



Net0Pathways through impRoved IAMs across Sectors, diMensions, and scAles

Deliverable 4.2

Data, source code and documentation of bulk and specialty material representation in IAMs

Deliverable 4.2
November 2025



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1. Introduction

1.1 Motivation and outline

Over the next years and decades, the demand for bulk and specialty materials is expected to increase significantly (GRO, 2024). This will be driven by increased demand for infrastructure and capital across multiple sectors (buildings, transport, industry), and an increased need for electricity generation and distribution. Global electricity demand is driven by both a growing and increasingly affluent population, as well as by climate change mitigation strategies (B. J. Van Ruijven et al., 2019).

Decarbonisation strategies in particular will have a significant impact on the demand of both specialty materials, needed for (notably renewable) electricity generation, and bulk materials, due to an increased need for infrastructure for distribution and storage of electricity (Deetman et al., 2018). Renewable energy generation technologies are significantly more material intensive than conventional fossil generation (Bazilian, 2018; Kleijn et al., 2011; Vidal et al., 2013). For example, fossil-based power plants typically require 4-110 tonnes of steel per MW, whereas solar photovoltaic systems and wind turbines show 150 and 120-160 tonnes per MW, respectively (Liang et al., 2022) (Deetman et al., 2021). Similar trends apply to other bulk materials – such as aluminium and concrete – as well as minor metals often considered critical, such as copper and rare earth elements.

As a result, there is a requirement to better understand the material requirements of future infrastructure stocks, across multiple sectors, and how these stocks develop across different scenarios. These scenarios should explore the implications of climate change mitigation action, but also the different levers that might affect the volume and material intensity of these stocks, including circularity, access to energy services, etc.

In order to address these questions, as part of the PRISMA project, Integrated Assessment Models and Life Cycle Assessment methods have been further adapted and developed. This Deliverable contains concise descriptions of the developments in different models, as well as links to documentation and source code of the new modules. In some cases online repositories of the new modules are not yet publicly available (awaiting finalisation and peer-reviewed publication of scientific papers), in which case we have shared the code on the PRISMA project shared drive (access is available on request).

Chapter 2 describes the IAM improvements concerning bulk materials and circular economy-based mitigation options. This covers the activities in PRISMA task 4.3 (Circular economy-based mitigation options) by the IAM teams (PBL, IIASA, E3M, PIK & CMCC). It includes 1) improving the endogenous representation of bulk material processes, e.g. by linking material

demand to service provisions and by better representing material efficiency, recycling, reuse and remanufacturing, and 2) bidirectionally soft-linking material-enhanced LCA tools.

Chapter 3 provides an overview of the developments in life cycle inventory (LCI) data and their integration with IAMs to enable prospective assessments of material and energy systems. For PSI, which leads the development of the **Premise** and **Pathways** frameworks, this chapter covers the LCA-related activities carried out under Tasks 4.3 and 4.4. These include the establishment of standardized interfaces between IAM outputs and LCA databases, the creation of scenario-consistent LCI datasets, and the quantification of environmental and human health impacts along future transition pathways. Task 4.4 specifically focuses on improving the representation of **key specialty and critical materials** within IAM-linked LCA inventories to better capture their supply chains, resource requirements, and environmental implications in low-carbon transition scenarios.

For the IAM teams involved in Task 4.4 (PBL, IIASA, and PIK), this chapter also reflects their complementary developments aimed at enhancing the depiction of specialty material supply and demand within their respective models. These efforts include refining model outputs to higher sectoral and technological resolution and facilitating feedbacks from LCA results (e.g., material intensities and environmental externalities) back into IAM scenarios. Together, these activities form a coherent framework that strengthens the linkage between IAMs and LCA for analyzing the **material–energy nexus** that emerge in climate mitigation pathways.

1.1.1 References

Bazilian, M.D., 2018. The mineral foundation of the energy transition. *The Extractive Industries and Society*, 5(1), pp.93-97.

S. Deetman, S. Pauliuk, D. P. Van Vuuren, E. Van Der Voet, and A. Tukker, 'Scenarios for Demand Growth of Metals in Electricity Generation Technologies, Cars, and Electronic Appliances', *Environmental Science and Technology*, vol. 52, no. 8, pp. 4950–4959, 2018, doi: 10.1021/acs.est.7b05549.

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2. IAM improvements on bulk materials and circular economy-based options (Task 4.3)

2.1 IMAGE (PBL)

2.1.1 Objective

The IMAGE model projects, among other things, the access and provision of services needed for human well-being and associated energy use and greenhouse gas emissions. However, besides energy demand, the access to services may require capital and infrastructure, and associated material and resource use. Provision of these materials may have substantial environmental implications and also affects energy demand through the need of mining, refining, smelting, and other industrial activities.

For this reason, an explicit representation of material resource demand, consistent with projections of service provision, are crucial for a better understanding of environmental implications of different scenarios and policy responses. To appropriately represent this demand and potential policy responses or circularity strategies, it is critical to represent services and their associated material requirements, as well as stocks, and outflows of the materials.

2.1.2 Methodology

The IMAGE model was updated in order to explicitly represent bulk and critical energy transition minerals (IEA)¹, and their relevant dynamics. This work builds upon existing modules which represent the requirement of different infrastructure and capital in order to meet energy and other needs. More specifically, the IMAGE model contains representation and projections of residential and commercial floorspace, requirement of transport vehicles (including cars, busses, aircraft, trains and ships), electricity generation capital disaggregated across different technologies (fossil, nuclear, and renewable), as well as electricity transmission and storage requirements.

These sectoral projections have been coupled to a detailed stock-flow representation, in the form of a new sub-module within the IMAGE model. This stock-flow model gets capital requirements from the rest of IMAGE, and then tracks marginal, vintage, and depreciation of capital, and associated material use and outflows. This allows for projections of material demand, availability of scrap and secondary materials, and exploration of different circularity strategies (changing material intensity, lifetime extension, use of scrap and secondary flows, changing service demand, etc.).

¹ <https://www.iea.org/topics/critical-minerals>

The stock-flow modelling expands upon the ODYM-RECC model (Pauliuk et al. 2019), making specific modifications for the IMAGE model. Specifically, stocks of the following materials are explicitly included:

- Metals (bulk): Steel, Aluminium, Lead
- Metals (critical energy transition minerals, so also related to task 4.4): Copper, Lithium, Nickel, Cobalt, Manganese, Neodymium, Tantalum
- Non-metallic minerals: Concrete, cement, brick, Sand and gravel
- Other materials: Rubber, wood, plastics, glass

2.1.3 Implementation

The IMAGE-Materials sub-module is soft-linked with the rest of the model, exchanging annual projections of electricity generation capacity, residential floorspace, and requirement for vehicle stocks. Following, the IMAGE-Materials module, which then determines required new capital stocks and associated material demand. The stock modelling ensures that new capital stocks (and associated material demand) take into account the need to replace depreciating stock, and the availability of secondary and scrap materials which may be available for recycling. Following, the demand for materials is sent back to the energy sub-model in order to account for feedbacks on the energy demand system due to changes in steel and cement demand.

2.1.4 Resources

- IMAGE-Materials online repository & documentation:
 - <https://github.com/imagepbl/image-materials>
 - Note #1: This repository is not currently public. We will provide a public instance of this repository by December 2025. We will provide a link in an updated version of the deliverable.
- Open-access version of original stock and material modelling which acted as a basis of IMAGE-Materials:
 - Note #2: This can be removed once an open access version of IMAGE-Materials is made available as per Note #1.
 - Buildings model: <https://github.com/SPDeetman/BUMA>
 - Electricity model: <https://github.com/SPDeetman/ELMA>
 - Vehicles model: <https://github.com/SPDeetman/VEMA>

2.1.4 References

Pauliuk, S. (2019). Documentation of part IV of the IRP-RECC model framework: Open dynamic material systems model for the resource efficiency-climate change nexus (ODYM-RECC), v2.2. Retrieved from <https://osf.io/preprints/socarxiv/y4xcv>

2.2 MESSAGEix (IIASA)

2.2.1 Objective

The MESSAGEix modeling framework has integrated material cycles with the energy system over the past few years by adding (i) an explicit representation of bulk material commodities including manufacturing, use and end-of-life, (ii) linking materials demand to specific activities and service demands, and (iii) representing circular economy strategies to lower emissions and other environment impacts of material cycles.

