

## Spotlights

### **Bullet 1: Critical context and background information on the problem addressed**

Tracking waste and material flows is essential for developing the circular economy and supply chain resilience

### **Bullet 2: A brief overview of the key finding of the study (or findings if necessary)**

A tool was developed to quantify waste and material footprints of activities in life cycle assessment (LCA) databases

### **Bullet 3: The most radical, creative, disruptive or innovative aspect of the manuscript**

Built to complement the Brightway LCA framework and ActivityBrowser, the tool is customisable and easy to use.

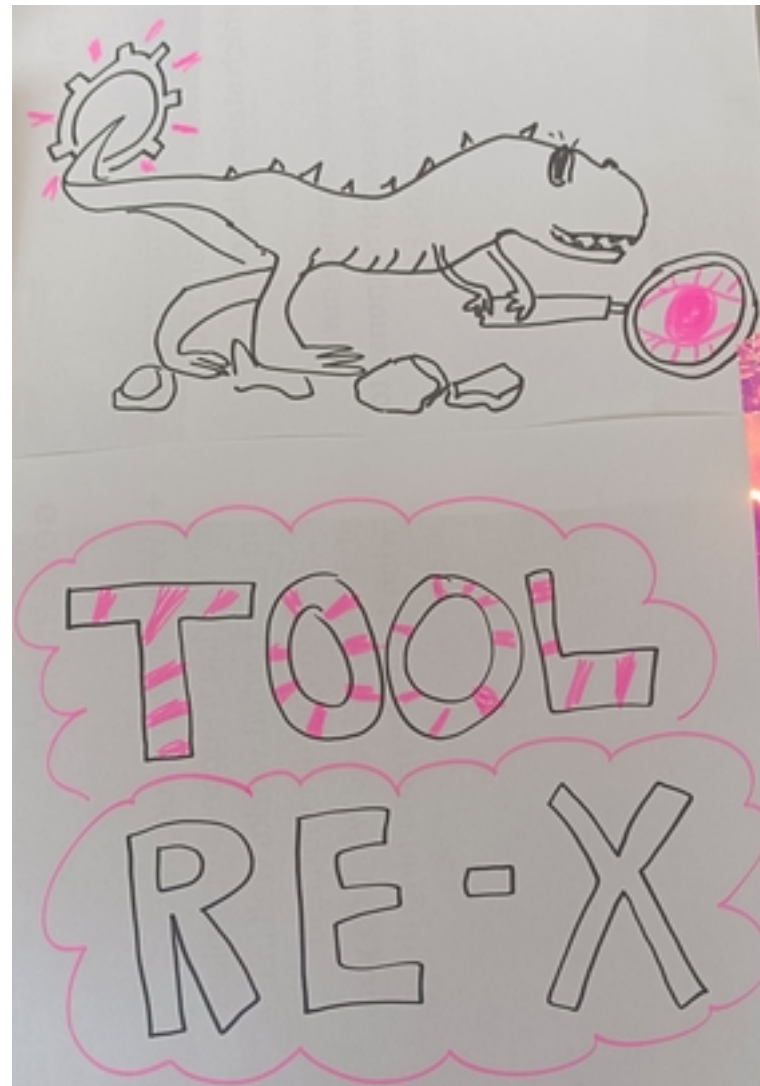
### **Bullet 4: The significance of the results to the environment, economics or society**

The tool can be used to identify pre-consumer waste and material hotspots that are often hidden in supply chains.

### **Bullet 5: Future vision or the most important implications for continued research**

Improved data availability and quality would enable more detailed and accurate waste and material footprinting.

## Graphical Abstract



## 24 Highlights

- 25 • T-reX, a new tool for quantifying waste and material  
26 flows in LCA.
- 27 • Assesses supply risks by calculating demand for critical  
28 materials.
- 29 • Simplifies quantification of user-specified waste and ma-  
30 terial categories.
- 31 • Rapidly identifies waste and material demand hotspots.
- 32 • Presents a case study of the battery supply chain.

# T-reX: A python package to quantify supply chain flows of waste and material in LCA databases

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## Abstract

Abstract word count: 164, Limit: 150

Minimising waste through the reuse of resources is the quintessential principle of the ‘circular economy’, but relies on our ability to identify and quantify waste and material flows. Thus, identifying and quantifying waste and material flows are of fundamental importance. Life Cycle Assessment (LCA) is powerful for this end, given its capacity to pinpoint hotspots of environmental impact throughout the life cycle of products and services, those where the implementation of circular principles could be most effective.

Introducing T-reX, a Python tool extending the Brightway framework for flexible quantification of user-defined supply-chain demands in current and future scenarios. This tool streamlines database manipulation for LCA practitioners and integrates methods to aggregate and analyse waste and material flows, facilitating rapid hotspot identification.

A case study on battery supply chains demonstrates the tool’s utility. T-reX quantifies and compares inventory demands and, thus, potential environmental burdens, aiding sustainable decision-making. It contributes to the development of the ‘circular economy’ by providing detailed material usage and waste generation analysis.

**Keywords:** circular economy, waste, material, life cycle assessment, critical raw material, supply chain

Total word count: 6000, Limit: 5000 (can be easily condensed)

## 1. Introduction

Section word count: 1450

To be split into two (sub) sections: Introduction and Background, can be easily condensed by 200 words

The development of a ‘circular economy’ has become a critical area of focus in the imperative pursuit of achieving sustainability objectives and curtailing our environmental footprint within planetary boundaries (European Commission, 2019, 2020; Government of the Netherlands, 2023, 2016; Pardo and Schweitzer, 2018; Ellen MacArthur Foundation, 2015). Fundamental to this development is a decrease in primary material consumption and a reduction of life cycle waste through the implementation of ‘re-X’ strategies (e.g., refuse, rethink, design for—and implementation of—repair, remanufacturing and recycling) (European Union, 2022; Alfieri et al., 2022; Parker et al., 2015). In addition to circular economy goals, contemporary geo-political tensions in an ever more globalised economy have highlighted the vulnerability of many advanced economies to intentional supply disruptions, wrought as an act of competition or outright hostility (Carrara et al., 2023; Hartley et al., 2024; Berry, 2023).

While some material demands are apparent in the final product and the waste generated may be inferred from knowledge of the use- and end-of-life- (EOL) phases, a significant proportion of these are often ‘hidden’ in the supply chain and thus not reported directly in the final results (Laurenti et al., 2016; Salviulo et al., 2021). It has been found that these material demands are highly representative of damage to human health and biodiversity’ (Steinmann et al., 2017) and that waste footprints have a ‘strong association’ with environmental damage (Laurenti et al., 2023). Thus, to reduce the negative externalities of consumption and improve supply chain resilience, it is essential to uncover, disaggregate, and quantify the material and waste footprints of human activities in as much detail as possible.

Life Cycle Assessment (LCA) is a useful method for the holistic estimation of the environmental impacts of products and processes. LCA can comprehensively evaluate these impacts across the entire life cycle—from ‘cradle to grave’—, often identifying critical hotspots and guiding prioritisation of actions. The standard approach is to apply Life Cycle Impact Assessment (LCIA) methods (such as ReCiPe (Huijbregts et al., 2016) and CML (Guinée et al., 2002)), which convert the inventory data into a set of impact scores based on the sum of the elementary flows. These scores are then aggregated into a single score for each impact category, which can be compared across products and processes.

