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The Circular Industrial Transformation System (CITS) model - Assessing the life cycle impacts of climate and circularity strategies

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ABSTRACT

The circular economy (CE) was introduced as a solution to mitigate increasing resource demand and to reduce environmental impacts. However, it remains a challenge to holistically assess long-term environmental impacts of CE strategies in complex, dynamic systems. To tackle this issue, we present the Circular Industrial Transformation System (CITS) model. CITS integrates dynamic stock modelling, material flow analysis and prospective life cycle assessment while being flexibly applicable to different products, materials and industry sectors across temporal and spatial scales. With that, the CITS model can assess the effect of circular strategies on long-term material flows and their respective environmental impacts, while including the effects of socio-economic developments, transformative climate policies, and a changing energy system. As a case study, the environmental impact reduction of both CE and climate change mitigation strategies was assessed for the German passenger car fleet until 2050. The results indicate that the occurring electrification of the passenger fleet is an effective strategy for reducing the global warming impacts of the automotive sector in the long-term, albeit aligned with the renewable energy transformation. CE strategies are most effective in reducing CO_2-eq. emissions in the short term. Particularly, CE strategies affecting the vehicle stock promise substantial reductions in CO_2-eq. emissions and primary material demand, while improved collection, sorting, and recycling have a limited impact. The results show that the CITS model can guide policies in effectively reducing environmental impacts in complex, dynamic systems by identifying system bottlenecks, trade-offs or synergies in industrial transitions.

List of abbreviations

Abbreviation	Description	Source
LCA	Life cycle assessment	
P-LCA	Prospective life cycle assessment	
MFA	Material flow analysis	
DSM	Dynamic stock modelling	
IAM	Integrated assessment model	
CITS	Circular Industrial Transformation System	
CE	Circular economy	
BEV	Battery electric vehicle	
ICE	internal combustion engine	
ODYM	Open Dynamic Material Systems Model	Pauliuk (2023)
RECC	Resource efficiency - climate change	Pauliuk and Heeren (2020)
GDP	Gross domestic product	
TC	Transfer coefficient	
GHG	Greenhouse gas	
HDPE	High density polyethylene	
LDPE	Low density polyethylene	
PP	Polypropylene	
PET	Polyethylene terephthalate	
PS	Polystyrene	
PVC	Polyvinyl chloride	
RCP	Representative Concentration Pathways	(Fricko et al., 2017; Riahi et al., 2017; Sacchi et al., 2022)
SSP	Shared Socioeconomic Pathways	(Fricko et al., 2017; Riahi et al., 2017; Sacchi et al., 2022)
PREMISE	Prospective Environmental Impact assessment	Sacchi et al. (2022)

(*continued on next column*)

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1. Introduction

1.1. Background

The current global economic system is predominately linear and fossil-based. This has resulted in a broad array of environmental problems that globally threaten ecosystems and humanity. These problems are summarized within the triple planetary crises - Climate change, biodiversity loss and pollution (Hellweg et al., 2023). The triple planetary crises are an aggregation of nine planetary boundaries, of which now already six have been crossed (Richardson et al., 2023). Although scientific consensus has been reached on these global threats, global economic activities and the corresponding material and energy use are projected to grow in the coming years (OECD, 2024a). These activities threaten to worsen the planetary crises and crossing of the planetary boundaries. As a solution to the increase in material and energy requirements, a circular economy (CE) was introduced to support sustainable development and reduce environmental pressure (MacArthur, 2014). A CE is defined as a regenerative system in which resource input, waste, emissions, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops (Geissdoerfer et al., 2017). The transition from the current linear and fossil economy towards a CE requires substantial changes in production, use and end-of-life of products and materials. For that, value retention options, or R-strategies, like remanufacturing, repair, reuse and recycling, were developed (Reike et al., 2018). Environmental impact reduction with R-strategies are demonstrated for both bulk materials, such as plastics and critical materials, like rare earth metals, due to the high impacts associated with their extraction and end-of-life (Minunno et al., 2020; Rossi et al., 2023). However, CE strategies may also result in additional environmental impacts, such as an increase in energy demand due to recycling, or re-use causing less energy efficient devices to be used (Barkhausen et al., 2024; Geissdoerfer et al., 2017).

1.2. Research gap

Although CE policies are often clearly mapped (Hartley et al., 2023), their effectiveness and impact reduction on a system level are frequently missing, making choices and prioritization difficult (Barkhausen et al., 2024). To comprehensively assess and monitor environmental impacts of CE policies, a dynamic impact assessment framework is required. Such a framework requires input on material demand, stocks and corresponding environmental impacts of production, efficiency during use, end-of-life and the effect of R-strategies. Such a model requires additional complexity as impacts vary over time, affecting the performance of R-strategies in the future (Barkhausen et al., 2024). In short, a complex modelling effort is required to effectively assess the environmental and material effects of R-strategies and transformative climate policies in the future. There are already several methodologies available that could form part of such a modelling effort. Firstly, Material flow analysis (MFA) models are available to assess flows of materials through the economic system (Brunner and Rechberger, 2016). Next, a dynamic stock model (DSM) can assess lifetime of and corresponding material 'storage' in specific products (Drewniok et al., 2023; Müller et al., 2014). A MFA combined with DSM can assess future material demand, data on stocks, flows and product material compositions (Drewniok et al., 2023). These models are key in determining waste management and CE strategies and particularly their mutual interaction (Wang et al., 2018).

