TRANSIENCE

TRANSITIONING TOWARDS AN EFFICIENT, CARBON-NEUTRAL CIRCULAR EUROPEAN INDUSTRY

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D4.7 – Environmental impact assessment

WP4 – Developing satellite modules

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EC Summary Requirements

1. Changes with respect to the DoA

No changes with respect to the work described in the DoA.

2. Dissemination and uptake

This deliverable serves the broader stakeholder community of TRANSIENCE—including decision-makers, researchers, and industry professionals—by presenting comprehensive and transparent life cycle assessment (LCA) methods, data, and results. As such, it serves as a key module for supporting informed decision-making in future energy system modelling and developing decarbonisation (and circular economy) strategies for the European industry—and beyond. This environmental LCA module is open source to ensure sustainability efforts are based on transparent data and approaches, enabling stakeholders across various sectors to use and apply the methods, data, and results.

3. Short summary of results (<250 words)

This deliverable introduces the environmental LCA module, as part of the Model for European Industry Circularity and Climate Change Mitigation (MIC3) framework. The LCA module is designed to calculate the lifecycle environmental impacts of products, industry transformations, and entire energy system modelling pathways of MIC3 modules in a flexible way using tailor-made (prospective) LCA databases. As such, it aims to validate the environmental performance of decarbonisation and circularity performance pathways and strategies to ensure that they are aligned with sustainability goals beyond impacts on climate change. In doing so, this LCA module aims to also provide key insights into the environmental trade-offs and co-benefits associated with industry transformations reflected in pathways produced using MIC3.

4. Evidence of accomplishment

This report and the repository published on GitHub: https://github.com/tomterlouw/lca_transience

In addition, related manuscripts:

- On Section 4.2: Terlouw, T., Moretti, C., Harpprecht, C., McKenna, R., & Bauer, C. (2025). On the global climate-effectiveness of hydrogen applications. Nature Energy, *In Review*.
- On Section 4.3: Terlouw, T., Harpprecht, C., & Bauer, C. (2025). GHG emissions of the global steel industry and the effectiveness of the European carbon border adjustment mechanism. *In preparation*.

Preface

The need to approach climate action, resource efficiency, and circularity performance as integrated, economy-wide, cross-cutting issues is gaining more and more attention, stimulating the development of new industrial policies in Europe and worldwide. Currently, however, there is little progress in conceptualising the circular economy and understanding its interactions with climate action. State-of-the-art modelling capacity to capture the interplay of the two agendas and their implications for energy-intensive sectors as well as to represent the European industry's transformation in line with the region's vision for climate neutrality is not yet fully developed. TRANSIENCE will undertake a comprehensive characterisation and assessment of circularity principles and measures vis-à-vis decarbonisation, by looking at the twin transition of European industries through the lenses of global competitiveness, innovation, and holistic sustainability. It will then produce MIC3, a consistent, fully open-source model ecosystem to assess industrial circularity, decarbonisation, and sustainability. A series of interoperable modules on the socioeconomic, service and product, material, industrial, energy-system, and environmental perspectives of the transformation of European industry will be developed and integrated, building on and opening the code of leading modelling tools. MIC3 will finally be used in extensive scenario modelling to produce diverse pathways toward a material-efficient, circular, climate-neutral, sustainable European industry. Transparency, openness, and knowledge sharing will be promoted, and technical capacities will be developed in four industrial agglomerations in the EU, moving beyond stakeholder consultation, onto model co-development, continuous validation of assumptions, co-creation of scenario modelling, evaluation of the desirability and usability of the developed model and insights, and eventually co-production of science and action.

ICCS – Institute of Communication and Computer Systems	EL
CEPS – Centre for European Policy Studies	BE
E3M – E3-Modelling AE	EL
Fraunhofer – Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V.	DE
HOL – HOLISTIC IKE	EL
PIK – Potsdam Institut für Klimafolgenforschung e.V.	DE
PNTEC – Park Naukowo-Technologiczny Euro-Centrum Spolka Z Ograniczona Odpowiedzialnoscia	PL
TECNALIA – Fundación Tecnalia Research & Innovation	ES
UU – Universiteit Utrecht	NL
WI – Wuppertal Institut für Klima, Umwelt, Energie gGmbH	DE
PSI – Paul Scherrer Institut	CH
UCL – University College London	UK

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Executive Summary

Deliverable D4.7 presents the description of the environmental life cycle assessment (LCA) module within the TRANSIENCE project, as part of the Model for European Industry Circularity and Climate Change Mitigation (MIC3) framework. The environmental LCA module introduces a flexible and transparent LCA approach that can integrate other MIC3 modules—such as energy system scenarios, material flow analysis (MFA), and industrial transformation pathways—to assess the environmental performance of industrial processes and systems throughout different assessment scales.

The environmental LCA module builds on existing open-source tools, such as the *premise* (Sacchi et al., 2022) framework for modifying background LCA databases and the *pathways* tool (Sacchi & Hahn-Menacho, 2024) for evaluating entire energy transformation scenarios. As such, this MIC3 module enables a (prospective) analysis of environmental trade-offs and co-benefits beyond (life cycle) greenhouse gas emissions, by integrating the MIC3 model scenarios. It covers a broad range of impact categories, including human health, resource scarcity, and biodiversity loss.

The environmental LCA module supports a modular approach that enables: (i) quantifying product-level emissions (e.g., for buildings, transport, and packaging), (ii) evaluating sector-level transformations, and (iii) assessing entire energy system model pathways. Further, it aims to incorporate spatially explicit modelling and regionalised environmental impact assessment methods. As such, this environmental LCA module ensures that decarbonisation and circular economy strategies are not only aligned with climate policies but also promote broader sustainability goals by considering a large set of environmental burdens, such as critical raw materials and human toxicity.

In this deliverable, we provide the description of the environmental LCA module (Section 2), the novelty and benefits of the module (Section 3), and exemplary results (Section 4) demonstrating the functionality of this integration, by using proxy data from various MIC3 models.

The current results and coupling between the energy system module variables and life cycle inventories are still at an early stage. The integration between MIC3 modules will be further harmonised in future iterations. The coupling and results presented here are thus illustrative and serve to demonstrate the functionality of the integration.

