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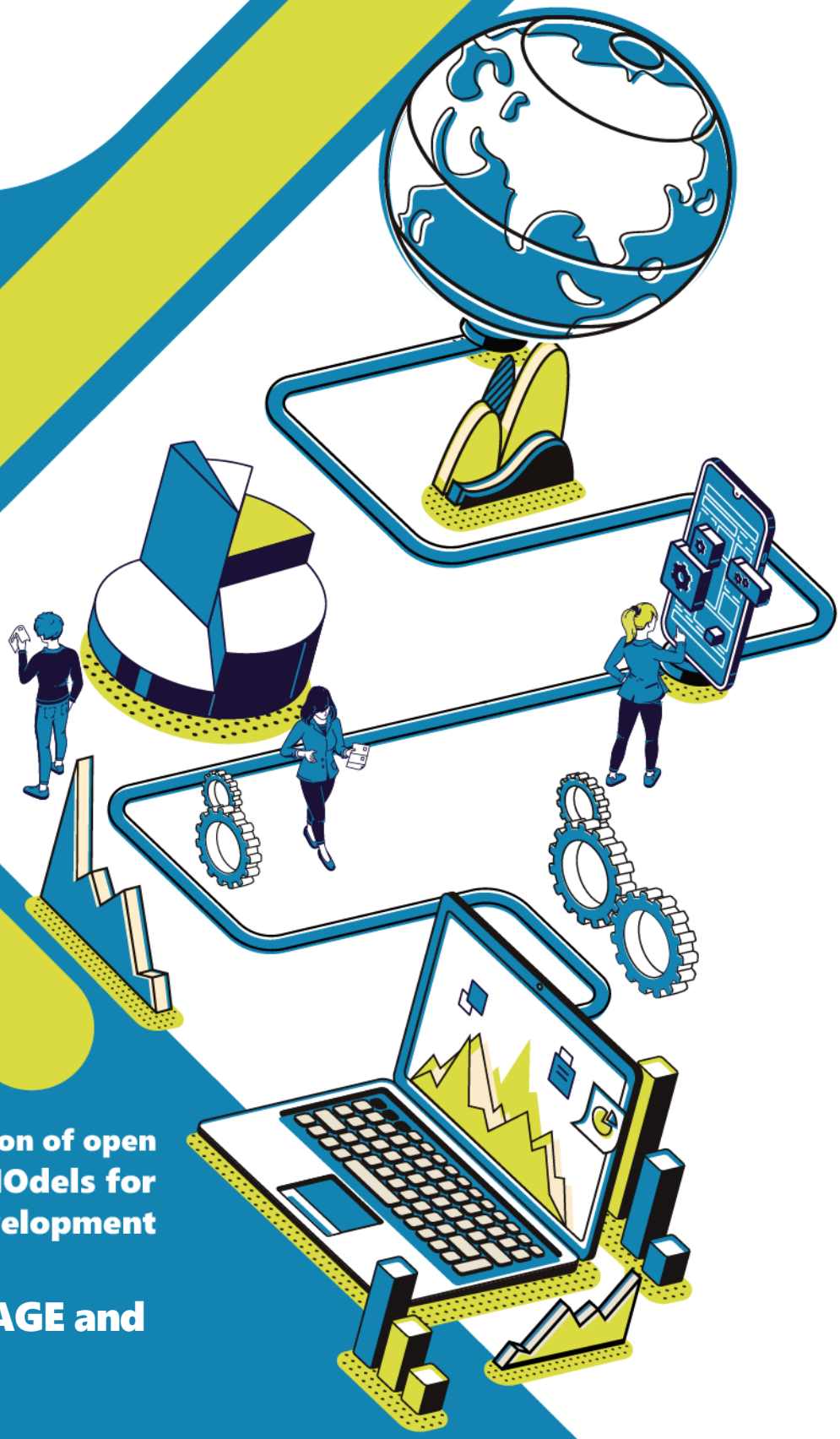

Delivering the next generation of open Integrated Assessment MOdels for Net-zero, sustainable Development

D4.1 – Expanded ENGAGE and circularity in IAMs

WP4 – Integrate & Expand

29/06/2025

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EC Summary Requirements

1. Changes with respect to the DoA

No changes.

2. Dissemination and uptake

The deliverable is intended for policymakers and the broader stakeholder community of DIAMOND focusing on industrial and circular economy policies, including modelling approaches. Notably, the deliverable can be of particular interest to general equilibrium and energy system modellers, to get informed on the approach used to enhance circularity representation in large-scale climate-economy models.

3. Short summary of results

Energy-intensive industries such as steel, aluminium, and cement are considered hard-to-abate sectors and are therefore central both to the economy and to decarbonisation efforts. These sectors are usually associated with circular economy strategies, such as material efficiency, recycling, and extending product lifetimes, which could offer additional mitigation potential. However, the technical complexity of production processes and the intricate value chain changes required have often led these factors to be represented through simplifications in large-scale integrated assessment models, if at all.

To address these gaps, we build upon the Environmental Global Applied General Equilibrium (ENGAGE) model, a dynamic computable general equilibrium (CGE) framework designed to analyse the economic, environmental, and sectoral impacts of policies related to resource efficiency and the circular economy. We first enhance the ENGAGE model by improving the representation of the aluminium and steel sectors, increasing the level of detail in production processes and raw materials, and then by adding the cement sector, with the aim of allowing an explicit representation of the circular economy in these key industrial sectors. Then, we present a structured process for a robust link between OMNIA and ENGAGE that aims to harness the strengths of both models, providing both a detailed representation of industrial technologies and their energy consumption, as well as material flows needed for assessing circular economy policies. Finally, we identify entry points for transferring information and results from the OMNIA-ENGAGE model to other IAMs, such as GCAM and OPEN-PROM, and outline the process for running dedicated model intercomparison scenarios during the project.

4. Evidence of accomplishment

This report.

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Preface

DIAMOND will update, upgrade, and fully open six Integrated Assessment Models (IAMs) that are emblematic in scientific and policy processes, improving their sectoral and technological detail, spatiotemporal resolution, and geographic granularity. It will further enhance modelling capacity to assess the feasibility and desirability of Paris-compliant mitigation pathways, their interplay with adaptation, circular economy, and other SDGs, their distributional and equity effects, and their resilience to extremes, as well as robust risk management and investment strategies. This will be done via integration of tools and insights from psychology, finance research, behavioural and labour economics, operational research, and physical science. The project will develop a transdisciplinary scientific approach to legitimise the implementation process and cocreate research questions that stretch the frontiers of climate science, as well as establish vibrant communities of practice to transparently open model enhancements and to develop capacities, thereby lowering the entrance barriers to the established IAM community.

ICCS	INSTITUTE OF COMMUNICATIONS AND COMPUTER SYSTEMS	EL
BC3	ASOCIACION BC3 BASQUE CENTRE FOR CLIMATE CHANGE - KLIMA ALDAKETA IKERGAI	ES
CESAR	KRATENA KURT	AT
CICERO	CICERO SENTER FOR KLIMAFORSKNING	NO
CYI	THE CYPRUS INSTITUTE	CY
E4SMA	ENERGY ENGINEERING ECONOMIC ENVIRONMENT SYSTEMS MODELING AND ANALYSIS SRL	IT
HOLISTIC	HOLISTIC IKE	EL
COMILLAS	UNIVERSIDAD PONTIFICIA COMILLAS	ES
ISINNOVA	ISTITUTO DI STUDI PER L'INTEGRAZIONE DEI SISTEMI (I.S.I.S) - SOCIETA'COOPERATIVA	IT
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Executive Summary

Energy-intensive industries such as steel, aluminium, and cement are considered hard-to-abate sectors and are therefore central both to the economy and to decarbonisation efforts. These sectors are usually associated with circular economy strategies, such as material efficiency, recycling, and extending product lifetimes, which could offer additional mitigation potential. However, the technical complexity of production processes and the intricate value chain changes required have often led these factors to be represented through simplifications in large-scale integrated assessment models, if at all.

In this report, we outline the enhancement of the existing Environmental Global Applied General Equilibrium (ENGAGE) model, a computable general equilibrium (CGE) framework, by enhancing the representation of steel and aluminium, and adding the cement sector. These updates allow for a more explicit treatment of material flows, energy use, and circular economy options within industrial processes, and hence enable improved modelling of circularity in decarbonisation pathways.

Notably, in the steel sector, we disaggregate iron ore mining and split primary iron production into blast furnace (BF) and direct reduced iron (DRI) production routes, which allows modelling of the trade of pig iron, as a product of BF, and sponge iron, as the product of DRI, in scenarios where primary iron production could be geographically decoupled from final steel production. Steel scrap is also divided into high-quality (HQS) and low-quality (LQS). For aluminium, the mining of bauxite, the raw material for primary aluminium production has been explicitly modelled, and the production of aluminium has been subdivided into four sectors representing the production of alumina from bauxite, the production of primary aluminium, secondary aluminium production and the production of aluminium scrap (RAP). The cement sector is added in ENGAGE using the GTAP-Circular Economy database, including limestone mining, clinker production, and cement grinding and blending, with clinker production being further separated using physical production data converted into monetary terms.

On top of these structural improvements, we develop a framework and a stylised template for a robust linkage between ENGAGE and OMNIA, one of the DIAMOND project's six global IAMs, featuring an improved regional disaggregation of the EU and rich representation of the global energy system. In the iterative process established, OMNIA defines energy system configurations and emission pathways, which are parsed into ENGAGE to assess economy-wide equilibrium impacts. ENGAGE then returns to OMNIA the adjusted demand levels for materials and sectoral activity, which are then used by the latter to update energy demand and technology deployment. The feedback loop continues until convergence, typically within five iterations or a predefined threshold. The objective is to harness the strengths of both models, providing a detailed representation of industrial technologies and their energy consumption, as well as material flows needed for assessing circular economy policies. Since the linkages offers the option for either uni- or bi-directional flow of information with convergence in both models (and within multiple iterations), it is more nuanced than a typical model soft link.

We also outline ways for transferring insights from the OMNIA-ENGAGE framework to help improve the representation of circularity performance in other IAMs, like GCAM-Europe and OPEN-PROM in DIAMOND. For steel, ENGAGE can provide results and feed them into the other IAMs as assumptions on scrap availability, costs, and technology shares, while in aluminium and cement, it could influence adjustments to production shares and coefficients to reflect less reliance on primary materials. On the demand side, ENGAGE-OMNIA results could allow models to better capture how circular economy strategies affect material demand by adjusting elasticities or explicitly modelling demand reductions through improved resource efficiency. Based on these, we finally discuss how the improved representation of circularity performance in these models can drive intercomparison exercises focusing on capturing circular economy dynamics in key industrial sectors.

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Contents

1 Introduction 1
2 Description of the new ENGAGE circular economy 3
2.1 Structure of the steel sector 4
2.1.1 Enhancements in the steel sector 4
2.1.2 Geographical disaggregation 9
2.1.3 Results of steel sector disaggregation 9
2.2 Structure of the aluminium sector 12
2.2.1 Enhancements in the aluminium sector 12
2.2.2 Geographical disaggregation 14
2.2.3 Results of aluminium sector disaggregation 15
2.3 Structure of the newly added Cement sector 16
3 Linkage with OMNIA 18
3.1 Overview of the OMNIA model 18
3.2 Representation of key industry sectors in OMNIA 18
3.2.1 Steel 19
3.2.2 Aluminium 21
3.2.3 Cement 22
3.3 Conceptual linkage between ENGAGE and OMNIA 23
3.4 Information flows in ENGAGE-OMNIA under example scenarios 25
3.4.1 Reference scenario 25
3.4.2 Policy scenarios 26
4 Route for intercomparison with OPEN-PROM 27
4.1 Summary of the OPEN-PROM model 27
4.1.1 Industry model in OPEN-PROM: general approach 28
4.1.2 Structure of the Iron and Steel Sector in OPEN-PROM 29
4.1.3 Structure of the Aluminium Sector in OPEN-PROM 29
4.1.4 Structure of the Cement Sector in OPEN-PROM 30
4.2 Circular economy representation in OPEN-PROM 31
4.3 Enhanced representation of circular economy in OPEN-PROM 32
5 Route for intercomparison with GCAM-Europe 34
5.1 Summary of GCAM-Europe model 34

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5.1.1 General structure of industry sectors 36
5.1.2 Structure of the iron and steel sector 37
5.1.3 Structure of the aluminium sector 38
5.1.4 Structure of the cement sector 39
5.2 Circular economy representation in GCAM-Europe 40
5.3 Enhanced representation of circular economy in GCAM-Europe 40
6 Towards model inter-comparison 43
7 References 45
8 Appendix 50

Figures

Figure 1. Schematic representation of the value flows in the steel sector. 7

Figure 2. Largest producers of iron ore, pig iron, sponge iron, and primary steel form BOF and EAF in the new disaggregation of ENGAGE. Values are presented in monetary terms (millions of USD/year) and percentage of the total world production. 11

Figure 3. Largest producers of secondary steel and scrap in the new disaggregation of ENGAGE. Values are presented in monetary terms (millions of USD/year) and percentage of the total world production. 12

Figure 4. Schematic representation of the value flows in the aluminium sector 13

Figure 5. Largest producers of Bauxite, Aluminium Scrap, Primary and Secondary Aluminium in the new disaggregation of ENGAGE. Values are presented in monetary terms (millions of USD/year) and as share of total global production (% of annual production) 15

Figure 6. Largest producers of cement and clinker in monetary terms (millions of USD/year) and as share of total global production (% of annual production) 17

Figure 7. Steel sector structure in OMNIA 20

Figure 8. Aluminium sector structure in OMNIA 22

Figure 9. Cement sector structure in OMNIA 23

Figure 10. Diagram of the conceptual linkage and information flow between ENGAGE and OMNIA 24

Figure 11. Regional disaggregation in GCAM-Europe 34

Figure 12. Graphical representation of EEA trade structure 36

Figure 13. Technology representation of the iron and steel sector in GCAM as employed in this study (Speizer et al., 2023) 38

Figure 14. Technology representation of the aluminium sector in GCAM as employed in this study 39

Figure 15. Technology representation of the cement sector in GCAM as employed in this study 40

Figure 16. Summarised representation of steel, aluminium and cement sectors in GCAM-Europe, and projected modifications to link with ENGAGE-OMNIA scenarios 42

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Figure 17. Annual production of iron ore by regions in ENGAGE for the base year 50

Figure 18. Annual representation of production of commodities of the primary steel pathway by regions in ENGAGE for the base year 51

Figure 19. Annual production of commodities of the secondary steel pathway by regions in ENGAGE for the base year 52

Figure 20. ENGAGE's representation of the annual trade flows of primary materials for steel production in the base year 53

Figure 21. ENGAGE's representation of the annual trade flows of primary iron in the base year 54

Figure 22. ENGAGE's representation of annual trade flows of primary steel in the base year 55

Figure 23. ENGAGE's representation of annual trade flows of secondary steel in the base year 56

Figure 24. Annual production of commodities of the aluminium sector by regions in ENGAGE for the base year 57

Figure 25. ENGAGE's representation of annual trade flows of bauxite and aluminium scrap in the base year 58

Figure 26. ENGAGE's representation of annual trade flows of primary and secondary aluminium in the base year 59

Figure 27. Annual production of cement and clinker by regions in ENGAGE for the base year 60

Figure 28. ENGAGE's representation for annual trade flows of cement and clinker in the base year 61

Tables

Table 1. Detail of the 28 OMNIA regions used for the geographic representation in ENGAGE-OMNIA 3

Table 2. Sectoral structure of the updated new ENGAGE model 4

Table 3. Assumptions for the fraction of steel that cannot be produced from end-of-life scrap 6

Table 4. Prices in 2017 USD/ton used to convert physical and monetary data in the steel industry 8

Table 5. Prices for commodities in the aluminium sector in 2017 USD/kg according to UCL's MFA. 13

Table 6. Prices for clinker in 2017 USD/ton from BACI 16

Table 7. Steel production technology costs assumptions 20

Table 8. Steel production technology non-cost assumptions 21

Table 9. Key data sources for the aluminium sector 22

Table 10. Key data sources for the cement sector 23

Table 11. List of model regions in GCAM-Europe 35

Table 12. Summary of links between GCAM-Europe and ENGAGE-OMNIA for different scenarios 42

Table 13. Summary of the main model characteristics and of the proposed linkage. 44

Table 14. Correspondence between ENGAGE steel related sectors and PIOLab activities 50

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1 Introduction

This deliverable aims to demonstrate how combining different modelling approaches can improve the representation of circular economy in integrated assessment models, with a particular focus on energy-intensive industries such as steel, aluminium and cement. In this report, we present a methodology for linking the enhanced global macroeconomic model ENGAGE (referred in this document as new ENGAGE model) with the newly developed global energy systems model, OMNIA (developed under Task 3.7), providing a synergistic framework for assessing how increased circularity can help reduce emissions in energy-intensive industries. We also describe how this modelling framework can be leveraged by the wider IAM (Integrated Assessment Model) community, by usings data, insights, assumptions, and outputs from this enhanced representation to extend the two IAM models participating in the DIAMOND project, OPEN-PROM and GCAM-Europe.

A circular economy is a system which maintains the value of products, materials and resources in the economy for as long as possible and minimises the generation of waste. This means a system where products are reused, repaired, remanufactured or recycled (EUR-Lex, 2025). The primary objective of circular economy is to minimise waste and maximise the efficient use of resources. Unlike the traditional linear economic models, which follows a 'take, make, dispose' approach, the circular economy is regenerative by design. It seeks to extend the life of products, materials, and resources by keeping them in use for as long as possible.

The circular economy can play a crucial role in decarbonisation pathways by reducing greenhouse gas (GHG) emissions across the entire lifecycle of products and services, especially by reducing the needs for producing and processing energy-intensive materials. It transforms how goods are designed, produced, used, and disposed. By prioritising circular design principles, such as durability, modularity, and recyclability, the demand for energy-intensive raw materials may be reduced. In the production phase, the use of recycled or reusable inputs significantly lowers energy consumption compared to virgin material processing. Moreover, circular business models such as product-as-a-service and shared consumption, further reduce emissions by decreasing the volume of goods produced and distributed. During the use phase, products designed for repair extend their functional lifespan, reducing the frequency of replacement and associated emissions. At the end-of-life stage, strategies, such as remanufacturing and recycling, reduce emissions from waste decomposition and incineration processes.

While the extent of circular economy actions is increasingly recognised for their potential to support decarbonisation, most economic and energy system models face significant limitations in representing these strategies (Yang et al., 2023). These models are typically structured around linear economic assumptions, focusing on production, consumption and energy flows, and often lack the granularity to capture material loops, product life extension, and non-market-based exchanges such as reuse, repair, and sharing. Moreover, circular economy interventions such as product-as-a-service models, modular design, and remanufacturing are difficult to quantify within traditional modelling frameworks.

The ENGAGE and OMNIA models have been developed to represent the recycling of steel and aluminium at the end-of-life, accounting for both secondary production from scrap and primary production from virgin materials and more material-efficient production of cement. While recycling is only one component of the circular economy, its consistent integration into economic and energy models improves the accuracy of emissions projections, enables more realistic assessments of resource

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efficiency scenarios, and deepens the understanding of the circular economy's role in decarbonisation pathways. In the case of cement, the focus is mainly on resource efficiency strategies as recycle and reuse measures are more limited (more details on this are discussed later in the text). Therefore, in this report, references to circular economy primarily encompass recycling and resource efficiency measures.

This report is structured in five main sections:

- Section 2 presents the new ENGAGE circular economy model, detailing the process for expanding its industrial sector representation (steel, aluminium, and cement) and aligning its geographical disaggregation with OMNIA.
- Section 3 describes the robust linkage between ENGAGE and OMNIA. It outlines OMNIA's industrial sector structure, explains how circular economy measures are integrated through the linkage with ENGAGE, and illustrates this with scenario-based examples of information flows between the models.
- Section 4 briefly introduces the OPEN-PROM model and describes its current representation of circular economy elements. It explains how outputs from the ENGAGE-OMNIA linkage can enhance this representation.
- Section 5 briefly presents the GCAM-Europe model and follows a similar structure to Section 4, outlining how it can incorporate circular economy insights from the ENGAGE-OMNIA framework to improve sectoral modelling.
- Section 6 synthesises the key features of the three IAMs —OMNIA, OPEN-PROM and GCAM-Europe— and the benefits of integrating ENGAGE data and insights on CE strategies into these IAMs. It outlines the plan for model intercomparison and identifies the key variables that will be analysed across models and scenarios.

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2 Description of the new ENGAGE circular economy

The ENGAGE model (Environmental Global Applied General Equilibrium) is a dynamic computable general equilibrium (CGE) framework designed to analyse the economic, environmental, and sectoral impacts of policies related to resource efficiency and the circular economy. It offers a detailed examination of flows in the economy emphasising the global interplay of resources, trade, and policy interventions. Developed to overcome the limitations of traditional CGE models, ENGAGE provides disaggregated sectoral coverage, focusing on representing the circularity in the lifecycle of material-intensive industries such as aluminium, iron and steel (Nechifor et al., 2020; Winning et al., 2017). To develop the new version to be linked with OMNIA, changes have been made to both the geographic and sectoral structure of ENGAGE. We first provide an overview of these structural changes before going into detail on enhanced sectoral representation in the next section. The foundational data source in ENGAGE has been updated to the recently released GTAP-Power 11 (Chepeliev, 2023) and the geographical representation of the global economy has been refined from 19 to 28 regions to facilitate the direct linkage with OMNIA. The detail of the new regionalisation of the ENGAGE model aligned with OMNIA is presented in Table 1.

Table 1. Detail of the 28 OMNIA regions used for the geographic representation in ENGAGE-OMNIA

Region	Description	Region	Description
AFE	Eastern Africa	MEA	Middle East (Gulf States)
AFN	Northern Africa	ANZ	Australia and New Zealand
AFW	Western Africa	USA	United States
AFZ	Southern Africa	CAN	Canada
NIG	Nigeria	MEX	Mexico
CHN	China	BRA	Brazil
JPN	Japan	CHL	Chile
SKT	South Korea, Taiwan	LAM	Latin America
IND	India	ENE	Non-EU Eastern Europe
ASO	South Asia	ENW	Non-EU Western Europe
ASC	Central Asia	EUE	Eastern Europe Union
MDA	Mediterranean Asia	EUM	Mediterranean- Europe Union
ASE	Southeast Asia	EUW	Western Europe Union
IDN	Indonesia, Philippines, Vietnam	RUS	Russian Federation

The ENGAGE model is based upon standard Walrasian general equilibrium assumptions such a market clearance, zero profits, and utility maximisation/cost minimisation of representative agents. All industries are modelled through a representative firm, which maximises its profits in perfectly competitive markets (Nechifor et al., 2020). The production functions of each economic sector to create a level of sectoral output are specified using a series of nested constant elasticity of substitution (CES) functions. Domestic and foreign inputs are not perfect substitutes and therefore are modelled using the "Armington assumption", which accounts for product heterogeneity between different world regions. A representative consumer in each region receives household income, defined as the service value of national primary factors. The national income is allocated between aggregate household consumption, public consumption and savings. A money metric measure of economic welfare, the equivalent variation, can be computed from the model output.

ENGAGE uses national accounts data and a system of non-linear equations to solve for a baseline equilibrium, against which policy shocks can be implemented. ENGAGE uses the latest GTAP database

as a main data source, which is combined and enhanced with other databases according to the specific requirements and applications. The ENGAGE model is written in GAMS and based upon the GTAP9inGAMS model in MPSGE developed by Lanz & Rutherford (2016).