Specifically, as part of the PRISMA project, the following activities were pursued: (i) improving the representation of bulk materials in MESSAGEix-Materials, (ii) coupling building services and circular economy strategies represented in MESSAGEix-Buildings to material production and recycling in MESSAGEix-Materials, and (iii) linking MESSAGEix to the Premise and Pathways prospective LCA tools developed by PSI (see Section 3).

2.2.2 Methodology

The improvements build on previous work that introduced a material-flow representation on both supply and demand to MESSAGEix-GLOBIOM. In the course of PRISMA WP4 the MESSAGEix-Materials model (Unlu et al. 2024) has been specifically improved to accurately mirror actual material production and demand. Besides the comprehensive improvement of the existing model parametrization, new features and methods were introduced. Most notably the capability to link the material flows from dedicated demand sector modules like MESSAGEix-Buildings has been established. This capability allows to endogenize material demands to assess the impact of sector-specific demand-side policies. The methodological improvement also serves as a framework for future demand model linkages.

The MESSAGEix-Materials model represents the flow of the following materials explicitly:

- Steel and relevant precursor materials
- Cement
- Aluminum and relevant precursor materials
- Chemicals including ammonia, methanol, ethylene, propylene and aromatics

The following improvements were implemented:

- The regional material production activity and capacity is calibrated based on best publicly available data sources.
- Current recycling flows of metals and future recycling potential have been calibrated.
- The regional demand projections have been updated based on most up to date historical commodity demands and socio-economic projections ([SSP 3.1 release](#)).
- Regional technology specific characteristics are explicitly modelled (e.g., small-scale steel production in India).
- The regional energy consumption of industry has been calibrated to match most recent international energy flow data.

- Soft-link to the material stock-turnover from MESSAGEix-Buildings (Mastrucci et al. 2021) which allows assessing circular economy strategies in the buildings sector, including lifetime extension, space commoning, switching construction methods (e.g., wood-based construction), and material recycling at the end of the building lifecycle.
- The representation and calibration of recycling of metals and concrete has been improved in MESSAGEix-Materials.

2.2.3 Repositories and publications

Links

[MESSAGE-ix-Materials - technical documentation](#)

[MESSAGE-ix-Materials 1.2.0 - release notes](#)

[MESSAGE-ix-Materials module](#)

References

Ünlü, G., Maczek, F., Min, J., Frank, S., Glatter, F., Natsuo Kishimoto, P., Streeck, J., Eisenmenger, N., Wiedenhofer, D., and Krey, V.: MESSAGEix-Materials v1.1.0: representation of material flows and stocks in an integrated assessment model, *Geosci. Model Dev.*, **17**, 8321–8352, <https://doi.org/10.5194/gmd-17-8321-2024>, 2024.

Mastrucci, A., van Ruijven, B., Byers, E. et al. Global scenarios of residential heating and cooling energy demand and CO₂ emissions. *Climatic Change* **168**, 14 (2021). <https://doi.org/10.1007/s10584-021-03229-3>.



2.3 GEM-E3 (E3M)

2.3.1 Introduction

Applied economic models that are used to assess the impacts of energy and climate policies are usually calibrated in Input Output tables (monetary transactions), national accounts (monetary transactions) and energy balances (physical volumes). Depending on the granularity of the models the representation of economic activities is usually clustered under industrial branches rather than under products and materials are aggregates of different components – aggregated by value. Hence applied economy wide models very rarely capture bottom – up details regarding material extraction, production and use. The explicit representation of materials in physical terms is useful in applied economic analysis in many ways as it provides:

- Better understanding of the supply chains and material dependencies of key technologies.
- Identification of suppliers and users of materials
- Better capture of energy and carbon intensities of manufactured products
- Higher detail of substitution possibilities and carbon intensity of production chains

In the current study we focus on the role of materials in a context where the energy system decarbonizes and manufacturing processes of key industries change. The decarbonization process includes among other system changes the following:

i) RES deployment substituting fossil based power generation

The materials used to manufacture RES technologies differ significantly from those used to manufacture combustion/fossil power technologies as they involve fundamentally different technologies and processes. RES mainly require silicon, glass, aluminium, copper, semiconductors whereas fossil fired power plants require steel, nickel based superalloys and concrete. Both require steel, aluminium and copper but at different proportions.

ii) Substitution of Electric Vehicles vs Conventional Vehicles

These two technologies have very different material requirements as the EV uses fewer moving mechanical parts but far more electrical and electrochemical materials – especially battery metals and lightweight structural alloys while the conventional ICE car depends more on iron, steel, and aluminium, but far less on copper and lithium.

iii) Substitution between primary and secondary production in hard to abate sectors

Decarbonisation in hard to abate sectors like steel involves switching between different production technologies e.g. moving from the Blast Furnace – Basic Oxygen Furnace process (BF-BOF), which is the dominant method of primary steel production worldwide today to the Electric Arc Furnace (EAF) essentially implies less extraction, less use of coal and more electricity, hydrogen, nickel and chromium.

iv) Adoption of circular economy measures

Circular economy measures imply changes both in production and consumption. Recycling and lifetime extension are only a few to mention from the wide range of

options available.

The objective of this study is to further develop the data and mechanisms in applied economic modelling so as to better capture material stock/flows allowing to have a more precise accounting of energy requirements, GHG emissions and material-technology dependencies.

2.3.2 Methodology used to link bulk materials and/or CE measures with the GEM-E3-CIRC model

The starting point for improving the representation of materials in applied economic modelling is the GEM-E3-CIRC model and the GTAP v11 CE database. The GEM-E3-CIRC model² is a further development of the GEM-E3 model³ that took place in the CIRCOMOD project. The developments that take place in the context of this study relate to:

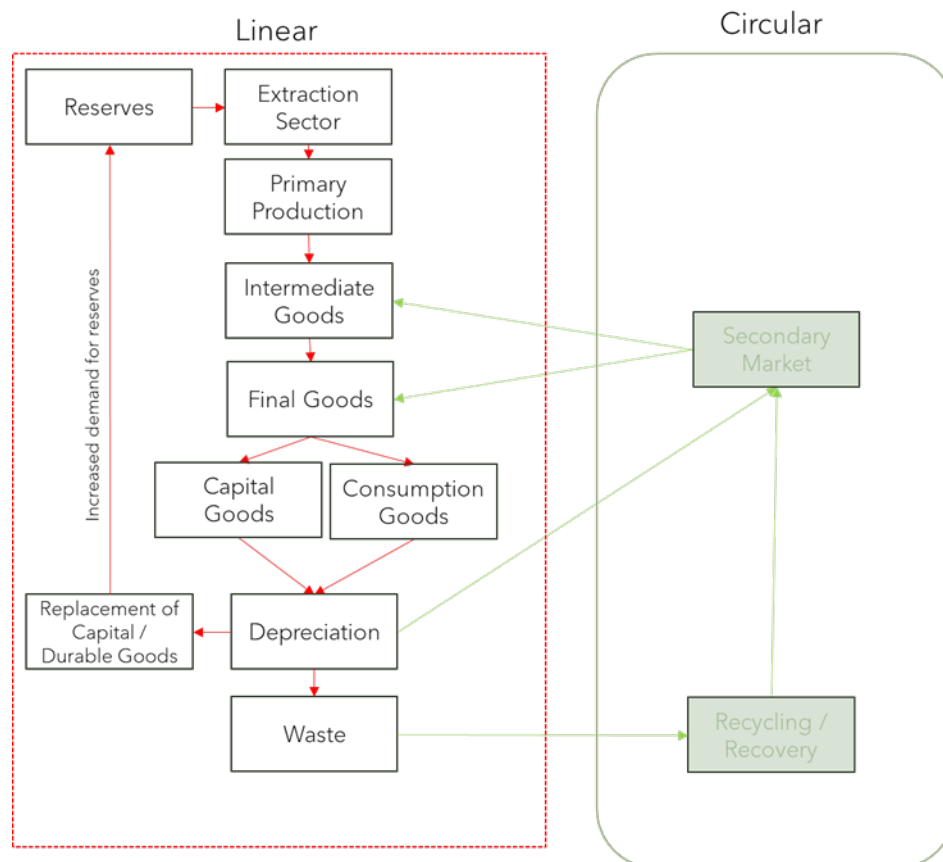
- i) Improvement of the data and accounting framework of materials
- ii) Endogenous decision on scrapping / lifetime extension of products
- iii) More analytical representation of production of steel and alternative production processes

The GEM-E3-CIRC is a global model developed on the blueprints of the GEM-E3 model. The model covers 43 countries/regions linked with endogenous bilateral trade following the Armington assumption where domestically produced goods are considered as imperfect substitutes to imported goods. It is recursive-dynamic, capturing all years until 2050 in a five-year time step. Firms minimize their costs and use multi nested Constant Elasticity of Substitution (CES) as a production function. Consumers maximize welfare subject to their income. Capital mobility is user defined. Five labor skills are identified per economic activity and labor supply is derived through an empirical supply function that inversely relates wages and unemployment rate. The model explicitly represents the manufacture of clean energy technologies and has been extended to include circular economy options regarding the discrete representation of extraction, primary, secondary and recycling activities. The default version of the GEM-E3 model adopted a linear production / consumption structure without identifying resource scarcity and secondary markets. Recycling is a separate economic activity that sells solely to the secondary market. Higher demand for secondary products increases the demand for recycling which is used as a factor input (scrap/waste).