Code metadata	
Current code version	v.1.0
Link to code repository	https://github.com/tomterlouw/lca_transience
Legal code license	BSD 3-Clause
Code versioning system used	Git
Software code language	Python
Particular tools, services, modules used	Premise module: https://github.com/polca/premise Pathways module: https://github.com/polca/pathways
Compilation requirements, operating environments & dependencies	Tested with Python 3.11 and the modules listed in the lca_transience.yaml file
Link to documentation/manual	https://github.com/tomterlouw/lca_transience/blob/main/README.md

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1 Introduction

TRANSIENCE aims to support the transition towards a circular and climate-neutral industry by developing a dynamic modelling framework, called the Model for European Industry Circularity and Climate Change Mitigation (MIC3), to assess sectoral and circular transformation pathways in Europe. The MIC3 framework builds upon existing data infrastructures and methodological advancements, among others, in Life Cycle Assessment (LCA), energy systems modelling, and material flow analysis. A key component of the MIC3 framework is the environmental LCA module.

The environmental LCA module introduced in this deliverable plays a key role in assessing the life cycle environmental impacts of products (e.g., steel and ammonia production processes), industrial transformations (e.g., the steel industry), and entire energy transition pathways developed within MIC3 (e.g., the whole European energy system). It builds upon the existing prospective LCA framework *premise* (Sacchi et al., 2022), which allows modifying background LCA databases, and *pathways* (Sacchi & Hahn-Menacho, 2024), which allows quantifying the environmental burdens of entire energy transformation scenarios (using modified LCA databases). This environmental LCA module is a key element of the broader modelling framework (MIC3) described in Deliverable D3.4 of the TRANSIENCE project—a deliverable that identifies key linkages between the various MIC3 modules, including the environmental LCA module, such as fetching data flows coming from the OPEN-PROM energy system module, the FORECAST and ITOM industrial modules, and potentially the material flow analysis (MFA) module. Figure 1 provides an overview of how the LCA module is integrated within the MIC3 framework. The placement of the LCA module is highlighted in the dashed black lines of Figure 1.

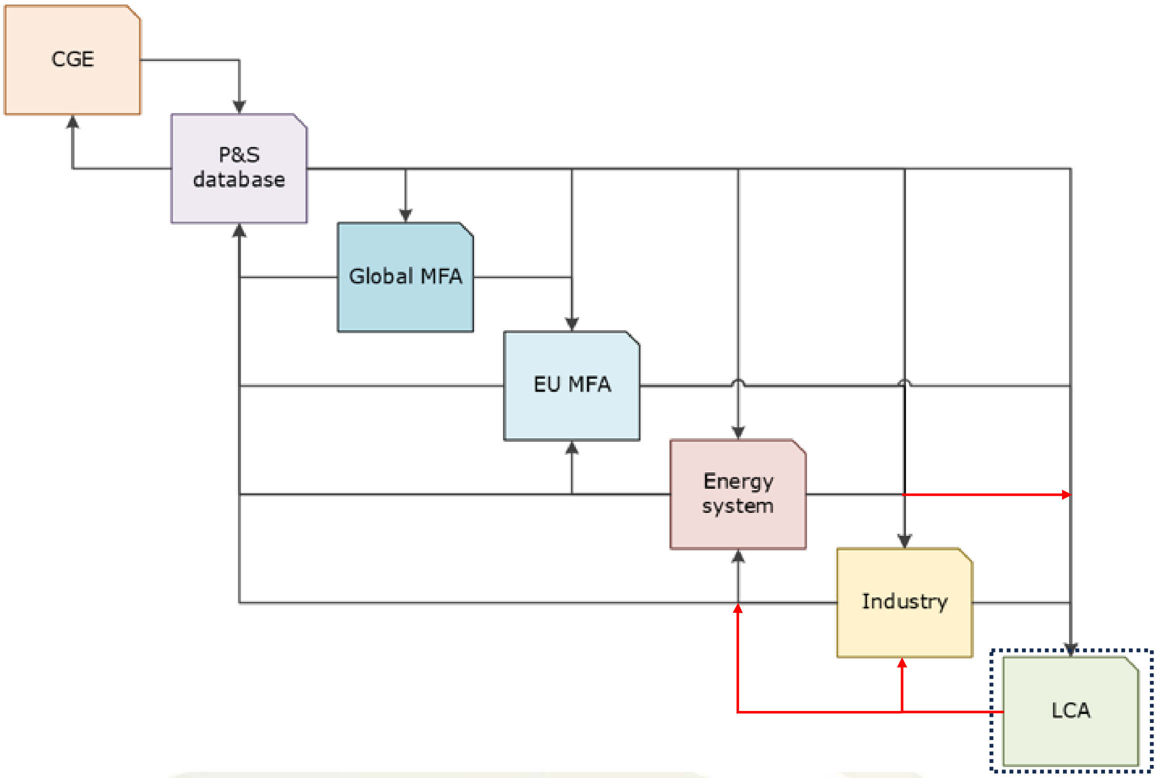

Figure 1. Planned interfaces among MIC3 modules with the environmental module highlighted within a dashed black squared box. This Figure is reproduced from TRANSIENCE D3.4. Note the additional (compared to previous versions of this figure) red-coloured lines to illustrate the potential exchanges from MIC3 modules and possible bidirectional exchanges to the industrial and energy system models.

The environmental LCA module incorporates prospective LCA capabilities into the MIC3 framework by evaluating and validating the climate change impacts derived from the MIC3 modules. It also enables the assessment of environmental trade-offs and co-benefits—e.g., on (critical) raw materials and human health—of products as well as industrial and energy system transitions beyond climate-related impacts. Overall, the following activities are reported in this document:

- The development of an environmental LCA module that integrates prospective LCA by using data from energy system scenarios and material flow analysis, to quantify life cycle environmental impacts inter alia on climate change, human health, and resource scarcity (see Section 4.1). The integration of biodiversity impacts is underway.
- Linking to MIC3 modules to incorporate scenario-specific energy transitions in the LCA (see Section 2 for explanation and Section 4.2 for results) in a flexible way and applicable to industrial processes, products (buildings, transport, packaging), and entire industry and energy system transformation scenarios.
- The design of the module to quantify non-GHG environmental burdens in a spatially explicit way, enabling regionalised impact assessments (see Sections 3, 4.2, and 4.3).
- The provision of product-specific quantification of embodied carbon emissions in EU-produced vs. imported goods and services (see Section 4.3).

These support informed decision-making to ensure that mitigation strategies and pathways, developed in MIC3, are also aligned with broader sustainability targets. This detailed overview of the environmental LCA module is broken down into module description (Section 2), illustration of the contribution and novelty compared to the state-of-the-art (Section 3), and a presentation of preliminary findings (Section 4).