With the objective of allowing an explicit representation of the circular economy in key industrial sectors, the aluminium and steel sectors have been represented in detail and the cement sector has been added, increasing the total number of sectors from 33, in the previous version of ENGAGE, to 47, in the linked model, as shown in Table 2. This sectoral representation allows for representation of policies that foster circularity in the supply chain of these sectors and the inclusion of new production pathways, such as those based on hydrogen and other low emission technologies.

This document summarises the process and main assumptions for the creation of the new ENGAGE model and presents the resulting structure of this detailed representation for the newly created sectors.

Table 2. Sectoral structure of the updated new ENGAGE model

Acronym	Sector	Acronym	Sector
AGR	Agriculture and food	CEM	Cement
B_M	Bauxite mining	CLK	Clinker
I_M	Iron mining	MTP	Metal products
O_M	Other mining	MVT	Motor vehicles and transport equipment
WOP	Wood products	ELE	Electronic equipment
PPP	Paper	MAE	Machinery and other equipment
CRP	Chemical, rubber and plastic products	OMA	Other manufacture
ALU	Alumina	CNS	Construction
PAP	Primary aluminium	COA	Coal
SAP	Secondary aluminium	OIL	Crude oil
RAP	Recycled aluminium (scrap)	GAS	Gas
BF	Blast furnace	P_C	Petroleum & Coke
BF-CCS	Blast furnace with CCS	NUP	Nuclear power
DRI	Direct reduction of iron (gas or coal)	CFP	Coal-fired power
DRI-H2	Direct reduction of iron (hydrogen)	GFP	Gas-fired power
BOF	Basic oxygen furnace	WIP	Wind power
DRI-EAF	DRI based EAF	HYP	Hydroelectric power
HQS-EAF	Scrap based EAF	OFP	Oil-fired power
LQS-EAF	Scrap based EAF	OTP	Other power
HQS	High quality steel scrap (home + prompt)	SOP	Solar power
LWS	Low quality steel scrap (obsolete)	TnD	Transmission and distribution
NFM	Non-ferrous metals	RCY	Recycling
NMM	Non-metallic minerals	TRA	Transport
		SER	Services
	New aluminium sectors		Main users of steel and aluminium
	New steel sectors		Energy supply sectors
	New Cement sector		

2.1 Structure of the steel sector

2.1.1 Enhancements in the steel sector

The steel sector was already disaggregated by primary and secondary production in the previous version of ENGAGE (Winning et al., 2017). In this version, it has been further split according to specific production pathways. This allows further refinement of the representation of circularity in the sector

and allows modelling of constraints in the use of secondary steel in manufacturing due to technical limitations associated with steel quality from secondary production (discussed later in the text).

Iron ore mining has been disaggregated from the original 'other mineral mining' (O_M) sector in the original ENGAGE version. The primary production of iron has been split further into blast furnace (BF) and direct reduction (DRI) iron making processes. This explicit representation of iron making will allow for modelling of the trade of pig iron (the product of BF) and sponge iron (the product of DRI) in scenarios where primary iron production could be geographically decoupled from final steel production. Further down the production stream, the pig iron is transformed into steel in basic oxygen furnaces (BOF) and the sponge iron into steel via electric arc furnaces (DRI-EAF).

Steel scrap has been split into two parallel flows: high quality (HQS) and low quality (LQS) scrap. LQS represents the end of life (obsolete) scrap, which due to sorting inefficiencies tends to present a higher degree of impurities which limits the quality and therefore applications of the steel produced from it. HQS, on the other hand, represents scrap that comes directly from manufacturing processes; therefore, it is well sorted and has a low level of impurities, allowing for the creation of secondary steel of a similar quality to primary steel. As an approximation, it has been assumed that scrap labelled as home and prompt scrap[1] constitute HQS, while end of life or obsolete scrap makes up LQS.

Even though, in reality, these two types of scrap can be processed in the same electric arc furnaces (and even mixed), in the model, it has been assumed that each of these qualities of scrap are processed by a distinct technology: high-quality scrap EAF (HQS-EAF) and low-quality scrap EAF (LQS-EAF). This allows for distinguishing between the outputs of EAF processes and limits the applications of the LQS derived steel in industries where higher quality is required, for example for steel sheets and plates used in the automotive industry (Transition Asia, 2023). To represent this restriction to supply part of the final demand of steel by the LQS-EAF pathway, we use the definition from Harvey, (2021) of "intolerant" demand fraction, which represents the share of the final demand that is not tolerant to contamination with tramp elements, and therefore cannot be produced from end-of-life scrap due to quality limitations. As pointed out by Harvey, there is no systematic data to define the fraction that this intolerant demand represents from the total demand and rough estimates need to be made. For ENGAGE, we used the assumptions made by Harvey and adapted them to our representation of the steel sector. These assumptions are that products made from bar and shaped steel are more tolerant to impurities, while rolled steel are intolerant. This assumption was applied to each country's production of semi-finished steel and the aggregated results by steel demanding sector is presented in Table 3, which shows the fractions of the steel demand by sectors on a global scale that is assumed to be intolerant to impurities, and therefore needs to be produced from HQS or primary iron rather than from low quality scrap (LQS).

[1] Home scrap refers to scrap that is recirculated inside the steel mill factory and prompt scrap that originates as leftovers of industrial manufacturing of final products. Both of these are highly homogeneous materials and therefore include low levels of impurities which allows their recycling into high grade steels.

Table 3. Assumptions for the fraction of steel that cannot be produced from end-of-life scrap

Steel demanding sectors	Share of intolerant demand
Manufacture of fabricated metal products	0.31
Manufacture of machinery and equipment n.e.c.	0.64
Manufacture of office machinery and computers	0.32
Manufacture of electrical machinery and apparatus n.e.c.	1
Manufacture of radio	0.32
Manufacture of medical	0.51
Manufacture of motor vehicles	0.72
Manufacture of other transport equipment	0.92
Manufacture of furniture	1
Construction	0.18

Note: fractions of the final use sector that cannot be produced from LQS, based on Harvey, (2021); n.e.c. = not elsewhere classified

It is worth noting that the assumption used by Harvey is very broad, as it does not differentiate between the uses of the different semi-finished steels. An argument could be made that a steel sheet used for the body of a home appliance does not require the same mechanical properties than a steel sheet used for the body of a car – a typical example of intolerant steel – thus being more tolerant to steel contamination. However, no data was found to systematically account for these variations in use of steel.

Overall, our assumptions in Table 3 imply a global limit of 42% of the steel demanded by the manufacturing sectors that cannot be produced from LQS and requires a higher quality feedstock.

All the flows of materials and energy for steelmaking are summarised in Figure 1, where continuous lines are flows of steel related commodities and dashed lines are flows of energy.

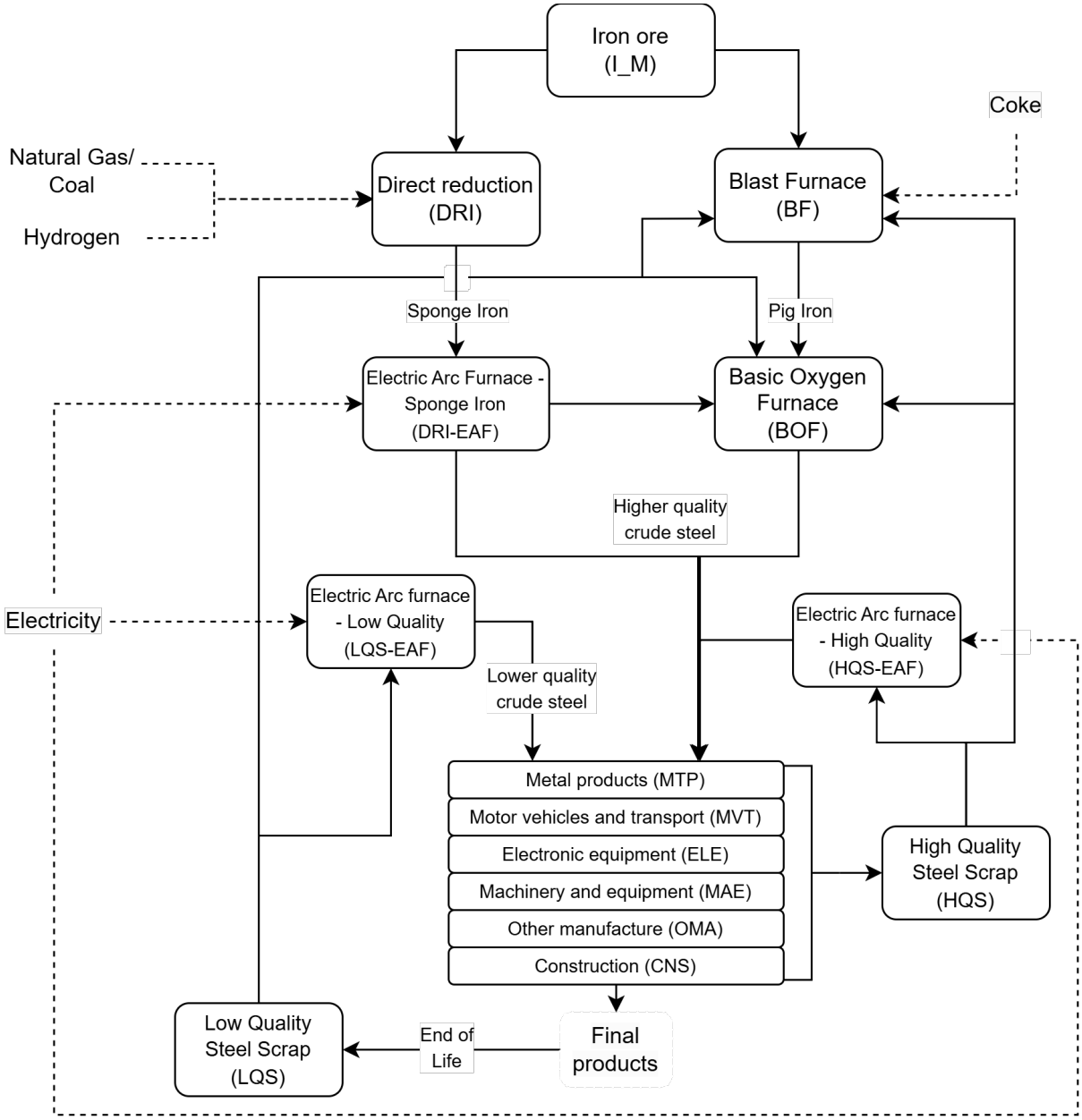

Figure 1. Schematic representation of the value flows in the steel sector.

The data used to define all the sectors in which the steel industry is split was obtained from the PIOLab dataset (Wieland et al., 2022). This dataset includes physical input-output tables of the steel sector, disaggregated into 30 activities and 32 countries and regions, with a particular focus on Europe and those economies prominent in mining of iron ore, production of steel and use of steel for final products. This dataset was chosen as it reconciles several sources and keeps self-consistency for production, trade and use of the relevant commodities of the steel industry. In addition, it is the only dataset that we are aware of that allows to identify end-of-life scrap, which permits creating restrictions to the use of this feedstock in highly circular scenarios. Table 4 present the list of countries and regions included in PIOLab, while Table 14 in the Appendix shows the steel related activities included in PIOLab and how they have been matched to the sectors defined in the new version of ENGAGE.

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Table 4. Prices in 2017 USD/ton used to convert physical and monetary data in the steel industry

	Iron ore	Scrap	Pig iron	Sponge iron	Steel
Austria	60	335	299	288	873
Belgium	81	390	381	295	818
Czech Republic	84	284	365	257	817
Germany	79	373	369	123	928
Spain	78	357	363	286	808
Finland	61	302	320	257	960
France	75	325	420	310	845
Greece	61	294	343	257	643
Italy	77	326	325	255	847
Netherlands	69	432	435	323	871
Poland	76	327	361	257	802
Sweden	89	395	299	360	965
Slovakia	78	297	330	257	751
United Kingdom	78	303	415	257	849
United States	83	320	357	318	954
Japan	69	355	402	292	683
China	65	318	409	235	662
Canada	78	230	370	257	912
South Korea	69	357	304	282	708
Brazil	46	310	321	257	684
India	61	440	291	284	737
Mexico	61	493	356	216	803
Russia	65	179	313	239	574
Australia	54	317	343	257	764
Taiwan	61	322	343	257	763
Indonesia	50	337	375	318	786
RoW Asia Pacific	47	299	335	265	637
RoW America	55	292	314	284	673
RoW Europe	64	278	300	283	605
RoW EU27	61	296	325	264	766
RoW Africa	63	283	356	280	690
RoW Middle East	86	287	386	240	612

Prices obtained as average Free on Board (FOB) values of trades from (UN Comtrade, 2024)

Free on board (FOB) prices obtained from Comtrade for the year 2017 (UN Comtrade, 2024) and presented in Table 4 were used to calculate the monetary values of production, use and trade of commodities in PIOLab. It is worth mentioning that a case-to-case process was performed to prepare Comtrade data, which included removing outliers and merging several categories of traded commodities to get a better representation of the variety of qualities of steel and steel alloys traded by different regions and countries. As the last column of Table 4 makes evident, the price of steel was assumed to be the same regardless of the shape and quality of the product.

Iron ore (I_O) was split from the other mining sector. The remaining steel related sectors were created in the GTAP database by splitting the iron and steel sector (I_S in ENGAGE). In this case, the total output of I_S matches the total output of the new final steel producing sectors: BOF, DRI-EAF, HQS-EAF and LQS-EAF, while the inputs to I_S match the inputs to the intermediate feedstock producing sectors: BF, DRI, LQS and HQS. In other words, the value added of the original I_S sector is split between the value added of the steel producing part and value added of the intermediate feedstock producing part.

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2.1.2 Geographical disaggregation

The transformation of the data from the 32 PIOLab regions to the 28 OMNIA regions was performed in two stages. First, the PIOLab data was split into the 160 countries present in GTAP 11, and later, the data at GTAP 11 regional disaggregation was aggregated to the 28 OMNIA regions.

To distribute production data from PIOLab data into GTAP regions, production data from the Steel Statistical Yearbook produced by the World Steel Association (WSA) was used (World Steel Association, 2018). This report includes country by country statistics of production of iron ore, iron and steel separated by production pathway. Production from each PIOLab region was distributed to country level proportionally to each country's production data in WSA. In this way, the total production from PIOLab is maintained and WSA data are used as weights for the disaggregation. BF was distributed using data of pig iron production, BOF using crude steel from basic oxygen furnace and open-hearth furnace, DRI using sponge iron production and EAF using crude steel from electric arc furnace production. As EAF production in the WSA data does not distinguish between feedstock used for the production, the production of EAF in PIOLab was split into DRI-EAF, HQS-EAF and LQS-EAF proportionally to the relative availability of feedstock for each of the processes: sponge iron for DRI-EAF and HQS and LQS for scrap-based EAF. The availability is calculated as the local production minus exports plus imports of each of the feedstocks.

In the case of steel scrap (HQS and LQS), a different dataset had to be used for the disaggregation at country level, as WSA does not provide data on steel scrap production. In this case the GLORIA (Global Resource Input-Output Assessment) database (Industrial Ecology Virtual Laboratory, 2021). This database is a global multi-regional input-output database with monetary flows between 97 sectors in 164 countries and regions and considers an explicit representation for a 'material recovery' sector. It was assumed that all the input from GLORA's material recovery sector to the steel production sector corresponds to steel scrap. Therefore, the shares of total scrap production were split at the country level using the relative input of the recovery sector into the steel sector in GLORIA. As there is no other reliable dataset that allows to differentiate HQS and LQS scrap production at country level, the share of HQS to LQS from PIOLab was kept for every country within the same PIOLab region.

The geographical disaggregation of trade was done using WSA physical import and export data (World Steel Association, 2018). The total trade was assumed to be the values provided by PIOLab, but the exports from and imports to each of the more aggregated regions according to WSA were used to distribute the values among the countries at GTAP11 level. As WSA only presents export and import data for iron ore, pig iron, direct reduced iron, steel scrap and steel, the same shares were used for the different qualities of scrap (LQS and HQS) and for steel from different processes and origins (BOF, DRI-EAF, HQS-EAF and LQS-EAF).

2.1.3 Results of steel sector disaggregation

Figure 2 summarises the results of the steel disaggregation, presenting the main producers of the commodities associated to the primary production of steel. This figure shows that China dominates the production of primary steel via the BF-BOF route, with almost two thirds of the total production by this route. India is the dominant producer of steel via the DRI-EAF route followed by the Middle East region.

Figure 3 presents the main producers of the commodities of the secondary production pathway of steel.

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Here we see a more diversified production of steel. China, as expected due to its large production of steel, produces more than half of the world's prompt scrap, but it uses a large fraction of it as feedstock for the BF-BOF pathway and its relative share of the production of secondary steel from prompt scrap is reduced to around one third of the world's production, followed by India and the USA. With regards to the production of end of life (obsolete) scrap, the USA, China and Europe (specifically Mediterranean and Western Europe) dominate its production and the production of EAF steel using this material. A spatial representation of this data is presented from Figure 17 to Figure 19 in the Appendix, while Figure 20 to Figure 23 present the flows of the traded commodities between different ENGAGE regions.

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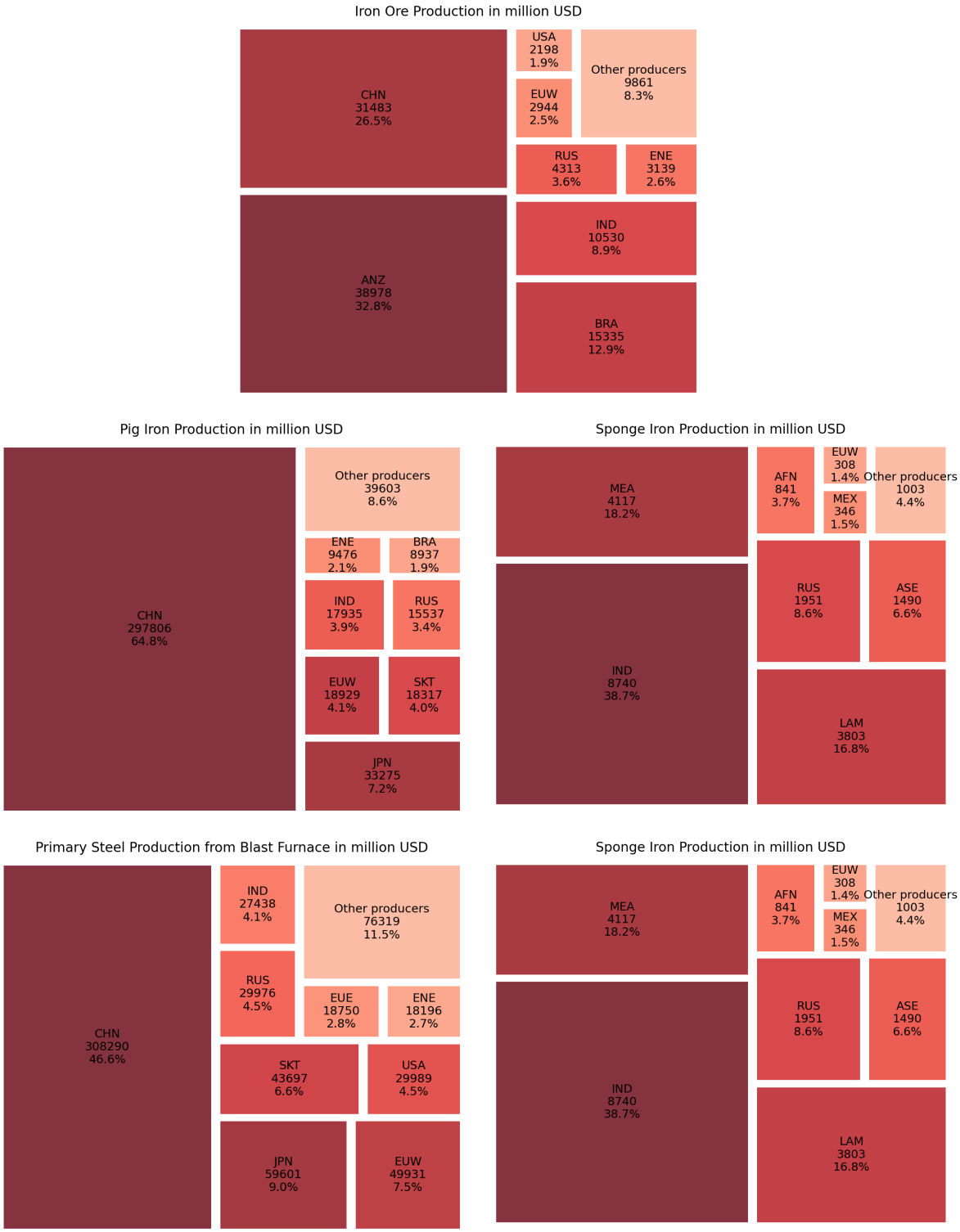

Figure 2. Largest producers of iron ore, pig iron, sponge iron, and primary steel form BOF and EAF in the new disaggregation of ENGAGE. Values are presented in monetary terms (millions of USD/year) and percentage of the total world production.

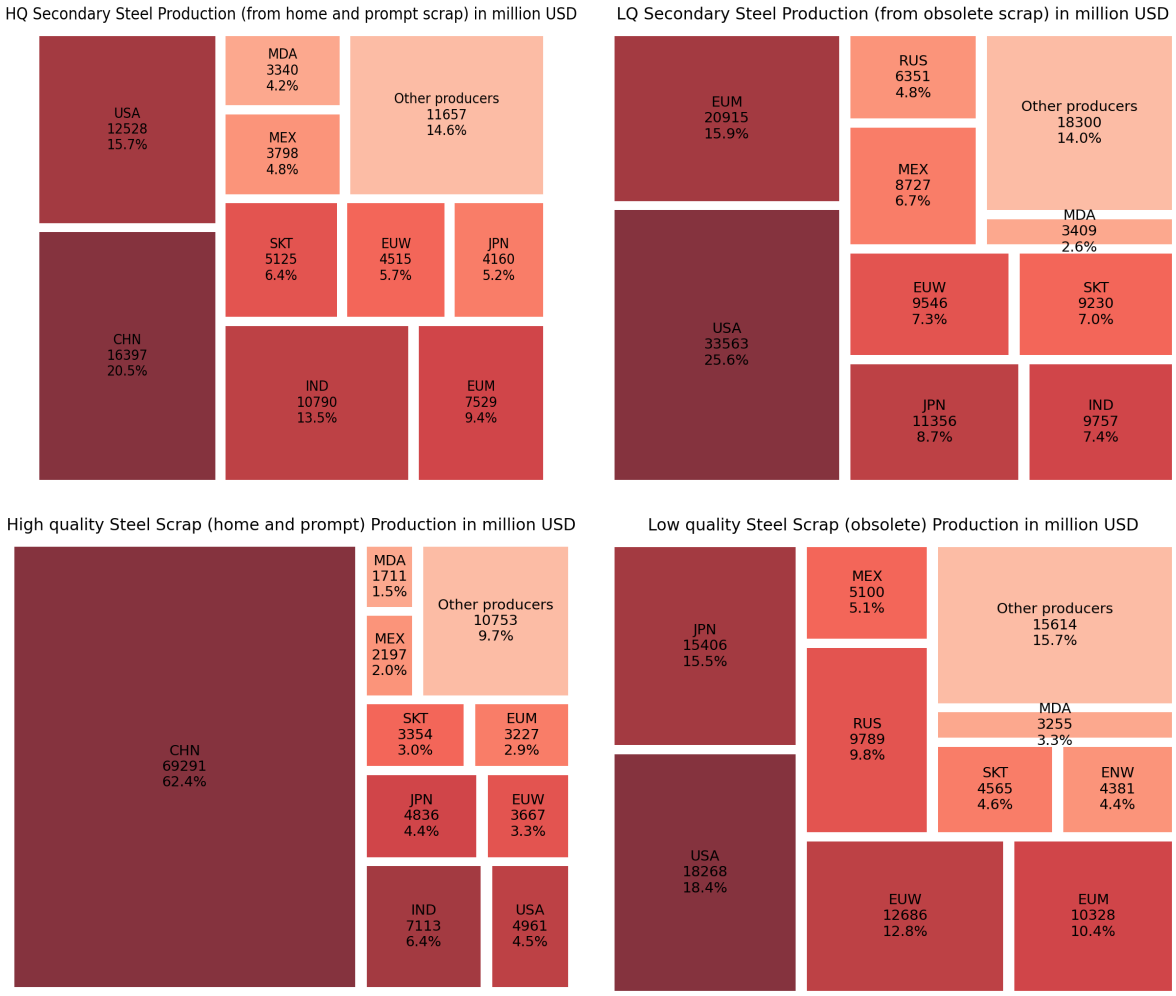

Figure 3. Largest producers of secondary steel and scrap in the new disaggregation of ENGAGE. Values are presented in monetary terms (millions of USD/year) and percentage of the total world production.