² Paroussos et al (2025) “The GEM-E3 Circular Economy model” in D 5.3 “Integrating CE extensions in applied (CGE) models for climate policy analysis”

³ Capros et al (2017) “GEM-E3 Reference Manual”

Figure 1 Circular economy in GEM-E3-CIRC



Source: Paroussos et al (2025) "The GEM-E3 Circular Economy model"

2.3.2.1 Improving material flow representation

The main databases available to calibrate the GEM-E3-CIRC model are the EXIOBASE⁴ and GTAP⁵ v 11 circular economy database. The model is mainly using the GTAP circular dataset as it is comprehensive and has a detailed representation of the key materials (non metallic minerals, iron ores, aluminium ores, copper ores). However, GTAP has monetary values. In this study we updated and expanded the physical volume data collected from USGS, World Steel association, OECD (steel outlook), ICSG, UN Comtrade, Global Cement and Concrete Association (GCCA), UN Environment – IRP Global Material Flows Database. When data were not available, indirect methods (e.g. using prices to derive quantities from the GTAP monetary transactions) were employed. Particular focus on the database expansion has been given on the materials required to manufacture conventional and clean energy technologies. The table below summarises the additional information that has been used to refine the material representation in the Input Output table and associated investment matrix of GEM-E3.

⁴ <https://www.exiobase.eu/>

⁵ https://www.gtap.agecon.purdue.edu/events/GTAPVSS/v6n2-2025/GTAPVSS_v6n2.pdf

	Project size used (MW)	Steel (t)	Cement (t)	Copper (t)	Aluminium (t)
PV	64	2,564	2,404	192	1,346
Onshore wind	83	10,000	4,167	417	167
Gas CCGT (plant only)	100	3,103	1,222	150	20

Source: Calculations using the material intensities and cost assumptions from the U.S. National Renewable Energy Laboratory (NREL) Renewable Energy Materials Properties Database (REMPD) and NREL Annual Technology Baseline 2024 and EIA/EPRI cost data for typical capital costs per kW; the IEA and Energy Transitions Commission datasets for copper and aluminium intensities in renewable technologies. The World Steel Association and JRC / Carrara et al. (2021) meta-analysis for wind-turbine concrete and steel quantities.

2.3.2.2 Multiple production process per economic activity

In the GEM-E3-CIRC model the production technology of each economic activity is largely defined by a CES production function (apart from the power generation sector where a discrete representation of technologies is made). In this version of GEM-E3 an activity analysis module has been added that distinguishes between different production technologies in the steel and cement sectors.

In particular for sectors where technology choices are many (steel, cement, power), we replaced the one⁶ CES “technology” nest with a set of discrete production activities (technologies). Each activity has fixed input coefficients per unit of output (Leontief), fixed emission factors, and capacity. The model chooses the cost-minimising mix of activities endogenously.

2.3.3 Implementation

In the model CES production functions are formulated in a nested separability scheme, involving reserves (R), capital (K), different types of occupations / labour (L), energy (E), materials (M) and other inputs. The exact nesting scheme is selected to match available econometric data on KLEM substitution elasticities, the sector specific production technology features and/or the choice of soft linking the GEM-E3 model with bottom-up models. The optimal production behaviour can be represented in the primal or the dual formulation. In the model the dual formulation is used, and the long run unit cost function is of the nested CES type with factor-augmenting technical change, i.e. price diminishing technical change. The firm (at branch level) decides its supply of goods or services given its selling price (perfect competition) and the prices of production factors. The firm supplies its goods and selects a production mix so as to maximise its profit within the current year, given the fact that the firm cannot change the stock of productive capital within this period of time. The firm can change its stock of capital the following year, by investing in the current one. Since the stock of capital is fixed within the current year, the supply curve of domestic goods is upwards sloping and

⁶ There is not exactly one as CES allows for factor substitution – but it is constrained by the substitution elasticity without having a technology specific cost characterisation.

exhibits decreasing return to scale⁷.

Extraction/Mining of materials takes place using the available reserves and the rest of the production factors (top level CES nesting decision). Reserves can either be fixed (fixed supply depleted over time following extraction) or updated using information on yet to find reserves and exploration rates. In the default model setup reserves are fixed / exogenously – pathway provided in the baseline.

Primary production takes place using the output of the mining sector and the rest of the production factors (top level CES nesting decision).

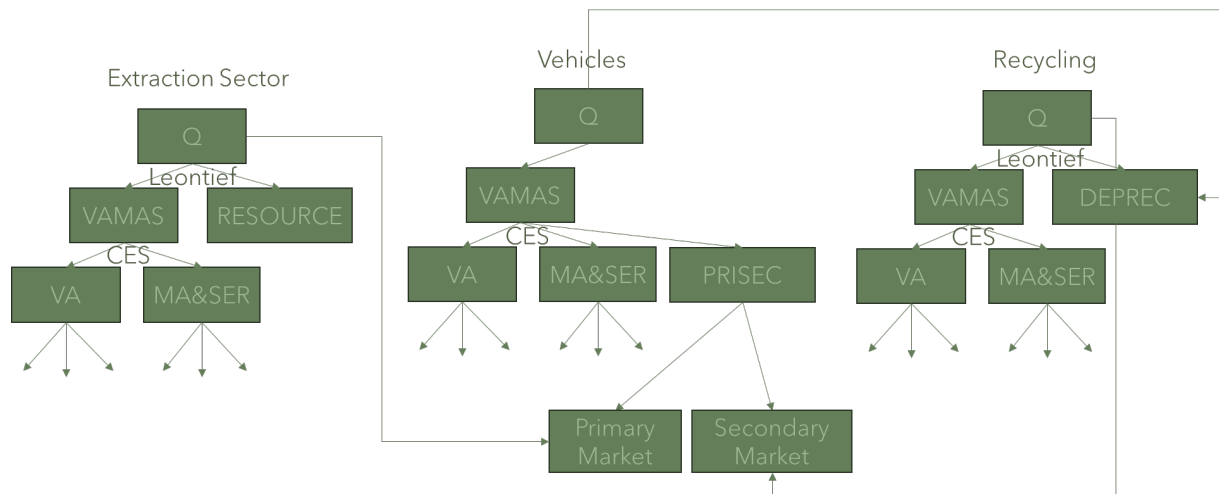
Secondary production takes place using recycled material as main production input and the rest of production factors.

The GEM-E3 representation of the **recycling sector** departs from the statistical accounting of GTAP. In the GTAP SAM the main factor inputs for recycling are the materials themselves (e.g. for steel recycling the main inputs are primary iron and steel and metal products). Retaining this production structure and recycling output would assume a relatively constant recycling rate in the economy that would be disconnected from the production and consumption of durable goods that include steel.

To this end the GEM-E3-CIRC model has been extended to account for the **stock of selected durable** goods (buildings and vehicles). Key stocks related to infrastructure and capital goods are not identified in this version. The stock of durable goods is dynamically updated through a motion equation that includes depreciation and investments / expenditures in durable goods. Depreciation rates are endogenous and are determined by the lifetime of goods and any expenditure associated to extend this lifetime. An endogenous recycling rate is used (empirical function of relative prices or primary and secondary production).