Several LCIA methods include, to some extent, waste generation (Swiss Federal Office for the Environment (FOEN), 2021; Hauschild and Potting, 2004; CEN (European Committee for

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Standardization), 2019) and material consumption (Arvidsson et al., 2020; Swiss Federal Office for the Environment (FOEN), 2021). These methods, however, are generally limited in their scope (especially for waste), do not allow for flexible quantification of specific waste and material types, and often provide results in characterised units that are abstract or difficult to interpret (e.g., Umweltbelastungspunkte (UBP)).

In the context of a mineral-hungry renewable energy transition and recent geo-political tensions, more attention is being paid to the security of supply of materials, especially those considered ‘critical raw materials’ (CRMs) (Commission et al., 2023; Hool et al., 2023; Mancini et al., 2013; Carrara et al., 2023; Hartley et al., 2024; Salviulo et al., 2021). While LCA seeks to model the technosphere (a.k.a. the anthroposphere), its focus is often on the environmental impacts of the system—the endpoints—rather than the primary material flows themselves.

A relatively new method, termed the crustal scarcity indicator (CSI) (Arvidsson et al., 2020), was developed to assess long-term global scarcity of minerals in LCA. This method introduced crustal scarcity potentials (CSPs) measured in kg silicon equivalents per kg element, derived from crustal concentrations. CSPs, provided for 76 elements, reflect the long-term global elemental scarcity based on crustal concentration proxies. The CSI, calculated by multiplying CSPs with extracted masses, effectively gauges the impact of elemental extraction.

While useful for its stated purpose, the CSI presents its midpoint results in an abstract unit (kg-Si eq.) that is difficult to interpret and compare with other impact categories. Furthermore, the CSPs are not available for all elements (or more complex materials), and the method does not allow for the quantification of material demands in terms of mass or volume.

### 1.1. Waste in LCA

Though often described simply as a ‘material with a negative economic value’ (Guinée et al., 2004), waste is a nebulous concept, and one whose definition is poorly delineated and variable across space and time. Moreover, from a systems perspective, the notion of waste is anathema to the circular economy, and it is far more useful to consider the identity and nature of the specific material flows. Thus, precise and detailed categorisation of these is essential to understand the ‘circularity’ of an activity and its life cycle externalities. There is a conspicuous gap in the understanding of the waste footprint of human activities and their relationship with environmental damage (Laurenti et al., 2023). Conventional LCAs consider waste as a ‘service’ (Guinée and Heijungs, 2021) and typically use generic waste processing models (Beylot et al., 2018) that break the causal link between the functional unit and the waste-associated impacts.

In LCA, waste flows are not considered as fundamental biosphere exchanges, but rather as technosphere flows. Waste produced by an activity is transferred to a relevant waste treatment activity where it is accepted ‘burden-free’ and transformed into a combination of emissions and other waste ‘products’ (Guinée and Heijungs, 2021). There can be several treatment steps in this pathway leading, ultimately, to a mass of material being deposited in a landfill. In this system of waste accounting, the impacts

apportioned to the waste-producing activity are a sum of those incurred by the transport, treatment, and final disposal of the waste into terrestrial or aquatic environments. In particular, the extensive work of Doka (2024) has contributed significantly to understanding the environmental impacts of waste treatment processes and the long-term impacts of disposal.

A significant portion of a product’s total waste is generated during earlier stages such as resource extraction, transportation, and manufacturing, often remaining ‘invisible’ in traditional LCA practices (Laurenti et al., 2016). This oversight in measuring and communicating a cradle-to-grave product waste footprint (PWF) highlights a gap in circular economy indicators. Traditional LCA does not typically view waste as having environmental significance by itself, focusing instead on emissions and resource use resulting from waste treatment. The environmental significance of waste and its correlation with other indicators has been the subject of extensive research. For example, studies have shown that popular resource footprints can cover a significant portion of environmental impact variance in product rankings (Steinmann et al., 2017). However, correlations between various environmental indicators are not always consistent, as seen with the carbon footprint, which often does not correlate with other impact assessment scores (Laurent et al., 2012). The aggregation of waste in PWFs raises concerns among LCA experts, regarding the uncertainties introduced by aggregated measures, as well as the potential misrepresentation of environmental performance due to differences in waste types (Chen et al., 2021; Huijbregts et al., 2010).

Moreover, existing LCA methodologies offer limited direct indicators at the impact assessment level, providing sparse information on the impacts of waste. This limitation becomes particularly evident when attempting to identify waste generation hotspots within a product’s life cycle. Addressing these hotspots is crucial for advancing towards circularity, however, there is a lack of a convenient and flexible way to calculate waste flows in LCA and a pressing need for more comprehensive methods that can effectively quantify waste flows and, therefore, contribute to a better understanding of a product’s total environmental footprint. Laurenti et al. (2023) developed a method to calculate the waste footprint of a product or service based on solving the demand vectors of the activities, also presenting simple measures to quantify waste hazardousness and circularity. In that study, it was shown that the waste footprint correlates well with other LCIA methods, particularly human health. The method presented, however, is limited in its scope and flexibility, is computationally intensive, difficult to use, is not easily reproducible, and suffers from errors due to double counting. The T-reX tool presented herein provides a more flexible, transparent, and user-friendly approach to quantifying waste flows in LCA. Moreover, the T-reX tool is not limited to waste but can be used to quantify any supply-chain flow, such as water, gas, and critical raw materials.

### 1.2. The T-reX Tool

To better assess waste and material flows in LCA, we have developed a Python program built on the Brightway frame-

work (Mutel, 2017a) and designed to track these exchanges by translating them into indicators and ‘pseudo’ LCA impact (LCIA) categories. In this study, we present the T-reX tool that enables LCA practitioners to manipulate their databases to allow them to easily aggregate the mass and volume of any desired exchange, and to create flexible categories that differentiate between material categories, waste types, and EOL handling.

While methods with similar aims exist, they lack customisability and specificity (Swiss Federal Office for the Environment (FOEN), 2021) or can be cumbersome to apply and suffer from errors due to multiple counting (Laurenti et al., 2023).

The purpose of the T-reX tool is not to quantify the environmental impacts of material consumption and waste production, but rather to quantify the material and waste flows themselves, even those that are finally consumed by waste treatment processes. It provides, thus, not an impact assessment in the traditional sense, but an accounting of the material consumed and waste generated by a product or service inside of the technosphere, regardless of the end-of-life fate of these flows. By definition, the development of the ‘circular economy’ necessitates the reduction and ultimate elimination of waste—though whether this objective is thermodynamically impossible has long been the subject of lively debate by Ayres (1999), Reuter and van Schaik (2012) and many others. In any case, avoiding material consumption and generation of waste is of critical importance. By allowing LCA practitioners to easily classify and quantify these exchanges, the T-reX tool provides a practical means to identify hotspots and opportunities for waste reduction and material efficiency.

## 2. Methodology

Section word count: 2000

This section is divided into two parts. In subsection 2.1, we describe the T-reX tool, in subsection 2.3, we describe the methodology used to calculate the waste and material footprints in the case study.