2.2 Structure of the aluminium sector

2.2.1 Enhancements in the aluminium sector

The aluminium sector has been disaggregated from the original non-ferrous metals (NFM) sector in the original ENGAGE version (see Table 2). In addition, the mining of bauxite (B_M), the raw material for primary aluminium production has been split from the other mining extraction sector (O_M) that represents the aggregated activities of mining metallic ores. With the aim of modelling economic circularities in the sector, the production of aluminium has been subdivided into four sectors representing the production of alumina (ALU) from bauxite, the production of primary aluminium (PAP), secondary aluminium production (SAP) and the production of aluminium scrap (RAP). The conceptual flow of materials, value and use of commodities of these sectors is shown in Figure 4. The blocks represent sectors that are modelled in ENGAGE. Continuous lines are flows of aluminium related commodities and dashed lines are flows of energy.

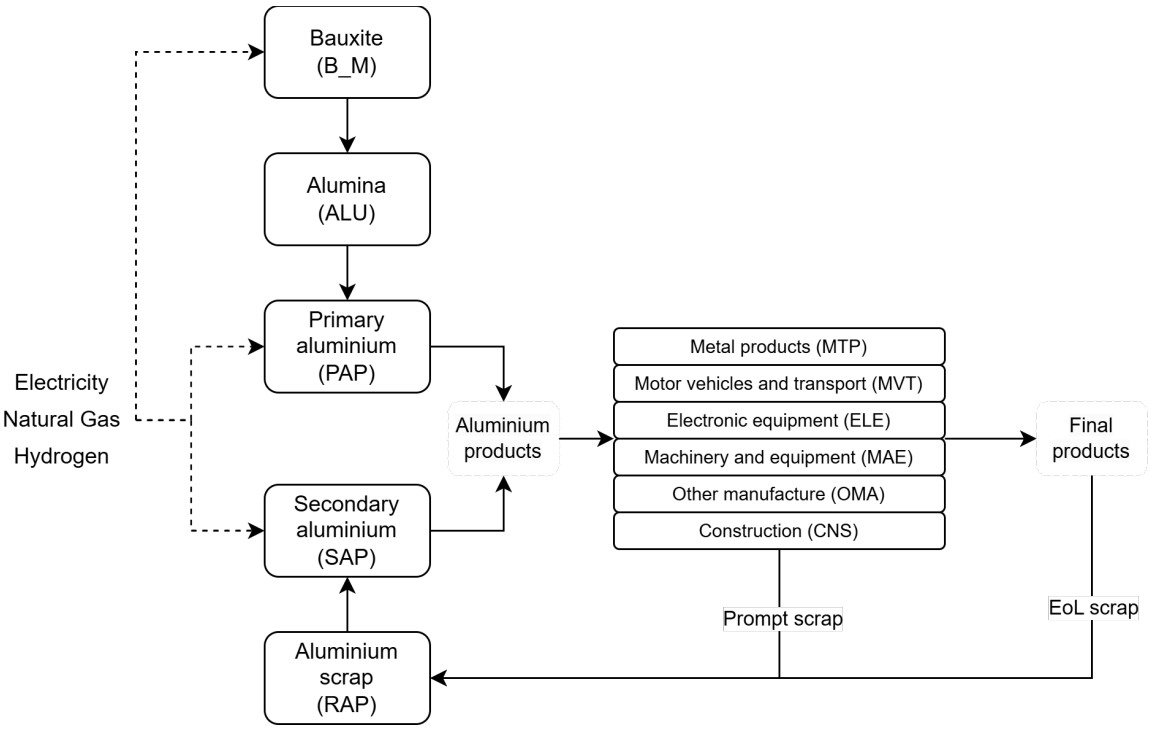

Figure 4. Schematic representation of the value flows in the aluminium sector

The data for defining the three aluminium sectors were based on an internal UCL material flow analysis (MFA) that leveraged data from the International Aluminium Institute (IAI) (IAI, 2024) and country-specific sources. This MFA traces the whole life cycle of the aluminium production process from its primary products to its end-of-life scrap, including the production, trade and use of five sectors: B_M, ALU, PAP, SAP and RAP at a ten-region level disaggregation of the global aluminium industry. These ten regions and the prices used to convert the physical to monetary flows are presented in Table 5. As the MFA has been developed for a ten-region spatial disaggregation, the data was further disaggregated to the 28 regions used in OMNIA, as listed in Table 1. The disaggregation approach is described in detail in section 2.2.1.

Table 5. Prices for commodities in the aluminium sector in 2017 USD/kg according to UCL's MFA.

	B_M	ALU	PAP	SAP	RAP
China (CHN)	0.05	0.41	1.98	1.98	1.30
Europe (EU)	0.05	0.38	2.13	2.13	1.38
United Kingdom (UK)	0.53	0.66	2.23	2.23	1.44
North America (NA)	0.07	0.41	2.42	2.42	1.44
South America (SA)	0.03	0.29	2.03	2.03	1.53
Japan (JPN)	0.31	0.47	2.00	2.00	1.36
Other Asia (OA)	0.05	0.40	2.08	2.08	1.50
Middle East (ME)	0.12	0.35	1.97	1.97	1.23
Other Producers (OP)	0.03	0.34	1.82	1.82	1.34
Rest of the World (ROW)	0.06	0.38	3.53	3.53	1.10

B_M: bauxite, ALU: alumina, PAP: primary aluminium, SAP: secondary aluminium, RAP: aluminium scrap
Source: Prices obtained as average Free on Board (FOB) values of trades from (*UN Comtrade*, 2024)

2.2.2 Geographical disaggregation

The geographical disaggregation of the MFA data (10 regions) into the finer spatial representation used in OMNIA was performed using weights obtained from the GLORIA (Global Resource Input-Output Assessment) database (Industrial Ecology Virtual Laboratory, 2021). This database is a global multi-regional input-output database with monetary flows between 97 sectors in 164 countries and regions. Each of the 164 regions included in GLORIA were matched to one of the macro-regions in the MFA. For simplicity, "regional level" refers to this macro-regional aggregation, while "country level" pertains to the detailed representation in GLORIA. Once the split of each commodity was performed at the country level, these data were aggregated to the 28 regions included in OMNIA.

As GLORIA has an explicit representation of bauxite mining (B_M), the split of this sector was performed by distributing the regional values into each country within that region proportionally to the values in the GLORIA database.

In the case of alumina (ALU), as this commodity is not represented in the GLORIA database, the split of production was performed proportionally to the availability of bauxite in each country (as bauxite is the main feedstock for alumina production). The availability of bauxite was calculated as each country's production subtracting exports and adding imports.

In the case of the production and use of aluminium scrap (RAP), GLORIA does not have an explicit representation of this industry and commodity. However, it has a representation of the whole material recovery sector, which aggregates all recycled materials. As for steel scrap, we have assumed that all input from GLORIA's material recovery sector to the production of aluminium corresponds to aluminium scrap. Therefore, the split of the aluminium scrap sector was performed by distributing the regional values proportionally to the use of material recovery by the aluminium producing sector in GLORIA.

In the case of primary and secondary aluminium production (PAP and SAP), GLORIA only has representation of total aluminium production. Therefore, for PAP, data from the Unites States Geological Survey (USGS) was used. This dataset holds physical information of production at the country level (USGS, 2024). After transforming the USGS data to monetary flows using assumptions in Table 5, the primary production at regional level was split proportionally to USGS country-specific production.

For the secondary production of aluminium, it was assumed that the secondary production of aluminium is proportional to the use of aluminium scrap. Therefore, these data from GLORIA were used as weights to distribute the secondary production of aluminium from regional to country level.

The country level relative shares of PAP and SAP were applied to the total aluminium data in GLORIA to split the trade of these products. For this, it was assumed that producers do not have a preference on what kind of aluminium to export, so they do it proportionally to their production. In the case of alumina, as this was not present in the GLORIA database, the split of trade was performed using the BACI trade database (Gaulier & Zignago, 2010) considering the category "Aluminium oxide: other than artificial corundum", which corresponds to the alumina commonly used for aluminium production.

Disaggregating trade flows for the different aluminium sectors required adjusting the GLORIA trade matrix to match realistic patterns. Adjustments ensured that intra-regional flows adhered to production and the remaining feedstock in each region was in line to the production of the corresponding downstream commodity.

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2.2.3 Results of aluminium sector disaggregation

After performing the split of bauxite production from 'other mining' and the four aluminium sub-sectors from 'non-ferrous metals', the data was incorporated into the GTAP database using Splitcom, a software that performs splits on classical GTAP databases ensuring internal balancing based on user defined weights (Horridge, 2021). In this section, we present the main features of the resulting split. Figure 5 shows the relative production of the ten largest producers across the aluminium production subsectors.

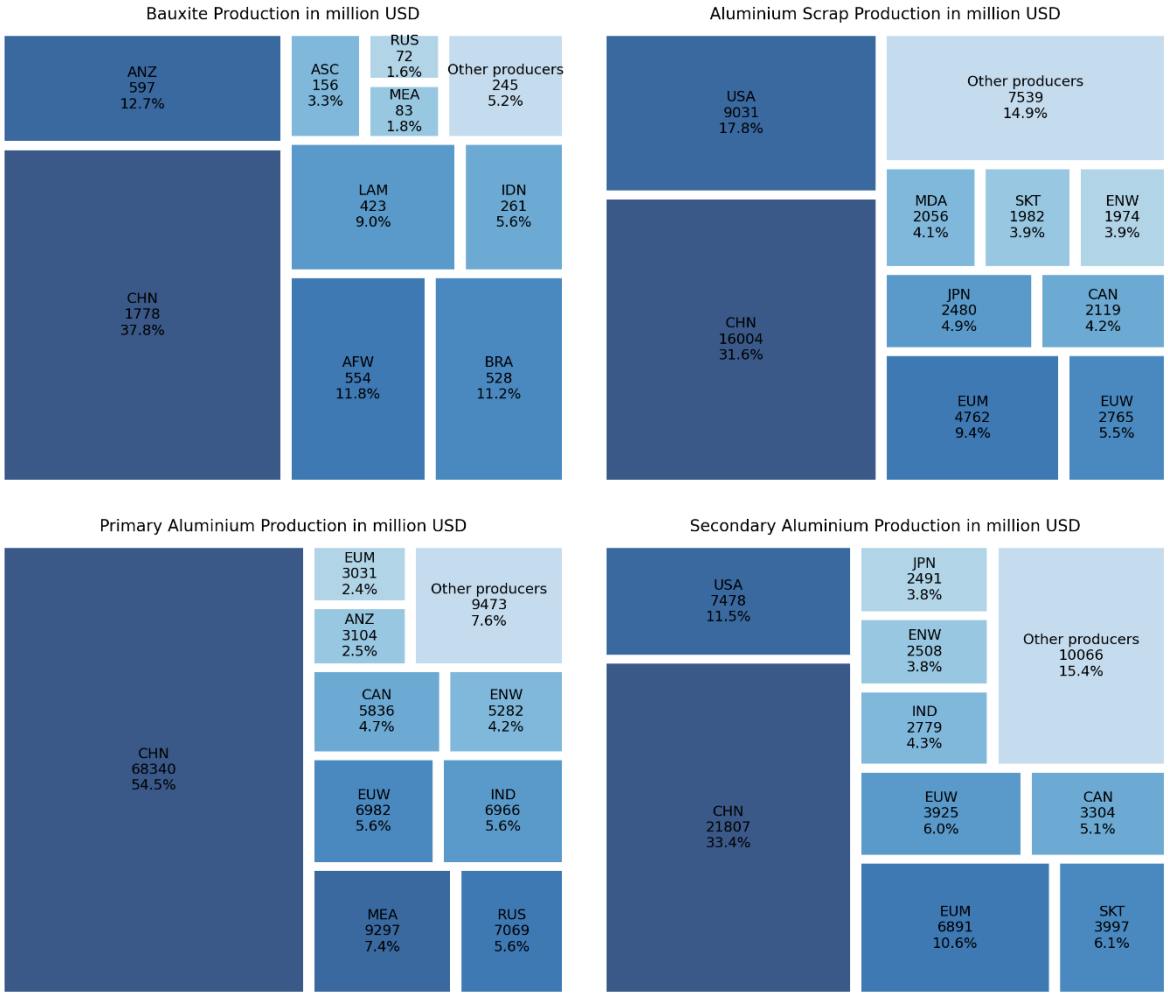

Figure 5. Largest producers of Bauxite, Aluminium Scrap, Primary and Secondary Aluminium in the new disaggregation of ENGAGE. Values are presented in monetary terms (millions of USD/year) and as share of total global production (% of annual production)

As shown in Figure 5, China dominates the production of all components of the aluminium supply chain. Regions without direct access to bauxite, such as USA, Canda, Europe, Japan, South Korea focus mostly on secondary production from scrap. A representation of these data on a spatial level, as well as the trade flows of these commodities are presented in the Appendix, from Figure 24 to Figure 26.

2.3 Structure of the newly added Cement sector

Circular economy efforts in cement concentrate on reducing clinker input and boosting material efficiency because "cement recycling", although technically possible, remains limited and not scalable in the near term (Dunant et al., 2024). Since most CO_2 emissions come from clinker production, reducing the clinker-to-cement ratio and overall cement demand offers the largest emission reduction gains. Significant additional emission reductions can also be achieved by partially substituting clinker with alternatives such as calcined clay or limestone (IPCC, 2022). Additionally, using concrete more efficiently, through leaner design, higher-strength mixes, or replacing concrete with other material, lowers the need for new cement production (Ali & Markkanen, 2023). As viable recycling of hardened concrete is still in its infancy, cutting clinker use and optimising concrete applications are seen as the primary near-term pathways for emission reduction in the global cement sector and it is the focus of the approach in this new version of ENGAGE.

Following this logic, a more direct approach was used when adding the cement sector to the new ENGAGE. We use the recently released GTAP-CE (Circular Economy) which includes a separated cement (CEM) sector that has been separated from the original non-metallic minerals (nmm) sector, as described by Chepeliev et al. (2022). The full GTAP country level representation was subsequently aggregated to the 28 OMNIA regions. The CEM sector here includes all the supply chain of cement and its derivates, from the mining of limestone, clinker production and cement griding and blending. In a next step, the clinker (CLK) production and trade were separated from the CEM sector. For modelling clinker production, we use the same dataset used in OMNIA, which was obtained from Andrew (2019). We transformed it into monetary terms using clinker prices obtained from BACI (Gaulier & Zignago, 2010) and presented in Table 6.

Table 6. Prices for clinker in 2017 USD/ton from BACI

Region	Clinker price	Region	Clinker price
AFE	58.6	MEA	35.7
AFN	39.3	ANZ	38.2
AFW	38.2	USA	41.5
AFZ	63.2	CAN	38.2
NIG	38.2	MEX	51.2
CHN	33.7	BRA	38.2
JPN	36.8	CHL	38.2
SKT	34.1	LAM	42.0
IND	49.8	ENE	42.7
ASO	42.6	ENW	40.9
ASC	44.4	EUE	44.2
MDA	33.1	EUM	35.0
ASE	33.7	EUW	54.6
IDN	40.6	RUS	36.1

Note: prices are calculated averages (weighted by value) of exports of codes 252321, 252329 and 252390 in BACI

For modelling trade, data from BACI was used to calculate the trade flows in monetary terms between regions. As mentioned previously for other sectors, this data had to be cleaned from outliers before using for price calculations.

As the original cement sector in GTAP-CE includes the production and trade of clinker, the values

obtained for the clinker sector were deducted from the cement sector to avoid double counting.

Figure 6 below presents the main producers of cement and clinker by the disaggregation used in OMNIA.

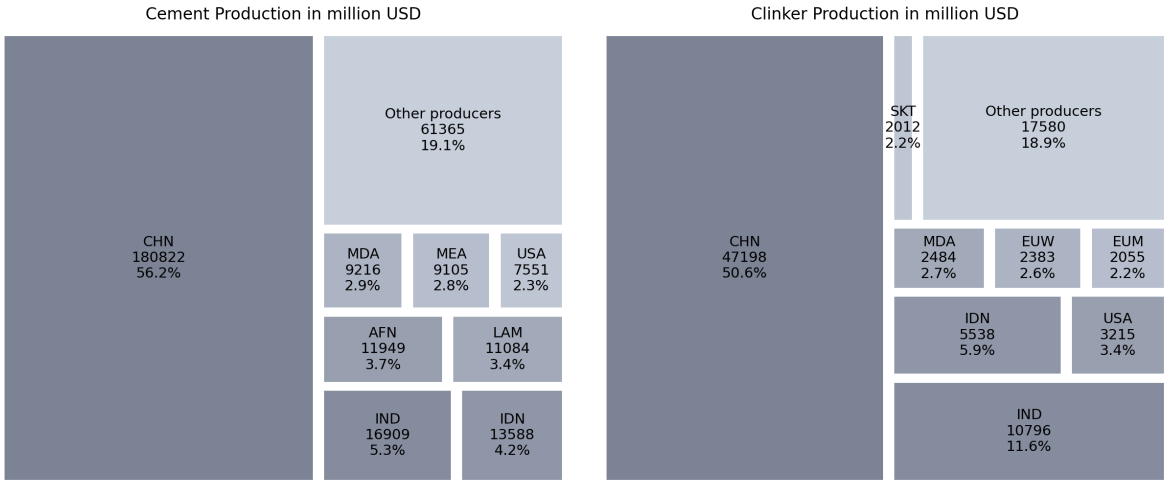

Figure 6. Largest producers of cement and clinker in monetary terms (millions of USD/year) and as share of total global production (% of annual production)

From Figure 6, China leads the production of both cement and clinker (accounting for more than 50% of the global production of both commodities). Other major producers include India and Indonesia, though their production levels are significantly lower in comparison. A representation of these data on a spatial level is presented in the Appendix in Figure 27, and the main trade flows of these commodities are presented in Figure 28.

3 Linkage with OMNIA

3.1 Overview of the OMNIA model

The OMNIA (Open-source MuNdus Integrated Assessment model) is a customised, open-access global IAM based on the TIMES framework (Loulou et al., 2016) that will be released in deliverable D4.2 of this project. Its key strength is in its rich representation of the global energy system, representing all energy sectors, including energy resources, their transformation into energy commodities (petroleum products, electricity, hydrogen, biofuels etc.), and their consumption in end use sectors (industry, transport, buildings, and agriculture). This system structure is represented for each of the 28 regions of OMNIA (see Table 1).

Sectors are represented based on current energy producing and consuming technology stocks, e.g., numbers of power plants, blast furnaces, vehicles, buildings etc. Based on exogenous projections of future energy service demands (mobility, cooling, industrial output), the model provides a technology-rich basis for estimating how energy system investments and operations evolve over a long-term, multiple-period time horizon. The use of a granular technology level also means that in addition to energy use and investments, emissions of GHGs can also be tracked by technology and sector in each of the regions.

In representing the global energy system, OMNIA also enables regional energy demands to be met by both domestic resources and traded commodities. Regions are connected via pipelines or shipping routes, enabling the trade flow of the main energy commodities, including fossil fuels, bioenergy, and hydrogen-based fuels. Current infrastructure capacity enabling trade is represented, e.g., LNG liquefaction and regasification, with investment requirements for its expansion.

The TIMES framework, which underpins this model, is described in detailed in Loulou et al. (2016). It is developed and maintained by the Energy Technology Systems Analysis Programme (ETSAP), one of the Collaboration Programmes of the International Energy Agency (IEA). It has been extensively used across many countries and also provided the basis for the TIAM family of global integrated assessment models (Pye et al., 2025; Welsby et al., 2021). The model paradigm can be characterised as partial equilibrium, optimisation-based, with an objective of welfare maximisation over the model time horizon.

The OMNIA model expands the open-source TIMES-GEO model, which serves as its foundation (Chiodi et al., 2023). In addition to improving the spatio-temporal resolution of TIMES-GEO, OMNIA integrates a climate module to estimate global average temperature changes and set temperature-based-climate targets and introduces a new water module to assess interdependencies between energy production and water consumption. It also significantly improves the representation of key industrial sectors considered in this task. It keeps the open-source philosophy and therefore all data used in OMNIA originates from publicly available sources. This includes the energy balances used to calibrate the model in 2019, which are sourced from the UN (UN, 2019).

3.2 Representation of key industry sectors in OMNIA

OMNIA represents all key industrial subsectors. Three of these sectors—aluminium, steel, and cement—have been modelled with additional detail, using a process-oriented representation. This is to enable

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the linkage of OMNIA to ENGAGE, and subsequently to explore the impact of circular economy policies for low-carbon transition pathways. Each of these detailed subsectors are described briefly below. We note that, to the extent possible, the production statistics for each sector used in OMNIA are consistent with those detailed above for ENGAGE.

Key modelling characteristics of these sectors are summarised below:

- Demands for manufactured industrial products are exogenously imposed to the model and can be differentiated by scenario.
- Industrial products are not traded between regions.
- Demand projections include assumptions, based on the chosen scenario, as to the levels of production in different regions.

By coupling with OMNIA with ENGAGE, insights on future demand and trade of industrial commodities will be informed by the economy as a whole.

3.2.1 Steel

The steel production sector includes three main pathways for steel production, two of which are classified as primary steel pathways, producing virgin steel, while the third one is a secondary production pathway based on melting down recycled steel in an Electric Arc Furnace (EAF). The two primary production pathways are Blast Furnace-Basic Oxygen Furnace (BF-BOF) and Directly Reduced Iron-Electric Arc Furnace (DRI-EAF). Both pathways essentially involve removing oxygen from iron ore, in a process called 'reduction', to produce iron. The blast furnace route relies on coke and coal as the reducing agent, producing molten 'hot metal' or pig iron. This process is energy intensive and results in high levels of emissions. To produce steel, the pig iron is fed into a basic oxygen furnace, where the carbon content is further reduced, from 4-5% down to 0.25%. DRI uses an alternative reduction approach, using natural gas to produce the required syngas (CO plus H_2), with iron left in a solid state. Avoiding melting at this stage reduces the energy requirements and associated emissions. The produced sponge iron is then melted down in an EAF to produce crude steel.