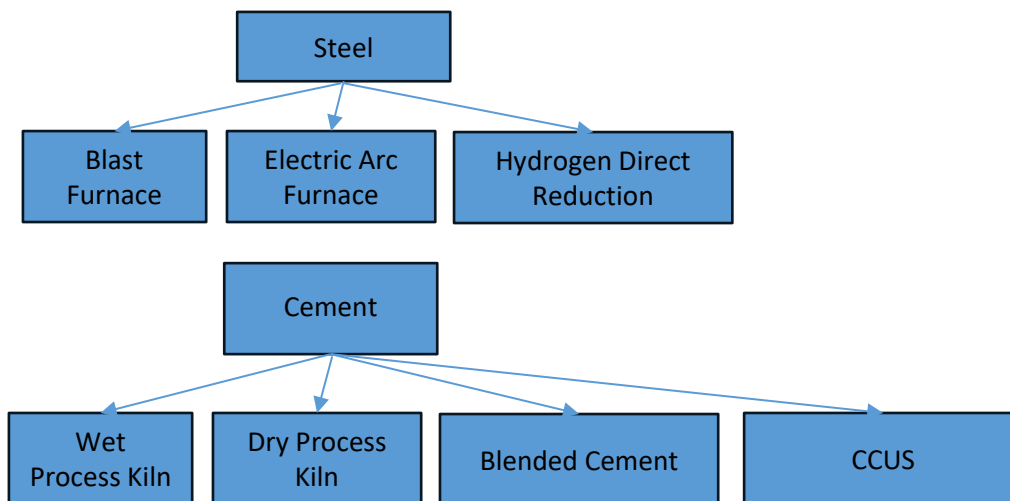
⁷ This description applies only to the most rigid of the capital mobility assumptions that are available in the model variants, where capital is assumed immobile across sectors and countries in static terms. When capital is assumed malleable across sectors and/or countries, then the capital stock by sector can adjust even in static terms, but the overall capital resources available to the economy within each time-period are constant.

Figure 2: Production circuit of extraction, recycling and final products



The model has been further updated to feature multiple processes per economic activity. This has been done for the cement and steel manufacturing sectors.

Figure 3 Multiple production processes for steel and cement



For **steel** the following production processes have been identified:

1. BF–BOF (Blast Furnace–Basic Oxygen Furnace): Uses iron ore and coke to produce pig iron, then refines it with oxygen to make steel.
2. EAF (Electric Arc Furnace): Melts scrap steel or direct reduced iron (DRI) using electricity as the main energy source.
3. H₂–DRI + EAF (Hydrogen Direct Reduction + EAF): Uses hydrogen instead of coal to reduce iron ore to DRI, then melts it in an EAF

The production function of each process has been calibrated to the shares presented in the

table below.

Table 1 Production structure of steel processes

Production Factor (share in total production)	BF–BOF	EHF based) (Scrap-	H ₂ –DRI + EAF
Capital	30%	20%	35%
Labour	10%	15%	15%
Iron ore / Scrap (Steel input)	25%	40%	20%
Electricity	5%	15%	10%
Coal / Coke / Hydrogen	25%	0%	10%
Other	5%	10%	10%
Total	100%	100%	100%

For **cement** the following production processes have been used:

1. **Wet process kiln:** Mixes raw materials with water to form slurry, then heats it in a rotary kiln – older and energy-intensive.
2. **Dry process kiln:** Uses dry-ground raw meal and preheater/precalciner systems – modern standard with lower energy use.
3. **Blended cement production:** Mixes clinker with additives (slag, fly ash, limestone) to reduce clinker ratio and emissions.
4. **Carbon-neutral / CCUS-integrated process:** Combines dry kilns with carbon capture and low-carbon fuels to minimize CO₂ emissions.

The production function of each process has been calibrated to the shares presented in the table below.

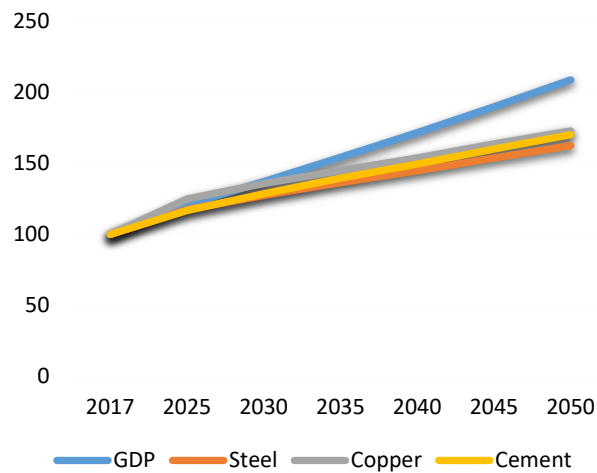
Table 2 Production structure of cement processes

Production Factor	Wet Process	Dry Process (Modern)	Blended / CCUS-Integrated
Capital	20%	25%	35%
Labour	15%	15%	15%
Raw Materials (limestone, clay, additives)	20%	25%	20%
Electricity	10%	15%	20%
Coal / Fuel / Alt. fuels	30%	15%	5%
Other (maintenance, emissions control, O&M)	5%	5%	5%
Total	100%	100%	100%

2.3.4 Pilot Simulations

The model version has been used to make a preliminary baseline projection of key materials. As indicated above, GDP grows faster than the materials indicating the relative dematerialization of the economy. Hence the demand for materials is driven mostly by the composition of economic growth and less by its scale.

Figure 4: Primary production of Steel, Copper and Cement - World (2017 =100)



Source: GEM-E3-CIRC. The global demand for primary steel, copper and cement in the pilot baseline simulation is projected to increase by 60% on average despite the doubling of GDP indicating both the material productivity and dematerialization of the economic system.

2.4 REMIND-MAgPIE (PIK)

2.4.1. Objective

While REMIND-MAgPIE provides advanced global decarbonisation scenarios, it so far lacks detailed material flow representation. To fill this gap and better represent material requirements and circular-economy based mitigation options, REMIND-MFA, a global material flow analysis module was developed. REMIND-MFA will be coupled with REMIND to simulate global material cycles alongside the energy system and technological transitions in primary basic material production.

2.4.2 Methodology

REMIND-MFA focuses on the three major basic materials: steel, plastics, and cement. It covers 12 global regions and projects material flows up to 2100.

The model applies a dynamic, stock-driven demand modelling approach, where material demand is linked to GDP per capita and historical material use patterns. Further linking material demands to service provision for key sectors (floorspace in buildings and vehicle use) is currently under development, with a first bottom-up model for cement demand arising from floorspace demand in buildings being implemented recently.

REMIND-MFA includes material trade across the entire lifecycle—from raw materials to finished goods and scrap—while incorporating a novel price-sensitive trade mechanism based on discrete-choice modelling.

2.4.3 Implementation

The model was implemented using the flodym software library, which was specifically developed in the context of REMIND-MFA; it was designed to handle high-dimensional data structures for flows and stocks. This enables efficient data processing and visualisation and offers a flexible modelling environment suitable for a wide range of MFA applications, with a focus on rapid adaptability and extensibility. The library has already been adopted by several external users.

REMIND-MFA was designed to be open-source and modular, with a clear focus on usability and interoperability. The model was further designed to depict circular economy strategies in the data input. Scenario design and translating circular economy strategies into model inputs is one focus of future work.

2.4.4 Usage and results

Preliminary results of REMIND-MFA on material demands, stocks, primary and secondary material production are available in the common definitions reporting format of the IAMC.

REMIND-MFA will be soft-linked to REMIND in the future, informing material demands and secondary material availability, while REMIND provides the MFA with endogenous socioeconomic trajectories and technology pathways (e.g., share of bioplastics and chemical

recycling) as well as material prices. Together, they provide a comprehensive lifecycle perspective on climate mitigation of bulk material production, spanning production technologies, demand-side mitigation, and end-of-life strategies, enabling profound analysis of global circular economy potentials and industrial decarbonisation strategies.

