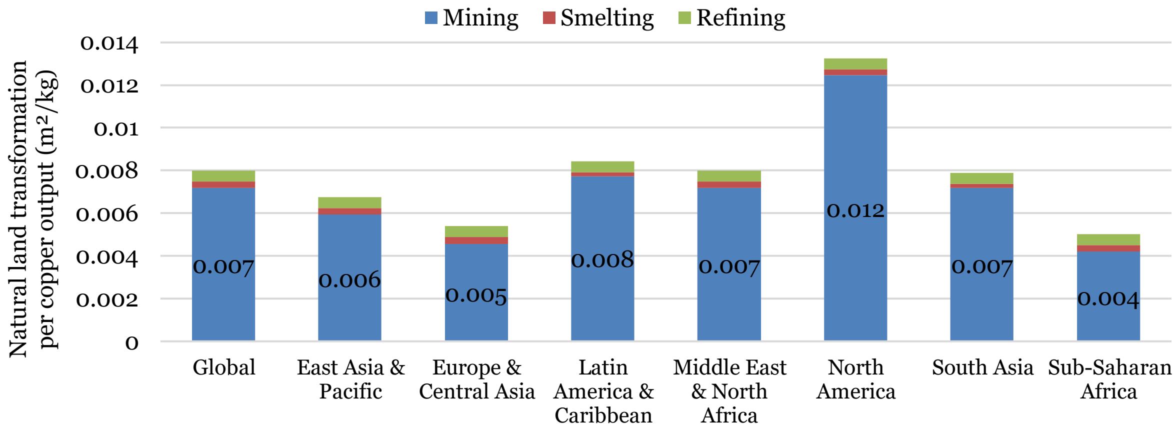

Figure 13: Regional averages for natural land transformation per output of copper in each stage.