However, the MFA-DSM combination alone lacks the assessment of environmental impacts over the full life cycle of materials and future dynamics of changes within and outside the system. For that, Life cycle assessment (LCA) methodology can be used. However, static LCAs, such as in case studies, are limited when assessing dynamic systems and future scenarios, as these require adaptations in both the foreground and background system of an LCA. Foreground scenarios include changes within the analysed system, e.g. direct adaptations in technology input data and (circular) policy assumptions within the respective system. Background scenarios refer to changes that affect the LCA processes behind the framework, such as socio-economic developments (GDP, population) and energy system transitions. To effectively include these changes in the background system, prospective (P-) LCA methodologies have been developed that link LCA inventories to future energy and cost scenarios (Mehta et al., 2023; Thonemann et al., 2020). P-LCA requires input on future consequences of interactions between economy, society and biosphere, which can be obtained from Integrated assessment models (IAMs) (Sacchi et al., 2022; Stegmann et al., 2022).

Recent studies increasingly integrated MFA and P-LCA in multiple manners as summarized by Barkhausen et al. (2023). Also elements of P-LCA, MFA and DSM were already linked to assess environmental consequences of various CE strategies within sectors or industries (Barkhausen et al., 2023, 2024; Kamran et al., 2021; Liu and Nowack, 2022; Ohms et al., 2024). Other existing frameworks include the resource efficiency - climate change (RECC) model framework and the Open Dynamic Material Systems Model (ODYM) open-source framework (Pauliuk, 2023; Pauliuk and Heeren, 2020). This framework includes a dynamic MFA and environmental impacts along the life cycle, which are linked to individual motorized transport. However, the existing MFA and LCA models still lack the unified IAM background scenarios of P-LCA (Sacchi et al., 2022). Additionally, these frameworks lack the reproducibility and flexibility to apply to different systems, sectors and materials and their corresponding end-of-life, including recycling rates.

1.3. Research goal & scope

Based on the defined research gaps, the key question is how to holistically assess the long-term environmental impacts of CE strategies in complex, dynamic systems. In particular, this requires an assessment of synergies and trade-offs between different industry transitions and strategies while including the effects of socio-economic developments and a changing energy system.

To effectively assess environmental consequences of CE strategies throughout multiple product groups and sectors, a future modelling approach that combines DSM, MFA, P-LCA with IAM scenarios that can be flexibly applied is required. Such a framework should be applicable to different sectors, to both bulk and critical materials at different spatial scales. This can help identifying impactful R-strategies and climate policies to reduce material use and environmental impacts for sectors transitioning towards a circular, carbon neutral and environmentally sustainable economy. With that, support can be developed for decision making, on integrated long-term strategies and policy measures across a range of scenarios. Here, we introduce an integrated model framework that combines dynamic stock modelling, material flow analysis and prospective life cycle assessment, named Circular Industrial Transformation System (CITS) model. CITS was designed to quantify the circularity and life cycle impacts that result from long-term developments in material & product demand, stocks, and waste generation for defined product groups and industry sectors. Its key goals are to assess the long-term environmental impact of circular R-strategies (e.g., refuse, reduce, reuse, recycling) and identifying synergies and trade-offs between CE targets and transformative climate policies in future scenarios.

First we introduce the background, methodological set up, and data requirements of the CITS model framework in the methodology section. As a case study, the CITS model framework is then applied to assess the effectiveness of CE and climate change mitigation strategies in reducing the environmental impact of the German passenger car fleet until 2050. The results are then analysed and form the basis of discussing the effectiveness and limitations of the CITS model in assessing complex and dynamic industry transitions. The article closes with conclusions on the case study, the benefits of such a model framework and recommendations for further research.

2. Methodology

2.1. The modelling framework

CITS consists of three modules: the DSM (1), MFA (2) and (P-LCA) (3) (Fig. 1). Each module operates individually and requires its own data inputs. In module 1, the DSM uses historic production data together with product lifetime distributions in order to calculate the annual product stocks, production, and waste generation over time. Future production data is projected, mostly in relation to GDP and population projections. The MFA, module 2, uses product composition databases to determine the bulk material composition (plastic and metal types and quantities) in defined product groups or sectors. Additionally, the material flows according to historic and current data and assumptions are defined here. In module 3, the P-LCA quantifies the environmental impact of each process in the product life cycle. LCA inventory data is used in this module, which can be adapted in both spatial and temporal scale. CITS uses information from both foreground and background scenarios to assess future impacts. Background scenarios provide data on demographic development, natural environment, the wider economy and energy availability, which are used as input in module 1 and 3 (Fig. 1). This information is supplied by integrated assessment models (IAM) (Riahi et al., 2017). Foreground scenarios provide inputs for product group or sector-specific changes, such as CE strategies or technological developments, and require specific information about which data points in what module require adaptation, which can vary depending on the system selected. The full model has a high data demand, for which example data sources are given per module in Table 1.

2.2. Dynamic stock module

The methodology of the DSM follows a similar principle to that of Van Straalen et al., 2016. The DSM determines the number of products which are in stock, the demand for new products and materials, and the quantity of waste generated each year. The DSM calculates the historical stocks using the historical consumption and lifetime distribution of products. The cumulative distribution function of the lifetime distribution determines the number of products of a cohort (all products produced in one year) left in use after a given time. The Weibull distribution function is considered the most suitable for describing discard behavior and has been applied in multiple studies, including electronic equipment in the European Union (Li et al., 2020; Van Straalen et al., 2016; Wang et al., 2018). The sum of products in stock (S) at a time (t) is the sum of all those products per produced cohort that are still in use. With a Weibull distribution, S follows the following equation (1):

$$S(t) = \sum_{n \in N(t)} \left(1 - e^{-((t-T_n)/\lambda_n)^{k_n}}\right) C_n \tag{1}$$

Where $S(t)$ is total the stock of products at year t, N(t) is the set of cohorts that have been produced by year t, T_n is the year of production of cohort n, λ_n and k_n are the scale and shape parameter of the Weibull distribution of cohort n respectively and C_n is the historical consumption of cohort n (the amount of products made at year of production). Historical stock data is required as an input dataset.