### 2.1. The T-reX tool

The T-reX tool is a Python package that allows one to calculate the waste and material inventory footprints of any product or service in LCA databases. Metadata of the T-reX tool is presented in the supplementary information [ADD LINK]

Developed in the Python programming language (version 3), the T-reX tool extends the brightway2 LCA framework, utilising the components `bw2data`, `bw2calc`, and `bw2io` (Mutel, 2017a). Additionally, the `wurst` package is used to facilitate database searching and data transformation at the exchange level (Mutel, 2017b). Integration with `premise` package (Sacchi et al., 2022) enables the user to easily create and manipulate prospective LCA databases. The T-reX tool is also compatible with `ActivityBrowser` (Steubing et al., 2020) an open-source graphical user interface for LCA. The T-reX tool is installable via the Python Package Index (PyPI) (McDowall and Lanphear, 2023b) and is open source under the CC-0 licence. The full

source code for the T-reX tool is indexed on Zenodo (McDowall and Lanphear, 2023a) and under further development in the GitHub repository (McDowall, 2024). The tool is designed to be used with `ecoinvent` databases (Wernet et al., 2016), but could be adapted to other databases as well by changing the search criteria. Currently, it has been tested with all available system models of `ecoinvent` 3.5–3.10 (Wernet et al., 2016).

The program can be used directly from the command line, or imported as a Python module, in which case, the user can access the individual functions and modules. In the simplest case, the user can run the program with the default settings, which will calculate the waste and material footprint of the `ecoinvent` database. The user can also customise the program to calculate the waste and material footprint of a custom database, or a prospective database based on future scenarios. The program is designed to be modular so that the user can easily customise the program to their needs.

The supplementary information [ADD LINK] contains a list of the constituent modules of the T-reX tool, with a brief description of their functions. More extensive details can be found in the user guide and documentation of the program (McDowall, 2023).

#### 2.1.1. Generation of prospective LCA databases

Future waste and material footprints can be projected using the `future_scenarios` module, which uses `premise` to generate prospective scenario databases based on the configuration in `user_settings`. These prospective databases can be custom-defined by the user or can be constructed with the future projections of the integrated assessment models such as `IMAGE` (Stehfest et al., 2014) and `REMIND` (Aboumahboub et al., 2020), which offer a range of options aligned with the Shared Socioeconomic Pathways (SSPs) (Meinshausen et al., 2020) that can be paired with a variety of mitigation scenarios.

#### 2.1.2. Database expansion

The `explode_database` module uses `wurst` to deconstruct LCA databases into a list of individual exchanges representing all of material and energy flows in the technosphere model. This dataset being converted into a `pandas DataFrame` and stored as a binary `.pickle` file for subsequent analysis.

#### 2.1.3. Waste and material flow identification and categorisation

The `search_waste` and `search_material` modules apply user-defined search parameters from `queries_waste` and `queries_materials` to identify relevant waste and material flows in the list of technosphere exchanges generated by `explode_database` and categorises them accordingly. The results of the search functions are stored in `.csv` files for subsequent use in the T-reX tool’s workflow.

#### 2.1.4. Waste exchanges

In the default configuration, there are 10 waste categories which are further divided by their unit of measurement (kilograms and cubic meters) to create a total of 20 waste methods. The waste categories are:



- digestion
- composting
- open burning
- incineration
- recycling
- landfill
- hazardous
- non-hazardous
- carbon dioxide
- total

Table 1: WasteFootprint search results for the database ‘ecoinvent cutoff 3.9.1, REMIND, SSP2, PkBudg500, 2100’.

Waste exchanges	Unit	Exchange count
digestion	kilogram	4
composting	kilogram	26
open burning	kilogram	535
incineration	kilogram	2171
recycling	kilogram	137
landfill	kilogram	1530
hazardous	kilogram	1928
carbon dioxide	kilogram	119
total	kilogram	29524
digestion	cubic meter	16
composting	cubic meter	0
open burning	cubic meter	0
incineration	cubic meter	2
recycling	cubic meter	0
landfill	cubic meter	2
hazardous	cubic meter	437
carbon dioxide	cubic meter	0
total	cubic meter	4360

The logic of screening for waste exchanges is based on a set of boolean search queries (‘AND’, ‘OR’, and ‘NOT’) that are applied in a list comprehension to the names of every exchange in the LCA database (see ‘search\_queries.py’ for the full list). In this way, the search queries enable classification into categories (such as ‘hazardous solid’ and ‘incineration liquid’) and permit the identification of waste exchanges in addition to those directly connected to waste treatment processes. The search queries are tailored to the specific database and the user can easily modify them to suit their needs. In the default settings, there are a total of 18 waste classifications (9 categories, each separated into liquid and solid waste) For example, the identification of ‘non-hazardous solid’ waste exchanges is based on the following search query; AND=[‘waste’], NOT=[‘hazardous’, ‘radioactive’], UNIT=[‘kilogram’] (this can also be inferred and confirmed by comparison with the difference between the results of ‘total solid’ and ‘hazardous solid’). Table 1 presents a list of waste exchanges identified in the prospective database built from ‘ecoinvent 3.9.1’ according to the IAM model ‘REMIND’ with the RCP ‘PkBudg500’ in the year 2100. Note that the carbon dioxide waste category does not include emissions to the atmosphere. This category is based solely on the accounting of carbon capture and storage (CCS), which is included in many prospective databases as direct sequestration in reservoirs as well as solvent capture.

### 2.1.5. Material exchanges

In addition to the waste categories, the `queries_materials` module defines the material demand categories, which are based on the EU Critical Raw Materials (CRM) list for 2023 (Commission et al., 2023). The CRM list is a list of 30 materials that are considered critical to the EU economy and are at risk of supply disruption. Further materials of interest were added to the search list, including helium, electricity, petroleum, sand, water, and natural gas. The identity of the materials considered and their categorical groupings are easily customisable by the user. A full list of 59 materials included in the default configuration is provided in the supplementary material.

The logic for the identification of material exchanges with the T-reX tool differs from that used to identify waste exchanges in that the search queries are based on the names of the so-called relevant ‘market activities’ for the material of interest. That is, for material  $x$ , all exchanges with the name ‘market

for material  $x$ ’ are identified and subsequently apportioned a (‘pseudo-biosphere’) material demand exchange of the same sign and magnitude as the original exchange. A useful feature of the T-reX tool is that, in cases where there are several markets for one material or material group, the program can easily aggregate these exchanges. For example, exchanges with markets for the rare-earth-elements (REEs) ‘market for cerium’, ‘market for dysprosium’, ‘market for erbium’, etc. can be aggregated into a single indicator category for REEs. Similarly, the total demand for all critical raw materials (CRMs) can be easily calculated in the same manner.

As discussed in the introduction 1 there are some existing material demand methods in the standard LCIA method sets, including the ‘crustal scarcity indicator’ (which provides only an aggregated, abstracted endpoint) (Arvidsson et al., 2020) and the (deprecated) EDIP 2003 material use indicators (which provide endpoints in fundamental units) (Hauschild and Potting, 2004). In these methods, the material demand is calculated based on the total mass that is extracted from the environment, thus, their focus is essentially solely on the mining-related exchanges that bring these materials from the biosphere into the technosphere. In the T-reX tool, however, the accounting for material demand is based on exchanges solely within the technosphere. This offers a different perspective, allowing for the estimation of overall supply-chain material demands that consider the entire life cycle of an activity, including non-direct impacts on the market such as co-production of other materials. Consider a demand for an activity containing a metal, for example; while the existing material use methods allow one to calculate the total mass of that metal that is extracted from the environment, the T-reX tool can provide insight into the broader supply-chain impacts of the demand for this metal. If

the production other materials are attributed to the production of this metal, these would appear as negative material demands in the T-reX results—supply chain pressure for one material can result in lessening of supply chain pressure for another. In the results of the Li-ion battery case study in [subsection 3.2](#), we will see that this is indeed the case for the demand for nickel, which, because of such effects, is counter-intuitively negative despite the presence of nickel in the final products.