Appendix 3: Additional results of LCA impact quantification

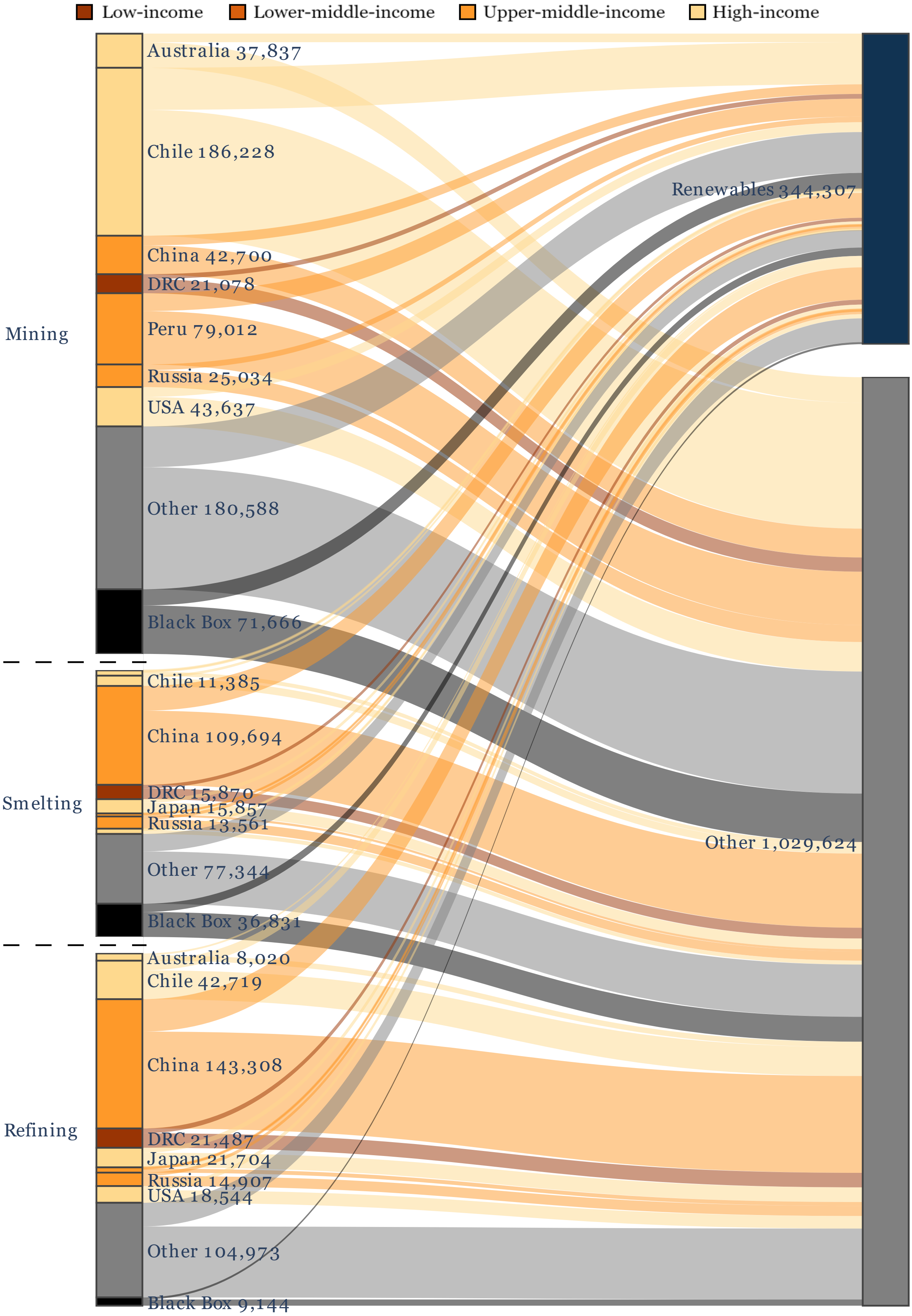

Figure 14: Contribution of stages to the GHGE allocated to the Dutch consumption of copper in 2019, in tCO_2e, from the LCA approach. Due to overlaps, not all labels are shown.