To project future product stocks, the historic stock data and their relation to socioeconomic indicators (GDP and population) is assessed. If a strong correlation and/or causation for either one is observed, the selected indicator is used to project future stocks by applying a suitable formula that matches historical developments and expected behavior. Many consumption goods follow an S curve correlated with higher GDP per capita. Hence, for most future stocks CITS assumes a nonlinear growth relationship between sector growth, population (P) and GDP through an S- curve. Similar formulas were used in other studies projecting product consumption (Daioglou et al., 2014; Groenenberg et al., 2005; Stegmann et al., 2022). This results in the following equation (2):

$$S = \alpha^* P^* \ e^{-\beta^* \frac{P}{GDP}} \tag{2}$$

Where α and β are fitted using the historical data using a logarithmic transformation and linear regression respectively. Using the historic and projected stock of cohorts of products, waste generation is calculated together with the lifetime distributions, determining how much of each cohort reaches end-of-life every year. Lastly, the leftover product stock - now reduced due to products having become waste - is balanced with the *demanded* stock, resulting in the annual production requirements for new products. These calculations together provide us with the annual product stocks, production and waste generation.

Furthermore, the dynamic stock module includes the functionality for technological transition, i.e., the replacement of one product or technology by another product or technology. This transition was represented by a logistic curve (Meade and Islam, 1995; Nemet et al., 2023). Parameters k and t_0 are used to describe the share of consumption of the new product type with respect to the consumption of both types (3):

$$\%_{new\ product} = \left(1 + e^{k\ *\ (t-t_0)}\right)^{-1} \tag{3}$$

Two calibration points are required to determine the parameters. These can be obtained from historic datasets. The final outcomes from the Dynamic stock module are used as input for the MFA assessment.

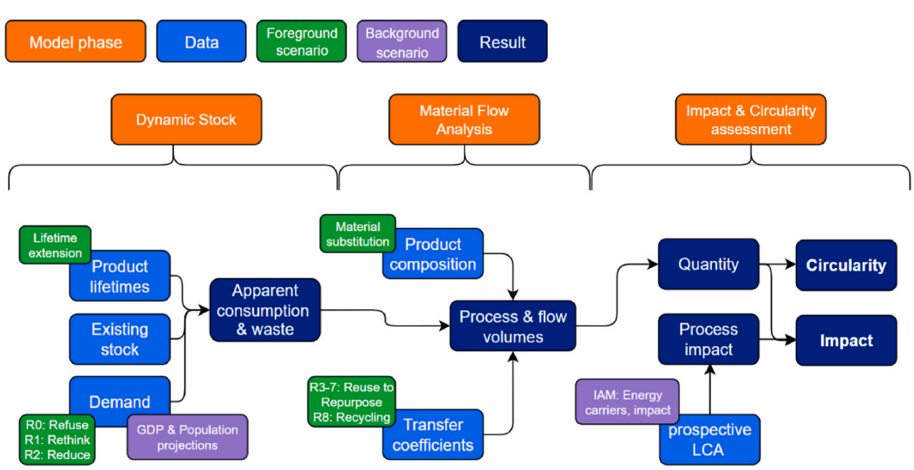

Fig. 1. Overview of the CITS framework, including the three modules and their corresponding data inputs, foreground scenarios, and background scenarios.

Table 1
Data requirements required for the CITS model and the automotive case study, respectively.

Module	Data name	Potential sources for data input	Automotive case study data input
Dynamic Stock	Product lifetime distributions	OECD, grey or scientific literature	Held et al. (2021)
Dynamic Stock	Historical consumption or stock data	Eurostat, European product federations	Historical trade data (Eurostat DS-056120); use from passenger vehicle registrations ACEA; OECD Historical data, 2024
Dynamic Stock	Historical GDP for scaling	Eurostat	Historical GDP (Eurostat NAMA_10_GDP)
Dynamic Stock	Projected GDP	PREMISE scenarios	GDP projections from SSP 2.0 database, SSP2Middle-of -the-road scenario (Sacchi et al., 2022)
Material flow analysis	Product material compositions	Grey or scientific literature, inventory databases	(Hennequin et al., 2023), ecoinvent (Wernet et al., 2016)
Material flow analysis	Life cycle stages of products (production, manufacturing, use, sorting, recycling)	Eurostat, grey or scientific literature, inventory databases	End-of-life vehicles - reuse, recycling and recovery, totals (Eurostat ENV_WASELVT), Recycling rates for metals, plastics (Hestin et al., 2015; Soo et al., 2017) Rubber data from (ETRMA, 2022)
Impact assessment	Inventory data of processes (corresponding to life cycle stages)	Grey or scientific literature, inventory databases	Ecoinvent (Wernet et al., 2016; Schwarz et al., 2021; Pauliuk, 2023)
Impact assessment	Integrated assessment modeling; background processes for energy per region	IAM models, e.g. IMAGE	IAM Base, RCP19 (Riahi et al., 2017)
Impact assessment	Background LCA dataset	Eurostat, grey or scientific literature, inventory databases	Material extraction and composition from Ecoinvent (Wernet et al., 2016)
Foreground scenario	Assumptions on changes due to foreground scenarios	Scientific literature, assumptions	25% increase on consumption r-strategies, 50% decrease of losses in value chain

2.3. Material flow analysis (MFA)

The MFA module converts the yearly product consumption and waste mass data from the stock module into yearly mass flows along the value chain, e.g. primary material consumption and disposal volumes. The total MFA system can be described as a set of processes connected by material flows. A product material composition is used to translate the products into material volumes. This is translated into mass balances for each product, material, region and year. These mass balances are based on sets of process yield coefficients, named Transfer Coefficients (TCs). The value of the TCs depend on the product, material, year, sector and scenario. The TCs determine which share of material in a system process flows towards another process. Hence, the system of TCs describes a network of processes and flows and their relative sizes. This data structure facilitates the flexible modification of processes and the reconfiguration of the system's architecture. New processes can easily be appended and integrated into the dataset.