#### 2.1.6. Creation of custom ‘pseudo-biosphere’ databases

Custom ‘pseudo-biosphere’ databases are created by `make_custom_database` module. This module collates the waste and material categories that were present in the databases, producing an `.xlsx` file that is imported back into the Brightway2 project as a biosphere-database named ‘T-reX’.

#### 2.1.7. LCIA method management

The `method_editor` module manages the addition, deletion, and verification of the custom LCIA methods used in the T-reX tool. This module uses the custom ‘pseudo-biosphere’ databases created by `make_custom_database` to create these waste and material footprint LCIA methods that have the same unit as the respective technosphere exchange. The methods are stored in the Brightway2 project and can be used for calculating the waste and material footprints of activities in the LCA database in the same way as with other LCIA methods. Since ‘waste is not a service’ ([Guinée and Heijungs, 2021](#)), a characterisation factor of -1 is applied to the waste footprint methods (with the exception of CCS exchanges), changing the perspective from waste consumed by treatment to waste generated by the activity.

### 2.2. Exchange editing

The `exchange_editor` module loads the `.csv` files created by the search functions and appends ‘pseudo-biosphere’ exchanges to the matching activities in the LCA database. This is the most computationally intensive part of the T-reX tool, as (depending on the search configuration) there are generally more than 100,000 exchanges to be appended to the database.

#### 2.2.1. Database Verification

The `verify_database` module calculates LCA scores for randomly selected activities using Waste Footprint and Material Demand Footprint methods to confirm that the T-reX tool has processed the database correctly.

### 2.3. Case Study Methodology

#### 2.3.1. Activities

This case study investigated five types of Li-ion batteries, each represented by specific market activities:

- Li-ion, NMC111, rechargeable, prismatic
- Li-ion, LiMn2O4, rechargeable, prismatic
- Li-ion, NCA, rechargeable, prismatic
- Li-ion, NMC811, rechargeable, prismatic
- Li-ion, LFP, rechargeable, prismatic

#### 2.3.2. Methods

In addition to the Waste Footprint and Material Demand footprint methods created by the T-reX tool, the following standard LCIA methods were applied for comparison:

- ReCiPe 2016 v1.03, midpoint (I)
- EF v3.0 no LT
- EDIP 2003 no LT
- Crustal Scarcity

#### 2.3.3. Databases

The primary source of life cycle inventory data for this case study was ecoinvent 3.9.1 cutoff. Additionally, the T-reX tool was used to create prospective database sets using the REMIND model with the following Representative Concentration Pathways (RCPs):

- **SSP2 -base:**  
representing ca. 3.5°C increase in global temperatures to 2100
- **SSP2-PkBudg500:**  
meeting Paris climate goals, ca. 1.3°C increase to 2100

For each pathway, databases were created with `textttpremise` ([Sachi et al., 2022](#)) and processed with the T-reX tool over the time series: 2020, 2040, 2060, 2080, 2100.

#### 2.3.4. Calculations

For each combination of activity, method, and database, a single score ‘LCIA’ was calculated along with details of the top contributing processes. Additionally, for the Waste and Material Footprint methods, a contribution analysis was performed. This involved utilizing the `bwa.compare_activities_by_grouped_leaves` function from the `brightway2_analyzer` package [Mutel \(2016\)](#), an additional component of the Brightway2 LCA framework. This function performs graph traversal on the impact matrix of the LCA object to a specified cutoff and groups the resulting leaves by their CPC codes. This provides insight into the products and sectors in the supply chain of the activity that carry the most responsibility for the final footprint.

## 3. Results

Section word count: 1400

### 3.1. T-reX tool

An example of the output from the application of the T-reX tool has been included in the supplementary material. The manipulated ecoinvent databases can be recreated using the code and instructions available in the package documentation ([McDowall, 2023](#)).

### 3.2. Case study: Li-ion batteries

As described in subsection 2.3, this case study calculated the waste and material footprints (as well as a variety of other indicators) for the unaltered inventories of five Li-ion batteries with the functional unit being 1 kg of the battery at market. The purpose of this simple case study was to test, verify, and demonstrate the functionality and limitations of the T-reX tool. This section includes some highlights of the results and the full results are available in the supplementary material. Because the T-reX methods are integrated into the brightway project as if they were LCIA methods, the results can be visualised in the same way. In the supplementary material, there are screenshots of selected results obtained using the ActivityBrowser software, including contribution analysis and a Sankey diagram that disaggregates the final footprint result over the activities in the supply chain.

#### 3.2.1. Temporal and scenario variation in waste and material footprints

Figure 1 shows the total solid waste footprint for the five Li-ion batteries in the case study from 2020 to 2100 under the SSP2 scenario using the baseline and PkBudg500 RCPs of the REMIND model. The NMC811 battery has the largest footprint, producing over 50 kg of waste per kilogram of battery produced. The LiMn2O4 battery has the smallest footprint, producing less than 4 kg of waste per kilogram of battery. In each case there was a slight downward trend in the waste footprints between 2020 and 2100. This is most notable in the period between 2020 and 2040 and is attributable to the relatively rapid decrease in fossil-fuel use that is included in the models over this time. For the total waste generated by these batteries, there was very little difference observed between the baseline and PkBudg500 RCPs.

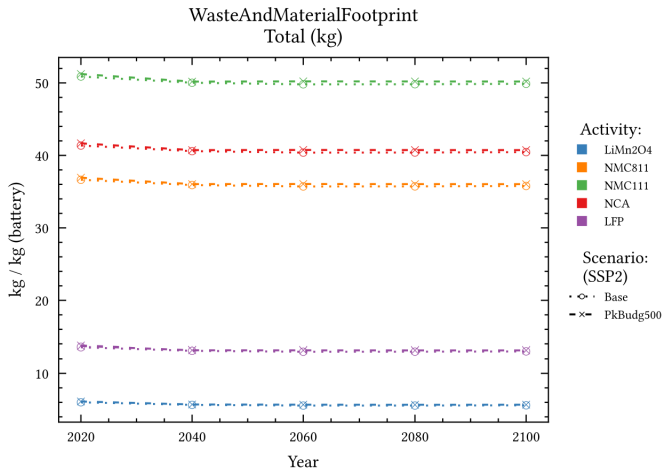


Figure 1: Total solid waste footprints for the five Li-ion batteries in the case study from 2020 to 2100 under the SSP2 scenario using the baseline and PkBudg500 RCPs of the REMIND model.

The inclusion of carbon capture and storage (CCS) in the prospective databases using the PkBudg500 RCP is evident in Figure 2, which shows a rapid increase in the production of

carbon dioxide ‘waste’ over the period from 2020–2040 that is not seen in the baseline scenario. This result highlights the fact that (frequently) downward trends in global warming impacts calculated with prospective databases using standard LCIA methods are dependent on the assumptions made about the introduction of CCS technology. The actual deployment of these technologies—approximately 37 Mt CO<sub>2</sub>/yr as of 2023 (Dziejarski et al., 2023)—falls far short of the levels projected in many of the RCP scenarios (Sacchi et al., 2023).