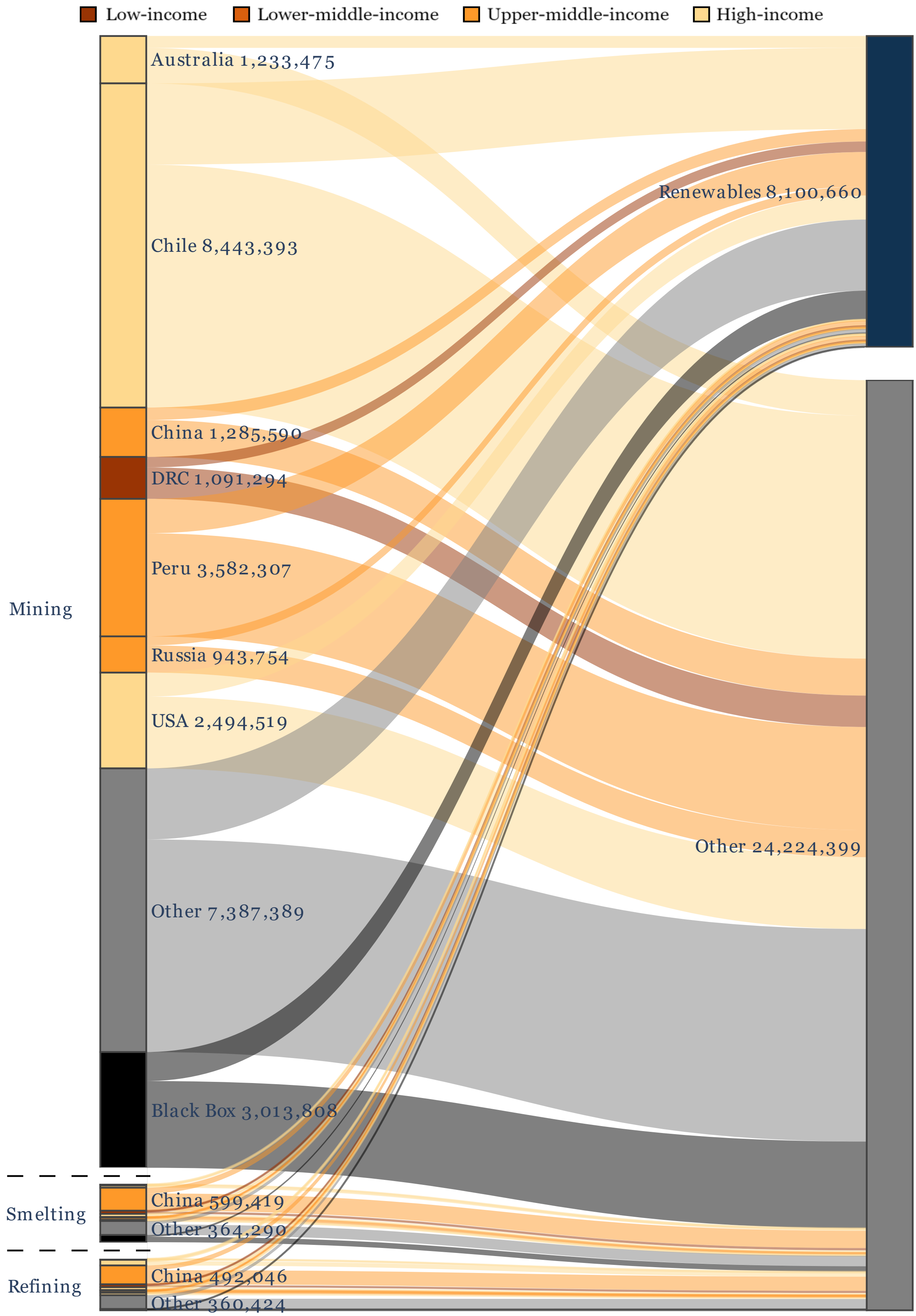

Figure 15: Contribution of stages to the water depletion allocated to the Dutch consumption of copper in 2019, in m^3 of water, from the LCA approach. Due to overlaps, not all labels are shown.

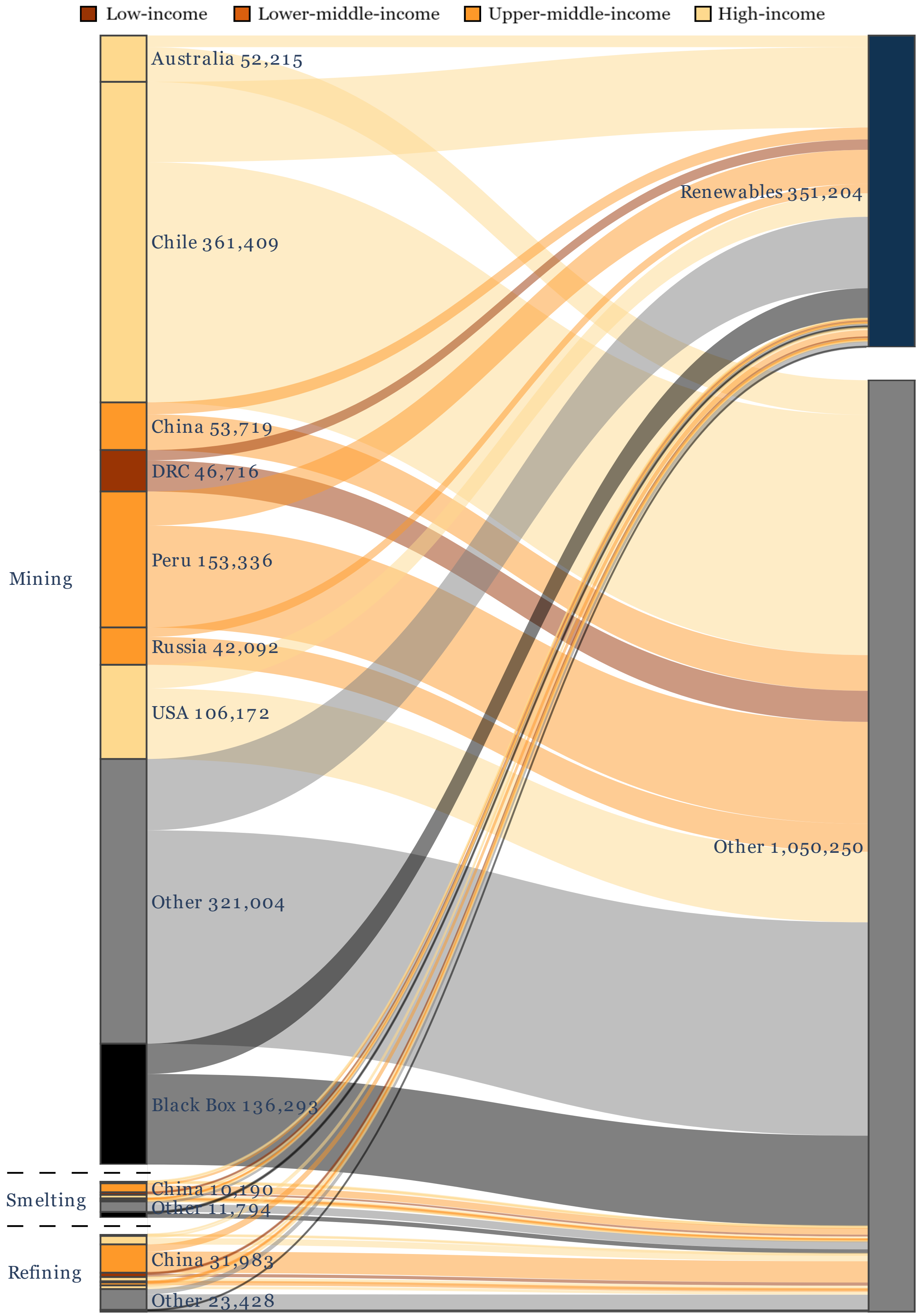

Figure 16: Contribution of stages to the natural land transformation allocated to the Dutch consumption of copper in 2019, in m², from the LCA approach. Due to overlaps, not all labels are shown.