With a script, for each case i, the MFA data is compiled into a set of linear equations represented by a square matrix M (size $m \times m$), an output vector S_i (size $m \times 1$), and a flow size vector F_i (size $m \times 1$). The variable m denotes the number of material flows in the system, or equivalently, the number of equations required to solve the mass balance. The relationship can be expressed as follows:

$$M_i F_i = S_i \tag{4}$$

This formulation states three constraints that the system must satisfy.

a. The flows into and out of the "Stock" process must adhere to specified volumes.
b. The processes must maintain a balance between incoming and outgoing material flows.
c. If multiple flows exit a single process, their ratios must follow the TCs.

The entries of output vector S_i are set to zero for equation types *b* and *c*. For equations of type a, the entry value represents the consumption and disposal values derived from the DSM. The complete mass balance of the system is resolved using a linear matrix solver, yielding the vector F_i that describes the material volumes within each flow for case i.

Subsequently, the material flows are aggregated into process sizes by summing all flows exiting a process. An additional process for in-stock product volumes is incorporated based on DSM results, which is subsequently integrated in the P-LCA module for impact assessment together with the material balances and the process sizes.

2.4. Impact assessment (prospective LCA)

2.4.1. Linking MFA with LCA data

The P-LCA module assesses the environmental impacts associated with the TCs and processes defined in the MFA and DSM. In traditional LCAs, material flows within the defined system boundaries are integrated with impacts occurring in processing, such as refining, manufacturing, transport or assembly. To align the LCA inventory processes with an MFA approach, the inventories are adapted by removing material flows that are part of the MFA from the LCA data inventory input. This creates modular LCA inventories for processes and untracked materials within the life cycle steps along the systems value chain (Haupt et al., 2018). The material impacts that are part of the MFA are assessed separately. The total impact of the defined system is the sum of the MFA material impact with the modular LCA inventories that include processes and impacts of untracked materials. For inventory data from ecoinvent datasets, ISIC Classifications, ISIC Sectors, and CPC Classifications are used to separate exchange types into primary material data, transforming processes and waste activities. The P-LCA module in CITS uses these ecoinvent classifications to assess and delete material inventory data using Brightway2 (Mutel, 2017).

2.4.2. Background scenario's; premise and IAM

Traditional LCAs are limited to assessing the environmental impact at a static moment in time. However, the background processes, mainly electricity and heat generation, are prone to change. The modular LCA inventories and background processes, which use ecoinvent 3.9.1 as a key source (Wernet et al., 2016), require adaptation depending on the prospective future scenario. These prospective adaptations reflect future scenarios that describe changes in the global energy system. To adapt the background processes and modular LCA, PREMISE IAM scenario models are used, which are combined with Brightway2 (Sacchi et al., 2022). Several scenarios are available through the PREMISE software and they are linked to outcomes of existing integrated assessment models (IAM) (P2) and based on SSP/RCP scenarios (Fricko et al., 2017; Riahi et al., 2017; Sacchi et al., 2022). The SSP's are "Shared Socio-economic Pathways" which are narratives describing socioeconomic global developments. The SSP's are divided into 5 base categories, each of which come with datasets on the underlying assumptions for socio-economic factors such as GDP developments. The RCPs refer to "Representative Concentration Pathways". These scenarios are used in a variety of global models, leading to a more harmonized comparison between models regarding potential climate developments (Riahi et al., 2017). Currently, CITS uses two PREMISE background scenarios based on the PBL IMAGE model. The first one, SSP2-Base, refers to a 3.5 °C global temperature increase by 2100 due to limited implemented climate policies. The second one, SSP2-RCP19, refers to a maximum global temperature increase of 1.5 °C by 2100. Details on the background scenarios for impact are presented in Table S1. These scenarios could be complemented by other IMAGE scenarios or scenarios from a different IAM.

2.4.3. Impact assessment method

The ReCiPe2016 is applied as LCIA methodology, where both midpoint (18) and endpoint (3) indicators are assessed (Huijbregts et al., 2017). Different versions of the ReCiPe2016 can be applied to the framework, with different background assumptions for aggregation to endpoint, cultural perspective, local or global perspective and corresponding indicators (De Bruyn et al., 2010; Huijbregts et al., 2017).

2.5. Output indicators

The following key output indicators are calculated by CITS per defined foreground scenario and year.

1. Total product or material consumption and waste volumes of the system, in tonnes per year. This indicator is an intermediate result following from the dynamic stock module. The result of background and foreground scenarios can be monitored with this indicator.
2. Technology intensity, in tonnes per year. This indicator represents the volume of material processed by a technology used at a stage in the life cycle. This indicator can be of aid when assessing capacity for processing technologies required under the background and foreground scenarios.
3. Circularity indicators, including the avoided primary material use in the analysed system through CE strategies such as refuse, reduce, reuse or recycling. Furthermore, it includes the amount of produced recyclates in relation to total waste generated, which can be combined with a factor accounting for the quality of the recycled material.
4. The environmental impact of the full system, across defined temporal and spatial scales. This includes 18 LCA impact categories separately, or aggregated into one indicator (Shadow price, in €).