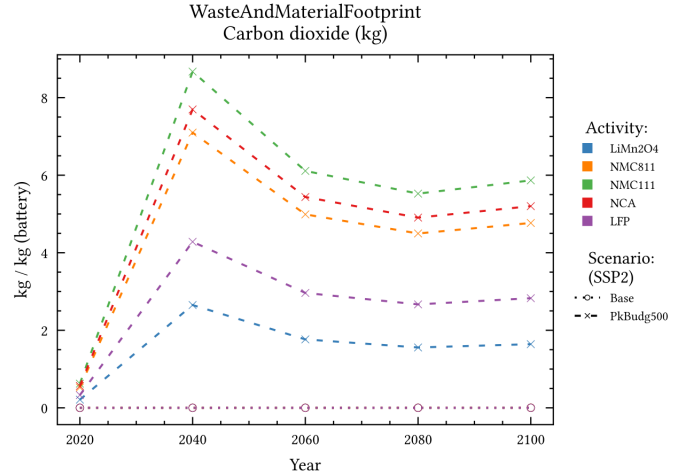


Figure 2: Carbon dioxide waste (from carbon capture and storage) footprints for the five Li-ion batteries in the case study from 2020 to 2100 under the SSP2 scenario using the baseline and PkBudg500 RCPs of the REMIND model.

For the phosphate demand footprints that are depicted in Figure 3, the LFP (lithium iron phosphate) battery has a much larger footprint than the other batteries, consistent with its composition. In this case, the phosphate footprint of all batteries is shown to decrease over the period from 2020–2100, and the RCP scenarios are seen to converge between 2020 and 2040.

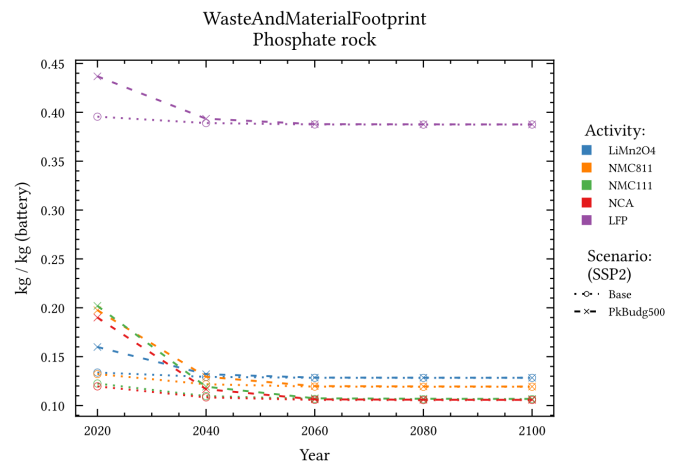


Figure 3: Phosphate material demand footprints for the five Li-ion batteries in the case study from 2020 to 2100 under the SSP2 scenario using the baseline and PkBudg500 RCPs of the REMIND model.



### 3.2.2. Contribution of 'top-processes' in the supply chain

Figure 4 shows the contribution of the 'top-processes' to the cobalt footprint of the LiMn<sub>2</sub>O<sub>4</sub> battery under the baseline scenario from 2020–2100. The total footprint is seen to almost triple, from 2.2 kg/kg in 2020 to 6.2 kg/kg in 2100. This result is likely a reflection of the electrification of the transport sector that is included in the REMIND model. The fractional contributions of the top processes remains relatively steady over the coming century in this case.

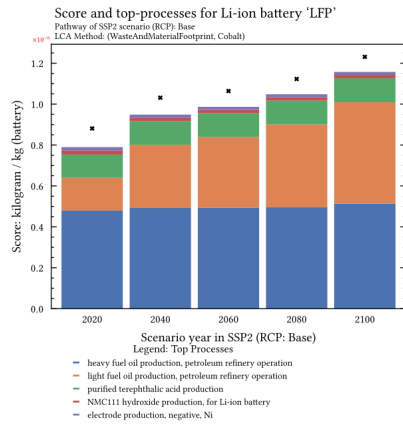


Figure 4: Contribution of 'top-processes' to the case study from 2020 to 2100 under the SSP2 scenario using the baseline and PkBudg500 RCPs of the REMIND model.

### 3.2.3. Contribution of sectors in the supply chain

Figure 5 shows the contribution of sectors (grouped by CPC) to the total natural gas footprint of the LFP battery under the PkBudg500 pathway. In this example, the relative contribution of the sector '47160: Electronic integrated circuits' is seen to decrease from 11% in 2020 to 6% in 2100, while over the same period the contribution of the sector '46430: Parts of primary cells, primary batteries and electrodes' increases from 29% to 38%. The method used to calculate these contributions involves traversing the supply chain branches to a certain level (max. 4, in this case), cutting a specified point (5% in this case), and grouping the value of the 'leaves' by their CPC code. The results, therefore, will depend on how deeply the user would like to inspect the supply chain. Additionally, the utility of these results is dependent on how well the CPC codes define the processes in the supply chain for the particular case.

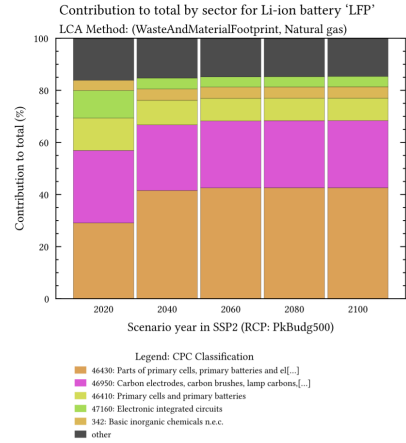


Figure 5: Contribution of industrial sectors to the liquid waste footprint of the NCA battery from 2020 to 2100 under the SSP2 scenario using the PkBudg500 RCP of the REMIND model.

### 3.2.4. Comparison with 'similar' methods

A comparison of the results from the T-reX tool's 'Coal (black)' demand method with the LCIA method 'EDIP 2003 - coal no LT' is shown in Figure 6. In this case, both the trends and the magnitude of the scores were very similar, both demonstrating a general decrease in the use of coking coal in the battery's footprints. Such comparability was also observed for other fossil-fuel-related methods (e.g., natural gas and petroleum), and to a lesser extent, for some of the metal demand methods (e.g., zinc and cobalt). Correlation between standard LCIA methods and T-reX methods, is not generally to be expected, however, due to fundamental differences in the way that the methods are constructed. In standard LCIA methods, impact scores are derived exclusively from the magnitude of the exchanges between the biosphere and the technosphere, that is, extraction and emission. In the T-reX methods, the footprint scores are based on an accounting of either waste generated or material demand, both of which are technosphere-technosphere exchanges in terms of LCA modelling. For the material demand methods especially, this distinction is critical. For example, application of the EDIP 2003 or the CSP methods for a given metal will provide a score that is proportional to the amount extracted by mining, whereas the T-reX method provides an aggregation of the exchanges with the market for that metal. The T-reX method, therefore, considers cases of co-production, recycling, and substitution, providing a picture of the supply-chain pressures that are not captured by the standard LCIA methods. This makes the T-reX methods more sensitive to the modeling choices (e.g., allocation) that are generally embedded in LCA databases.