2.4.5 Repositories and publications

Both the REMIND-MFA model and the flodym library are available as open-source repositories:

- **REMIND-MFA:** <https://github.com/pik-piam/remind-mfa>
- **flodym library:** <https://github.com/pik-piam/flodym>

In addition, the flodym library is described in the following publication:

- **Dürrwächter et al. (2025).** flodym: A Python package for dynamic material flow analysis. Submitted to: Journal of Open Source Software. <https://joss.theoj.org/papers/92b6faa2d82b8694f4ad5d394053ef32>

All listed repositories and publications explicitly state PRISMA project support.



2.5 WITCH (CMCC)

2.5.1 Objectives

To address the critical gap between energy system transitions and their underlying material requirements, we developed a dedicated material module fully integrated in WITCH. This development responds directly to the growing need to account for material flows and circular economy strategies within long-term climate policy scenarios. Building on the insights of a recent systematic review of circular economy integration in IAMs (Magalar et al., 2025), which highlighted persistent data gaps and methodological limitations, the new module enables the dynamic representation of material stocks, inflows, and outflows, as well as the explicit implementation of circular economy strategies across 20 world regions.

2.5.2 Methodology

The material module is structured around three main steps: (i) the development of a dynamic material flow module integrated into the WITCH model, (ii) the implementation of circular economy strategies, and (iii) the estimation of material-related emissions via a soft-link with the life cycle assessment tool Premise.

The material flow module (top section of Figure 5) calculates stocks, inflows, and outflows of materials for technologies in electricity generation, transmission and distribution infrastructure, and road passenger transportation. It covers both bulk materials (steel, aluminium, cement) and critical raw materials (copper, manganese, lithium, nickel, cobalt, and rare earth elements). Dynamic material intensity coefficients are derived by combining baseline material intensities from peer-reviewed literature and LCA databases with time- and region-specific inputs, including technological market shares, efficiency improvements, and behavioral assumptions. These coefficients are then applied to WITCH's endogenous technology deployment projections to quantify material demand trajectories over time.

Material outflows are calculated using the technology-specific depreciation function already used in WITCH, which determines the retirement of capital stocks based on their lifetime and investment dynamics. This approach ensures internal consistency between technology turnover and material flows, as both are governed by the same model structure. Material inflows, in turn, are driven by new investments projected endogenously by the model, allowing material requirements to respond dynamically to evolving technology pathways under different scenarios.

Circular economy strategies (blue circles throughout Figure 5) are represented using the 10R framework (Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover), which provides a comprehensive hierarchy of measures to minimize resource use and environmental impacts. These strategies are operationalized in the model through parameter adjustments at different stages of the modeling chain and are structured around three circularity loops (narrow, slow, and close), which capture distinct mechanisms of

circular economy policies implementation. Narrowing loops involves reducing material use by demand reduction and material efficiency improvement; slowing loops extend product lifetimes and increase intensity of use; and closing loops focus on reusing and recycling materials to keep them within the system.

In practice, CE strategies are implemented at multiple levels: as pre-processing adjustments to material intensities parameters (e.g., smaller car adoption, lightweighting, material substitution); as modifications to WITCH's behavioral and technological parameters during model execution (e.g., car sharing, teleworking, carpooling, mode shift, lifetime extension, repairing); and as post-processing assumptions (e.g., recycling and reuse rates). These interventions affect key drivers such as vehicle demand, technology lifetimes, and material intensities, thereby influencing material flows throughout the technology lifecycle.

In the post-processing phase (bottom section of Figure 5), WITCH scenario outputs are linked to Premise, which provides region- and time-specific emission coefficients for material production based on evolving energy systems and supply chains. This soft-link allows us to estimate material-related emissions under different climate and CE scenarios and to quantify avoided emissions resulting from the implementation of CE strategies by comparing material demand across scenarios.



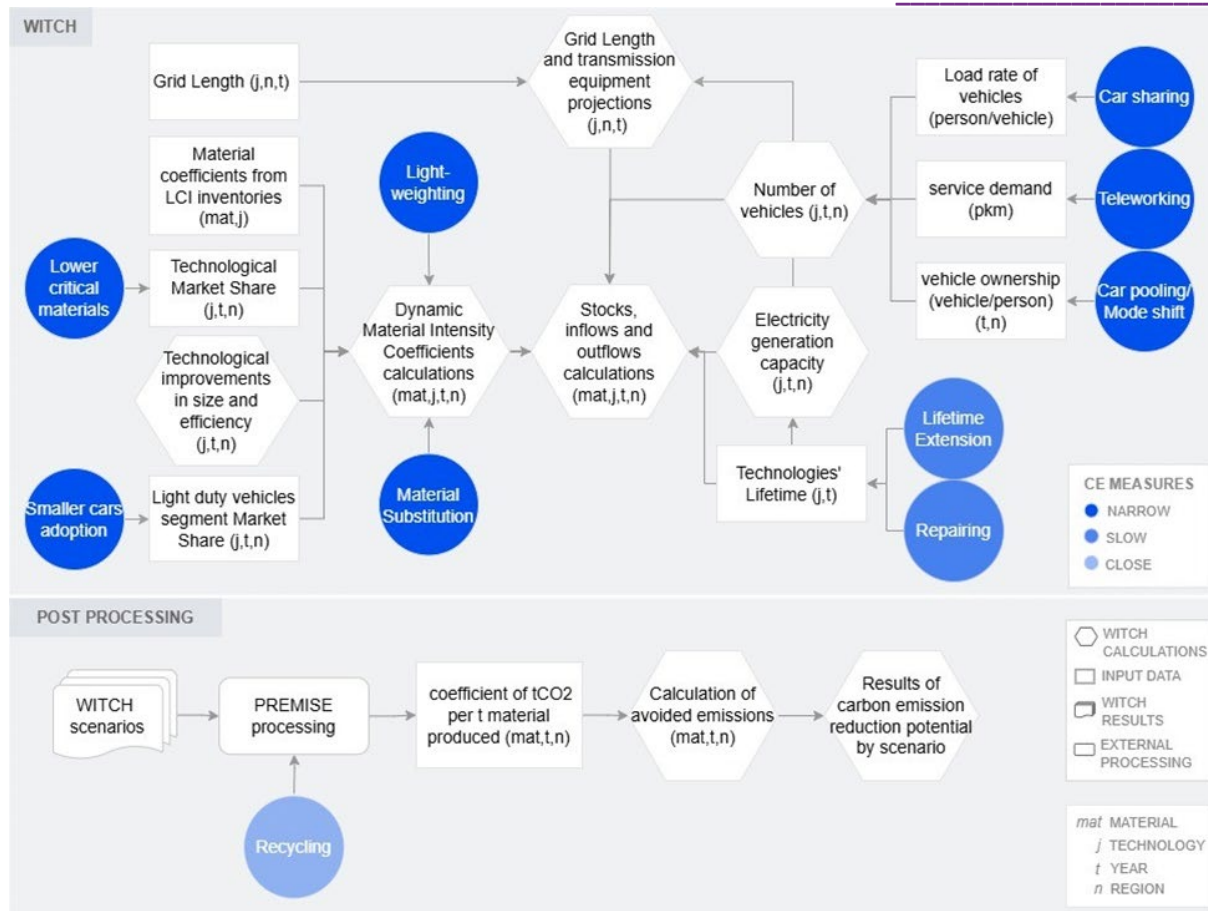


Figure 5: Integrated framework for modeling material flows and circular economy strategies in WITCH. The diagram illustrates the three main components: dynamic material flow calculations within WITCH (top), circular economy interventions applied at different modeling stages (blue circles), and post-processing emission quantification via soft-link with Premise (bottom).

2.5.3 Results and data

Preliminary results are available for material demand, stocks and outflows under different circular economy scenarios (narrow, slow, close) across 20 world regions. The analysis currently covers aluminium, copper, steel, cement, copper, with results formatted according to the IAMC template and made accessible through the PRISMA Zenodo repository (<https://doi.org/10.5281/zenodo.17671245>). Model runs including the implementation of CE strategies are still ongoing, and the full set of scenario results will be released shortly, following the IAMC reporting structure.

2.5.4 Publications

Magalar, L., Verdolini, E., Szklo, A (2026). Unlocking Circular Economy Policies in Integrated Assessment Models. Resource, Conservation and Recycling. Resources, Conservation and Recycling, Volume 225,2026,108614, <https://doi.org/10.1016/j.resconrec.2025.108614>.