3. Case study: German automotive industry

3.1. Background

In Germany, the automotive industry is a major economic sector. 30% of the 16 million produced cars in the EU 2021 were produced in Germany (International Organization of Motor Vehicle Manufacturers (OICA), 2022)(European Commission, 2020). Additionally, 20% of the 246 million passenger cars registered in the EU (in 2020) are used in Germany (European Automobile Manufacturers' Association (ACEA), 2022). 12 million cars reached their end of life in 2019 in the EU (European Commission, 2020). Both metals and plastics are key material inputs into the automotive sector, with 80% and 15% of the weight of passenger cars respectively (Mehta et al., 2023). 8% of annual global plastics production is used in the automotive sector (Geyer et al., 2017). Furthermore, the transport sector contributes for about a quarter to the EU's total CO_2 emissions, of which 71.7% was a result of road transportation from the automotive use, and of this, 61% is attributed to passenger cars (European Union, 2022).

To tackle the global warming impacts of passenger cars, the European Union agreed on prohibiting the registration of new internal combustion (ICE) cars that emit GHG emissions by 2035 (European Commission, 2023), which is expected to foster the transition to battery electric vehicles (BEV). Currently, only 0.5% of the EU car fleet is electric and 1.8% hybrid (European Automobile Manufacturers' Association (ACEA), 2022). Furthermore, the European Union has established a proposal for requirements on both design and end-of-life of vehicles to increase circularity and decrease environmental impacts (European commission, 2020). This regulation focuses on both vehicle body parts as well as critical metals from car batteries.

In short, the automotive industry is required to undergo two different transitions to reduce its environmental impact, namely electrification and circularity. Fortunately, there is high potential in the automotive sector for especially circularity strategies including repair, recycling and re-use. On the other side, carbon emissions must be reduced, which is to be reached through electrifying the full passenger fleet.

In this case study, the CITS model is applied to assess the effectiveness of several CE strategies in reducing environmental impacts during the sectors transition towards an electric automotive fleet and changing energy supply scenario due to climate change policies. These results can identify and support effective policies and mitigation strategies.

3.2. Data requirements & sources

A summary of data inputs for the different modules for the case study is presented in Table 1. The lifetime distribution of both BEV and ICE cars is assumed to be of Weibull shape with a mean value of 14.8 years (Held et al., 2021). Therefore, the parameters are scale $\lambda = 16.7$ and shape $k = 2.4$.

It was assumed that the transition towards electric passenger car production is complete in 2035. A logistic curve was assumed for the growth of the electric car production, as described in Section 2.3, fitted by two datapoints for the share of consumption of electric passenger vehicles: 12.4% in 2020 and 24.5% in 2022. This leads to the parameters for the logistic curve being: $k = -0.4148$ and $t_0 = 2026.2$. The share of BEV in total vehicle consumption in 2035 is required to be 100% in accordance with EU legislation (European Commission, 2022). The modelled logistic curve puts the share of electric vehicles in stock at 98.6% in 2035.

For calculating the future product demand in the DSM, population projections from Eurostat (2023a) were used. GDP projections were calculated by applying the relative change of GDP projections from OECD (2024b) to the base year value of 2022 from Eurostat (2023b). The resulting α and β in the projection formula (equation (2)) were fitted as 0.7363 and 0.00612 respectively.

The MFA was structured in several life cycle steps, including primary material, assembly, and end-of-life processes. The scope of the MFA and P-LCA is set on the German automotive sector on a yearly basis, starting in 2020 and up until 2050. The LCA includes the full life cycle from cradle-to- grave, see supplementary information 1 and Fig. S1. The steps and the corresponding transfer coefficients are included in Table S2. Product material compositions are extracted from ecoinvent 3.9.1 for car parts which include a glider, powertrain and battery for the BEV car and the glider and engine for the ICE car (Tables S3–S5). Tyre composition data was obtained from literature. For the processes, modular LCA inventories of the life cycle stages defined in the MFA are collected from literature and ecoinvent. The modular LCA inventories that were developed for the LCA all have a similar functional unit, being 1 kg of output product. Additional information on goal, scope and inventory dataset are presented in supplementary information 2. Additional info on the inventories and ecoinvent adaptations is given in the SI and in Tables S7–S8. The ReCiPe 2016 (Hierarchist) methodology was selected. Additionally, the shadow price methodology developed by De Bruyn et al., 2010) is included, which is a single output environmental impact indicator which can be directly translated to economic impacts (De Bruyn et al., 2010). To limit the scope of the study, global warming potential is highlighted as outcome, which is reported in kg CO_2-eq.

3.3. Foreground and background scenarios

The foreground scenarios were assessed based on potential policy interventions that reinforce specific CE strategies, which are specified in supplementary information 3 (Fig. S2). The interventions consist of multiple different mitigation measures (Table 2). The mitigation measures adapt specific input parameters within the three CITS modules using a defined increase or decrease. This increase or decrease show the sensitivity of the assessed parameters and align with the potential consequences of defined mitigation measures and subsequent policy interventions. In the baseline intervention, no additional mitigation measures are assumed. In the DSM and MFA interventions, material efficiency mitigation measures are implemented, which affect the modules with a defined sensitivity as reported in Table 2. For the MFA mitigation measures, a 50% increase in efficiency of the subsequent processes was assumed. For the DSM, a 25% increase or decrease in value was assumed, depending on the mitigation. The full overview of the mitigations and how these are comprehensively translated to the different modules is available in Table S12. The changes in the parameters of the MFA and DSM towards their final value implemented as a linear change towards 2050. The final demand of both BEV and ICE cars under the modelled interventions is presented in supplementary information 4 (Fig. S3). The climate policy scenario is implemented in all interventions, where the background energy system within the P-LCA module is adapted in line with emission reduction from the energy sector as assumed in SSP. This is either the *SSP2-Base* (defined as F) and *SSP2-RCP19* (defined as R) scenario. Supplementary information 5 (Fig. S4) presents the electricity impacts separately for the PREMISE background scenarios used.

Table 2
Scenario names and the corresponding adaptations assumed in the three modules separately. F = Base, R = RCP19. Baseline represents no adaptations made to the module.