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2 Module description

The environmental LCA module, as part of the MIC3 model, is built on two previously developed open-source Python packages: *premise* (Sacchi et al., 2022) and *pathways* (Sacchi & Hahn-Menacho, 2024). The Python package *premise* enables the modification of background LCA databases (based on the LCA database *ecoinvent*) using external energy system model scenarios, while *pathways* allows for quantifying the environmental impact of entire industrial or energy system model transformation scenarios. Moreover, *brightway* (Mutel, 2017) is used to calculate separate LCA impacts of processes. In TRANSIENCE, building upon those three Python packages, we establish the connection between the different MIC3 modules to allow for the quantification of the environmental impacts of (industrial) products, (industrial) energy transformations, and entire energy system model pathways developed within MIC3. In the following sections, we briefly explain the (preliminary) concept of the environmental LCA module within MIC3.

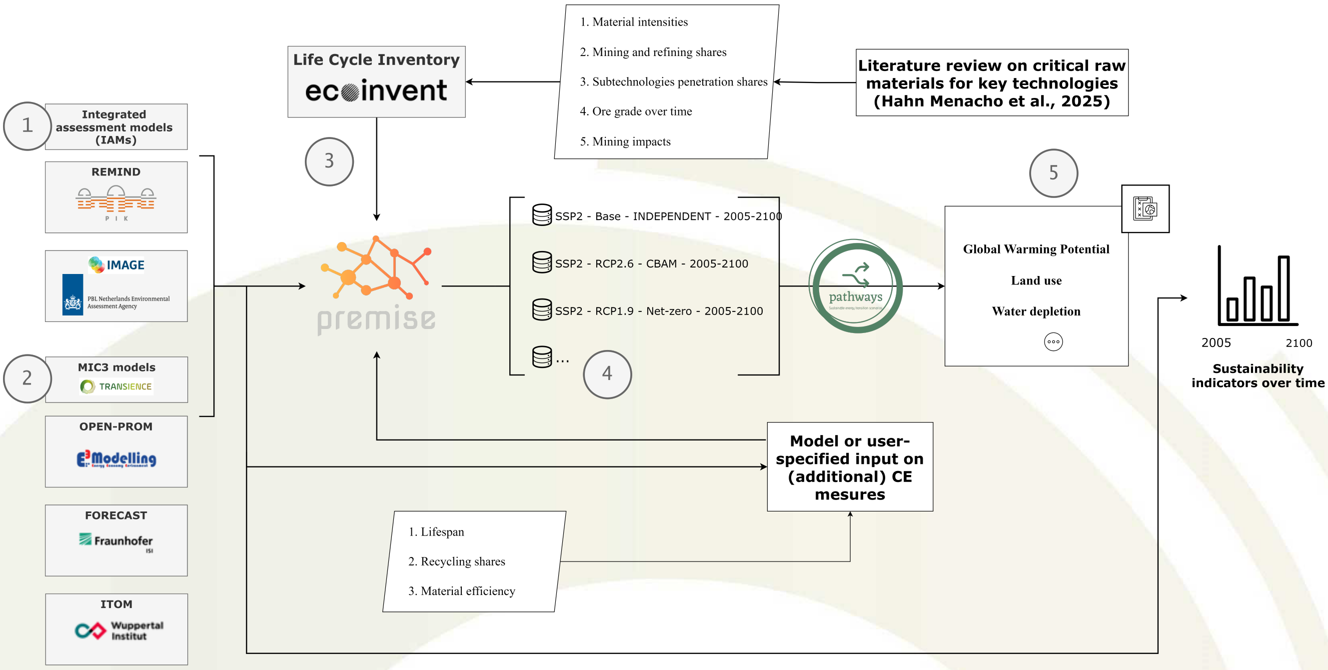

Figure 2. Overview of the environmental LCA module and connections between energy system, integrated assessment, material flow and industrial models. The figure is based on the work of Hahn Menacho et al. (Hahn Menacho et al., 2025) **and has been modified to make it representative for MIC3. CE = circular economy.**

2.1 Concept

The environmental LCA module requires life cycle inventory data of processes and activities, sourced from the *ecoinvent* database (step '3' in Figure 2). Here, we use ecoinvent 3.10 (Wernet et al., 2016), using the system model 'cut-off by classification' (i.e., an LCA system model that excludes upstream processes for recycled or waste materials). The *ecoinvent* database represents nearly all relevant supply chain processes in the current global economy that are associated with the production of goods and services. It includes both upstream and downstream processes, capturing the associated environmental flows within each process, such as energy use, emissions to air, water, and soil, as well as material inputs and outputs. It provides geographically and technologically differentiated datasets across multiple sectors. In the context of this module, the database is used as a source of background LCA data. One drawback of conventional background LCA databases is that they represent a snapshot of the current global economy or a specific point in time, which may limit their relevance for calculating prospective environmental burdens.

However, the background LCA database can be modified considering 'external' system scenarios, for example, those based on integrated assessment models (IAMs) (Riahi et al., 2017; Skea et al., 2021; Van Vuuren et al., 2021) to consider prospective developments based on various development trajectories (Sacchi et al., 2022), which is illustrated in step 1 of Figure 2. Here, such a modification of a background *ecoinvent* database is performed using open-source Python package *premise* (Sacchi et al., 2022). Possible scenarios from IAMs that can be considered for modifying an *ecoinvent* database are those from REMIND (Luderer et al., 2015), IMAGE (Van Vuuren et al., 2021), or TIAM-UCL (see step '1' in Figure 2). The complete documentation of *premise* (Sacchi et al., 2022) can be found online[1].

It is worth noting that *premise* integrates the system model outputs—e.g., scenarios consistent with limiting global warming to 2°C—of such IAMs by modifying various economic sectors in the *ecoinvent* database—e.g, electricity, steel, cement, mobility (e.g., cars and trucks), and fuels. As such, *premise* modifies, among others, existing market activities (equivalent to supply mixes in certain regions) for those sectors and updates parameters such as process efficiencies, pollutant emissions, technology market shares, and lifetimes of life cycle inventories of processes. In addition, *premise* integrates additional life cycle inventories of (low carbon) technologies relevant for future development pathways. Finally, *premise* can integrate (multiple) additional model scenarios beyond those of IAMs (step 4 in Figure 2). This is especially relevant in TRANSIENCE, since we aim to include the outputs of various modules (the MIC3 modules considered in step 2 of Figure 2):

- OPEN-PROM (overarching energy system model with a detailed representation of the EU).
- ITOM (industrial module focusing on the European steel, plastics, and cement industry).
- FORECAST (spatially explicit industrial module focusing on methanol, ammonia, ethylene, and primary steel sector development in Europe).

It is also noteworthy that the MFA modules of MIC3 directly report their transformations (regarding efficiency and shares of primary versus secondary materials) to the above MIC3 modules. As such, MFA considerations are therefore indirectly considered if those MIC3 module outputs (with MFA considerations) are used in modifying background LCA databases. The new (prospective) modified LCA databases can be exported, using *premise*, and written to a local disk file. Next, these modified (prospective) background LCA databases can be used to calculate the LCA impacts of individual processes at any time by using the open-source framework *brightway* (Mutel, 2017).