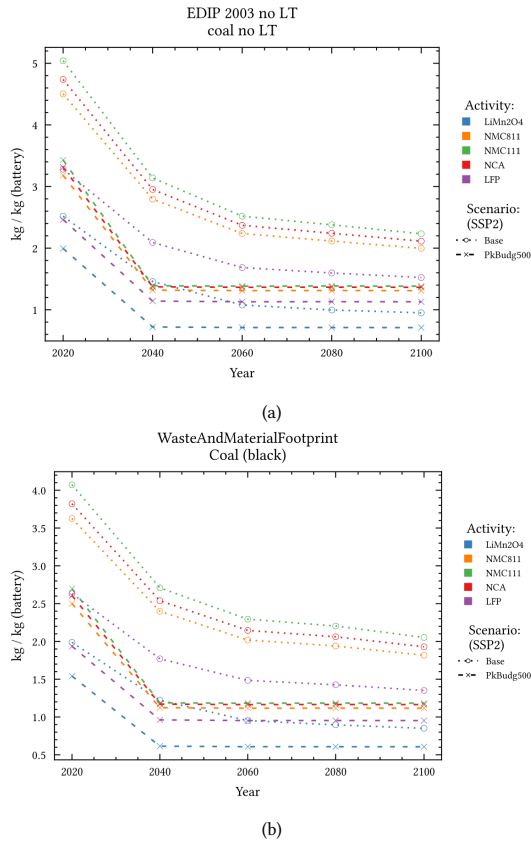


Figure 6: Comparison of LCIA method ‘EDIP 2003 - coal no LT’ (a) with the ‘T-reX - Coal (black)’ (b) in the case study from 2020 to 2100 under the SSP2 scenario using the baseline and PkBudg500 RCPs of the REMIND model.

### 3.2.5. Comparison with other studies

Laurenti et al. (2023) used an alternative method for calculating the waste footprint of 1400 activities in ecoinvent version 3.5, which contains only a generic ‘market for battery, Li-ion, rechargeable, prismatic’. The inventory of this battery most closely resembles that of the NMC 111 battery in this case study. Table 2 presents a comparison of the results from the two studies, where possible. For liquid, solid, and recycled waste, the results were closely aligned, however for hazardous waste, Laurenti et al. reported 95% of the total waste, whereas the T-reX tool reported only 3%. The reason for this discrepancy is explained by the fact that in the method of Laurenti et al., a “waste flow was regarded as hazardous when the hazardousness was clearly stated in its subsequent waste treatment activity”. The authors continue: “It should be noted that the high hazardousness ratios for many products might indicate a weakness in the validity of this measure”. In the T-reX method, the source database is exploded into a list of separate exchanges, and only those explicitly defined as hazardous are marked as such.

Table 2: Comparison of the results from the T-reX battery case study (database: ecoinvent 3.9.1 REMIND SSP2 Base 2020, activity: Li-ion NMC 111) with those from Laurenti et al. (2023) (database: ecoinvent 3.5, activity: ‘Li-ion’).

Indicator	T-reX	Laurenti et al.
Total solid waste (kg/kg)	50.9	62.5
Total liquid waste (kg/kg)	3.53	3.63
Hazardous waste (kg/kg)	1.47	62.6
Recycled waste (kg/kg)	1.59	1.98

## 4. Discussion

Given that both waste generation and material demand are often strongly associated with the environmental impacts of an activity, it is important that they are included in the LCA. While there are numerous examples of existing and proposed methods that attempt to provide endpoint LCIA scores through convoluted formulae or subjective weighting, there is little consensus on their application and their complexity and lack of transparency can make them difficult to use and interpret.

The T-reX tool, in contrast, gives LCA practitioners a simple, flexible, and transparent way to calculate the supply chain waste and material footprints, delivering results in standard units as direct aggregations of the relevant demand inventories. Once the databases have been processed with the T-reX tool, the user can then easily apply the T-reX methods to calculate the supply-chain waste and material footprints for any activity in the same way that they would calculate any LCIA indicator.

The simple case study presented in this paper demonstrates both the utility and the limitations of the T-reX tool. It was shown the T-reX tool was able to calculate categorised aggregates and contribution analyses of both the waste generated and material demands in the present and future supply chains of the Li-ion batteries under consideration. Further, integration of the T-reX methods as ‘pseudo-LCIA’ methods allows the user to easily make use of the T-reX tool in their preferred LCA software, be it code-based like brightway2 or graphical like ActivityBrowser.

One main limitation of the T-reX tool is that it does not yet provide specific information (in a readily accessible format) on the composition of the waste generated, which would be needed to thoroughly assess the environmental impacts of this waste. Currently, the user would need to manually explore the ‘waste inventory’ produced by the application of the T-reX to determine if, for example, the waste generated represents an actual loss of resources, or is simply a transfer of the ‘overburden’ in mining activity, which is classified as ‘inert waste’. A methodic classification of waste exchanges and the end-of-life fates will be facilitated by the more detailed and disaggregated data that is seen in each successive release of ecoinvent (FitzGerald et al., 2023).

Furthermore, the utility of the T-reX tool in studies of future supply chains is limited by the fact that the currently available prospective databases focus largely on changes in the energy, steel, cement, and transport sectors (Sacchi et al., 2023). As demonstrated in the results of the case study—where there was

often very little scenario-temporal change in many waste and material footprint indicators—the utility of prospective LCA is restricted if there is little adaption of the future background inventories. In particular, the inclusion of scenarios with future waste processing technology would greatly improve our predictions of waste and material flows. A strong focus on enhancing these prospective databases is, thus, of critical importance to the future of prospective LCA, and by extension, to the development of the circular economy.

Section word count: 450

## 5. Conclusions

Section word count: 250

We have written the T-reX tool, an extension to the bright-way LCA framework that enables the user to calculate the waste and material footprints of a product or service in an LCA database. It explodes the database, identifies upstream waste and material exchanges, edits them, and writes matching custom ‘pseudo’ LCIA methods. These exchanges become pseudo-biosphere flows and thus, the footprint can be calculated as with the existing LCIA methods. The T-reX tool can be easily customised by the user to calculate the footprints of other supply-chain flows such as water, gas, and critical raw materials.

This paper extends the state of knowledge by exploring the relationship between various waste aggregation methods and environmental damage indicators, contributing to a deeper understanding of life cycle waste inventories and their association with supply-chain risk and potential environmental damage.

## Data availability

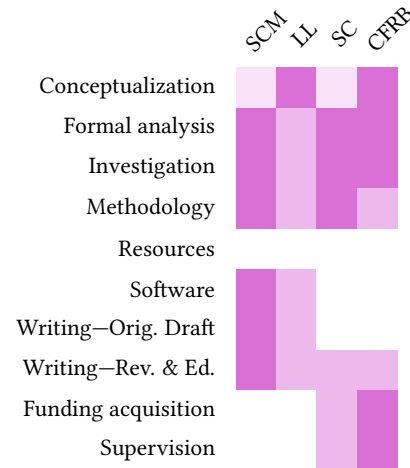
All data used in this analysis are publicly available online under the noted sources. The T-reX tool is installable via the Python Package Index (PyPI) and is available at <https://pypi.org/project/T-reX>. The full source code for the T-reX tool is available at <https://www.github.com/Stew-McD/T-reX>. A user guide and comprehensive documentation are available at <https://T-reX.readthedocs.io>.

## CRedit authorship contribution statement

Co-authors, please check this and change as necessary.

**Stewart Charles McDowall:** Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Elizabeth Lanphear:** Conceptualization, Methodology, Software, Validation, Writing - review & editing. **Stefano Cucurachi:** Conceptualization, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Carlos Felipe Blanco:** Conceptualization, Writing - review & editing, Supervision, Project administration, Funding acquisition.