Intervention name	Dynamic stock module mitigations	MFA module mitigations	Sensitivity	P-LCA module
Baseline (F)	*Baseline assumptions*	*Baseline*	–	SSP2-Base
Baseline (R)	*Baseline assumptions*	*Baseline*	–	SSP2-RCP19
Stock (F)	Lifetime extension, demand, sharing	*Baseline*	25% increase in sharing and lifetime, 25% decrease in demand	SSP2-Base
Stock (R)	Lifetime extension, demand, sharing	*Baseline*	25% increase in sharing and lifetime, 25% decrease in demand	SSP2-RCP19
MFA (F)	*Baseline assumptions*	collection, sorting, recycling, dismantling, manufacturing	50% process efficiency increase	SSP2-Base
MFA (R)	*Baseline assumptions*	collection, sorting, recycling, dismantling, manufacturing	50% process efficiency increase	SSP2-RCP19
ALL (F)	Lifetime extention, demand, sharing	collection, sorting, recycling, dismantling, manufacturing	Combination of MFA and stock mitigations	SSP2-Base
ALL (R)	Lifetime extention, demand, sharing	collection, sorting, recycling, dismantling, manufacturing	Combination of MFA and stock mitigations	SSP2-RCP19

4. Results

Stocks and material flows of the automotive sector in Germany until 2050 are present in Fig. 2 for (a) the baseline and (b) with all interventions included. The baseline still resembles a largely linear economy with a high primary material input of 3.16 Mt (Fig. 2a). Although the system is linear, most material volumes undergo dismantling, shredding and sorting at end-of-life. However, the assumed decrease in quality due to the mixed nature of materials results in the recyclate not being reusable in the automotive sector itself. These materials are defined as avoided products and leave the system boundaries (2.36 Mt). Reuse and recycling in the baseline are limited, which are needed to keep materials in a closed loop system. When including all policy interventions, the circularity of the automotive sector substantially increases (Fig. 2b). This is visible through increased dismantling, reuse and recycling flows going back into the automotive system. Primary material input is strongly reduced, similar to the total quantities of avoided product in the system. This is a result of the mitigation strategies, which assumes a decrease in demand of automotive vehicles. In total, the amount of recycled and reused materials exceeds the primary material demand in the All system (0.38 Mt and 0.74 Mt respectively). These material flows depict the model's capability to compare the effect of mitigations on material flows in a system, in such as way that effects of CE strategies are showcased.

Additionally, the material volumes per process within the value chain over time, volumes per life cycle step as well as total waste generation can be assessed accordingly (Fig. 3). Primary material and material volumes at different stages in the value chain are strongly affected by the interventions from the foreground scenarios. The material volumes ending up as losses in landfill & incineration are reduced significantly by MFA interventions such as improved collection, sorting, and recycling, up until 60% by 2050. MFA mitigations also result in a significant increase in mechanical recycling until 2035, after which it stabilizes. Stock interventions reduce mechanical recycling quantities, mainly due to reduced consumption and stocks, which are visualized in Fig. S3. Hence, when only MFA interventions are implicated, the mechanical recycling capacity must increase substantially which can result in a bottleneck at this life cycle stage. Whilst with all interventions in place, mechanical recycling volumes will only slightly increase. This example highlights the potential of the model to project the demand for different technology capacities in a system, such as the demand for recyclers in the automotive sector. Combining the stock and MFA interventions highlights the synergies that can be achieved when reducing total volumes via the stock module interventions with the MFA interventions for more circularity and material efficiency.

Primary material demand is to decrease slightly in the baseline scenario due to the extrapolation of GDP and decreased consumption in 2025. This will increase after 2030 due to the projected increase of automobiles, which is driven by GDP. Detailed primary material demands by material type in 2050 per intervention highlight effect on individual materials (Fig. 4). From the individual mitigations within the MFA interventions, dismantling decreases the total primary material demand the most, by 30%. This is due to an increase in material volumes ready for re-use or recycling with high quality, which directly replaces virgin materials within the system boundaries. Except for dismantling, individual mitigations within stock interventions can also reduce primary material demand significantly. Car sharing and decreased demand reduce primary material requirement with about 30% as well. When all mitigations within the MFA and stock interventions are implemented, primary material demand is reduced by more than 80%.

The global warming impact (CO_2-eq. emissions) of the German automotive sector per life cycle stage and intervention is depicted in