Magalar, L. Drouet, L (2026). Integrating Circular Economy Strategies into Integrated Assessment Models: A Case Study for Transport and Electricity Sector in the WITCH Model [Ongoing Work]



2.6 Update circular economy variable reporting

In a combined effort by the H2020 research projects CircEular, PRISMA and CIRCOMOD, the circular economy related variables across IAMs have been updated and harmonized, to enable further model comparison exercises and improve the basis for future studies. These new variables will be added to the common variables repository (link below) by December 2025 and consolidated after updates by January 2026.

Common definitions:

<https://github.com/IAMconsortium/common-definitions>



3. Integrating IAMs and LCA for Material-Critical Transitions (Task 4.4)

Task 4.4 aims to improve the representation of specialty material supply chains in IAM pathways. PSI's contribution focuses on developing open and standardized interfaces between Integrated Assessment Models (IAMs) and high-performance Life Cycle Assessment (LCA) models, notably *Premise* and *Pathways*. These libraries enable a prospective representation of material supply chains and their environmental and human health impacts. This supports the identification of resource-efficient and environmentally sound pathways for the climate transition.

3.1. Objective

The work centers on analyzing the life cycle demand of critical raw materials in key mitigation technologies under different transition scenarios. Covered technologies include electric and internal combustion engine vehicles, various renewable energy systems (wind, photovoltaics, concentrated solar power), nuclear energy, and energy storage solutions like batteries, fuel cells, and electrolyzers. The focus has been on 'critical raw materials' as identified in key policy reports and scientific literature, addressing global concerns about these materials.

3.2. Methodology

To address these objectives, the work advances along three complementary directions that connect to the goal of capturing life cycle material demand in IAM pathways.

3.2.1 Macro-level LCA of IAM scenarios

The first direction focuses on developing methodologies and software tools that extend prospective macro-level LCA of IAM scenarios, such as *Premise* and *Pathways*. These developments aim to make scenario assessment reproducible and effective for evaluating material demand trajectories together with their environmental and human health impacts.

The process of using LCA to do a macro-analysis of IAM scenarios is essentially a two-step workflow.

The first step is about generating futurized life cycle inventories databases, using *Premise*. Each database is specific to a scenario-time step. *Premise* dynamically transforms baseline LCI databases (e.g., ecoinvent) according to scenario projections from IAMs. This transformation covers key sectors, such as electricity generation, transport, fuels, industry, and materials, by updating technology mixes, efficiencies, regional interconnections, and emission intensities over time. The result is a series of harmonized, scenario-consistent LCI databases that reflect the evolving technological and geographical structure of the global economy. The process is fully automated, ensuring transparency, reproducibility, and interoperability with Brightway-based LCA frameworks. The workflow implemented by *Premise* is illustrated in Figure 6, and Table 3 summarizes the number of IAM production variables currently mapped in *Premise*. Since the beginning of the project, we have successfully established the mapping of MESSAGEix variables, improved existing mappings for REMIND and IMAGE, and are finalizing the integration of WITCH. Ongoing efforts focus on extending the mapping to finer

sectoral resolutions (particularly within industrial subsectors such as chemicals) to capture the evolving complexity of material production systems in future scenarios.

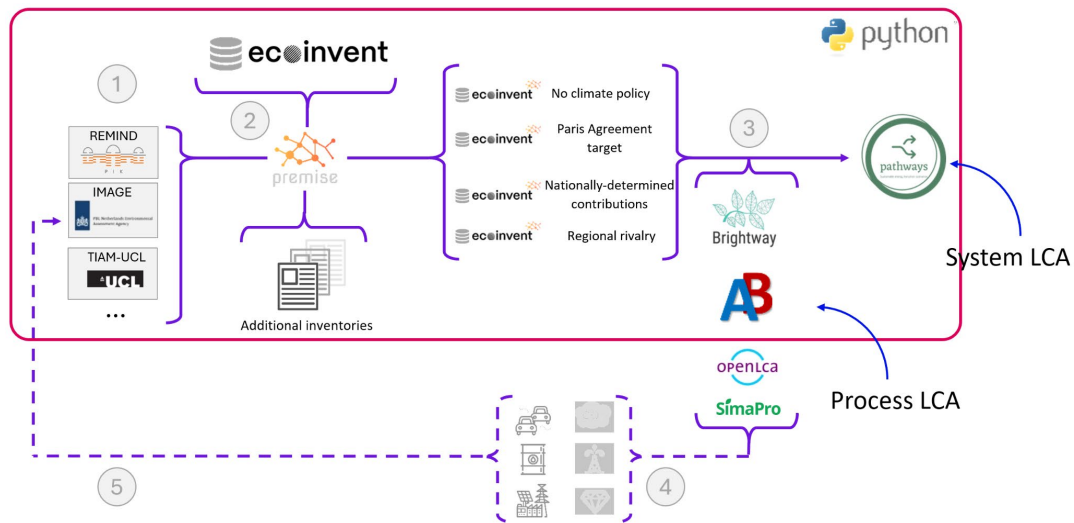


Figure 6: Workflow followed by Premise to integrate IAM scenario outputs into LCA databases. 1) A IAM scenario file is read by Premise. 2) Premise imports a copy of the LCA database Ecoinvent and imports additional inventories, such as those related to metals supply chains. 3) The LCA database is modified to align with a specific scenario and time step and can be exported to the main LCA software. Optionally, a data package can be created to be consumed by the Python library Pathways. Pathways allows to display environmental impacts and resource use of a system (e.g., sector, country, region, whole world) over time. The dashed line refers to the ongoing work of feeding LCA coefficients back to the IAM – see section 3.2.3 below.

Table 3: Number of production volume variables mapped to LCA via Premise, per IAM model. Other types of variables are mapped (e.g., efficiency and capacity variables) but are not shown here.

Sector variables/IAM	REMIND	REMIND-EU	IMAGE	MESSAGE-ix	WITCH	TIAM-UCL*	GCAM*
Electricity	20	20	28	26	14	36	22
Heat	24	24	38	26	0	2	0
Steel	6	6	13	12	0	13	8
Cement	2	2	5	2	0	1	2
Fuels	22	22	36	20	13	34	21
Ammonia	0	0	0	0	0	0	0
Methanol	0	0	0	0	0	0	0
High-value chemical	0	0	0	0	0	0	0
Paper	0	0	0	0	0	0	0
Biomass	2	2	4	3	2	2	2
Transport Two Wheelers	6	6	0	0	0	0	0
Transport Passenger Cars	30	30	5	0	3	14	0
Transport Bus	4	4	5	0	0	5	0
Transport Road Freight	20	20	38	0	0	45	0
Transport Rail Freight	3	3	5	0	0	3	0
Transport Sea Freight	3	3	8	0	0	18	0
Carbon Dioxide Removal	6	6	1	5	0	1	3
Final Energy	217	217	300	67	0	102	0
Other	4	4	4	3	4	4	4
Sum	369	369	490	164	36	280	62
* Models not part of the PRISMA consortium.							

The second step integrates these multiple temporally resolved LCI databases into a continuous analytical framework using the *Pathways* library. *Pathways* provides tools to collate and harmonize LCA results across time steps, enabling the exploration of transition dynamics and cumulative impacts along IAM trajectories. It supports the quantification of time-dependent environmental and human health burdens, as well as the life cycle demand of key materials, energy carriers, and technologies. The framework also allows disaggregation by scenario, sector, and region, facilitating a multi-scenario comparison of transition pathways. The workflow followed by *Pathways* is illustrated in Figure 7.