Finally, *pathways* (Sacchi & Hahn-Menacho, 2024) can be used to calculate LCA-based environmental burdens of entire industrial energy transformations (e.g., from ITOM or FORECAST, see step 5 in Figure 2) and energy system model scenarios (e.g., from OPEN-PROM). As such, different economic sectors can be analysed for LCA impacts beyond climate change, considering different future development trajectories.

2.2 Data

The environmental LCA module relies on substantial amounts of data from various sources, which are shown in Table 1. The input and output data are briefly described in the following sections.

[1] https://premise.readthedocs.io/en/latest/.

2.2.1 Inputs

The LCA module integrates a wide range of input data. In the future, the outputs of the environmental LCA module may also be used as inputs to other MIC3 modules (see Table 3). For example, data on the demand for critical materials, derived from this environmental LCA module, could inform projections of commodity price increases in MIC3 modules that analyse market dynamics.

For now, in the environmental LCA module, we use the model outputs of MIC3 modules as inputs to our LCA framework. Those outputs are used to transform background LCA databases, as well as calculate the environmental burdens of processes, industrial energy transition pathways, and entire energy system scenarios based on the modified background LCA databases consistent with the MIC3 modules and development trajectories.

One of the foundational data sources for the environmental LCA module within MIC3 is the background *ecoinvent* database (v. 3.10 used), which provides the life cycle inventory data of global economic processes (ecoinvent, 2023; Wernet et al., 2016). As previously discussed, life cycle inventory data is complemented by importing additional life cycle inventories, provided by *premise* (Sacchi et al., 2022).

First, to align with future socioeconomic and technological developments, the entire background LCA database is modified using scenarios from IAMs, such as IMAGE and REMIND (Luderer et al., 2015; Sacchi et al., 2022; Van Vuuren et al., 2021). Those global IAM scenarios ensure that the transformation of the global economy is not limited to Europe alone (obtained from MIC3 modules) but extends to the entire global economy covered in *ecoinvent* databases. This step is necessary to ensure that, in addition to the European economic transformations captured by the MIC3 modules, non-European datasets are also modified in line with selected global development scenarios (obtained from IAMs). Notably, this enables the coupling of European transition pathways (derived from MIC3 modules) with global IAM scenarios, allowing us to assess whether—and to what extent—developments outside Europe influence the environmental burdens of processes, industrial transformations, and entire energy system scenarios within Europe.

Table 1. Description of data used in the environmental LCA module.

Data type	Description	Source(s)
Background LCA database.	The background ecoinvent v3.10 database is used for the most relevant processes of the economy worldwide.	(ecoinvent, 2023; Wernet et al., 2016)
Integrated assessment model (IAM) scenarios.	IAM scenarios modify the entire background LCA database first, ensuring that the future economy changes not only in Europe but also globally.	(Luderer et al., 2015; Sacchi et al., 2022; Van Vuuren et al., 2021).
Energy system scenarios from OPEN-PROM.	Energy system model output from OPEN-PROM.	(E3Modelling, 2025)
Industrial energy transformation scenarios from ITOM.	Module output from ITOM. Data used for the European steel industry.	(ITOM, 2025; Schneider et al., 2025)

Data type	Description	Source(s)
Industrial energy transformation scenarios from FORECAST.	Module output from FORECAST. Currently, country-specific (preliminary) data are provided and used for the ammonia and methanol industry in Europe.	(Marius Neuwirth, 2024; Neuwirth et al., 2024)
Potential additional circular economy measures.	The possible option to apply user-specific modifications in the background LCA database, considering; (i) secondary raw materials, (ii) material replacements, (iii) lifetime extension of processes.	N/A

Second, further model inputs (to the environmental LCA module) are provided by energy system models within MIC3. OPEN-PROM delivers key outputs for energy system transformations across Europe (E3Modelling, 2025), while ITOM provides data specifically for the European steel industry (ITOM, 2025; Schneider et al., 2025) and potentially also for the cement and plastics sectors. Finally, FORECAST provides country-specific industrial transformation and production data to transform the ammonia, methanol, ethylene, and (potentially) the primary steel sector (Marius Neuwirth, 2024; Neuwirth et al., 2024).

Finally, the environmental LCA module may allow for user-defined integration of potential circular economy measures that can transform background LCA databases. It still needs to be discussed whether those direct inputs (to the LCA) will and need to be integrated since, as previously mentioned, material efficiencies and the shares of primary versus secondary material will flow directly from the MFA modules to other MIC3 modules (e.g., industrial modules), which will be used as energy system model input within the environmental LCA module. However, these can already be incorporated as modifications to the background LCA database and may include; (i) the extension of process lifetimes (for example, of facilities), (ii) modification of the amount of a material needed for a specific process (for example, reducing the amount of concrete in buildings), and (iii) the use of secondary raw materials (and material substitution strategies). These inputs may be customisable and are currently not associated with a fixed reference.

An example of such an input is provided below and in Table 2. In this example, there are two scenarios referring to development pathways in Europe: a low-carbon one (*WP1 NetZero_ce*) and a business-as-usual scenario (*WP1 NPI_ce*). The 'region' is specified to search for activities in a specific region (here, RER, representing the region of Europe). For example, in both scenarios, we can now specify; (1) the change in terms of efficiency of using steel in *ecoinvent* processes (diminished in the low-carbon scenario to 0.7, i.e., an efficiency improvement of 30% in 2050). Similarly, the user can specify a lifetime change for a specific search term (here, searching for *ecoinvent* processes related to "Facility"). In this case, all processes with 'Facility' in their name will increase the lifetime by a particular factor (e.g., in the low-carbon scenario for 2050, it is 0.85, meaning a 15% increase in its lifetime). In the future, such assumptions could be aligned with the ones used in other MIC3 modules, e.g., MFA modules.

Table 2. User-specific scenario for additional circular economy measures.

Model	Scenario	Region	Variables	Unit	2020	2030	2040	2050
ce_user	WP1 NetZero_ce	RER	Circular Economy|Efficiency|Steel	[-]	1	0.95	0.9	0.7

ce_user	WP1 NetZero_ce	RER	Circular Economy|Lifetime|Facility	[-]	1	0.98	0.94	0.85
ce_user	WP1 NPI_ce	RER	Circular Economy|Efficiency|Steel	[-]	1	1	1	1
ce_user	WP1 NPI_ce	RER	Circular Economy|Lifetime|Facility	[-]	1	1	1	1

2.2.2 Outputs

Section 4 presents exemplary results that illustrate how the MIC3 modules are integrated within the life cycle inventory database by providing preliminary results based on proxy data received from OPEN-PROM, ITOM, and FORECAST. In Section 4.1, we demonstrate how the background LCA database can be modified to quantify environmental burdens across different energy pathways and industries, for example, the entire European energy system (Section 4.1.1, OPEN-PROM) and the European steel industry (Section 4.1.2, ITOM). Consequently, the environmental LCA module can provide the outputs presented in Table 3.