The structure of the steel sector is largely based on Pye et al. (2022) and is presented below in Figure 7. BF-BOF is modelled as a single integrated process, as is DRI with EAF. This approach means that pig and sponge iron are not represented as explicit commodities in the model. Although this is a simplified representation, it is appropriate given that these commodities are not significantly traded.

Modelling of scrap steel is not traded either, and an estimate of regional and global availability is determined instead (aligned with ENGAGE). To mimic some level of flexibility provided by trade, a minimum level of use by region is determined, for example 80% of the scrap produced in a region would need to be used there. The remaining 20% produced by that region can be used in any other region, without restrictions. Note that the current year would reflect the scrap trade situation, with flexibility enabled in future years. Based on a linkage with ENGAGE, which does capture scrap trade, OMNIA would be run with a consistent representation of future scrap levels and trade by region.

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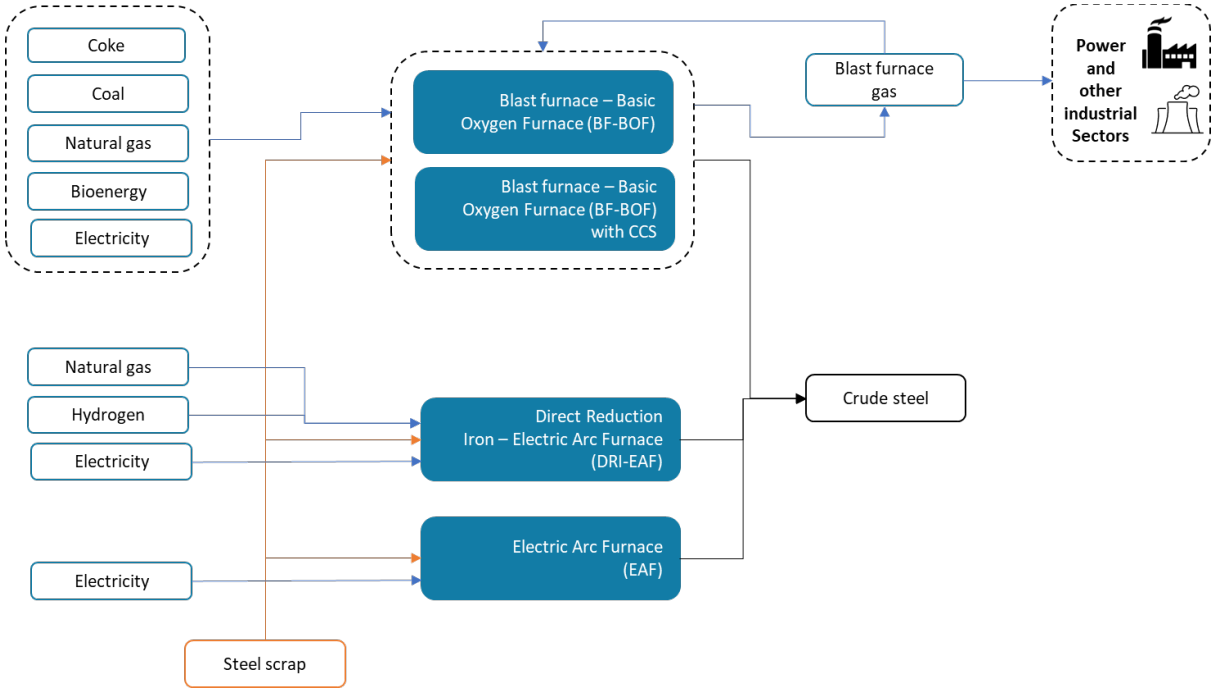

Figure 7. Steel sector structure in OMNIA

Production statistics for the steel sector are taken from PIOLab (Wieland et al., 2022), as in the ENGAGE model, while energy benchmarks are primarily sourced from IEA (IEA, 2020b). Technology cost estimates are sourced from a range of literature to determine individual cost components (Fischedick et al., 2014; van Sluisveld et al., 2021; Vogl et al., 2018). These are summarised in Table 7. Note that costs do not change over time but are rather estimates of fully commercialised production pathways; learning effects are applied as per the approach in Pye et al. (2022).

Table 7. Steel production technology costs assumptions

Technology name	Technology abbr.	CAPEX[1], $2005/t (Range)	CAPEX[1], $2021/t (Point estimate)	OPEX, % of CAPEX
Electric Arc Furnace	EAF	187-292	333	7.5%
Direct Reduction Iron and EAF	DRI-EAF	459-471	646	7.5%
Direct Reduction Iron with hydrogen and EAF	DRI-H2-EAF	459-471 (excl. H2 production)	646*	7.5%
Direct Reduction Iron with CCS and EAF	DRI-CCS-EAF		805	10%
Blast furnace and BOF	BF-BOF	490-597	764	7.5%
Blast furnace and BOF with CCS	BF-BOF-CCS	628-743	944	10%

[1] Upfront investment are not annualised. Point estimates for CAPEX used in the model, based on range median; * Under review

Further information on technical parameters for the above technologies is shown in Table 8.

Table 8. Steel production technology non-cost assumptions

Technology name	Technology abbr.	Energy input (GJ/t)[2]	Capture rate[1]	Scrap input (t)[3]
Electric Arc Furnace	EAF	2		1.1
Direct Reduction Iron and EAF	DRI-EAF	17		0.15
Direct Reduction Iron with hydrogen and EAF	DRI-H2-EAF	9		0.15
Direct Reduction Iron with CCS and EAF	DRI-CCS-EAF	17	90%	0.15
Blast furnace and BOF	BF-BOF	19		0.15
Blast furnace and BOF with CCS	BF-BOF-CCS	19	90%	0.15

[1] 90% capture rate assumed (Bataille et al., 2021; IEA, 2020b)
[2] For DRI-H2-EAF, based on (Vogl et al., 2018); 59 kg H2 per tonne steel, based on 15% scrap charge
[3] For primary production, these can vary significantly but are based on typical levels from the World Steel Association

3.2.2 Aluminium

In the model, aluminium production is disaggregated from the non-ferrous metals sector and split into primary and secondary (i.e. recycling) production. The key steps in primary aluminium production are aggregated into one process, i.e., refining, anode production and smelting, and process CO2 emissions from the anode are accounted for. A base year primary pathway is developed by using historical data on production, average energy intensity and specific fuel inputs (see Table 9).

Future low carbon routes then rely on electrically- and hydrogen-powered boilers and calciners with conventional or inert anodes (to remove process emissions). Anode production can switch to hydrogen for its thermal inputs and process CO_2 emissions can be captured via CCS. These simplified low carbon options account for ~98% of total energy and ~99% of emissions in the aluminium supply chain. A secondary aluminium production option is modelled with a scrap input, which may be defined by a particular scenario. The recycling option requires electricity and thermal energy inputs (using fossil fuels) in the base year but can operate with hydrogen and electricity options in the future.

The basic structure of the aluminium sector is shown below in Figure 8.

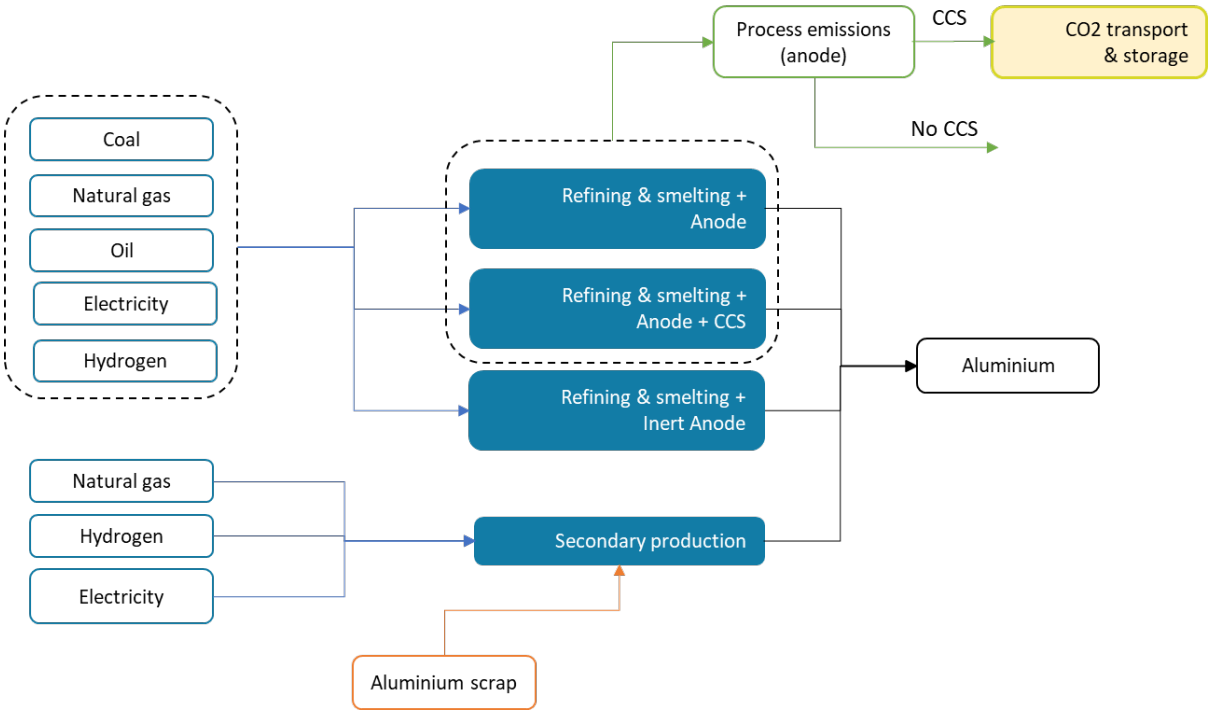

Figure 8. Aluminium sector structure in OMNIA

Key data sources for the aluminium sector are provided in Table 9.

Table 9. Key data sources for the aluminium sector

Dataset	Description	Source
Production statistics	Primary production available from the US Geological Survey.	USGS aluminium statistics (USGS, 2024)
	Secondary production provided at regional level and disaggregated to national level	UCL MFA based on (IAI, 2024)
Historic input energy mix	Energy consumption for primary aluminium production	International Aluminium data (IAI, 2019)
	Energy consumption for secondary aluminium production	(Peppas et al., 2023)
Technology parameterisation	Data aggregated as necessary e.g. refining and smelting considered together.	Mission Possible Partnership (MPP, 2023) (European Aluminium, 2023)

3.2.3 Cement

The cement sector is disaggregated from the non-metallic minerals sector and modelled to represent two key parts of the cement production process: clinker production in rotary kilns (based on wet and dry kiln technology), and cement production, involving the mixing of clinker with other aggregates. From an emissions perspective, clinker production is the dominant source, producing both process- and combustion-related CO_2 emissions. Process emissions are generated via the calcination process, where calcium carbonates are decomposed into calcium oxides, lime, and CO_2 by adding heat. Combustion emissions come from the use of fossil fuels necessary to generate the significant energy required to heat the raw materials (limestone aluminosilicate clay) to well over 1000 °C. The clinker is cooled down and then mixed with gypsum. The mixture is finally milled into a fine powder to produce cement.

The structure of the cement sector is shown in Figure 9 below. The structure features the current stock of dry and wet kiln technologies, and investment options that include more efficient kilns and those with CCS. The grinding process also has the option to use lower clinker blends, to produce low clinker cement. Differences in clinker-cement ratios between regions are captured to reflect current production practices.

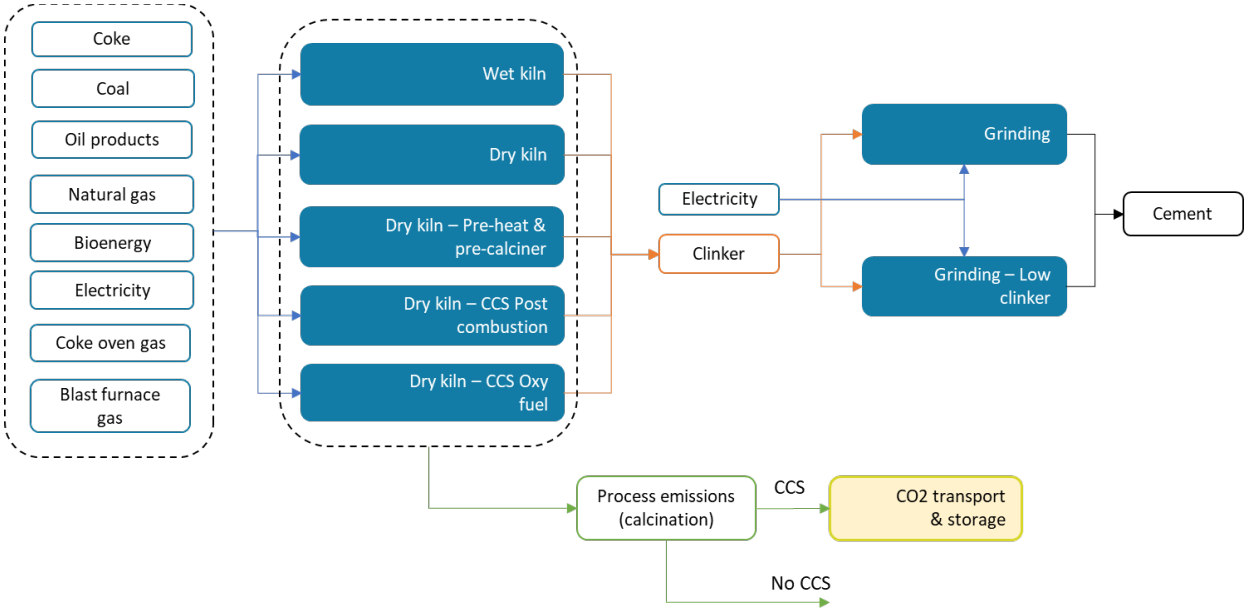

Figure 9. Cement sector structure in OMNIA

Key data sources for the cement sector are provided in Table 10.

Table 10. Key data sources for the cement sector

Dataset	Description	Source
Production statistics	Cement and clinker production by country, 2000-2023	GCP-CEM - The Global Carbon Project CEMent-process emissions dataset (Andrew, 2019, 2024)
Process emissions (from clinker production)	Process emissions, 2000-2023	GCP-CEM - The Global Carbon Project CEMent-process emissions dataset (Andrew, 2019, 2024)
Energy per tonne produced benchmarks	Data metric provided directly by GCCA, based on their GNR project. Only selection of countries provided.	Getting the Numbers Right (Global Cement and Concrete Association)(GCCA, 2024) ; IEA roadmap (IEA, 2018)
Technology costs	Current and future technology cost estimates	(Lerede et al., 2021)

3.3 Conceptual linkage between ENGAGE and OMNIA

IAMs typically do not include detailed representations of critical flows of materials along supply chains, as well as across the entire lifecycle of goods and services. As a result, they often overlook the potential effects that some circular economy actions, such as reuse and recycling of materials, may have on the economy, on the demand of specific commodities (e.g. secondary metals) and ultimately on decarbonisation strategies. To address this issue and incorporate a more comprehensive representation of circular economy opportunities for climate change mitigation in key industrial sectors, we aim to

establish a link between OMNIA and ENGAGE—which considers feedback between the two models.

This linkage will harness the strengths of both models. While OMNIA provides a detailed representation of industrial technologies and their energy consumption (which a global economic model such as ENGAGE does not model in detail), it lacks the representation of material flows needed for assessing circular economy policies. In particular, it does not capture the flow of materials through domestic and international supply chains—as the ENGAGE model does—from ore mining to scrap recycling, and how this translates into demand for energy services, a key input to OMNIA. Unlike ENGAGE, OMNIA does not represent trade in materials, goods and services, which are crucial to evaluate the impact of decarbonisation and circular economy policies across regions and sectors.

In the OMNIA-ENGAGE linking approach, energy system configurations and emission reduction pathways will be passed from OMNIA to ENGAGE, leveraging OMNIA's detailed technological representation of energy system transformation and the uptake of low-carbon industrial technologies. Based on this specific energy system configuration, ENGAGE determines an economy-wide equilibrium by adjusting upstream and downstream markets. Subsequently, the adjusted demand for goods and services, e.g. metals and construction materials, and changes in GDP will be fed from ENGAGE to OMNIA to update the demand requirements for such products in OMNIA, regional production profiles, and resulting energy demand. This process takes advantage of ENGAGE's capability of capturing how decarbonisation and circular economy policies impact material use, trade and supply along the entire economy, and how these changes in economic activity affect regional GDP. This conceptual flow of information and outputs is summarised in Figure 10.

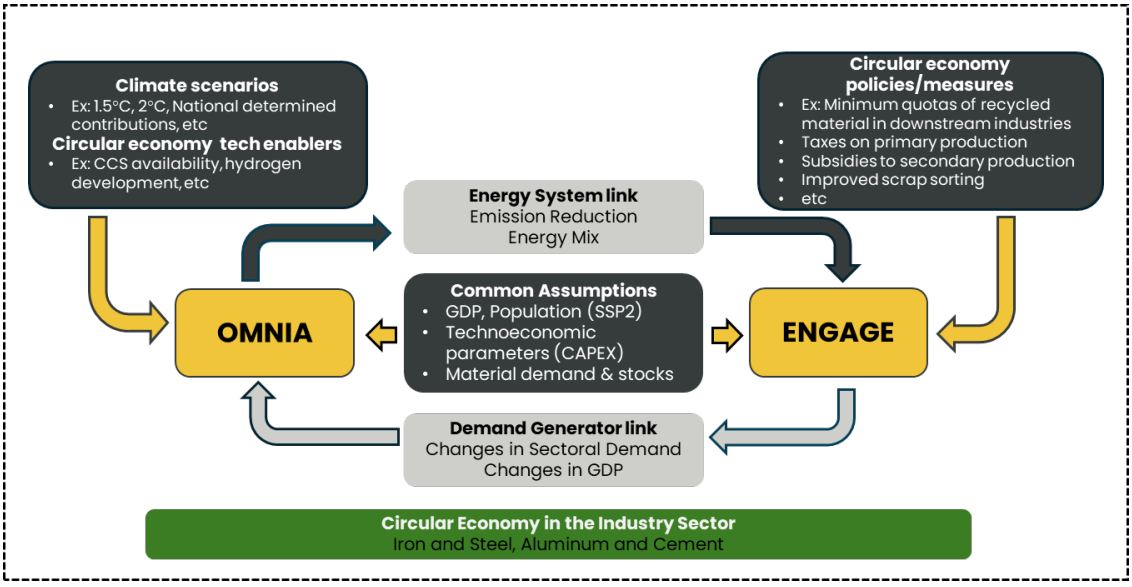

Figure 10. Diagram of the conceptual linkage and information flow between ENGAGE and OMNIA

At the core of the linkage are shared assumptions that are exogenously imposed on both models, i.e. socioeconomic pathways, technology costs and efficiencies, climate policies (i.e. carbon pricing), and material demand and stock dynamics, ensuring consistency across models on key scenarios assumptions.

The linkage is iterative, meaning that information is transferred multiple times between OMNIA and ENGAGE. With each feedback loop, the outputs of both models become more aligned by minimising

the changes in the energy system and demand generator. Depending on the question and scenario being assessed, the starting condition could be from either of the two models. The stopping criteria will be case specific and will require an *ad hoc* tuning process. In any case, due to time constraints, the linkage will be constrained to either 5 iterations or to a threshold value of less than 5% change in the energy system and demand generator after n iterations.

The linkage allows OMNIA to assess the implications of different decarbonisation pathways/net-zero targets in an integrated manner with circular economy policies, helping to highlight synergies, trade-offs, and rebound effects from an economy-wide perspective. In the same way, the linkage allows ENGAGE to incorporate detailed energy system dynamics into a macroeconomic analysis, enabling a more comprehensive evaluation of how decarbonisation pathways and circular economy policies affect economic performance, sectoral transitions, trade, and regional welfare. This leads directly to new IAM capabilities, as key economic activities related to circularity will be incorporated, eventually enabling to quantify how relevant policy interventions can contribute to energy, resource and emissions cuts, while increasing the technology granularity for key circular economy sectors under previous and new mitigation scenarios.

Various circular economy fostering measures can be assessed through this linkage. For example, establishing minimum requirements of secondary material content in final products, implementing taxes/subsidies incentives to increase scrap-based production, increasing material efficiency across supply chains, and introducing trade restrictions to encourage local recycling and reuse, among others.

Similarly, this modelling framework can be used to assess alternative climate scenarios, thereby enhancing our understanding of the impact of decarbonisation pathways on the use of resources. For example, it can explore trajectories aligned with 2°C and 1.5°C climate targets, as well as scenarios involving varying degrees of temperature overshoot.

3.4 Information flows in ENGAGE-OMNIA under example scenarios

3.4.1 Reference scenario

In the reference scenario, both models are expected to be aligned to reproduce similar regional emissions pathways as well as consistent energy system and industrial transformations through 2050. Special attention is given to the evolution of these trajectories over time, allowing for differentiation between short- and long-term impacts, as well as to the structural characteristics of the system in the final year, 2050. The specific characteristics of the reference scenario will be defined later in the project based on the agreed scenario protocol for Task 5.4. At this stage, an NDC baseline has been proposed as the reference scenario. This baseline assumes the implementation of the most recent NDC pledges to 2030, followed by a continuation of emissions beyond 2030, capped at the same level of GHG per unit of GDP per capita as in 2030. Note that there are other approaches for extrapolating NDC ambition (Sognnaes et al., 2021), which will also be considered in future scenario development.

The reference scenario in both models needs to represent a similar trajectory in terms of emissions, socioeconomic developments, energy system evolution, and industrial transformation to ensure consistency and comparability when assessing more ambitious climate and circular economy policy scenarios. Achieving this requires harmonised projections of demand and production of materials by

different technological pathways. Therefore, ENGAGE will adopt regional emissions trajectories, energy systems configuration, and secondary/primary production ratios for steel and aluminium from OMNIA to ensure alignment in the reference pathway. The harmonisation of common assumptions such as GDP, population techno-economic parameters and materials demand and stocks levels will help ensure internal consistency across models and improve the robustness of scenario comparisons.

3.4.2 Policy scenarios

Scenarios based on climate targets

In climate-driven scenarios, OMNIA will provide the starting conditions for the iterative exchange of information, as it offers more detailed bottom-up representation of emissions due to its granular technological representation. Therefore, OMNIA generates region-specific decarbonisation pathways and corresponding energy mixes, which are then used in ENGAGE to align its own decarbonisation trajectory and energy system with those of OMNIA. This is primarily done in ENGAGE by finding an appropriate level of a global carbon price that aligns regional emissions per capita with the targeted emissions trajectories from OMNIA. The alignment in regional emissions and energy systems modifies the relative prices in upstream and downstream industries changing production, consumption, trade and GDP in the economic model, which are then passed to OMNIA to update its sectoral demands (as shown in Figure 10). Subsequently, OMNIA is run again, incorporating the updated sectoral demands resulting from economy-wide adjustments. This iterative process is repeated until the convergence criterion is met. In this case, as the scenario is climate bounded, reaching a specific threshold in the change of CO_2 emissions between each iteration is an appropriate stopping criterion (for instance 5%, as suggested previously).