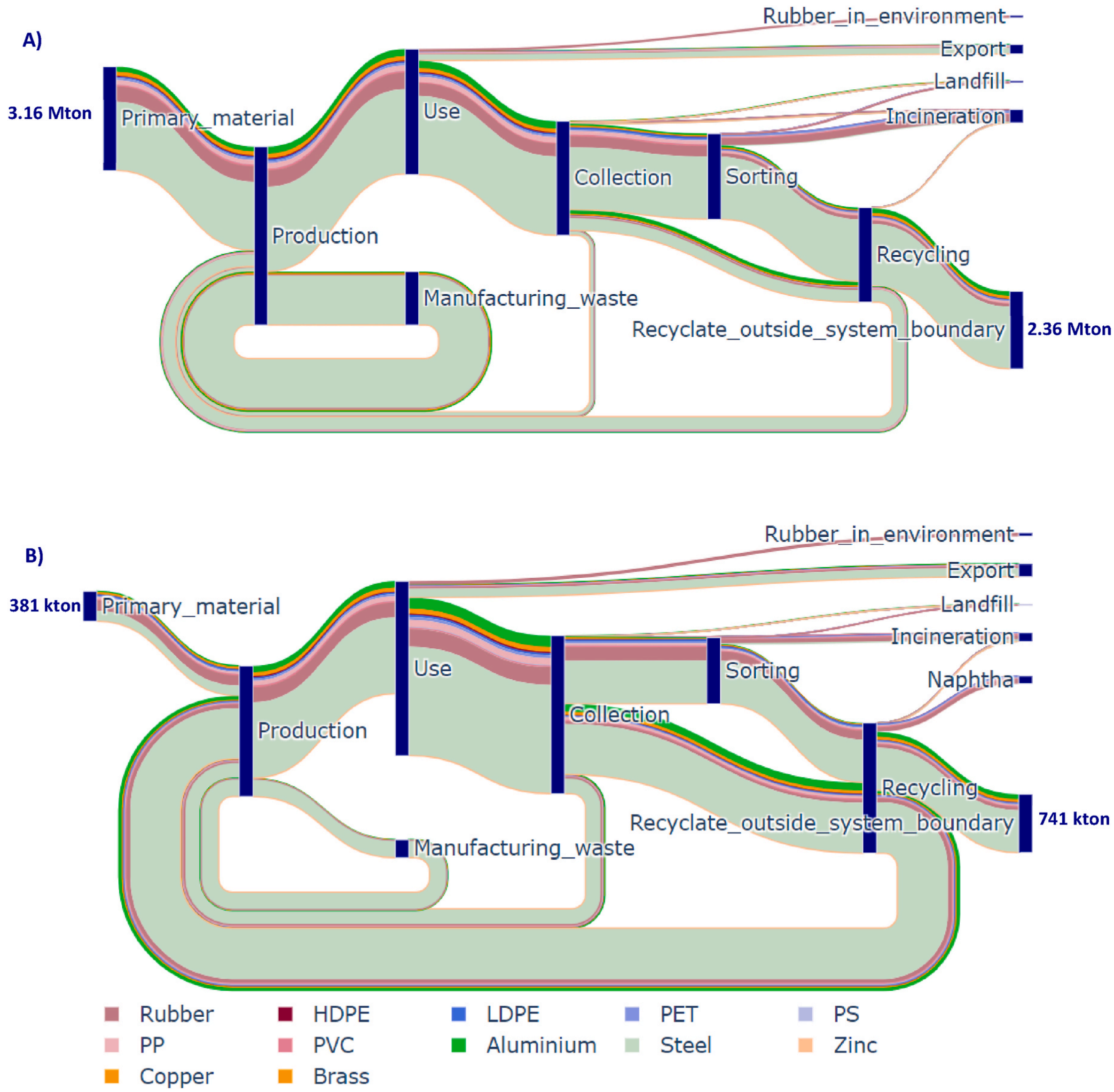

Fig. 2. Sankey diagram of the material flows and volumes in the automotive sector for Germany in 2050. A) Baseline situation with no additional interventions. B) All Stock and MFA interventions included. Abbreviations of plastics (HDPE, PP …) are elaborated in the list of abbreviations.

Fig. 5a. The aggregated 18 ReCiPe2016 impact indicators per interventions are available in Table S13. The total global warming impact of the German automotive sector in 2020 equals to about 60 Gt CO_2- eq. emissions, with the use phase being responsible for over half of the impact. The effect of climate policy mitigation implementation (depicted with (R)) reduces CO_2- eq. emissions most effectively. Without any interventions (baseline (F)), the GHG emissions decrease initially until 2030 due to the sector transitions to BEV but increase again due to a rise in emissions for electricity production in the SSP2 baseline scenario along with a continuous increase in vehicle demand. This highlights that electrification of the passenger fleet as standalone policy will not decrease CO_2- eq. emissions in the long term. Only when combined with the renewable energy transition, substantial reductions (>70%) in kg CO_2- eq. emissions can be achieved in 2050 (baseline (R)). Implementing stock interventions result in significant reductions, about 30% of global warming impacts in 2050 compared to the baseline intervention. This is due to an absolute decrease in primary material, manufacturing and recycling volumes and their related impacts. These interventions already show to be effective for emission reduction on shorter timescales, between 2025 and 2030 (Fig. 5b). Such interventions, which include car sharing and demand reduction, are particularly impactful when the energy system still includes a high share of fossil fuels and ICE cars are still used. In short, stock interventions might be more effective compared to climate change policies for short term emission reduction goals. MFA mitigations on global warming impact reduction potential is limited. As MFA mitigations occur mostly in the end-of-life processes, there is a limited role in the total impact of the sector over the full value chain.

5. Discussion

5.1. Model applicability and policy implications

The results of the automotive case study highlight key elements of the CITS model and its applicability to circular transition studies and decision-making processes. There are four focus applications for the CITS model: First, The CITS model compares the long-term effects of different CE strategies on a system level. Changes in primary material demands, as well as waste generation over time, can be evaluated while taking sectoral transitions into account, such as the electrification of the