The background LCA database has an identical format as the original *ecoinvent* database (in SQLite format), albeit with additional and updated activities that can be directly used within *brightway* (Mutel, 2017), ActivityBrowser, or can be even exported to be compatible with SimaPro.

Table 3. Potential outputs from the environmental LCA module.

Parameter	Description	Input to
LCA databases	Entire modified background LCA databases. The output of *premise* is a modified LCA database. From this database, one can calculate separate environmental impacts of processes (using *brightway2*) individually or on a system level (using *pathways*).	n.a.
LCA impact of processes	LCA impacts on specific (industrial) processes throughout all environmental impact categories.	MIC3 modules for validation.
LCA impact of energy transition scenarios	LCA impacts on entire industrial transformation pathways on all environmental impact categories.	MIC3 modules for validation.

Finally, Sections 4.2 and 4.3 provide deep dives on (i) the most climate-effective hydrogen applications and (ii) the carbon accounting effectiveness of the European Carbon Border Adjustment Mechanism (CBAM) in the context of the global iron and steel industry, respectively. Those results provide illustrative examples of additional case studies conducted in the context of TRANSIENCE.

3 Novelty, benefits, and future improvements of the module

The environmental LCA module represents a significant advancement in assessing the life cycle environmental burdens for energy-intensive industries and entire energy systems undergoing prospective transformations. As such, this module provides a prospective, modular, and interoperable framework integrating various MIC3 modules, enabling various stakeholders to systematically evaluate the environmental trade-offs and co-benefits of different decarbonisation and circularity performance strategies. Here, the novelty is distinguished between those within the existing scientific literature and that of the module itself compared to existing LCA frameworks. First, the novelties of the environmental LCA module as opposed to the current scientific literature are as follows:

- It is the first LCA-based assessment framework to analyse the LCA impacts of entire European transition pathways and industrial transformations, considering (multiple) well-established European energy system, industrial, and MFA models in the foreground and background.
- This environmental module allows quantifying environmental burdens across industrial processes, products (e.g., buildings, transport, packaging), and full energy and industry system transformations by linking to MIC3 modules, enabling calculating LCA impacts of scenario-specific transitions based on the MIC3 modules.
- Various deep dives are conducted that are specifically relevant for the industrial transformation towards a low-carbon European industrial energy sector by determining; (i) the most climate-effective hydrogen applications (for industries and society, overall) and (ii) the effectiveness of the European carbon border adjustment mechanism in the context of the European steel industry. For those deep dives, separate open-source frameworks are developed, to be published.

Second, the novelties of this environmental LCA module as opposed to previous work and available Python packages (on environmental LCA) are as follows:

- It enables a fully functional and integrated environmental LCA module to support the European industrial energy transformation, with seamless integration of all relevant MIC3 modules. To achieve this, preliminary configuration files (also known as correspondence tables) are initialised to couple variables from MIC3 modules to LCA processes. Also, scripts are written that directly allow for transforming ecoinvent databases, exporting those, and calculating the LCA-wide system impacts of those within the context of MIC3. Overall, this has led to a new repository, which is available on GitHub (https://github.com/tomterlouw/lca_transience).
- To achieve this, additional changes in *pathways* and *premise* have ensured fully functional workflow, where multiple external scenarios (beyond the IAMs, previously limited to one external scenario) can be integrated. In the context of TRANSIENCE, we integrate one existing IAM scenario, three MIC3 module output scenarios, and possibly additional user-defined circular economy measures, increasing the total number of scenarios transforming the *ecoinvent* database to five. The more external scenarios from MIC3, the more likely the database will be consistent with a MIC3 module (prospective) scenario—for example, low-carbon or business-as-usual (see Section 4.1).
- It possibly offers the option of applying user-defined circular economy measures within *premise*. As such, it may be possible to (i) apply such measures to extend lifetimes, (ii) change the share of primary vs. secondary materials, and (iii) modify materials utilised within processes or products

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directly using Excel files as input data format.

Finally, while other MIC3 modules can quantify operational CO_2-emissions, the environmental LCA module can calculate all relevant environmental burdens over the entire life cycle of processes, products, and services with associated supply chains, including, for example, life cycle GHG emissions, human toxicity, eutrophication, and (critical) raw materials. This enables the quantification of potential environmental trade-offs and co-benefits of energy system transformations and scenarios.

Thus, the current environmental LCA module already provides a functional foundation for assessing the environmental implications of products, industrial transformations, and energy system model outputs. However, several improvements are planned to further improve the accuracy, resolution, and interoperability. Planned improvements and future developments, part of the second project phase, include the following:

- Complete (non-proxy) energy system data from MIC3 modules. Replacing proxy datasets with finalised energy system model outputs will enable more accurate modelling of environmental impacts across scenarios and sectors. One challenge of the environmental LCA module is that we rely on substantial data requirements from most MIC3 modules, hence we are heavily dependent on them. Without harmonised input data—mostly regarding the energy system model outputs and pathways—the LCA results may be limited in accuracy.
- Harmonisation of input data from all output scenarios of MIC3 modules. For example, there is a need to agree on the future development pathways to be considered (e.g., low-carbon and business-as-usual). Also, it is necessary to further harmonise data formats, assumptions, and temporal/spatial resolutions across the MIC3 framework. This will improve compatibility and interoperability between MIC3 models, potentially preventing misalignments.
- Assessment, and potential integration, of regionalised impact assessment methods to quantify location-specific impacts on water and biodiversity—for example, using the Python package *edges* (Romain Sacchi & Alvaro Hahn Menacho, 2025). Incorporating regionalised methods will allow the LCA module to better capture spatially differentiated environmental burdens. This is particularly relevant for impact categories that have regionalised impacts, such as freshwater use, land occupation, and biodiversity.
- Possibly addressing uncertainties from the coupling of (evolving) technologies with corresponding market shares. As such, we may apply a global sensitivity analysis approach using *pathways* (Sacchi & Hahn-Menacho, 2024). This will allow us to quantify how variations in (critical) raw material intensity, technology efficiency, and market adoption influence environmental outcomes and (critical) raw material demands (Hahn Menacho et al., 2025).