Increased material efficiency in final products

In circular economy-driven scenarios, where material efficiency implies that less steel and aluminium are used for the fabrication of final products, ENGAGE will provide the starting conditions for the iteration, as it has a more detailed representation of material usage and flows. Given a material efficiency target, ENGAGE will estimate the required changes in the demand/supply of materials along the entire supply chain, e.g., iron ore, bauxite, steel, aluminium and final products, accounting for general equilibrium effects including potential rebound effects and trade implications. ENGAGE will also estimate reductions in the availability of scrap, as the manufacturing process is now more efficient, which could lead to a potential decrease in secondary steel production. The adjusted demands, together with the resulting changes in GDP, will be passed to OMNIA. Demand for steel, aluminium and cement, and the shares of primary and secondary production are adjusted accordingly. OMNIA will still have the freedom to identify most cost-effective technologies for meeting the updated production requirements. Under these new industrial constraints, OMNIA will recalculate the structure of the energy sector and associated CO_2 emissions and then pass the updated emissions and energy information back to ENGAGE. As pointed out in the previous example, this process will be repeated until a predefined convergence or stopping criterion is met.

4 Route for intercomparison with OPEN-PROM

4.1 Summary of the OPEN-PROM model

OPEN-PROM is an open-source, global energy system and Integrated Assessment model built on the PROMETHEUS framework (E3 Modelling, 2018). It simulates the evolution of energy demand, supply, and emissions on an annual basis from 2020 to 2100 for 41 countries/regions globally, with the capacity to adjust the time horizon or regional resolution depending on the analytical scope. The model can be used for scenario analysis, evaluating how energy demand and supply evolve under different climate policy and technology assumptions, and examining potential impacts of industrial decarbonisation strategies at national, regional and global scales. Moreover, OPEN-PROM uses dedicated R-based frameworks: *mrprom* for preparing input data and *postprom* for processing outputs to ensure data transparency, consistency, and reproducibility.

Regional coverage and flexibility

OPEN-PROM has a detailed regional breakdown covering 41 regions. This includes all EU Member States individually, major global economies (e.g. China, USA, India, Japan), and aggregated regions (e.g. Latin America, Sub-Saharan Africa, Middle East and North Africa). However, for the purposes of this analysis and linkage, the same disaggregation of the OMNIA-ENGAGE models will be adopted to ensure that scenario comparisons and model results are immediately consistent and easier to interpret, without additional data disaggregation steps. This approach ensures that differences in results do not simply reflect variations in regional definitions, as will be further highlighted in the following sections.

Main features

OPEN-PROM describes the energy system by linking primary energy supply, conversion, and final consumption across three main sectors: industry (split into 10 industrial sub-sectors), transport (split into 6 transport modes), and buildings (split into residential, services and agriculture). Energy demand is endogenously calculated within the model, following different approaches depending on the sector. In the residential and tertiary sectors, demand is determined using an econometric top-down approach driven by exogenous macroeconomic indicators (e.g., GDP, population, household income) and endogenously calculated energy prices and technology costs. In the industrial sector, demand for energy services is linked to the activity levels of specific subsectors (e.g., industrial production volumes) and fuel or electricity prices, reflecting an activity-based approach. For the transport sector, the model integrates activity drivers both for passenger and freight transport modes with a detailed vehicle stock simulation for road transport, while other transport modes are represented through activity-based equations that depend on GDP growth and fuel prices.

On the supply side, OPEN-PROM includes detailed representations of power generation and hydrogen production. Power generation is simulated through capacity investment and system operation decisions based on an annual load duration curve approach. The portfolio of power generation technologies includes conventional thermal and nuclear plants, as well as renewables and emerging low-carbon options (including solar PV, CSP, wind onshore and offshore, biomass with and without CCS, hydro, geothermal). Dispatch decisions consider variable operating and fuel costs, while investments in new

capacity respond to growing electricity demand, plant retirements, and capacity reserve margins. The competition of power technologies for new capacity additions depends mostly on their relative LCOE (Levelised Cost of Electricity) including capital, operating and maintenance, fuel and carbon costs. Hydrogen supply is modelled through five centralised production pathways including the traditional route, steam methane reforming (with and without CCS) and water electrolysis, that include capital, operational, and feedstock expenses. The model also considers technology lifetimes and early retirement for power and hydrogen production plants.

Technology uptake

In general, technology uptake throughout the energy system is driven by a cost-based substitution mechanism that incorporates capital, operational, and fuel costs, as well as parameters reflecting technological maturity and user preferences (e.g. in the transport sector) that determine the market share of different technology options. The model uses a logit function, which simulates the gradual diffusion of competing technologies in the market depending on their relative costs, rather than assuming an immediate switch to the least-cost option. It also incorporates endogenous premature scrapping of existing equipment, capturing the acceleration of technological change under ambitious climate policies or shifting market conditions due to specific policies

General Assumptions and inputs

- Population and GDP data are derived from the latest SSP2 scenarios (as for OMNIA-ENGAGE)
- Technoeconomic costs: are mostly derived from the WEO 2024/2023 (free dataset - (IEA, 2024)), the PRIMES EU Reference Scenario, and the IEA Technology Roadmaps Assumptions (IEA, 2020a)
- Historical Years for calibration: from 2010-2020

4.1.1 Industry model in OPEN-PROM: general approach

The industrial sector is divided into nine subsectors: Iron and Steel, Non-Ferrous Metals, Chemicals, Non-Metallic Minerals, Paper and Pulp, Food Drink and Tobacco, Engineering, Textiles, and Other Industrial sectors. It currently includes both non-substitutable electricity demand (e.g., lighting, ICT systems) and substitutable energy demand (e.g., process heat and steam for industrial processes). In the present model version, the representation of industrial energy use relies on a cost-based substitution mechanism. It includes premature scrapping to capture rapid technology shifts driven by energy prices or policy signals.

However, the current version of the model does not yet incorporate detailed technological pathways at the process level for key industrial activities. In the following sections, we describe the new modelling design currently under development. This new approach aims to introduce technologically rich details for critical energy and carbon-intensive subsectors and in particular, iron and steel, cement, and aluminium, to integrate the assessment of industrial decarbonisation, circular economy practices and material reuse potentials more effectively in line with the ENGAGE-OMNIA Circular Economy framework and the objectives of this deliverable.

In the enhanced industrial module under development, the evolution of material demand will be satisfied with the existing capacity stock at base year. In future years, the gap between existing capacity and the level of material demand (due to increased demand for materials or to decommissioned plants) is calculated at the sub sectoral level for each region and year, and it is then satisfied by the available technological options (potentially low-carbon technologies) that combine cost competitiveness with technological maturity and other relevant constraints. This mechanism mirrors the approach already implemented in the existing industrial module, where new investments respond to cost drivers and policy incentives, and the premature scrapping of existing capacity is explicitly included to capture rapid technology shifts driven by market and policy dynamics but with an improved technological detail for the sector of interest (steel, aluminium and cement).

4.1.2 Structure of the Iron and Steel Sector in OPEN-PROM

In the new design of the iron and steel sector, steel production is disaggregated into the three main existing routes: BF-BOF (Blast Furnace – Basic Oxygen Furnace), DRI-EAF (Direct Reduced Iron – Electric Arc Furnace) and scrap-EAF (scrap-based Electric Arc Furnace). The first two are based on coal and natural gas. Steel production data at the country level are retrieved from World Steel Association Statistics (World Steel Association, 2025) which provides the share between BOF and EAF production. For the disaggregation of DRI-EAF and scrap-EAF, Midrex statistics (Midrex, 2023) are used that provide the steel production capacity data (million tons per year per plant for each country) and the World Steel Association provides the sponge iron production by country.

Fuel consumption (final consumption by fuel) for the iron and steel sector is primary sourced from ENERDATA, and it is cross-checked with other energy statistics, in particular with the IEA database. The disaggregation into the three existing production routes is performed based on the types of fuel typically associated with each route, the corresponding production levels, and benchmark values for specific energy consumption of the route. Any remaining fuel consumption that cannot be attributed to one of the three routes is allocated to a generic iron and steel process.

The calibration of base year fuel consumption across technology routes is both complex and time-consuming and often highly sensitive to the regional disaggregation due to inconsistencies in energy balances and variations in national accounting practices. The OMNIA-ENGAGE linked model and OPEN-PROM operate with different regional definitions. Hence, OPEN-PROM will receive the fuel disaggregation by route as input from the OMNIA-ENGAGE framework, based on the regions of the latter for the base year/historical data. This approach avoids duplicating effort and supports better harmonisation across modelling activities.

Future decarbonisation pathways included in OPEN-PROM advanced routes such as DR-EAF BAT fed by natural gas, BF-BOF-BAT, BF-BOF with CCS, DR-EAF with CCS, and H2-DR-EAF (hydrogen-based DRI) and smelting reductions options SR and SR-CCS. Hydrogen supply is centralised in the model and can be characterised at the country level. Other electrified options with lower technology readiness levels (TRL) may also be included in future scenario assessments.

4.1.3 Structure of the Aluminium Sector in OPEN-PROM

The aluminium sector is a significant energy consumer and plays a crucial role in circular economy

strategies and industrial decarbonisation pathways as already outlined in this deliverable. As the modelling design is still under development, some elements of the representation and data sources may be refined or updated in future model versions as new datasets become available. For the base year calibration, aluminium production is disaggregated into the two main technological routes: primary production, based on bauxite refining (Bayer process) and Hall–Héroult electrolytic smelting with carbon anodes, and secondary production, which involves remelting recycled aluminium scrap in furnaces. Data sources for this calibration include the US Geological Survey (USGS, 2024), the International Aluminium Institute (IAI) (IAI, 2024), and regional aluminium recycling statistics (e.g., Alucycle (IAI, 2025)).

The balance between primary and secondary production is a key driver of future decarbonisation in the aluminium sector. In OPEN-PROM, this balance will be represented as an external scenario input and will be differentiated by region/country. Future projections of secondary aluminium production will be aligned with scenarios that consider scrap availability, circular economy measures, and projected global aluminium demand.

For future low-carbon technology pathways, the model will include options such as the adoption of inert anode electrolytic smelting (which eliminates process CO_2 emissions from carbon anodes), the application of carbon capture and storage (CCS) to conventional carbon-anode smelters, and the use of hydrogen or electrification for upstream calcination and process heat in alumina refining. These low-carbon pathways will be characterised by key technoeconomic parameters, including specific energy consumption, fuel mix shares, technology costs (CAPEX and OPEX), technical lifetimes, process emissions (including those from anode consumption), and CCS capture rates, if applicable. Regional variations in technology deployment and performance will be captured by applying region-specific multipliers to techno-economic parameters derived from literature and data sources. When possible, the same assumptions of OMNIA will be used.

4.1.4 Structure of the Cement Sector in OPEN-PROM

This section outlines the planned approach for representing the cement and clinker sector in OPEN-PROM. As this design is still under development, some aspects of the representation and data sources may be revised or updated in future model versions to incorporate updated datasets and reflect new developments in low-carbon cement production practices.

The cement and clinker sector are key energy-intensive industry that plays a central role in the decarbonisation of material production. In the current design, the model represents cement production as a single, integrated process that includes both clinker and the associated cement production through the clinker-to-cement ratio parameter that will be included as an input of the model derived by GCCA database (GCCA, 2024) for the available country in the base year and as projection from IEA Technology Roadmap for Cement (IEA, 2018). Although the steps of clinker and cement production are not modelled separately, the approach captures the overall energy use and emissions associated with cement manufacturing.

For the existing production capacity, the model employs a generic representation of an existing process, the dry-process rotary kiln technology, reflecting the fact that this technology is now utilised in nearly all cement plants worldwide. However, there are regional differences in the energy intensity of cement production, which will be captured through a region-specific calibration of the "existing" technology.

For future decarbonisation, the model will include an option for best available technology (BAT) dry-process kilns coupled with different options for carbon capture and storage (CCS), and an external scenario assumption on clinker substitution strategies. Specifically, the reduction of the clinker-to-cement ratio which involves increased use of supplementary cementitious materials like fly ash or slag will be modelled exogenously by reducing the demand for clinker production in line with circular economy and material efficiency pathways.

Historical cement production data are expected to be drawn from sources such as the USGS (USGS, 2025) and IEA statistics. At the same time, future demand projections will be based on external scenarios (e.g., IEA World Energy Outlook 2023 extended data (IEA, 2023)) and the IEA Cement Technology Roadmap (IEA, 2018) while ensuring consistency with the ENGAGE-OMNIA assumptions. A key input in the model is the clinker-to-cement ratio, which influences the share of primary and secondary materials used and, thus, the energy intensity of cement production. This ratio is managed as an external input to the model rather than calculated endogenously. Its evolution over time and by region will be aligned with external scenario assumptions (e.g., IEA Cement Technology Roadmap), reflecting improvements in material efficiency and circular economy practices. By treating the clinker-to-cement ratio as an input, the model can incorporate alternative material efficiency improvements (that may be aligned with ENGAGE) while respecting its current structure and limitations.

New cement process technologies will be characterised by specific fuel consumption (GJ per tonne of cement produced), fuel mix shares for blended fuels, technology costs (CAPEX, OPEX), maximum availability factor, technical lifetime, process emissions (CO2 per tonne of cement produced), and capture rate for CCS technologies. Regional variations in costs and deployment will be captured by applying regional multipliers to techno-economic parameters derived from literature and expert sources when available. When possible, the same assumptions of OMNIA will be used.

4.2 Circular economy representation in OPEN-PROM

OPEN-PROM is a simulation-based energy system model and does not currently include explicit representations of material flows including trade of feedstocks and waste. As such, it cannot endogenously model circular economy dynamics in terms of mass balances or material stock-flow interactions.

However, different circular economy strategies such as material efficiency improvements, increased recycling rates, or reduced primary material demand can be represented exogenously through scenario-specific assumptions on the activity level. For example, scenarios that represents high recycling rates or significant reductions in the use of a specific material can be captured by adjusting the input activity levels or material demands in relevant industrial processes. Moreover, the deployment of technologies with high scrap input (e.g., scrap-based electric arc furnaces) can be constrained or incentivised through additional constraints, allowing alignments with circularity-driven narratives. Subsidies for secondary production or penalties on energy-intensive primary routes can be used to accelerate the uptake of circular economy options if such policy signals are known or assumed in the scenario design.

In the iron and steel sector, the balance between primary production and secondary production (scrap-based steelmaking) is critical for circular economy pathways. In OPEN-PROM, this balance is represented as an external scenario input rather than calculated endogenously. Data on the share of scrap-based

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steel production can be directly retrieved from the OMNIA-ENGAGE models, ensuring alignment with circular economy strategies such as enhanced scrap collection, quality improvements for recycled steel, and increased recycling rates.

Similarly to iron and steel, in the aluminium sector, the distinction between primary aluminium production (from bauxite refining and electrolysis) and secondary aluminium production (from remelted scrap) is another key lever for circular economy implementation. OPEN-PROM calibrates separate energy intensities and fuel mixes for primary and secondary aluminium production, with the share of secondary production also treated as an external scenario constraint that can be differentiated by country/region. This share can be directly informed by OMNIA-ENGAGE scenario assumptions, enabling the model to reflect scrap availability, recycling policies, and circular economy strategies aimed at reducing the demand for new primary aluminium.

In the cement sector, circular economy practices are captured through the clinker-to-cement ratio, which determines the share of supplementary cementitious materials (e.g., fly ash, slag) and directly influences the overall energy and emissions intensity of cement production. While material flows are not explicitly represented in OPEN-PROM, the clinker-to-cement ratio is managed as an external scenario input and can be retrieved/calibrated to ensure alignment with OMNIA-ENGAGE model results for specific scenarios. This ensures that material efficiency improvements in the cement sector such as increased blending of clinker substitutes—are consistently reflected in scenario analyses.

In general, material efficiency measures such as lightweighting in end-use sectors or extending product lifetimes are captured in the form of adjusted activity levels (production) in OPEN-PROM. This ensures that reductions in primary material demand driven by circular economy strategies are consistently integrated within the energy system model and OPEN-PROM can be used to assess the potential impacts of circular economy measures for national, European and global decarbonisation pathways.

4.3 Enhanced representation of circular economy in OPEN-PROM

The harmonisation with the OMNIA-ENGAGE link, built upon the CGE structure of ENGAGE, which captures real material flows, trade patterns, and the impacts of specific circular economy policies, will enable OPEN-PROM to reflect circularity implications through more coherent and data-driven input assumptions. This linkage allows OPEN-PROM to simulate the impacts of circular economy scenarios based on more sophisticated, science and economy-based calculations, rather than relying solely on exogenous assumptions.

To support a coherent comparison exercise, OPEN-PROM will be run using the same regional definitions adopted in the OMNIA-ENGAGE framework. This alignment of regions ensures that differences in outcomes across models can be attributed to model structure and assumptions, rather than inconsistencies in spatial aggregation. The comparison will focus initially on the industrial sector, where a key assumption for harmonisation is that, in the calibration year (base year), technological routes that are comparable across models will be disaggregated consistently by fuel use and technology type. This is essential because both models rely on initial year data as the reference for future scenario projections and aligning the initial fuel and technology share is necessary to maintain comparability across scenarios. In fact, OPEN-PROM uses ENERDATA and IEA as the main source for calibrating fuel consumption in historical years, while OMNIA relies on the UN Energy Balances. The comparison will

therefore involve aligning fuel use and technological share for the base year across at least the following fuel categories: coal, natural gas, fuel oil, biomass, and electricity and for each industrial subsectors i.e. steel, cement and aluminium. These categories are also the main inputs to technoeconomic datasets used for modelling new low-carbon technologies in the industrial sector.

A critical element for comparison will be the technoeconomic data associated with these technologies. When possible, the techno-economic data will be aligned at least for the industrial technologies described in OMNIA and OPEN-PROM that have a similar level of technological detail. This will allow a direct comparison of technology costs (including both CAPEX and OPEX) and performance assumptions across models, which is important because these costs are a key driver of technology uptake in alternative scenarios. Fuel prices are treated as exogenous in both OPEN-PROM and OMNIA-ENGAGE. Therefore, comparing fuel price assumptions between the two models can help identify further sources of potential discrepancies in the results.

The link between OPEN-PROM and OMNIA-ENGAGE also extends beyond basic fuel and technology data, as OMNIA-ENGAGE provides key system-level drivers such as the energy system configuration derived from the OMNIA model and the associated CO_2 emissions for comparison. Moreover, the GDP changes that directly affect material demand from ENGAGE will be used in OPEN-PROM. Lastly, the results from OMNIA-ENGAGE framework will provides external scenario constraints on the share of primary and secondary production for steel and aluminium, reflecting raw material constraints (e.g., scrap availability) and trade of commodities. These drivers are not explicitly represented in OPEN-PROM but are crucial for aligning the representation of circular economy practices and material efficiency measures in the two models.

OPEN-PROM will integrate the main scenario assumptions developed within OMNIA-ENGAGE by adopting key inputs and aligning core drivers for each specific scenario. Referring to examples of scenarios presented in 3.4 we will provide here a high-level overview of how the insights and results deriving from the link between OMNIA-ENGAGE will be integrated also with OPEN-PROM to improve the representation of circular economy. Energy system configurations and material demand projections including GDP-driven changes will be used as external scenario constraints, allowing OPEN-PROM to replicate the broader system dynamics represented in OMNIA-ENGAGE.

For instance, following the example scenarios presented in 3.4, in the case of a **scenario based on a climate target**, OPEN-PROM will integrate the regional decarbonisation pathways and detailed energy mix provided by OMNIA-ENGAGE. The shares of low-carbon technologies and the evolving energy system structure will be adopted to ensure that OPEN-PROM reflects consistent decarbonisation strategies and their related CO_2 emissions and reduction in the scenario.

Similarly, for an eventual **scenario of increased material efficiency**, OPEN-PROM will adopt the adjusted material demands such as reduced steel and aluminium usage and associated decreases in scrap production generated by linking OMNIA and ENGAGE. In this context, the shares of primary and secondary production for steel and aluminium, the changes in sectoral production described in the model, will be updated based on OMNIA-ENGAGE outputs.

5 Route for intercomparison with GCAM-Europe

5.1 Summary of GCAM-Europe model

GCAM-Europe (Global Change Analysis Model - Europe) is a dynamic-recursive model based on GCAM (Calvin et al., 2019). This sophisticated integrated assessment model accounts with technology-rich representations of the economy, energy sector, land use, and water linked to a climate model that can be used to explore climate change mitigation policies including carbon taxes, carbon trading, regulations and accelerated deployment of energy technology. Regional population and labour productivity growth assumptions drive the energy, land-use and water systems employing numerous technology options to produce, transform, and provide energy services, as well as to produce agricultural and forest products and to determine land use and land cover. Notably, GCAM-Europe's geographical disaggregation is highly detailed for the European continent. GCAM, by default, divides the world in 32 regions, and the European continent is divided into five different regions: EU-12, EU-15, Europe Eastern, Europe-non-EU, and European Free Trade Association (EFTA). In GCAM-Europe, all 39 European countries are disaggregated into individual model regions (Figure 11). Having this level of detail allows exploring the country-level effects of European policy packages or transformational strategies, as well as the potential international effects (e.g., carbon leakage) for a representative set of non-European regions (27) over the world. The list of all the regions represented in the model are presented in Table 11.

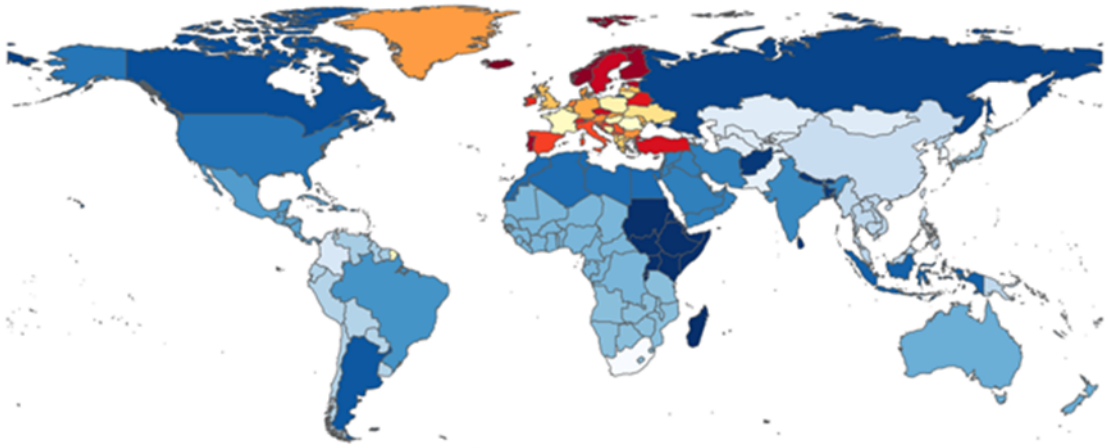

Figure 11. Regional disaggregation in GCAM-Europe.

Note: Yellow-to-red colours represent the regional groups that are explicitly disaggregated for this model. White-to-blue regions represent model regional groups that were part of the original model.

Table 11. List of model regions in GCAM-Europe

Model region (default)	Model region (new)	Model region (new)
Africa_Eastern	Austria	Lithuania
Africa_Northern	Albania	Luxembourg
Africa_Southern	Belarus	Macedonia
Africa_Western	Belgium	Malta
Argentina	Bosnia and Herzegovina	Moldova
Australia_NZ	Bulgaria	Netherlands
Brazil	Croatia	Norway
Canada	Cyprus	Poland
Central America and Caribbean	Czech Republic	Portugal
Central Asia	Denmark	Romania
China	Estonia	Serbia and Montenegro
Colombia	Finland	Slovakia
India	France	Slovenia
Indonesia	Germany	Spain
Japan	Greece	Sweden
Mexico	Hungary	Switzerland
Middle East	Iceland	Turkey
Pakistan	Ireland	United Kingdom
Russia	Italy	Ukraine
South Africa	Latvia	
South America_Northern		
South America_Southern		
South Asia		
South Korea		
Southeast Asia		
Taiwan		

In terms of sectors, the model expands (for the newly created European countries, and there may be differences by country based on data availability) in various dimensions. The representation of electricity grids and regional trade, as well as demand segments, allows to have more sectoral detail in the power sector by reflecting energy storage. In final energy demand, predominantly in buildings energy demand, new demand categories (e.g., hot water, cooking, or other appliances) and new technologies (e.g., heat pumps) are included, driven by high data availability for European countries. Behind the overall sectoral representation, there is a further deep-dive in terms of consumer group representation, relying on country-specific data (when available) in the food, transportation, and residential sectors.