Appendix 4: Correspondence diagram

Figure 17 illustrates the correspondence between the LCA and EEIOA Sankeys using a simplified example. In this scenario, three countries are examined with a limited number of interactions. For simplicity, upstream impacts are excluded, focusing solely on direct impacts. The direct impact from the mining stage is visually distinguished in yellow, while the direct impact from the processing stage is depicted in blue. The representations are equivalent, albeit observed from different perspectives. The direct impact, shown individually for each stage in the LCA Sankey by enlarging the column size, is projected onto two separate columns in the EEIOA. The first column indicates the sector where the emission occurs, and the second denotes the region where the impact is situated.

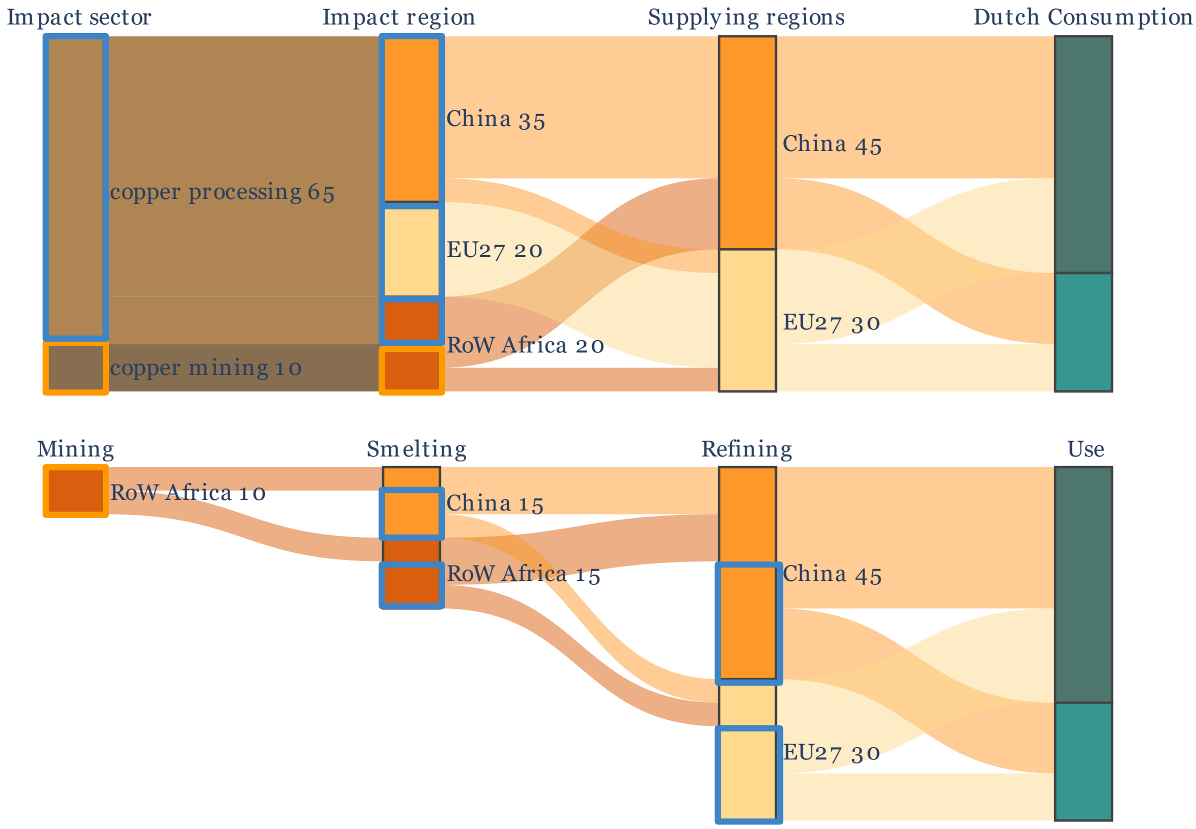

Figure 17: Correspondence diagram between the LCA and EEIOA Sankey diagrams. Random data for illustrative purposes. The orange boxes refer to mining impacts, while the blue boxes represent processing impacts (smelting and refining).