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4 Exemplary results

This section presents preliminary results of the environmental LCA module, using proxy data from the following MIC3 modules: OPEN-PROM, ITOM, and FORECAST. Section 4.1 discusses the scenarios considered and describes how environmental burdens are quantified for comprehensive energy system scenarios in Europe (based on OPEN-PROM) and various industrial pathways (based on ITOM), with a focus on the European steel industry.

Sections 4.2 and 4.3 provide two analyses conducted within the TRANSIENCE project. First, Section 4.2 shows an analysis of hydrogen applications that offer the most climate change mitigation potential. Second, Section 4.3 assesses the potential effectiveness of the EU Carbon Border Adjustment Mechanism (CBAM) of the global steel industry applied to the European context.

4.1 Modifying the background LCA database and quantifying the environmental burdens of various pathways and industries

Based on proxy data from various MIC3 modules, we aim to show the present functional state of the environmental LCA module. To achieve this, MIC3 model outputs are received from OPEN-PROM (entire energy system, scope: Europe), ITOM (steel industry, scope: Europe), and FORECAST (ammonia, methanol, ethylene, and primary steel, scope: country-specific results for Europe).

The outputs of those three MIC3 modules are used and combined into two different scenarios from 2025 to 2050 using a timestep of 10 years:

- **Business-as-usual**, assuming that the currently announced national developments in terms of climate policy will materialise.
    - Modifications:
        - OPEN-PROM modifies the European electricity market using the projected production volumes of electricity and the final energy requirements output are used to quantify the system impacts of the entire scenario in Section 4.1.1.
        - ITOM modifies steel markets in Europe by using the production volumes of steel production routes. Additionally, the final energy variables from ITOM are used to quantify environmental burdens in Section 4.1.2.
    - The combined scenario called 'Business-as-usual' refers to the following specific model scenarios: 'WP1 NPI' (OPEN-PROM) and 'INDEPENDENCE' (ITOM).

- **Low-carbon (or 2°C)**, assuming a transition towards a low-carbon (European) energy system to achieve (near) net-zero emissions by 2050.
    - Modifications:
        - OPEN-PROM, using the projected production volumes of electricity, the European electricity market is modified, and the final energy is used to quantify the system impacts of the entire scenario in Section 4.1.1.
        - ITOM, using the production volumes of steel production, steel markets are modified in Europe. Additionally, the final energy is used to quantify environmental burdens in Section 4.1.2.
        - FORECAST, using the production volumes, methanol and ammonia markets are modified for all European countries and Europe as a whole.

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- The combined scenario called 'Low-carbon' (or '2°C') refers to the following specific model scenarios: 'WP1 NetZero' (OPEN-PROM), 'CBAM' (ITOM), FORECAST (assuming it refers to a low-carbon scenario), and we apply additional circular economy measures (see Table 2 as an example).

As previously indicated, note that only proxy data is provided for this analysis. **The results presented are solely intended to demonstrate the functional state of the environmental LCA module**. As such, the MIC3 module scenarios have not yet been harmonised, nor has the consistency between IAM variables and life cycle inventories been reviewed by both parties.

4.1.1 The entire European energy system

For this exercise, we calculate the environmental impacts from the scenarios (business-as-usual and low-carbon), as described in Section 4.1, for the following environmental impact categories: climate change, human toxicity, and two (critical) raw materials, namely: lithium and iridium, to 2050, using a 10-year timestep. It is worth noting that we use the final energy variables of OPEN-PROM to establish those preliminary proxy results. As previously indicated, this is only to show that such an integration is already functional. Future integrations are expected to be (much) more accurate and smoother.

Those preliminary proxy results (Figure 3) already show that; (i) there is a substantial difference between the impacts of socio-economic pathways in terms of environmental burdens; logically, the low-carbon (net-zero) pathways nearly reach net-zero life cycle GHG emissions, although substantial residual emissions remain (that can later be distinguished between European and non-European residual emissions), and (ii) environmental trade-offs and co-benefits are also evident. For example, the low-carbon scenario also reduces human toxicity slightly; however, it results in higher requirements of critical materials such as lithium (mainly for electrified passenger transport) and iridium (higher electrolytic hydrogen requirements).

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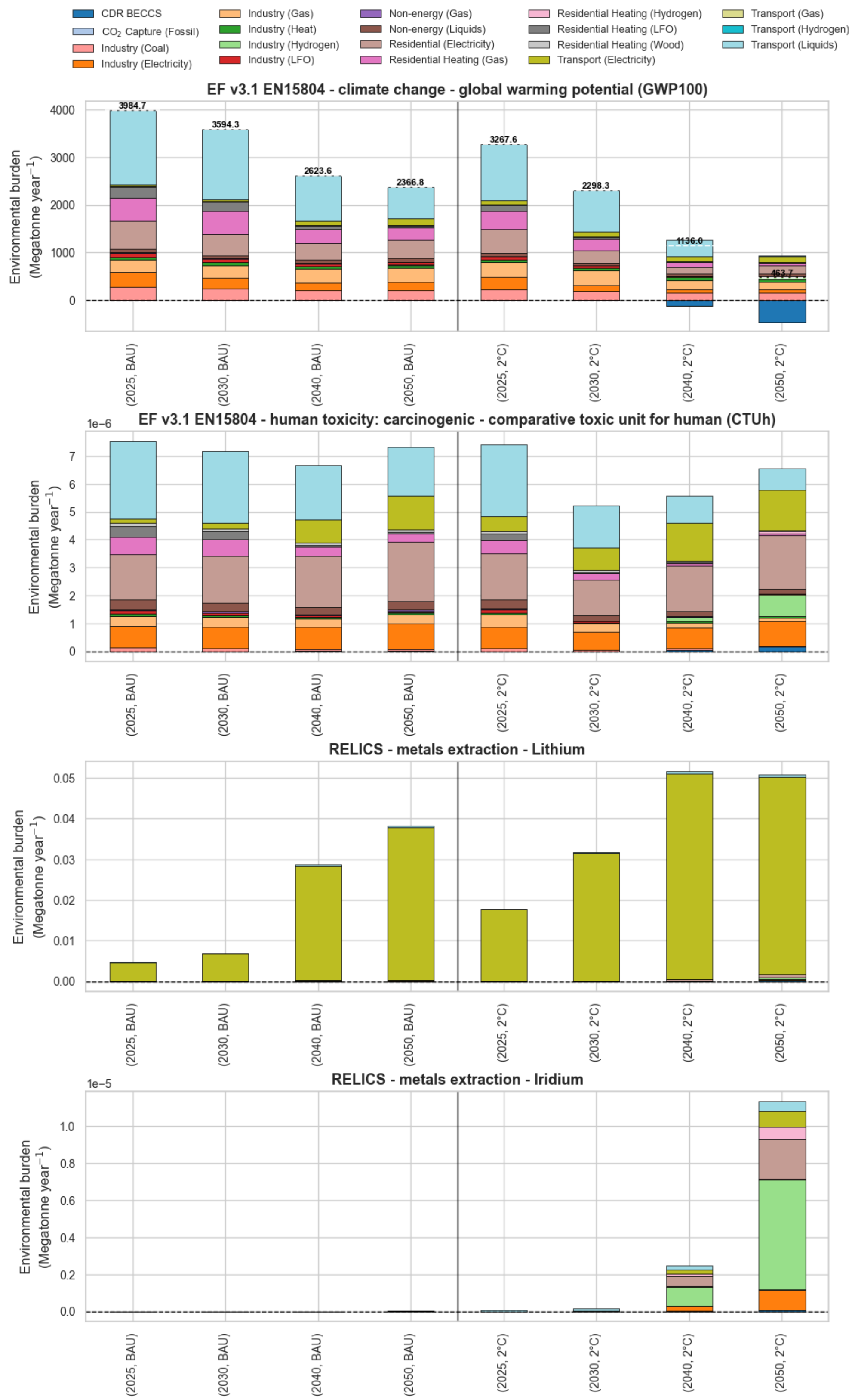