Relevant for the iron and steel industrial sector, the GCAM-Europe considers a trade structure to represent the European Economic Area (EEA) and reflects the internal free-trade market in the European Union, Norway and Iceland. By default, commodity trade in GCAM (covering energy, food and some industrial commodities like steel and ammonia) is reflected through Armington elasticities (Armington, 1969), defining the level of substitution at the international market, and also within each region between domestically produced and imported commodities. In the update for GCAM-Europe, the trade of EEA countries is represented as one block with the rest of GCAM regions (including the newly isolated ones in GCAM-Europe, e.g., United Kingdom) in the international market. Within the EEA countries, there is another level of trade, again modelled through Armington coefficients, representing within-EEA trade

(Figure 12). The costs of international trade (between EEA and non-EEA countries/regions, e.g. between Germany and USA) are identical as trade costs between non-EEA countries/regions (e.g. between Brazil and USA) for each commodity, but within-EEA trade (e.g. between Germany and Spain) has lower cost in this updated representation, aiming to reflect lower trade barriers (and smaller distances) within the EEA. Apart from this improved trade representation, this function allows to represent common trade policies of the EU or EEA (e.g., CBAM) more easily in future modelling exercises.

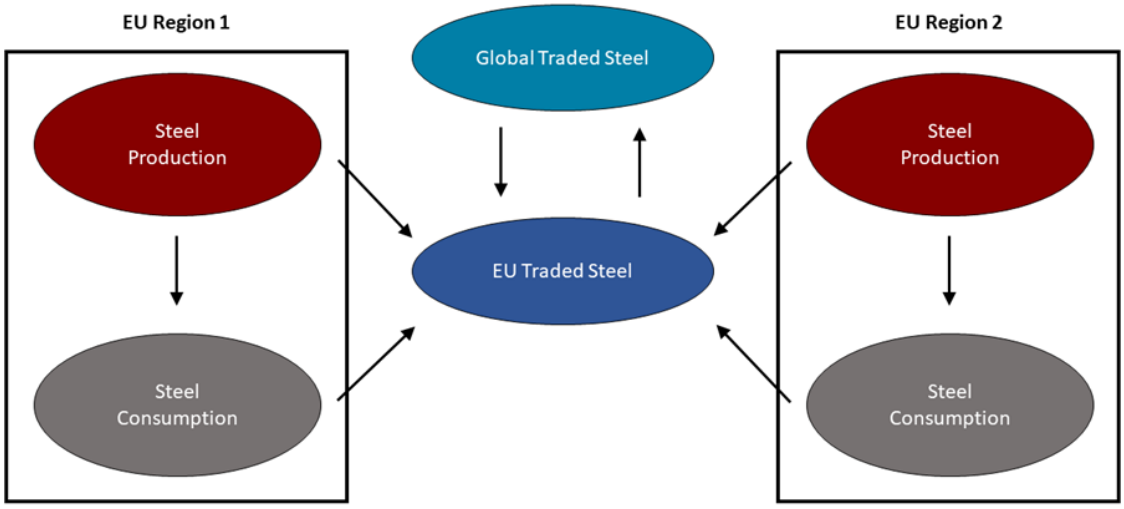

Figure 12. Graphical representation of EEA trade structure

5.1.1 General structure of industry sectors

GCAM-Europe represents six industrial sectors. In this deliverable, we will focus on the iron & steel, aluminium, and cement sectors. IEA energy balances or historical energy use are employed to calibrate the sectoral energy consumption, and historical data from different industrial associations is used to derive the sectoral outputs such as physical commodity flows. CO_2 emissions are implicitly calculated based on the fuel consumption and their inherent CO_2 contents. For each sector, the future industrial output growth is driven by GDP, income elasticities, and price elasticities.

The different industrial sectors' energy use is calculated using the future market shares of the different technologies and their fuel intensities. Energy use is subsequently multiplied by carbon emission factors to determine the total sectoral CO_2 emissions. In GCAM-Europe, the current and new technologies (i) compete for future market shares (S_i) using a logit-based discrete choice model (Eq. 1). The key inputs to this model include technology costs (p_i), share weights per technology ($\boldsymbol{a_i}$), and a logit exponent (γ).

$$\boldsymbol{S_i} = \frac{\boldsymbol{a_i p_i^{\gamma}}}{\sum_{j=1}^{N} \boldsymbol{a_j p_i^{\gamma}}} \qquad \textit{(Eq. 1)}$$

The technology costs (p_i) are calculated as a sum of exogenously specified non-energy costs ($/Mt) and endogenously calculated energy costs. The energy costs are computed by the model based on regional fuel prices ($/EJ) and the input fuel intensities (GJ/Mt) of the technologies. Furthermore, the price of carbon ($/t- CO2) is added to the cost of emissions associated with each technology in constrained

emissions scenarios. Meanwhile, the logit exponent (γ) and technology share weights (a_i) incorporate the impact of non-cost factors on the future market share. While the logit exponent determines the extent to which technology costs determine the market share, the technology share weights capture the impact of non-cost factors such as technology preferences, prevailing infrastructure, and barriers to technology deployment and implementation.

The technology share weights (a_i) are endogenously calibrated (based on historical market shares and costs) at the model base-year (2015). For existing technologies, these share weights are set to their 2015 values for all future model years. For newly introduced technologies, they are linearly increased from 0 in the base year until 2050, representing an increase in the development and acceptance of these technologies and an achievement of full competitiveness with other technologies by 2050.

Finally, industrial technologies are vintaged and operate until the end of their economic lifetime (phased retirement) unless the cost of operation reaches a point where it is no longer profitable (profit shutdown retirement). The lifetimes of industrial production facilities are also considered when estimating the future market share, and gross trade across regions is modelled using a logit-based Armington trade model (Zhao et al., 2022).

5.1.2 Structure of the iron and steel sector

GCAM-Europe incorporates a detailed representation of the iron and steel sector, considering existing technologies from blast furnaces (BF) and electric arc furnaces (EAFs) with either steel scrap or direct reduced iron (DRI) as the primary raw material, and emerging technologies that could allow for the decarbonisation of steel production by using CCS or hydrogen (Figure 13). The inclusion of this full suite of technologies allows for an assessment of the technological shifts that occur under emission mitigation scenarios.

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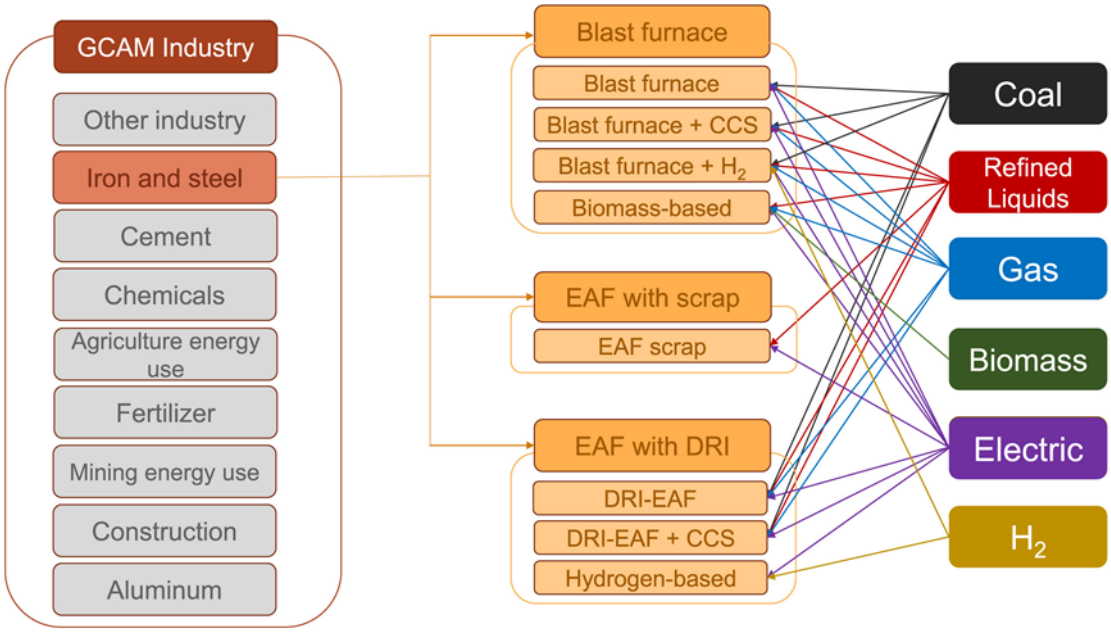

Figure 13. Technology representation of the iron and steel sector in GCAM as employed in this study (Speizer et al., 2023)

As detailed above, the technology share weights are endogenously calibrated with 2015 data. For EAF with scrap and BF, these share weights are also used for all the future model years; while for EAF with DRI, they are linearly increased by 2050. Further details can be found in Durga et al. (2024) and Speizer et al. (2023).

GCAM-Europe's steel industry sector is calibrated with historical data from a variety of sources. Currently, the data on crude steel production, apparent steel consumption (crude equivalent), imports and exports of semi-finished and finished steel products, and crude steel production by process (BF and aggregate EAF) are obtained from the World Steel Association (WSA) (World Steel Association, 2019). The EAF with DRI steel production is assumed to be equal to the historical DRI consumption (which is estimated using DRI production, imports, and exports data from WSA) (World Steel Association, 2021). The scrap-based EAF production is calculated by subtracting the calculated EAF with DRI production from the aggregate EAF production reported by WSA.

The total iron and steel energy use (by fuel) is obtained from the International Energy Agency's World Energy Balances (flow codes: IRONSTL, EBLASTFUR, TBLASTFUR, ECOKEOVS, and TCOKEOVS) (IEA, 2025). Total energy use data is used to disaggregate energy use by fuel for the prevailing steel production processes (BF, EAF with DRI, and EAF with scrap). The steel production non-energy costs are obtained from the Global Steel Cost Tracker (GSCT) database (Transition Zero, 2022). The GSCT database provides facility-level production cost data for BF and aggregate EAF technologies. These facility-level costs are averaged across countries and technologies to estimate the model input costs.

5.1.3 Structure of the aluminium sector

The aluminium production in GCAM-Europe involves two main steps: (1) alumina refining, to refine bauxite ore into alumina, and (2) aluminium smelting, to convert alumina to aluminium. Alumina refining

has multiple competing technologies, such as coal, refined liquids, gas, and biomass with and without CCS. Aluminium smelting uses alumina as an input and consumes electricity (Figure 14). The aluminium and alumina subsectors are calibrated using production and energy use data from the International Aluminium Association (IAA). This data from IAA is provided by broader aggregate regions and is down-scaled to individual countries and GCAM regions using country-level data on electrolytic aluminium production from the United States Geological Survey (USGS). For countries with recorded energy use but no production, energy use is adjusted to zero. The intensity coefficients for alumina/aluminium production technologies are estimated from IEA energy data and the country-level production data.

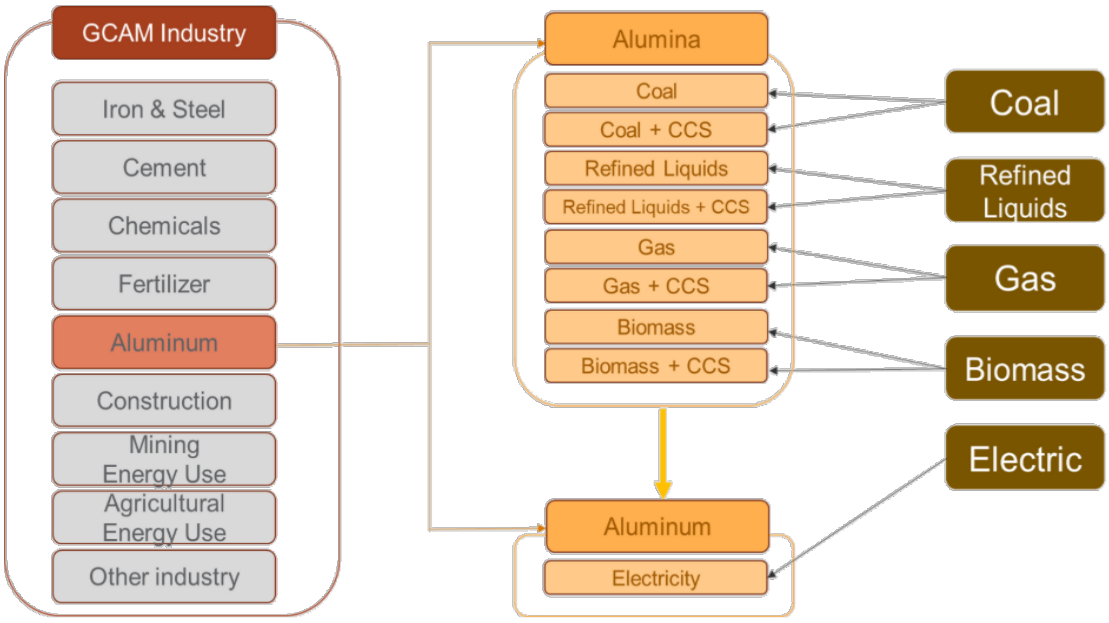

Figure 14. Technology representation of the aluminium sector in GCAM as employed in this study

5.1.4 Structure of the cement sector

GCAM-Europe includes a physical representation of the cement sector. It involves (1) the manufacture of cement (process heat cement) and the (2) final cement commodity. The first one produces cement, as well as fuel and limestone processes (Figure 15). From all of them, we track derived emissions of CO_2. The energy input-output coefficients are specific to each region, based on (IEA, 2007) tables. The limestone input-output coefficient is calculated to return the region's cement-related emissions reported by (Boden & Andres, 2017) and the regional fuel shares are calibrated through. Finally, there is a CO_2 capture and storage technology for cement production, wherein the CO_2 from limestone calcination (related to the industrial process) is captured. The costs of the capture technology are parameterised around Mahasenan et al. (2005).

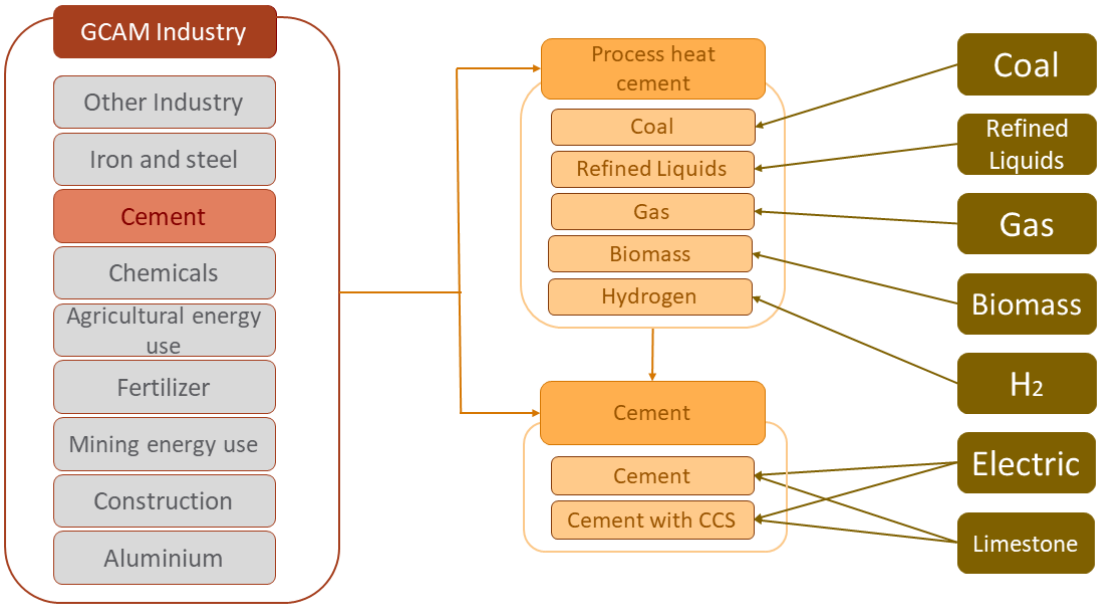

Figure 15. Technology representation of the cement sector in GCAM as employed in this study

5.2 Circular economy representation in GCAM-Europe

The representation of circular Economy in GCAM-Europe is currently limited and largely hidden in implicit parameters. Only in the iron and steel sector, the model explicitly represents circular economy through the use of scrap (applied in the technology EAF with scrap, see Figure 13). However, scrap is currently modelled as an unlimited global resource with a fixed cost. Its use relative to other technologies is determined by calibrated data in the base year (2015), providing a share weight (preference parameter) that governs its future use. In scenarios with strong climate action however, the use of scrap is growing strongly as the lower energy requirements relative to the use of primary steel is attractive from the point of least-cost climate change mitigation.

In the case of the aluminium, circular economy is not explicitly represented, but the use of secondary aluminium (aluminium scrap) is implicitly included in the energy requirements for aluminium production. Since aluminium production and energy requirements are taken from existing data, any energy/material savings from the use of secondary aluminium are included in the input-output (I-O) coefficients used in the model. The same is valid for the cement sector, where circular economy may also limit final cement demand. This demand is estimated by estimated global GDP elasticities, which implicitly considers any demand reductions driven by circular economy considerations in the past.

5.3 Enhanced representation of circular economy in GCAM-Europe

To better reflect real-world conditions and possibilities in the field of circular economy, GCAM-Europe will incorporate data from the ENGAGE modelling exercise in DIAMOND task 4.1. From the perspective of regional aggregation, outputs from the linked ENGAGE-OMNIA for the 5 aggregated European regions will be downscaled to the separate countries represented in GCAM-Europe. This will be achieved by applying the percentage change relative to the previous period calculated in the aggregated

ENGAGE-OMNIA regions to each of the included countries, and relative to the country-specific value of the previous year based on GCAM-Europe. While the application of structural model changes (e.g., adding additional technologies or resources to represent circularity) would depend on data availability and consistency with the current GCAM-Europe data structure, the representation of circular economy can be largely improved by adapting existing parameters and projections. Figure 16 shows a graphical representation of where these links with the ENGAGE-OMNIA scenarios can take place.

On the resource input side, circular economy can be enhanced for GCAM-Europe in several directions. In the case of iron and steel, where circular economy is partially represented explicitly through the modelling of scrap use, insights from ENGAGE results on realistic scrap availability, costs over time, and/or the final steel production using scrap-based technologies (see link (a) in Figure 16), can improve realism in future pathways of the sector under different scenarios. In the case of aluminium and cement, where the use of secondary inputs is implicit in I-O coefficients, findings from ENGAGE-OMNIA linkage can be represented implicitly by adapting the evolution of the coefficients for the original technologies to findings in ENGAGE-OMNIA scenarios (see link (b) in Figure 16). More specifically, based on the projected use of aluminium scrap to replace alumina and clinker substitutes (using "process heat cement" as approximate, see Figure 16) use in the ENGAGE-OMNIA scenarios, I-O coefficients in GCAM-Europe can be adapted to reflect the reduced use of primary production and materials, affecting energy and material use.

On the side of final demand for steel, aluminium and cement, GCAM-Europe uses stylised demand trajectories based on GDP and price elasticities. While historical circular economy applications are implicitly included in these elasticities, the model can be improved by considering final product demand (for steel, aluminium and cement) in ENGAGE-OMNIA scenarios with and without circular economy considerations (link (c) in Figure 16). Findings from ENGAGE-OMNIA can be represented either implicitly by adapting GDP elasticities, or explicitly by including a specific "resource" that replaces final demand for steel, aluminium and cement use.

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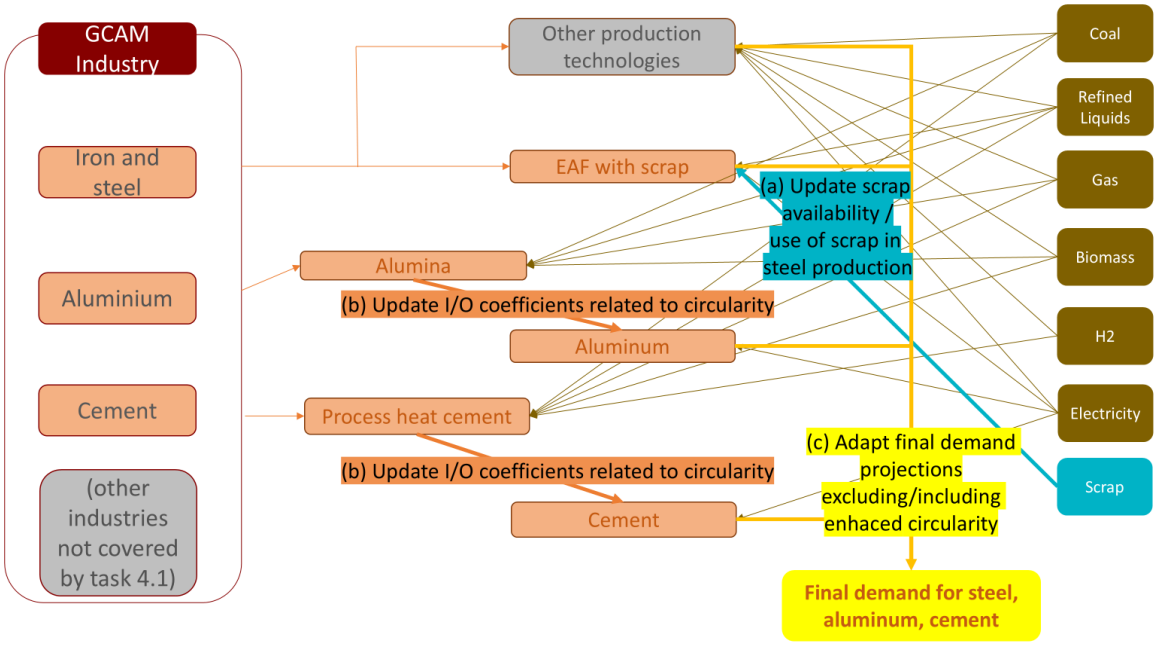

Figure 16. Summarised representation of steel, aluminium and cement sectors in GCAM-Europe, and projected modifications to link with ENGAGE-OMNIA scenarios

These three proposed links will be combined with the scenarios to be implemented in both models. Table 12 describes how these links would be combined for two example scenarios.