## Alternative CRediT statement



## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Supplementary material

The supplementary material contains the following:

1. List of waste and material categories
2. Example output of the T-reX tool
3. List of identified waste and material exchanges
4. Code (python script) used for case study
5. Inventory and methods used in the case study
6. Complete tabulated results of the case study
7. Complete visualisations of the case study

## References

1. Aboumahboub, T., Auer, C., Bauer, N., Baumstark, L., et al., 2020. Remind - regional model of investments and development - version 2.1.0. URL: <https://www.pik-potsdam.de/research/transformatio n-pathways/models/remind>.
2. Alfieri, F., La Placa, M.G., et al., 2022. Product reparability scoring system: Specific application to smartphones and slate tablets.

- Arvidsson, R., Söderman, M.L., Sandén, B.A., Nordelöf, A., et al., 2020. A crustal scarcity indicator for long-term global elemental resource assessment in lca. The International Journal of Life Cycle Assessment URL: <https://doi.org/10.1007/s11367-020-01781-1>.
- Ayres, R.U., 1999. The second law, the fourth law, recycling and limits to growth. Ecological Economics URL: [https://doi.org/10.1016/s0921-8009\(98\)00098-6](https://doi.org/10.1016/s0921-8009(98)00098-6).
- Berry, C., 2023. The Paradox of Green Growth: Challenges and Opportunities in Decarbonizing the Lithium-Ion Supply Chain. Springer Nature Switzerland.
- Beylot, A., Muller, S., Descat, M., Ménard, Y., et al., 2018. Life cycle assessment of the french municipal solid waste incineration sector. Waste Management URL: <https://doi.org/10.1016/j.wasman.2018.08.037>.
- Carrara, S., Bobba, S., Blagoeva, D., Alves Dias, P., et al., 2023. Supply chain analysis and material demand forecast in strategic technologies and sectors in the eu – a foresight study. URL: <https://doi.org/10.2760/334074>.
- CEN (European Committee for Standardization), 2019. En 15804 sustainability of construction works - environmental product declarations - core rules for the product category of construction products. URL: [https://standards.cen.eu/dyn/www/f?p=204:110:0:::FSP\\_PROJECT,FS\\_P\\_ORG\\_ID:62366,6202&cs=1C1F2C3C4C5C6C7C8C9CA](https://standards.cen.eu/dyn/www/f?p=204:110:0:::FSP_PROJECT,FS_P_ORG_ID:62366,6202&cs=1C1F2C3C4C5C6C7C8C9CA).
- Chen, X., Matthews, H.S., Griffin, W.M., 2021. Uncertainty caused by life cycle impact assessment methods: Case studies in process-based lci databases. Resources, Conservation and Recycling URL: <http://dx.doi.org/10.1016/j.resconrec.2021.105678>.
- Commission, E., Directorate-General for Internal Market, Industry, E., SMEs, Grohol, M., et al., 2023. Study on the critical raw materials for the eu 2023 – final report. URL: <https://doi.org/10.2873/725585>.
- Doka, G., 2024. Doka lca | publications. <https://www.doka.ch/publications.htm>. (Accessed on 01/24/2024).
- Dziejarski, B., Krzyżyńska, R., Andersson, K., 2023. Current status of carbon capture, utilization, and storage technologies in the global economy: A survey of technical assessment. Fuel 342, 127776. URL: <http://dx.doi.org/10.1016/j.fuel.2023.127776>, doi:10.1016/j.fuel.2023.127776.
- Ellen MacArthur Foundation, 2015. Towards a circular economy: Business rationale for an accelerated transition. URL: <https://www.ellenmacarthurfoundation.org/towards-a-circular-economy-business-rationale-for-an-accelerated-transition>.
- European Commission, 2019. The european green deal. URL: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2019:640:FIN>.
- European Commission, 2020. A new circular economy action plan for a cleaner and more competitive europe. URL: <https://doi.org/10.2779/05068>.
- European Union, 2022. Proposal for Ecodesign for Sustainable Products Regulation: Establishing a framework for setting ecodesign requirements for sustainable products and repealing Directive 2009/125/EC. Technical Report. URL: [https://environment.ec.europa.eu/publications/proposal-ecodesign-sustainable-products-regulation\\_en](https://environment.ec.europa.eu/publications/proposal-ecodesign-sustainable-products-regulation_en).
- FitzGerald, D., Bourgault, G., Vadenbo, C., Sonderegger, T., Symeonidis, A., Fazio, S., Mutel, C., Müller, J., Dellenbach, D., Stoikou, N., et al., 2023. Documentation of changes implemented in the ecoinvent database v3.10. database 3, 10. URL: <https://ecoinvent.org/wp-content/uploads/2023/11/Change-Report-v3.10.pdf>.
- Government of the Netherlands, 2016. A circular economy in the netherlands by 2050. URL: [https://circulareconomy.europa.eu/platform/sites/default/files/17037circulaireeconomie{\\_}en.pdf](https://circulareconomy.europa.eu/platform/sites/default/files/17037circulaireeconomie{_}en.pdf).
- Government of the Netherlands, 2023. National circular economy programme 2023-2030. URL: <https://www.government.nl/binaries/government/documenten/reports/2023/09/27/national-circular-economy-programme-2023-2030/NPCE+Circulaire+Economie+rapport+Engels.pdf>.
- Guinée, J.B., Gorée, M., Heijungs, R., et al., 2002. Handbook on life cycle assessment. operational guide to the iso standards. i: Lca in perspective. iia: Guide. iib: Operational annex. iii: Scientific background. URL: <https://www.universiteitleiden.nl/en/research/research-projects/science/cml-new-dutch-lca-guide>.
- Guinée, J.B., Heijungs, R., 2021. Waste is not a service. The International Journal of Life Cycle Assessment URL: <https://doi.org/10.1007/s11367-021-01955-5>.
- Guinée, J.B., Heijungs, R., Huppes, G., 2004. Economic allocation: Examples and derived decision tree. International Journal of Life Cycle Assessment URL: <https://doi.org/10.1007/BF02978533>.
- Hartley, K., Baldassarre, B., Kirchherr, J., 2024. Circular economy as crisis response: A primer. Journal of Cleaner Production URL: <https://doi.org/10.1016/j.jclepro.2023.140140>.
- Hauschild, M.Z., Potting, J., 2004. Spatial differentiation in life cycle impact assessment - the edip-2003 methodology. guidelines from the danish epa. URL: <https://api.semanticscholar.org/CorpusID:113556375>.
- Hool, A., Helbig, C., Wierink, G., 2023. Challenges and opportunities of the european critical raw materials act. Mineral Economics URL: <https://doi.org/10.1007/s13563-023-00394-y>.
- Huijbregts, M.A.J., Hellweg, S., Frischknecht, R., Hendriks, H.W.M., Hungerbühler, K., Hendriks, A.J., 2010. Cumulative energy demand as predictor for the environmental burden of commodity production. Environmental Science & Technology URL: <http://dx.doi.org/10.1021/es902870s>.
- Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., et al., 2016. Recipe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. The International Journal of Life Cycle Assessment URL: <https://doi.org/10.1007/s11367-016-1246-y>.
- Laurent, A., Olsen, S.I., Hauschild, M.Z., 2012. Limitations of carbon footprint as indicator of environmental sustainability URL: <http://dx.doi.org/10.1021/es204163f>.
- Laurenti, R., Demirer Demir, D., Finnveden, G., 2023. Analyzing the relationship between product waste footprints and environmental damage – a life cycle analysis of 1,400+ products. Science of The Total Environment URL: <https://doi.org/10.1016/j.scitotenv.2022.160405>.
- Laurenti, R., Moberg, A., Stenmarck, A., 2016. Calculating the pre-consumer waste footprint: A screening study of 10 selected products. Waste Management & Research: The Journal for a Sustainable Circular Economy URL: <https://doi.org/10.1177/0734242x16675686>.
- Mancini, L., De Camillis, C., Pennington, D., 2013. Security of supply and scarcity of raw materials: Towards a methodological framework for sustainability assessment. URL: <https://doi.org/10.2788/94926>.
- McDowall, S.C., 2023. T-reX documentation. URL: <https://T-reX.readthedocs.io/en/latest/index.html>. (Accessed on 01/11/2024).
- McDowall, S.C., 2024. T-rex: A program for life cycle assessment (lca) calculations of supply chain waste and material footprints. URL: <https://github.com/Stew-McD/T-reX>.
- McDowall, S.C., Lanphear, E., 2023a. T-rex. URL: <https://zenodo.org/doi/10.5281/zenodo.10431180>.
- McDowall, S.C., Lanphear, E., 2023b. T-rex · pypi. URL: <https://pypi.org/project/T-reX/>. (Accessed on 01/12/2024).
- Meinshausen, M., Nicholls, Z.R.J., Lewis, J., Gidden, M.J., et al., 2020. The shared socio-economic pathway (ssp) greenhouse gas concentrations and their extensions to 2500. Geoscientific Model Development URL: <https://doi.org/10.5194/gmd-13-3571-2020>.
- Mutel, C., 2016. Brightway2-analyzer. URL: <https://github.com/brightway-lca/brightway2-analyzer>. (Accessed on 01/12/2024).
- Mutel, C., 2017a. Brightway: an open source framework for life cycle assessment. Journal of Open Source Software URL: <https://doi.org/10.21105/joss.00236>.
- Mutel, C., 2017b. Wurst documentation. URL: <https://buildmedia.readthedocs.org/media/pdf/wurst/stable/wurst.pdf>.
- Pardo, R., Schweitzer, J., 2018. A long-term strategy for a european circular economy – setting the course for success. Produced for the Think2030 project.
- Parker, D., Riley, K., Robinson, S., Symington, H., et al., 2015. Remanufacturing market study. URL: <https://www.remanufacturing.eu/assets/pdfs/remanufacturing-market-study.pdf>.
- Reuter, M., van Schaik, A., 2012. Opportunities and limits of recycling: A dynamic-model-based analysis. MRS Bulletin URL: <https://doi.org/10.1557/mrs.2012.57>.
- Sacchi, R., Terlouw, T., Siala, K., Dirnhaichner, A., Bauer, C., Cox, B., Mutel, C., Daioglou, V., Luderer, G., 2022. Prospective environmental impact assessment (premise): A streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models. Renewable and Sustainable Energy Reviews URL: <http://dx.doi.org/10.1016/j>