Figure 3. Preliminary (proxy) results from integrating MIC3 model scenarios and calculating the environmental burdens of the entire European energy system using the OPEN-PROM module. BAU = business-as-usual.

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4.1.2 European steel industry

For this exercise, we assess the environmental burdens associated with different steel production pathways under two scenarios (business-as-usual and net-zero) from 2025 to 2050, using a 10-year timestep. The evaluated impact categories include climate change (GWP100), human toxicity (carcinogenic effects), and the extraction of two critical raw materials: lithium and iridium.

The scenarios reflect varying steel technology mixes, such as primary steel from blast furnace-basic oxygen furnace (BF-BOF), hydrogen-based direct reduced iron (H_2-DRI), natural gas DRI (NG-DRI), and secondary steel production via electric arc furnace (EAF) using scrap. These preliminary results—based on final energy demand projections from ITOM—demonstrate the capacity of our integrated framework to analyse both climate impacts and overall environmental trade-offs. Notably, while net-zero pathways sharply reduce GHG emissions (e.g., a drop from 218 $MtCO_2$-eq. in 2025 to 67 $MtCO_2$-eq. in 2040), they also lead to increased extraction of lithium and iridium due to greater deployment of batteries and electrolysis technologies, mainly in the background.

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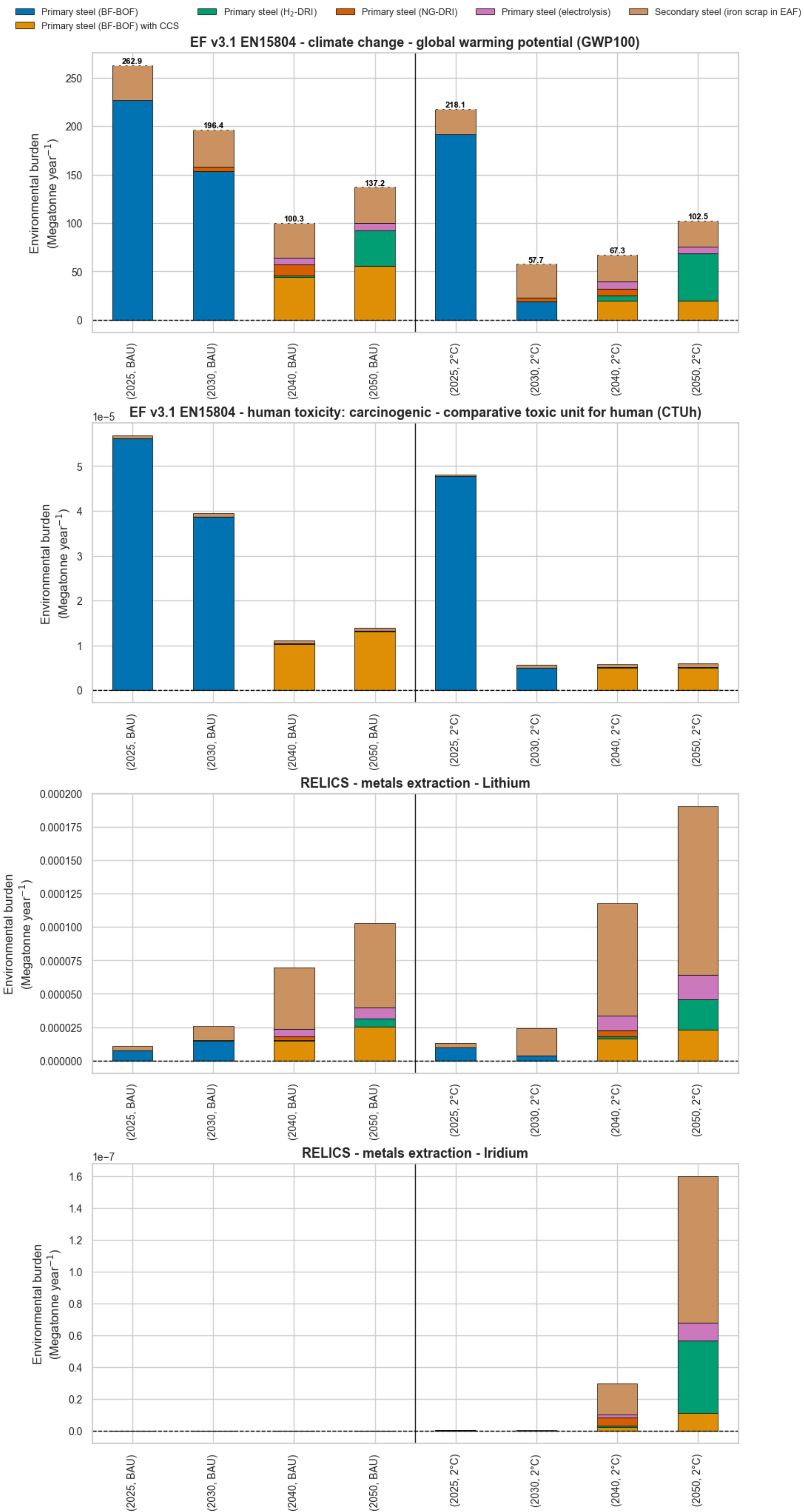

Figure 4. Preliminary (proxy) results from integrating MIC3 model scenarios and calculating the environmental burdens for the European steel industry of the ITOM module. BAU = business-as-usual.