Table 12. Summary of links between GCAM-Europe and ENGAGE-OMNIA for different scenarios

Reference	Climate policy	Circular Economy
• Harmonised final product demand projections for steel, aluminium, and cement. • Harmonised use or availability of scrap for secondary steel production	• Idem as reference, but with climate policies (e.g. carbon prices) on top of other assumptions.	• Updated I/O coefficients aligned with use of secondary aluminium and cement. • Updated scrap use/availability • Updated final product demand related to longevity projections of final products

6 Towards model inter-comparison

To understand how different IAMs can capture circular economy dynamics in key industrial sectors, namely steel, aluminium, and cement, the outputs from the ENGAGE-OMNIA linkage and the other two IAMs (OPEN-PROM, and GCAM-Europe) will be compared under a set of common scenarios. This comparison will assess the extent to which each model incorporates the new information on material reuse and recycling provided by the ENGAGE macroeconomic model, and how such integration influences the projected outcomes. The comparison will focus on a set of key indicators that are critical to understanding the evolution of industry in decarbonisation scenarios. These include:

- **Global CO_2 emissions:** trajectory of the total emissions at a global level.
- **CO_2 emissions at the sectoral level:** emissions of key sectors (e.g. steel, aluminium and cement) at regional level.
- **Share of fuels in energy mix** use of different fuels and resources to provide the required final energy per region.
- **Share of technologies in electricity generation:** fraction of the electricity generation by technology in each region.
- **Final demand for materials:** demand for steel aluminium and cement products by regions.
- **Technology shares for production:** shares of technologies in the production of key materials (e.g. steel and aluminium) produced by different technology pathways.
- **Total investment costs:** investment required to deploy the new infrastructure for producing goods and energy.
- **Impact of circular economy policies:** impact in emissions and the economy of circular economy measures compared with the impact of other mitigation actions.

Comparisons will be made across models (to evaluate the effect of different modelling structures and assumptions) and within each model (with and without the integration of circular economy data from ENGAGE). This will help understand how different modelling approaches capture and integrate circular economy policies and how future improvements can be guided.

Table 13 presents a summary of the main characteristics of each model and how the proposed link between the IAMs and ENGAGE will be implemented. It is important to note, however, that all three IAMs are currently undergoing modelling development. The precise implementation of the ENGAGE linkage, as well as the exact variables and metrics used for comparison, will need to be refined as the models become operational. Therefore, the intercomparison should be seen as an iterative process that will evolve as actual insights from model testing emerge.

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Table 13. Summary of the main model characteristics and of the proposed linkage.

		ENGAGE	OMNIA	OPEN-PROM	GCAM-Europe
Type of model		Recursive dynamic CGE	PE model on energy, water and land instantiated in the TIMES framework	Simulation, Recursive Dynamic Energy System Model	Dynamic PE
Timeframe of analysis		2017 to 2050 annual basis	2019 to 2100 5-annual basis	2010 to 2100 annual basis (flexible)	2015 to 2100 5-annual basis
Geographical representation		5 European regions + 23 RoW regions	5 European regions + 23 RoW regions	Harmonised to OMNIA: 5 European regions + 23 RoW regions	39 European regions + 27 RoW regions
Explicit representation of material flows		Yes, in monetary terms	No	No	No
Standard representation of circular economy	**Steel**	BF-BOF, DRI-EAF, scrap-EAF production of two scrap qualities	BF-BOF, DRI-EAF, scrap-EAF scrap as infinite feedstock	BF-BOF, DRI-EAF, scrap-EAF scrap as infinite feedstock	BF-BOF, DRI-EAF, scrap-EAF scrap as infinite feedstock
	Aluminium	Primary, secondary and scrap	Primary and secondary with exogenous shares of production.	Primary and secondary with exogenous shares of production.	Alumina and aluminium. Share of secondary captured by exogenous adjustment factor.
	Cement	One sector	clinker and cement	one sector	Process heat cement and cement
Improved representation of circular economy after linkage	**Steel**	Secondary production limited by scrap quality and availability. Shifts in demand due to endogenous GDP changes		Scrap use/availability. Shifts in demand due to endogenous GDP changes	Scrap use/availability. Shifts in demand due to endogenous GDP changes
	Aluminium	Secondary production limited by scrap quality and availability. Shifts in demand due to endogenous GDP changes		Updated primary and secondary shares.	Updated coefficient to represent alumina to aluminium energy and emissions
	Cement	Material efficiency		Updated efficiency from cement production.	Updated coefficient to represent process heat cement to cement energy use and emissions
Type of link with OMNIA-ENGAGE		Bidirectional feedback loop		Unidirectional. Inputs received from OMNIA-ENGAGE	
Variables that are received in the link		Energy generation by fuel/technology. CO2 emissions.	Demands for final products. Production of commodities by pathway. Changes in GDP.		

Notes: CGE: computed general equilibrium; PE: partial equilibrium; RoW: rest of the world

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8 Appendix

Table 14. Correspondence between ENGAGE steel related sectors and PIOLab activities

ENGAGE sectors	ENGAGE description	PIOLab activities
I_M	Iron mining	Mining
BF	Blast furnace	Blast furnace, Open hearth furnace
DRI	Direct reduction of iron	Direct reduction
BOF	Basic oxygen furnace	Basic oxygen converter
DRI-EAF	DRI based EAF	Electric arc furnace
HQS-EAF	Scrap based EAF	
LQS-EAF	Scrap based EAF	
HQS	High quality steel scrap (prompt)	Scrap preparation
LWS	Low quality steel scrap (obsolete)	
MTP	Metal products	Manufacture of fabricated metal products
MVT	Motor vehicles and transport equipment	Manufacture of motor vehicles, Manufacture of other transport equipment
ELE	Electronic equipment	Manufacture of office machinery and computers, Manufacture of medical, Manufacture of radio
MAE	Machinery and other equipment	Manufacture of machinery and equipment n.e.c., Manufacture of radio, Manufacture of electrical machinery and apparatus n.e.c.
OMA	Other manufacture	Manufacture of furniture
CNS	Construction	Construction

Note: n.e.c. = not elsewhere classified

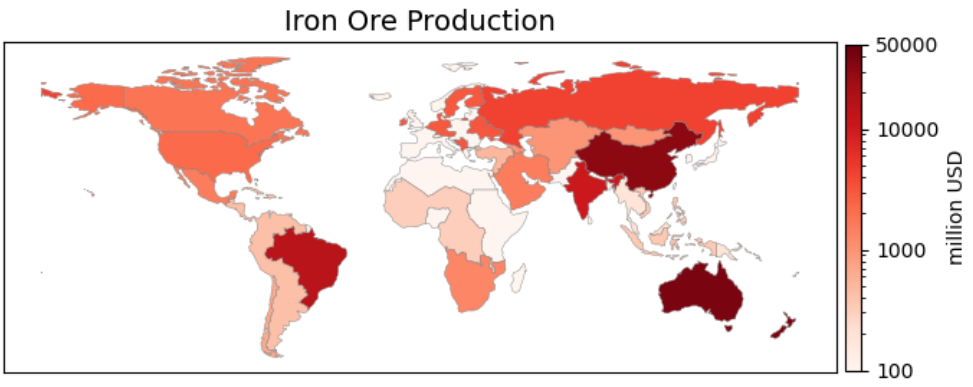

Figure 17. Annual production of iron ore by regions in ENGAGE for the base year

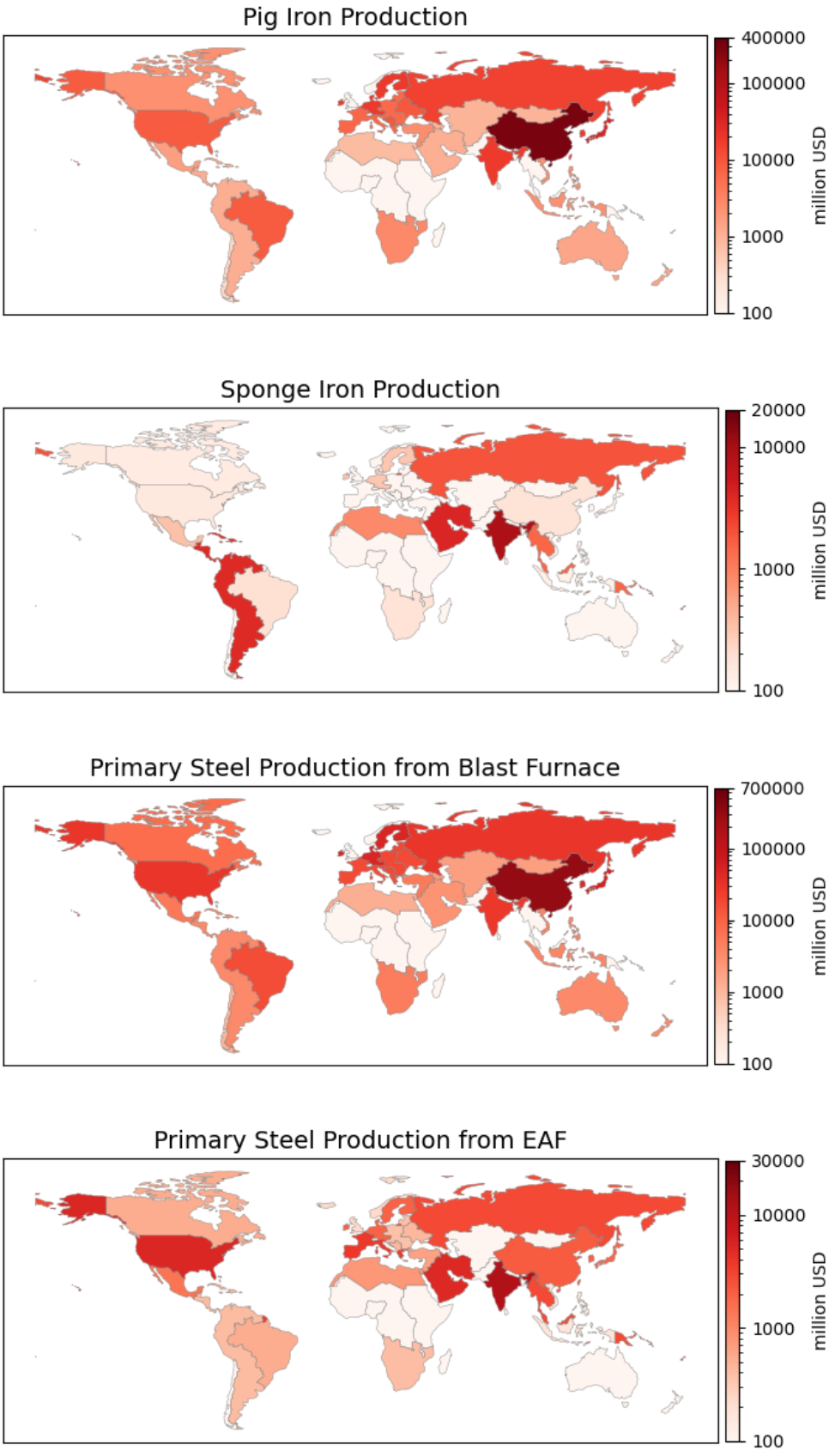

Figure 18. Annual representation of production of commodities of the primary steel pathway by regions in ENGAGE for the base year

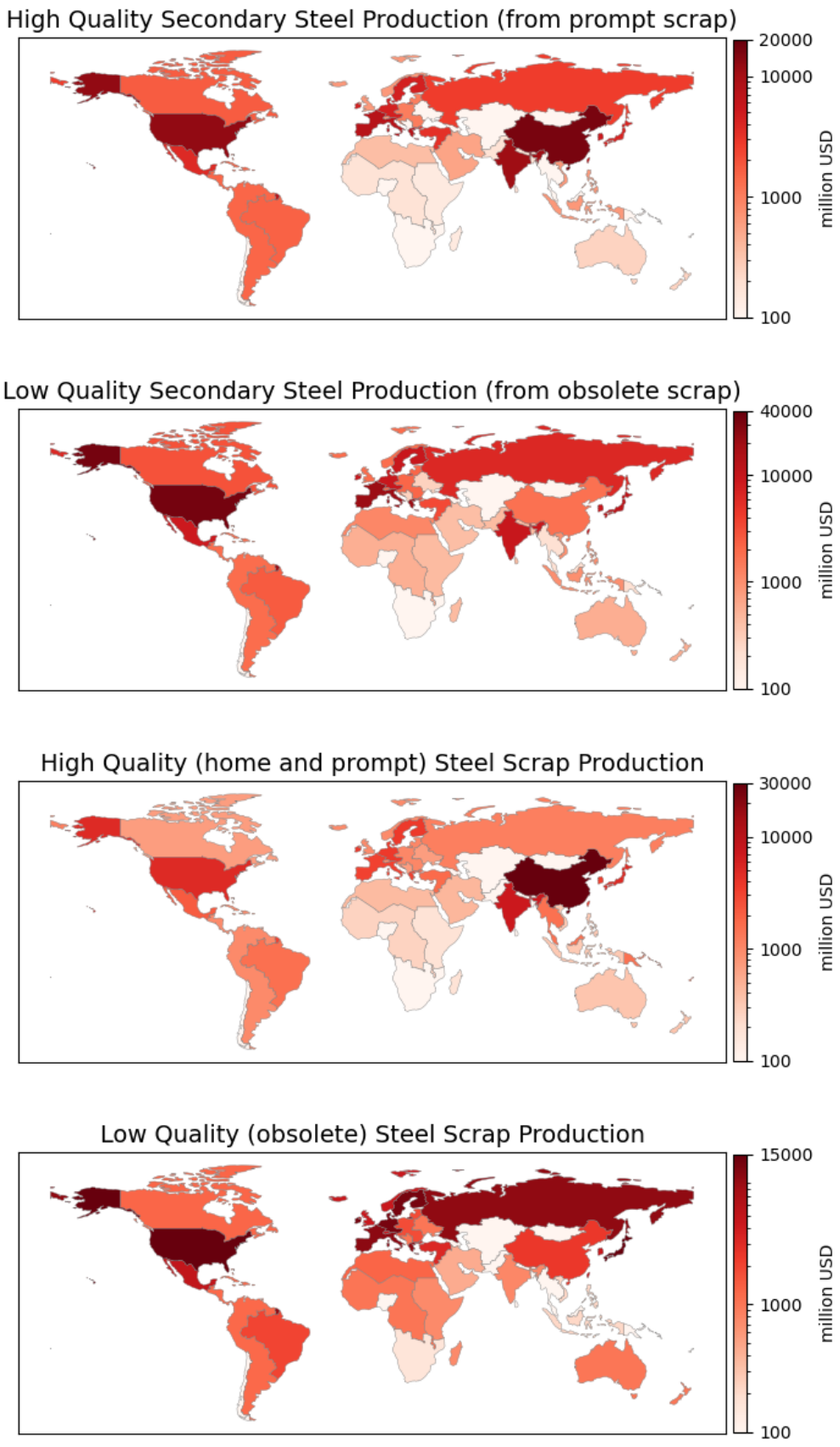

Figure 19. Annual production of commodities of the secondary steel pathway by regions in ENGAGE for the base year

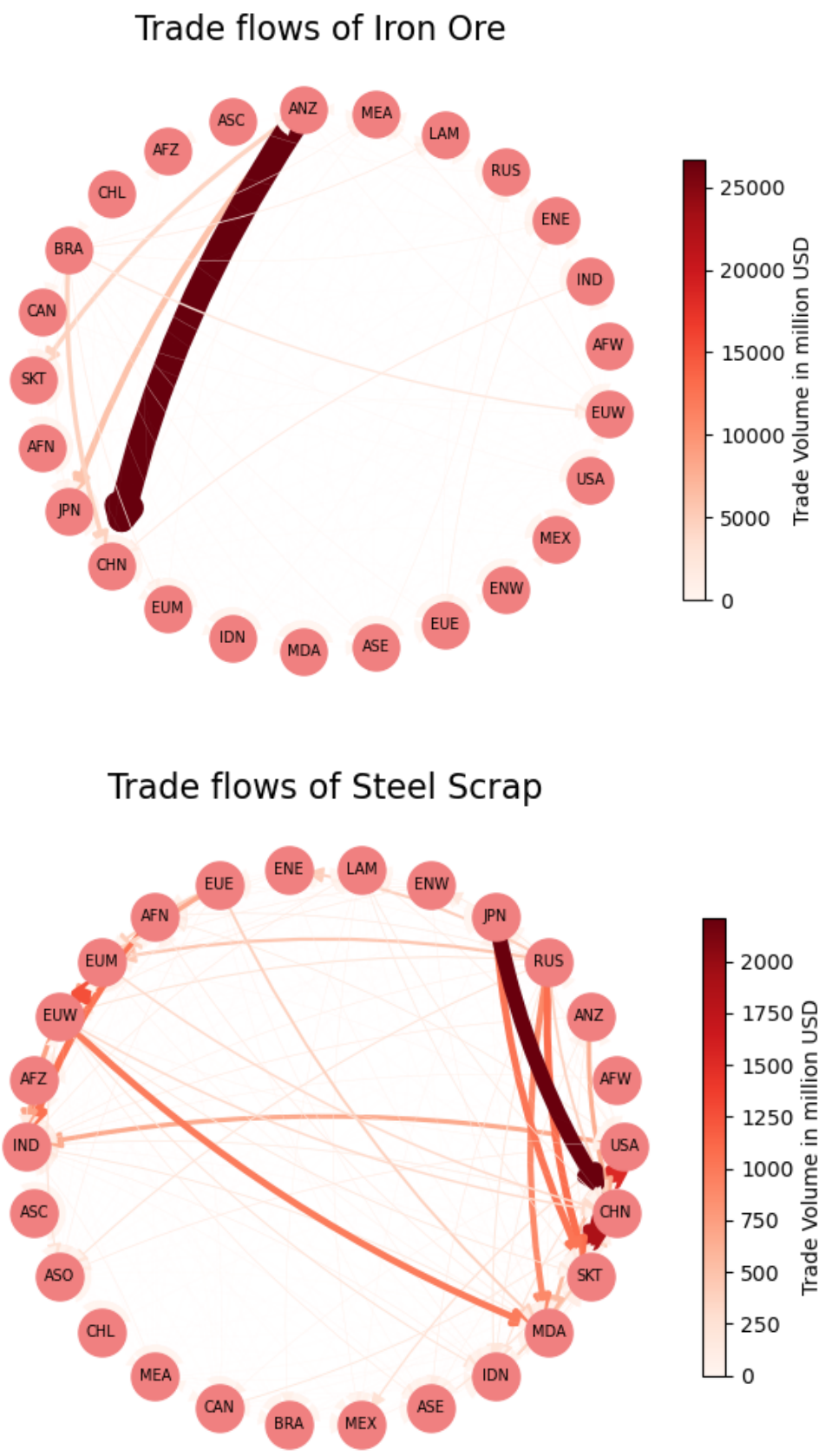

Figure 20. ENGAGE's representation of the annual trade flows of primary materials for steel production in the base year

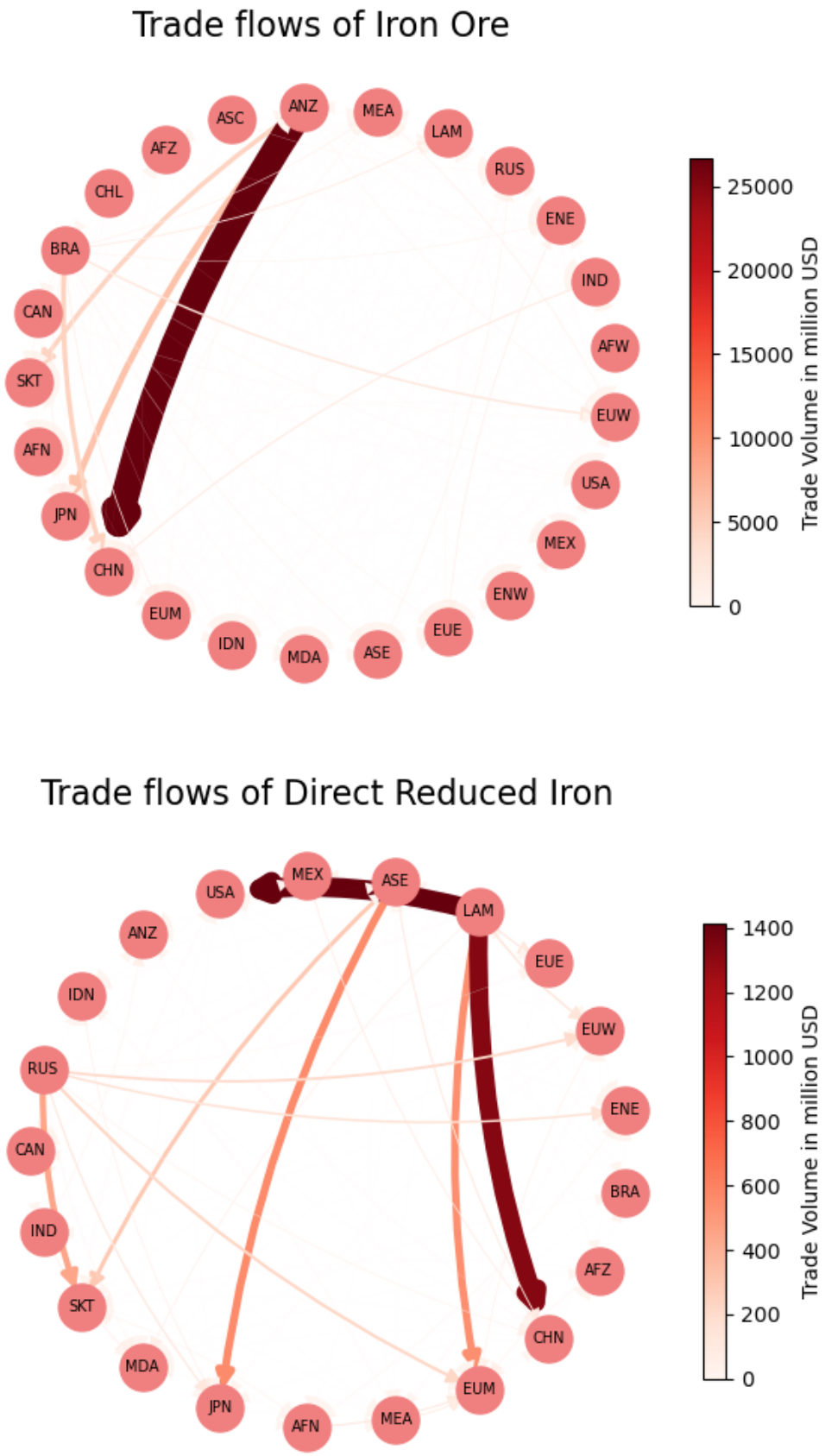

Figure 21. ENGAGE's representation of the annual trade flows of primary iron in the base year