863 .rser.2022.112311.

864 Sacchi, R., Terlouw, T., Siala, K., Dirnaichner, A., Bauer, C., Cox, B., Mutel, C.,  
865 Daioglou, V., Luderer, G., 2023. premise | Documentation. URL: <https://premise.readthedocs.io/>.

866

867 Salviulo, G., Lavagnolo, M.C., Dabalà, M., Bernardo, E., et al., 2021. Enabling  
868 circular economy: The overlooked role of inorganic materials chemistry.  
869 Chemistry – A European Journal URL: [https://doi.org/10.1002/](https://doi.org/10.1002/chem.202002844)  
870 [chem.202002844](https://doi.org/10.1002/chem.202002844).

871 Stehfest, E., van Vuuren, D., Bouwman, L., Kram, T., et al., 2014. Integrated  
872 assessment of global environmental change with IMAGE 3.0: Model de-  
873 scription and policy applications. Netherlands Environmental Assessment  
874 Agency (PBL). URL: [https://dspace.library.uu.nl/bitstre](https://dspace.library.uu.nl/bitstream/handle/1874/308545/PBL_2014_Integrated_Assessment_of_Global_Environmental_Change_with_IMAGE_30_735.pdf)  
875 [am/handle/1874/308545/PBL\\_2014\\_Integrated\\_Assessme](https://dspace.library.uu.nl/bitstream/handle/1874/308545/PBL_2014_Integrated_Assessment_of_Global_Environmental_Change_with_IMAGE_30_735.pdf)  
876 [nt\\_of\\_Global\\_Environmental\\_Change\\_with\\_IMAGE\\_30\\_73](https://dspace.library.uu.nl/bitstream/handle/1874/308545/PBL_2014_Integrated_Assessment_of_Global_Environmental_Change_with_IMAGE_30_735.pdf)  
877 [5.pdf](https://dspace.library.uu.nl/bitstream/handle/1874/308545/PBL_2014_Integrated_Assessment_of_Global_Environmental_Change_with_IMAGE_30_735.pdf).

878 Steinmann, Z.J.N., Schipper, A.M., Hauck, M., Giljum, S., et al., 2017. Resource  
879 footprints are good proxies of environmental damage. Environmental Sci-  
880 ence & Technology URL: [https://doi.org/10.1021/acs.es](https://doi.org/10.1021/acs.est.7b00698)  
881 [t.7b00698](https://doi.org/10.1021/acs.est.7b00698).

882 Steubing, B., de Koning, D., Haas, A., Mutel, C.L., 2020. The activity browser  
883 — an open source lca software building on top of the brightway framework.  
884 Software Impacts URL: [http://dx.doi.org/10.1016/j.simpa.2](http://dx.doi.org/10.1016/j.simpa.2019.100012)  
885 [019.100012](http://dx.doi.org/10.1016/j.simpa.2019.100012).

886 Swiss Federal Office for the Environment (FOEN), 2021. Swiss Eco-Factors 2021  
887 according to the Ecological Scarcity Method: Methodological fundamentals  
888 and their application in Switzerland. Technical Report. URL: [https:](https://www.bafu.admin.ch/bafu/en/home/topics/economy-consumption/economy-and-consumption-publications/publications-economy-and-consumption/eco-factors-switzerland.html)  
889 [//www.bafu.admin.ch/bafu/en/home/topics/economy-con](https://www.bafu.admin.ch/bafu/en/home/topics/economy-consumption/economy-and-consumption-publications/publications-economy-and-consumption/eco-factors-switzerland.html)  
890 [sumption/economy-and-consumption-publications/publ](https://www.bafu.admin.ch/bafu/en/home/topics/economy-consumption/economy-and-consumption-publications/publications-economy-and-consumption/eco-factors-switzerland.html)  
891 [ications-economy-and-consumption/eco-factors-switz](https://www.bafu.admin.ch/bafu/en/home/topics/economy-consumption/economy-and-consumption-publications/publications-economy-and-consumption/eco-factors-switzerland.html)  
892 [erland.html](https://www.bafu.admin.ch/bafu/en/home/topics/economy-consumption/economy-and-consumption-publications/publications-economy-and-consumption/eco-factors-switzerland.html).

893 Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B.,  
894 2016. The ecoinvent database version 3 (part i): overview and methodology.  
895 The International Journal of Life Cycle Assessment URL: [http://dx.d](http://dx.doi.org/10.1007/s11367-016-1087-8)  
896 [oi.org/10.1007/s11367-016-1087-8](http://dx.doi.org/10.1007/s11367-016-1087-8).