4.2 Deep dive 1: The most climate-effective hydrogen applications

The first deep dive explores which hydrogen applications offer the highest potential for climate benefits (i.e., their climate effectiveness), including hard-to-abate industrial sectors (e.g., steel, agriculture, and shipping), based on a comprehensive global dataset of both operational and planned hydrogen projects from the International Energy Agency (International Energy Agency, 2023). As such, we assess the GHG emissions associated with different end uses by considering the hydrogen production method, the geographic context, and the type of product or service potentially being replaced.

By evaluating the emissions intensity and substitution potential of each application, we identified where hydrogen deployment is likely to deliver the most significant emissions reduction potential. This analysis supports a more strategic use of limited low-carbon hydrogen resources by highlighting (industrial) sectors where hydrogen use is both technically feasible and justified in terms of GHG emission reduction potential. The results indicate the importance of prioritising hydrogen use for the most climate-effective applications (i.e., biofuels, iron and steel, and ammonia production).

Preliminary citation (Terlouw et al., 2025): *Terlouw, T., Moretti, C., Harpprecht, C., McKenna, R., & Bauer, C. (2025). On the global climate-effectiveness of hydrogen applications. Nature Energy, In Review.*

4.3 Deep dive 2: The effectiveness of the European Carbon Border Adjustment Mechanism (CBAM) for the global steel industry

CBAM is a carbon accounting method of the EU that is designed to prevent carbon leakage to non-European countries, protect its own industrial competitiveness, and drive the global shift to low-carbon steel production (European Union, 2025; Katharina Pausch-Homblé, 2022). To assess the effectiveness of CBAM, in terms of accounting for GHG emissions from the global steel industry, we conduct a detailed classification of emissions data from steel plants worldwide. As such, each plant with a corresponding emission source is categorised by scope—direct emissions (Scope 1), emissions from purchased energy (Scope 2), and other indirect emissions (Scope 3)—and evaluated for its inclusion in the current CBAM regulations.

We develop a comprehensive LCA framework to estimate the GHG emissions that fall within the scope of CBAM and those that do not, providing insights into its GHG emission coverage. As such, we evaluate how well CBAM captures the GHG emissions embedded in imported steel to the EU and identify where the mechanism still leaves gaps in the current situation and in future steel production scenarios and technologies.

Working paper in progress: *Terlouw, T., Harpprecht, C., & Bauer, C. (2025). GHG emissions of the global steel industry and the effectiveness of the European carbon border adjustment mechanism. In preparation.*

Bibliography

E3Modelling. (2025). *e3modelling/OPEN-PROM*. https://github.com/e3modelling/OPEN-PROM

ecoinvent. (2023). *ecoinvent 3.10*. https://ecoinvent.org/ecoinvent-v3-10/

European Union. (2025). *Carbon Border Adjustment Mechanism - European Commission*. https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en

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. https://doi.org/10.1016/J.RESCONREC.2025.108251

International Energy Agency. (2023, October). *Hydrogen Production and Infrastructure Projects Database*. Https://Www.Iea.Org/Data-and-Statistics/Data-Product/Hydrogen-Production-and-Infrastructure-Projects-Database. https://www.iea.org/data-and-statistics/data-product/hydrogen-production-and-infrastructure-projects-database

ITOM. (2025). *wupperinst/itom: Industry Transformation Optimization Model*. https://github.com/wupperinst/itom

Katharina Pausch-Homblé. (2022). EU climate action: provisional agreement reached on Carbon Border Adjustment Mechanism (CBAM). In *EU press release*. https://www.consilium.europa.eu/en/press/press-releases/2022/12/13/eu-climate-action-provisional-agreement-reached-on-carbon-border-adjustment-mechanism-cbam/

Luderer, G., Leimbach, M., Bauer, N., Kriegler, E., Baumstark, L., Bertram, C., Giannousakis, A., Hilaire, J., Klein, D., Levesque, A., Mouratiadou, I., Pehl, M., Pietzcker, R., Piontek, F., Roming, N., Schultes, A., Schwanitz, V. J., & Strefler, J. (2015). *Description of the REMIND model (Version 1.6)*. SSRN. https://ssrn.com/abstract=2697070

Marius Neuwirth. (2024). *FORECAST*. https://github.com/fraunhofer-isi/forecast-sites

Mutel, C. (2017). Brightway: An open source framework for Life Cycle Assessment. *Journal of Open Source Software*, *2*(12), 236. https://doi.org/10.21105/joss.00236

Neuwirth, M., Fleiter, T., & Hofmann, R. (2024). Modelling the transformation of energy-intensive industries based on site-specific investment decisions. *Scientific Reports 2024 14:1*, *14*(1), 1–19. https://doi.org/10.1038/s41598-024-78881-7

Riahi, K., Van Vuuren, D. P., Kriegler, E., Edmonds, J., O'neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., & others. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, *42*, 153–168.

Romain Sacchi, & Alvaro Hahn Menacho. (2025). *Edge-based life cycle impact assessment.* https://github.com/Laboratory-for-Energy-Systems-Analysis/edges/tree/main

Sacchi, R., & Hahn-Menacho, A. J. (2024). pathways: life cycle assessment of energy transition scenarios. *Journal of Open Source Software*, *9*(103), 7309. https://doi.org/10.21105/JOSS.07309

Sacchi, R., Terlouw, T., Siala, K., Dirnaichner, A., Bauer, C., Cox, B., Mutel, C., Daioglou, V., & Luderer, G. (2022). PRospective EnvironMental Impact asSEment (premise): A streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models. *Renewable and Sustainable Energy Reviews*, *160*, 112311. https://doi.org/https://doi.org/10.1016/j.rser.2022.112311

Schneider, C., Åhman, M., Lechtenböhmer, S., & Saurat, M. (2025). A defossilised EU petrochemical production system: Consequences for the meta-cluster in the Antwerp-Rotterdam-Rhine-Ruhr Area. *Energy and Climate Change*, *6*, 100173. https://doi.org/10.1016/J.EGYCC.2024.100173

Skea, J., Shukla, P., Al Khourdajie, A., & McCollum, D. (2021). Intergovernmental Panel on Climate Change:

Transparency and integrated assessment modeling. *Wiley Interdisciplinary Reviews: Climate Change*, *12*(5), e727. https://doi.org/10.1002/WCC.727;WGROUP:STRING:PUBLICATION

Terlouw, T., Moretti, C., Harpprecht, C., McKenna, R., & Bauer, C. (2025). On the global climate-effectiveness of hydrogen applications. *Nature Energy (In Review)*.

Van Vuuren, D., Stehfest, E., & Gernaat, D. (2021). *THE 2021 SSP SCENARIOS OF THE IMAGE 3.2 MODEL Oktober 2021*. https://doi.org/10.31223/X5CG92

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment*, *21*(9), 1218–1230.