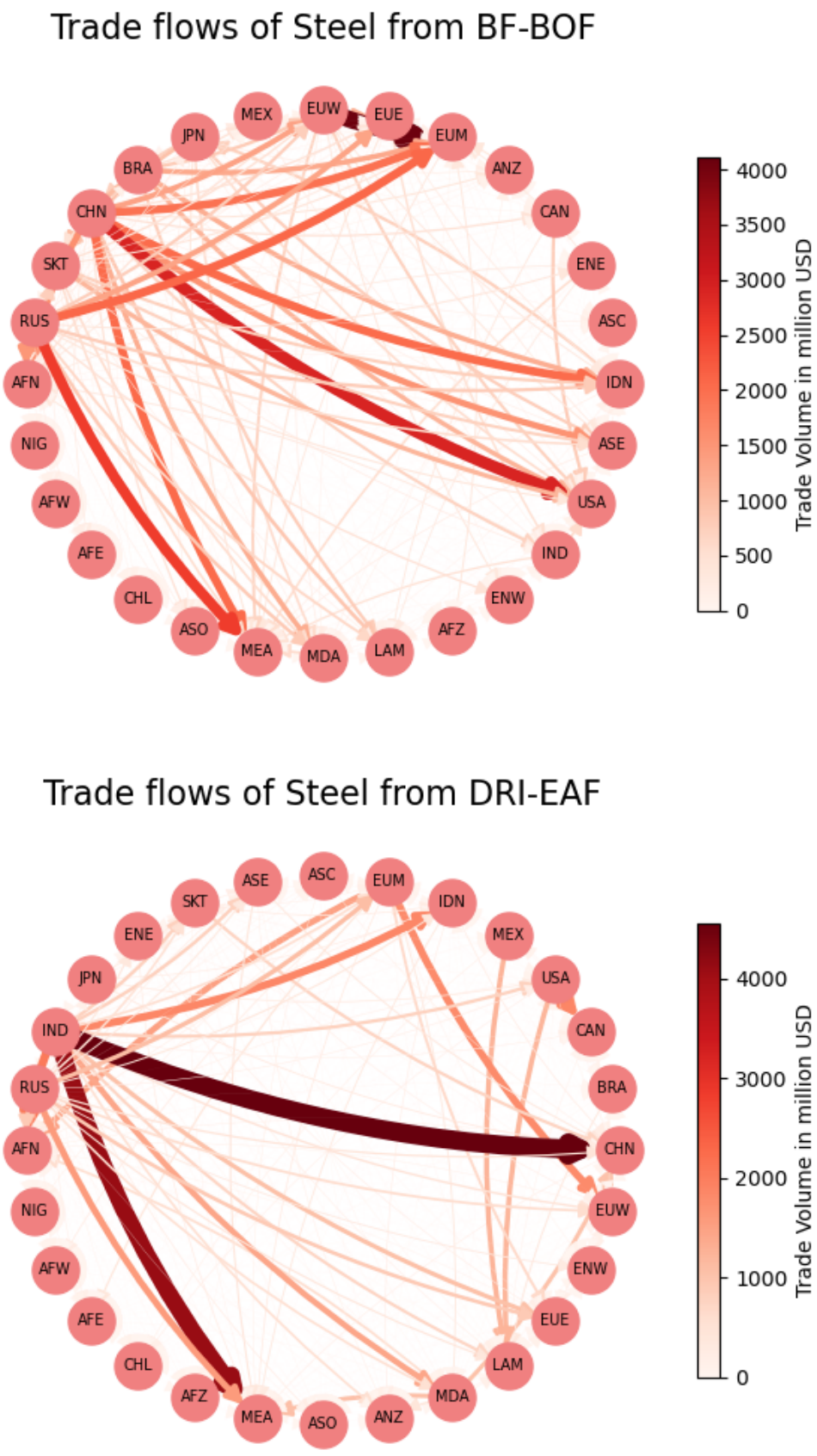

Figure 22. ENGAGE's representation of annual trade flows of primary steel in the base year

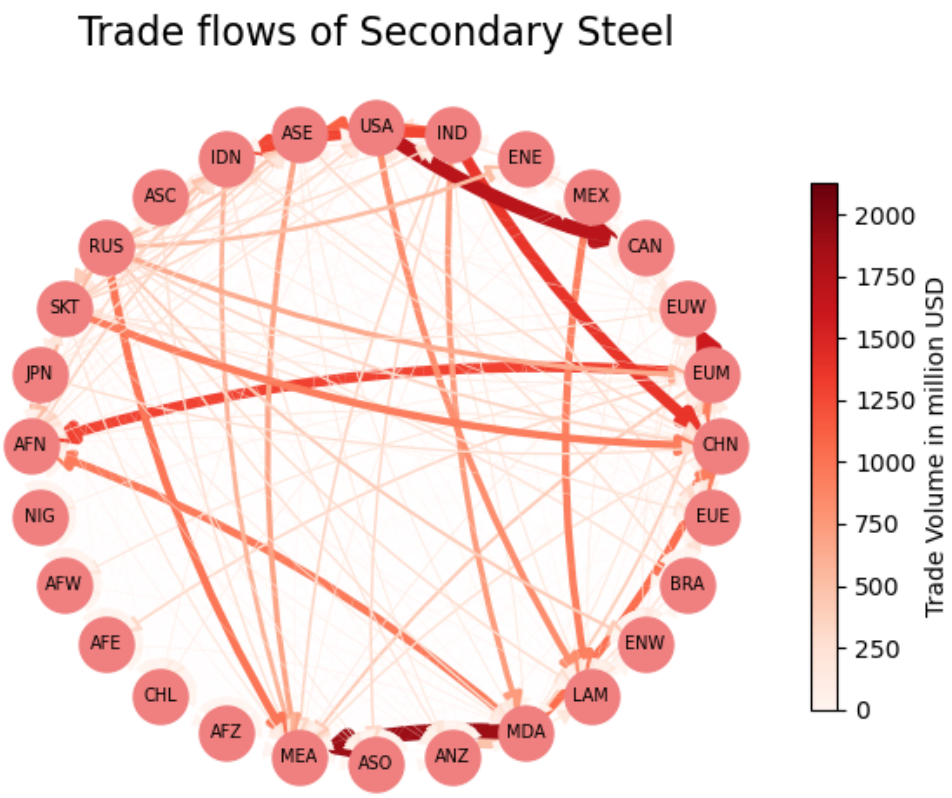

Figure 23. ENGAGE's representation of annual trade flows of secondary steel in the base year

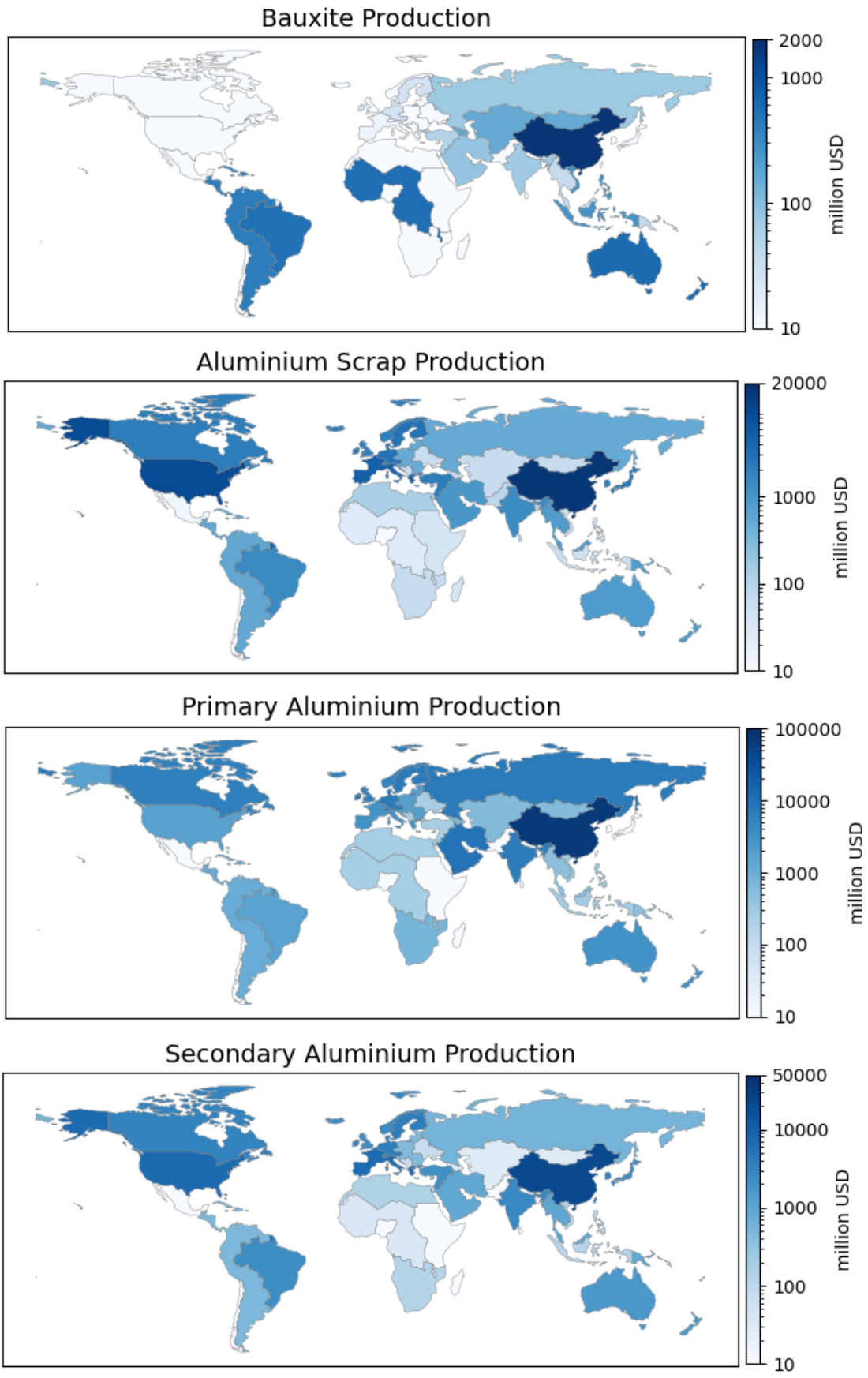

Figure 24. Annual production of commodities of the aluminium sector by regions in ENGAGE for the base year

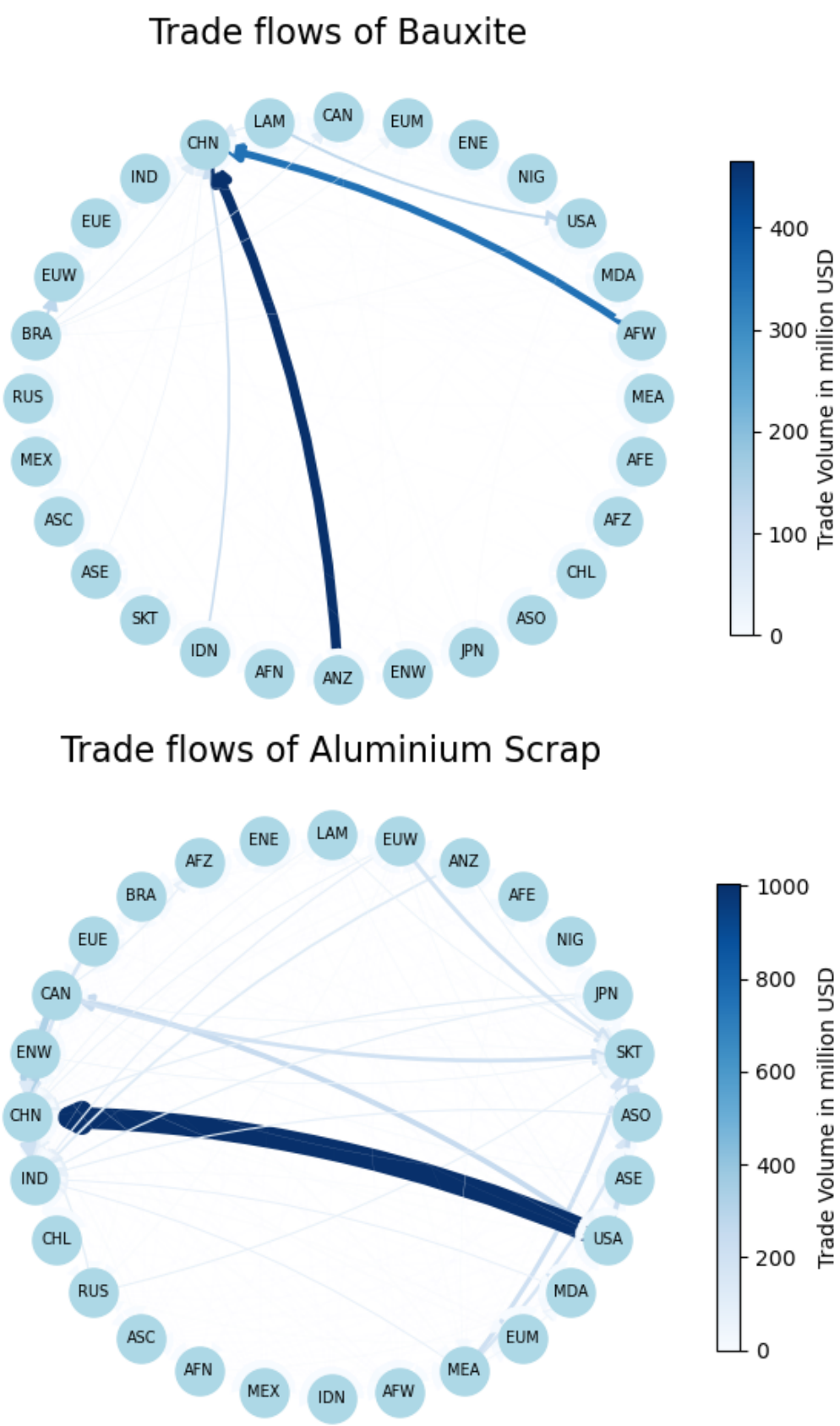

Figure 25. ENGAGE's representation of annual trade flows of bauxite and aluminium scrap in the base year

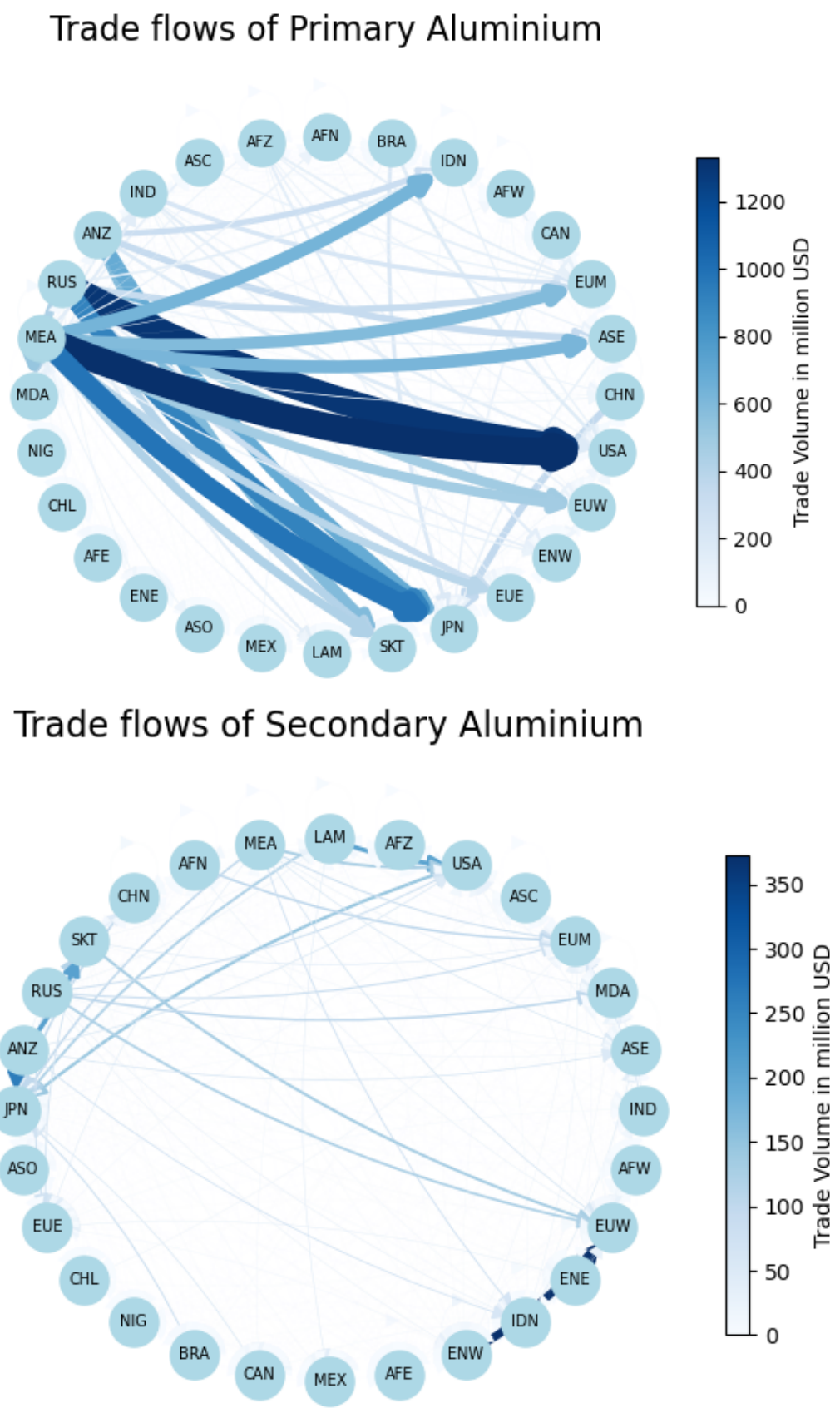

Figure 26. ENGAGE's representation of annual trade flows of primary and secondary aluminium in the base year

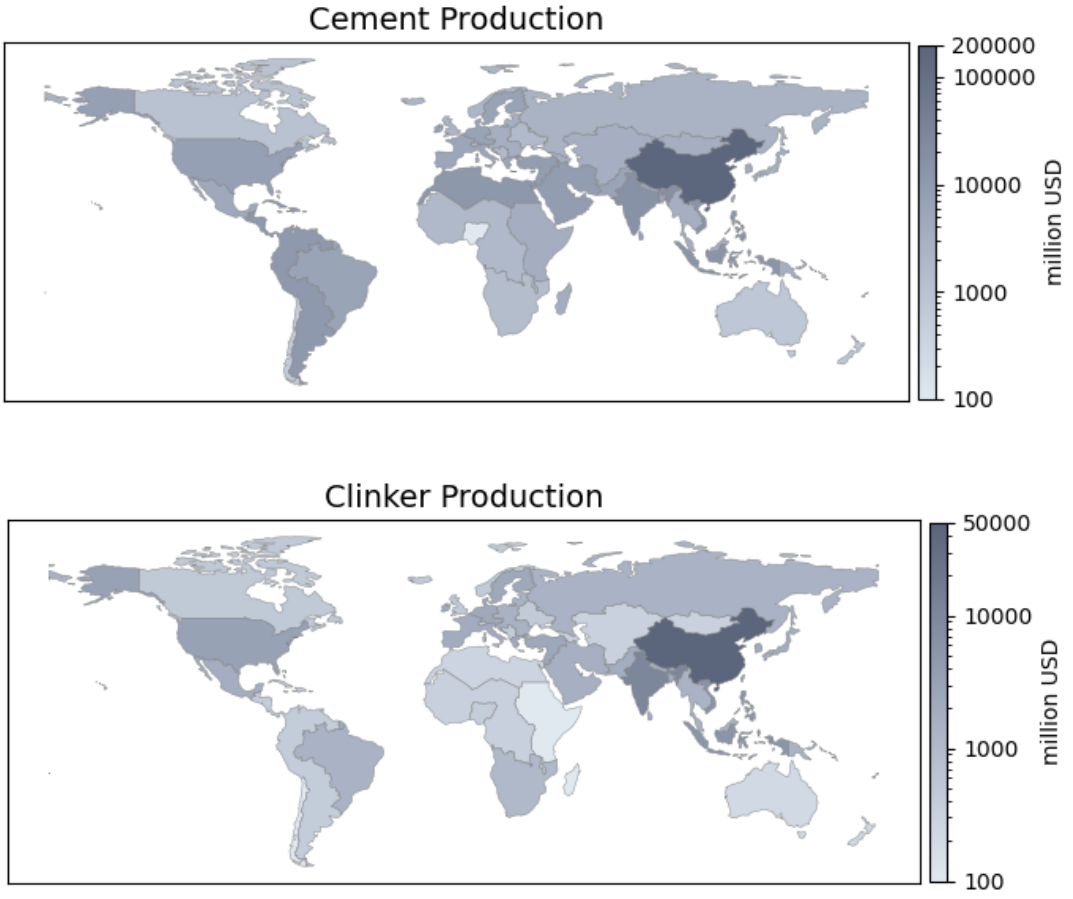

Figure 27. Annual production of cement and clinker by regions in ENGAGE for the base year

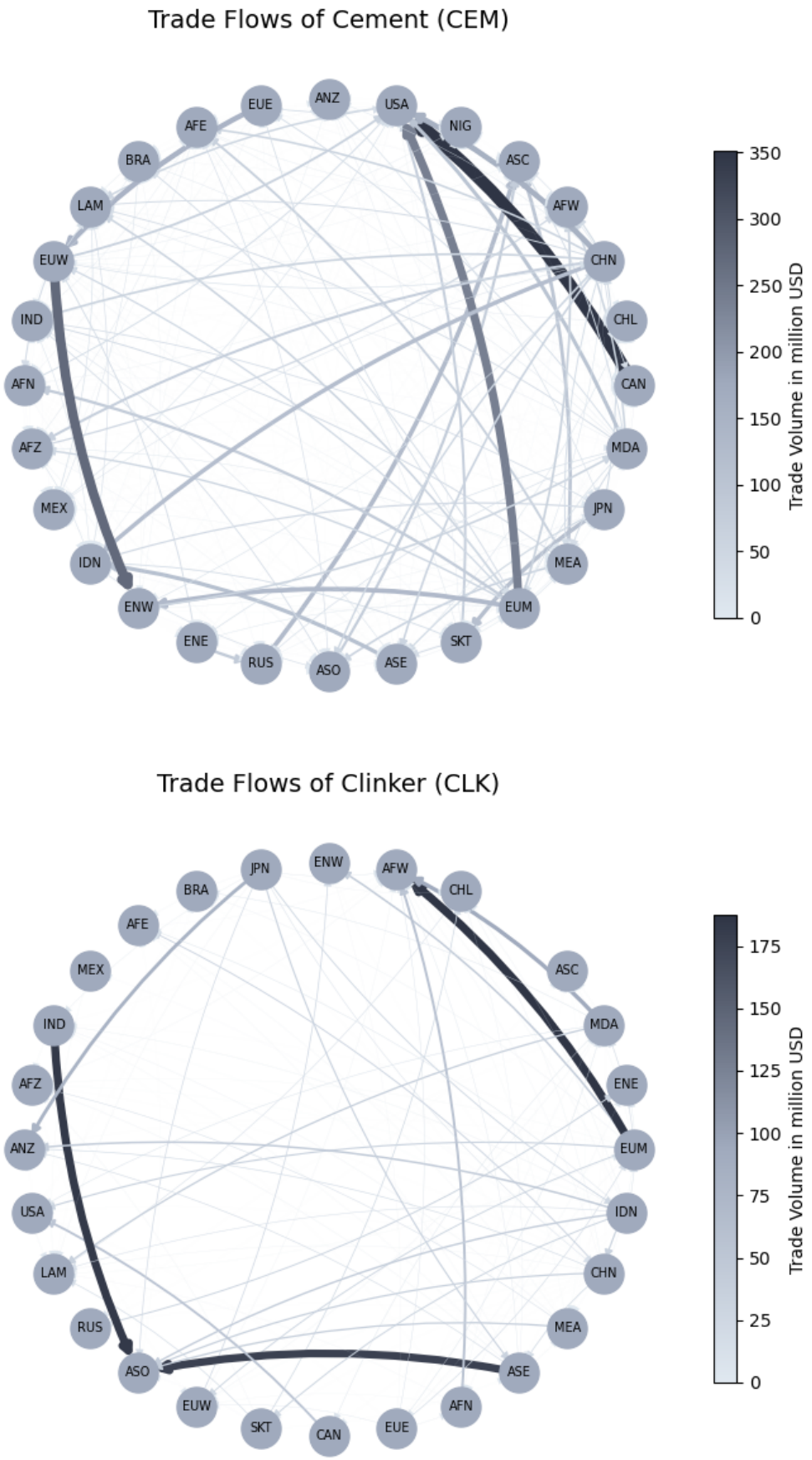

Figure 28. ENGAGE's representation for annual trade flows of cement and clinker in the base year