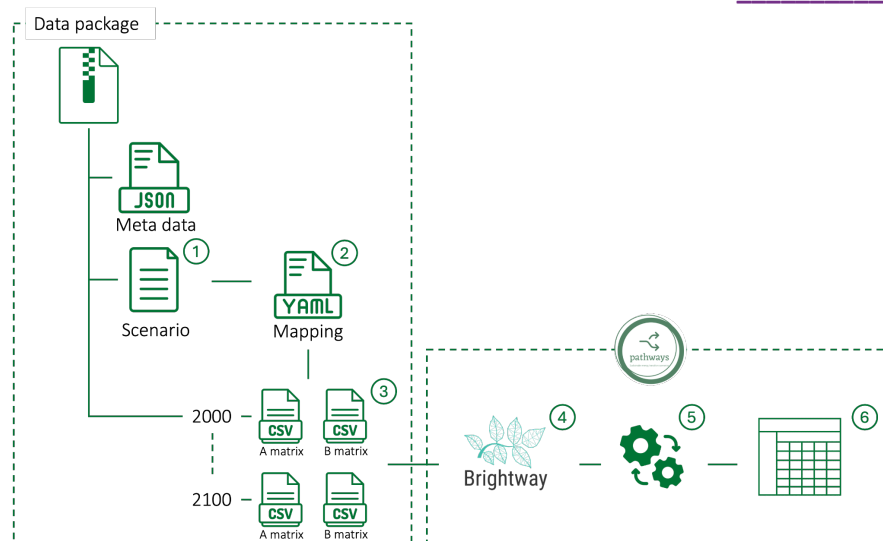


Figure 7: Workflow followed by Pathways. A data package created by Premise is read. The data package contains the IAM scenario data (production volumes, capacity building, efficiency changes) as well as, for each time step, a set of LCA matrices (technosphere and intervention matrices) describing the “futuraized” life cycle inventories. Pathways uses the LCA framework Brightway to compute the environmental impacts of each production volume variable over time. Results can be viewed per variable, sector, region or globally. Additionally, results can be disaggregated by the type of activity causing the impact and how these impacts distribution geographically.

The combination of *Premise* and *Pathways* enables the quantification of environmental impacts using LCA at the system scale.

For instance, Figure 8 illustrates this approach applied to global road freight transport as modeled in the REMIND SSP2-PkBudg1150 scenario (left panel). On a per-unit basis (middle panel), the life cycle impact of one ton-kilometer transported by the average global truck fleet (normalized to the impacts of today’s fleet) shows a decline in several indicators, including Global Warming Potential and other environmental impacts. However, when scaled to the growing overall transport demand (right panel), these unit-level improvements are offset, resulting in a net increase in total impacts. These increases are primarily driven by the disposal of toxic residual materials (such as battery waste and mining tailings) whose long-term leaching into the environment (>100 years) occurs once landfill containment barriers degrade.

Similarly, Figure 9 illustrates the implications of such large-scale dynamics for resource use indicators (i.e., land use, freshwater consumption, and metal demand) across three key sectors: global freight transport, electricity generation, and residential heat supply. The middle panel shows that, although emerging technologies exhibit lower metal-use intensity, the rapid expansion in overall demand more than offsets these efficiency gains, leading to a several-fold increase in total metal requirements compared to today. Note, however, that the potential to reduce primary extraction through recycling is not yet accounted for. Moreover, the choice of sub-technology (e.g., perovskite or copper indium gallium selenide (CIGS) photovoltaic cells within the broader photovoltaic family) can strongly influence the demand for specific metals,

as illustrated in Hahn Menacho et al. (2025). A Monte Carlo approach can be employed to account for the influence of sub-technology choice on overall metal demand.

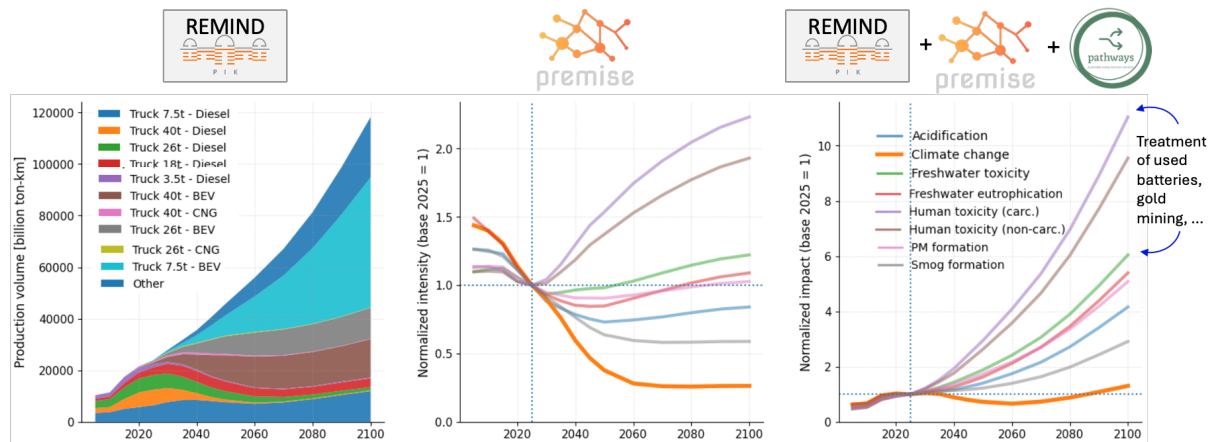


Figure 8: From IAM scenario to a quantification by Pathways. Left: Energy service variables for global freight transport by trucks, by size class and powertrain type, from REMIND 3.5, SSP2 - PkBudg1150, in billion ton-km (with a 66% change of a GMST inferior to 2 C). Middle: LCA score for the transport of 1 ton-km by the global truck fleet, normalized by the score in 2025, for several environmental indicators, based on projections from the same REMIND 3.5, SSP2 - PkBudg1150 scenario. Right: Scaled-up LCA score for the transport of freight by the global truck fleet normalized by the score in 2025, based on projections from the same REMIND 3.5, SSP2 - PkBudg1150 scenario.

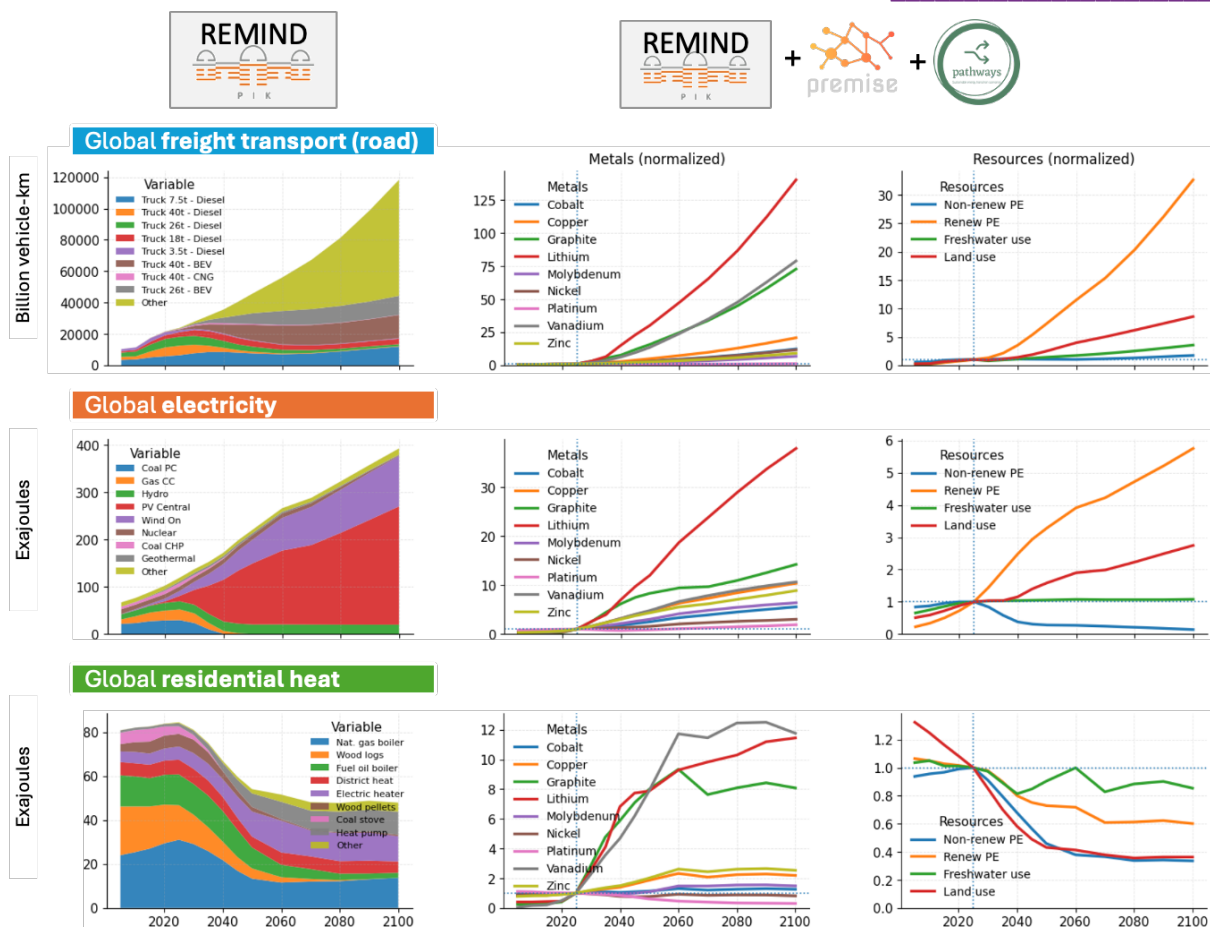


Figure 9: From IAM scenario to a quantification by Pathways. Left: Energy service or production variables for global freight transport by trucks (top), global electricity (middle) and global residential heat supply (bottom), based on projections from the REMIND 3.5, SSP2 - PkBudg1150 scenario. Middle: Corresponding scaled-up LCA score, normalized by the LCA score in 2025, for different metals. Right: Corresponding scaled-up LCA score, normalized by the LCA score in 2025, for different resources: freshwater use, land and primary renewable and non-renewable energy.

3.2.2 Inventories of materials required in low-carbon energy scenarios

The second direction involves systematic data collection from scientific literature and technical reports to update direct material intensity values for the identified technologies. Current LCI databases inadequately represent potentially scarce raw materials, particularly those used in small quantities, such as platinum group metals and rare earth oxides.

To fill this gap, we gather additional data on material requirements for key energy transition technologies. The **"WP4 Milestone No 6.xlsx"** (<https://doi.org/10.5281/zenodo.17579134>) Excel file contains detailed material intensity data for critical materials in various technologies. The file is structured with specific sheets for materials, technologies, and subtechnologies, each offering a range of data points processed to provide statistical values.

These updated intensities, when combined with the process-level information contained in ecoinvent, provide a comprehensive picture of material requirements across entire technology

supply chains. This approach also integrates new life cycle inventory data on end-of-life alternatives for energy technologies and mining activities.

3.2.3. Linking LCA feedback into IAM scenarios

The third direction explores bidirectional integration between LCA and IAM frameworks, investigating how LCA-derived insights can feed back into IAM scenario generation.

The material intensity data collected in section 3.2.2, combined with the prospective macro-level LCA framework described in 3.2.1, provides a foundation for understanding how technology choices in IAM scenarios drive material demand and associated environmental burdens. However, to close the loop, these LCA-derived environmental assessments need to be integrated back into the IAM's decision-making framework. This would allow IAMs to optimize transition pathways not only for energy system performance and climate targets, but also accounting for broader environmental impacts and material constraints across supply chains.

Within the PRISMA project, one approach to achieving this integration has been explored by monetizing life-cycle environmental impacts, which can then be integrated within IAM optimization (Bantje et al. 2025) (see Section 3.3). While this work extends beyond material demand to encompass the spectrum of environmental indicators available in LCA (e.g., toxicity, land use, water use) it demonstrates a methodological pathway for internalizing LCA-derived results into IAM's optimization framework. This approach illustrates how prospective LCA results can be transformed into economic signals that can be fed back into IAM scenario generation, allowing the model to account for environmental trade-offs and material criticality when optimizing energy system transitions. In this context, the REMIND team is developing an approach to implement these monetized environmental impacts as taxes for welfare-optimal internalization in the energy-economic modeling, thus allowing to generate scenarios that account for environmental externalities.

3.3. Repositories and Usage

Several open-source tools and datasets have been developed or extended in the framework of Task 4.4. These resources provide the methodological backbone for integrating the evaluation of material demand trajectories into IAM-LCA workflows.

Tools and methods developed:

- A. **Pathways:** Python package for prospective macro-level LCA of IAM scenarios (<https://github.com/polca/pathways>). This tool has contributed to the following publications:
 - **Sacchi, R., & Hahn-Menacho, A. J.** (2024). pathways: life cycle assessment of energy transition scenarios. *Journal of Open Source Software*, 9(103), 7309. doi: <https://doi.org/10.21105/joss.07309>
 - **Hahn Menacho, A. J., Sacchi, R., Bauer, C., Moretti, C., Panos, E., McKenna, R., & Burgherr, P.** (2025). The global environmental footprint of Switzerland's net-zero energy system uncovers impacts abroad. *Communications Earth & Environment*, 6(1), 266. doi: <https://doi.org/10.1038/s43247-025-02220-5>

- **Hahn Menacho, A. J., Sacchi, R., Bauer, C.,** Panos, E., McKenna, R., & Burgherr, P. (2025). The material-energy nexus in net-zero transition scenarios: exploring environmental trade-offs and uncertainties. *Resources, Conservation and Recycling*, 218, 108251. doi: <https://doi.org/10.1016/j.resconrec.2025.108251>
- B. **RELICS:** Python package to quantify resources extraction in LCA (<https://github.com/Laboratory-for-Energy-Systems-Analysis/relics>). This tool has contributed to the following publications:
 - **Hahn Menacho, A. J., Sacchi, R., Bauer, C.,** Moretti, C., Panos, E., McKenna, R., & Burgherr, P. (2025). The global environmental footprint of Switzerland's net-zero energy system uncovers impacts abroad. *Communications Earth & Environment*, 6(1), 266. doi: <https://doi.org/10.1038/s43247-025-02220-5>
 - **Hahn Menacho, A. J., Sacchi, R., Bauer, C.,** Panos, E., McKenna, R., & Burgherr, P. (2025). The material-energy nexus in net-zero transition scenarios: exploring environmental trade-offs and uncertainties. *Resources, Conservation and Recycling*, 218, 108251. doi: <https://doi.org/10.1016/j.resconrec.2025.108251>
- C. **Edges:** Library that allows flexible life cycle impact assessment, including geopolitical supply chain risk of raw materials at the technosphere level (<https://github.com/Laboratory-for-Energy-Systems-Analysis/edges/>). This tool has contributed to the following publication:
 - **Sacchi, R., Hahn Menacho, A. J.,** Seifudem, G., Agez, M., Schlesinger, J., Koyampambath, A., Saldivar, J. S., Loubet, P., & **Bauer, C.** (2025). Contextual LCIA Without the Overhead: An Exchange-based Framework for Flexible Impact Assessment. *International Journal of Life Cycle Assessment*. <https://doi.org/10.1007/s11367-025-02551-7>
- D. Framework for assessing external environmental costs using prospective LCA and monetary valuation, as described and used for deriving external cost estimates for energy provision technologies in the following publication:
 - **Bantje, D., Sacchi, R.,** Arendt, R., **Bauer, C., Luderer, G.** (2025). Prospective analysis of external environmental costs of energy provision. *Environmental Research Communications*. <https://doi.org/10.1088/2515-7620/ae055a>

Data collection:

As part of **WP4's Milestone 6**, the "**WP4 Milestone No 6.xlsx**" dataset compiles detailed material intensity data for **critical raw materials** across a range of energy and mitigation technologies. The file is organized into dedicated sheets for materials, technologies, and sub-technologies, each providing a comprehensive set of processed data and statistical indicators. This dataset complements and refines the material intensity information available in **ecoinvent** LCA database, with a specific focus on the demand for critical materials in key low-carbon technologies.

The dataset has been uploaded to **PRISMA's Zenodo repository** (<https://doi.org/10.5281/zenodo.17579134>), where users are encouraged to contribute to its continuous expansion. Complementary data collection efforts have also targeted **emerging end-of-life options for energy technologies** and **updated mining inventories**, which have been integrated into the LCA database to enhance completeness and representativeness. Detailed

documentation of the data integration procedures is available in the **Premise GitHub repository** (<https://github.com/polca/premise>). The compiled data form a key component of WP4's outcomes and have been used in the related peer-reviewed publications.

Improved IAM-based scenario input for prospective LCA:

- Improved granularity and reporting of sectoral transitions in transport and industry for prospective analysis. In particular, the variable mapping to **premise** was improved for the following (sub)sectors:
 - Process-based steel production
 - Transport (overall improved granularity for vehicle types and powertrains/fuel)
 - Final energy (allowing creation of final energy markets in the LCA model)
 - Liquid fuels

These improvements translate to broader coverage of transition described in IAM scenarios and thus more realistic representation of them within prospective LCA.

All listed publications explicitly state PRISMA project support.