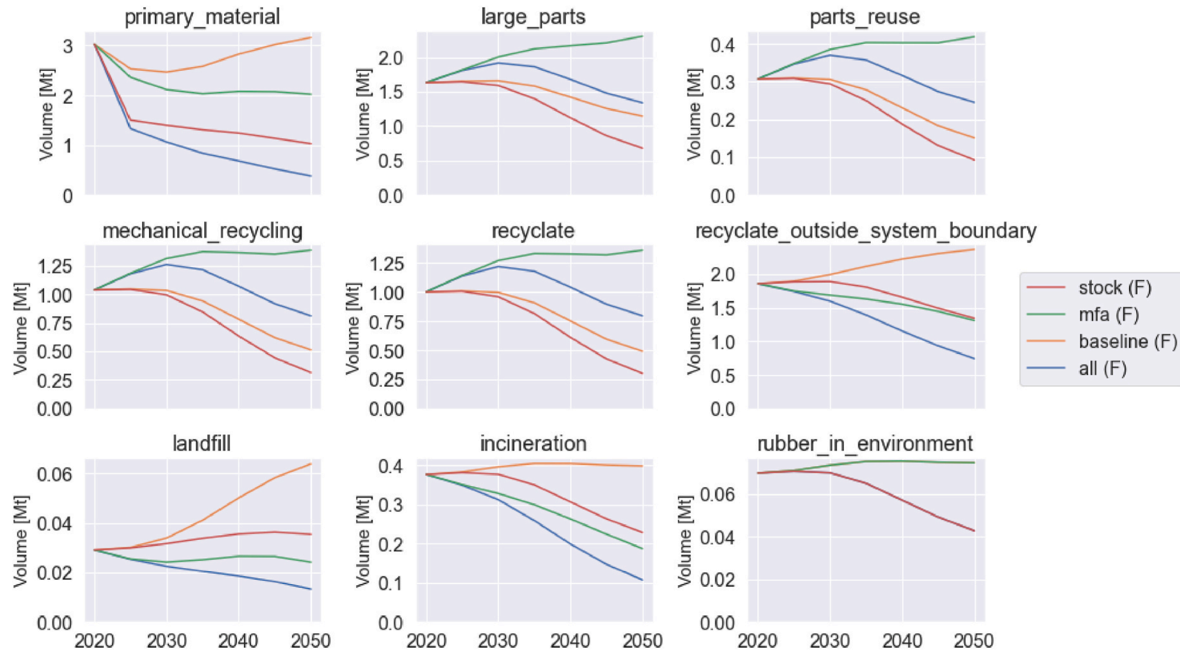

Fig. 3. Material volumes (in MT) of the automotive sector in Germany over time. The lines depict the volume per life cycle stage (Fig. 2) per intervention foreground scenario, including MFA (collection, sorting, recycling, dismantling, manufacturing) and Stock (Lifetime extension, demand, sharing). For rubber in environment, the 'stock' overlaps the 'all' intervention, whilst the 'MFA' overlaps the 'baseline' intervention.

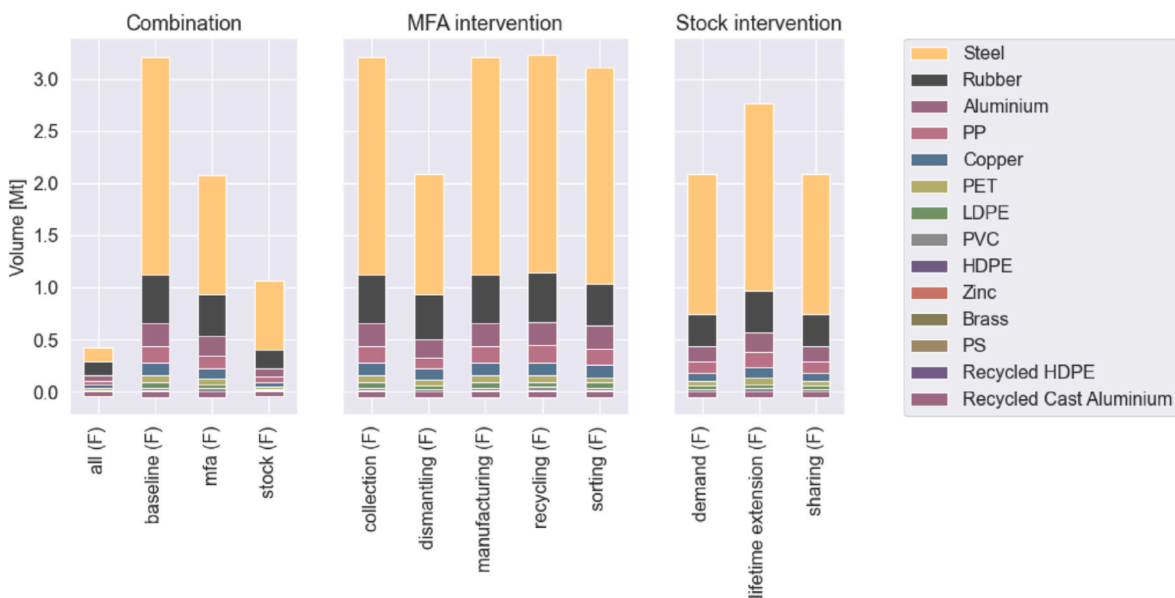

Fig. 4. Primary material volumes (in MT) required for the automotive sector in Germany in 2050 and material with all interventions (combined), MFA interventions (collection, sorting, recycling, dismantling, manufacturing) and Stock interventions (Lifetime extension, demand, sharing).

vehicle fleet. Such scenario studies with the CITS model will contribute to secure and resilient material supplies. Second, CITS highlights individual parts of the value chain which show the highest environmental impact or material losses, as well as potential technological bottlenecks along the value chain. For example, the automotive sector case study showed the increase in mechanical recycling capacity requirements under MFA mitigations. These mitigations and interventions are considered in the CITS model. Therefore, it is possible to assess the downstream or upstream effects in the value chain of policies and other changes in the system. Third, the CITS framework can estimate environmental impacts of a system across temporal and spatial scales. For example, the effect of a changing energy system in a region over time, which is included through a P-LCA approach, highlights the importance of renewable energy for CO_2 emission reduction in the automotive industry. And fourth, CITS can be used to identify trade-offs and synergies between different interventions and indicators, such as circularity and GHG emissions, or other environmental indicators. For example, without additional interventions, there is only a limited reduction in CO_2-eq emissions in the German automotive system until 2050, even though the passenger fleet will be fully electrified by then. Furthermore, the timing of different interventions can be highlighted. For the automotive sector, stock interventions were shown to me most effective on shorter timescales, between 2025 and 2030.

For policy recommendations, the CITS automotive case study

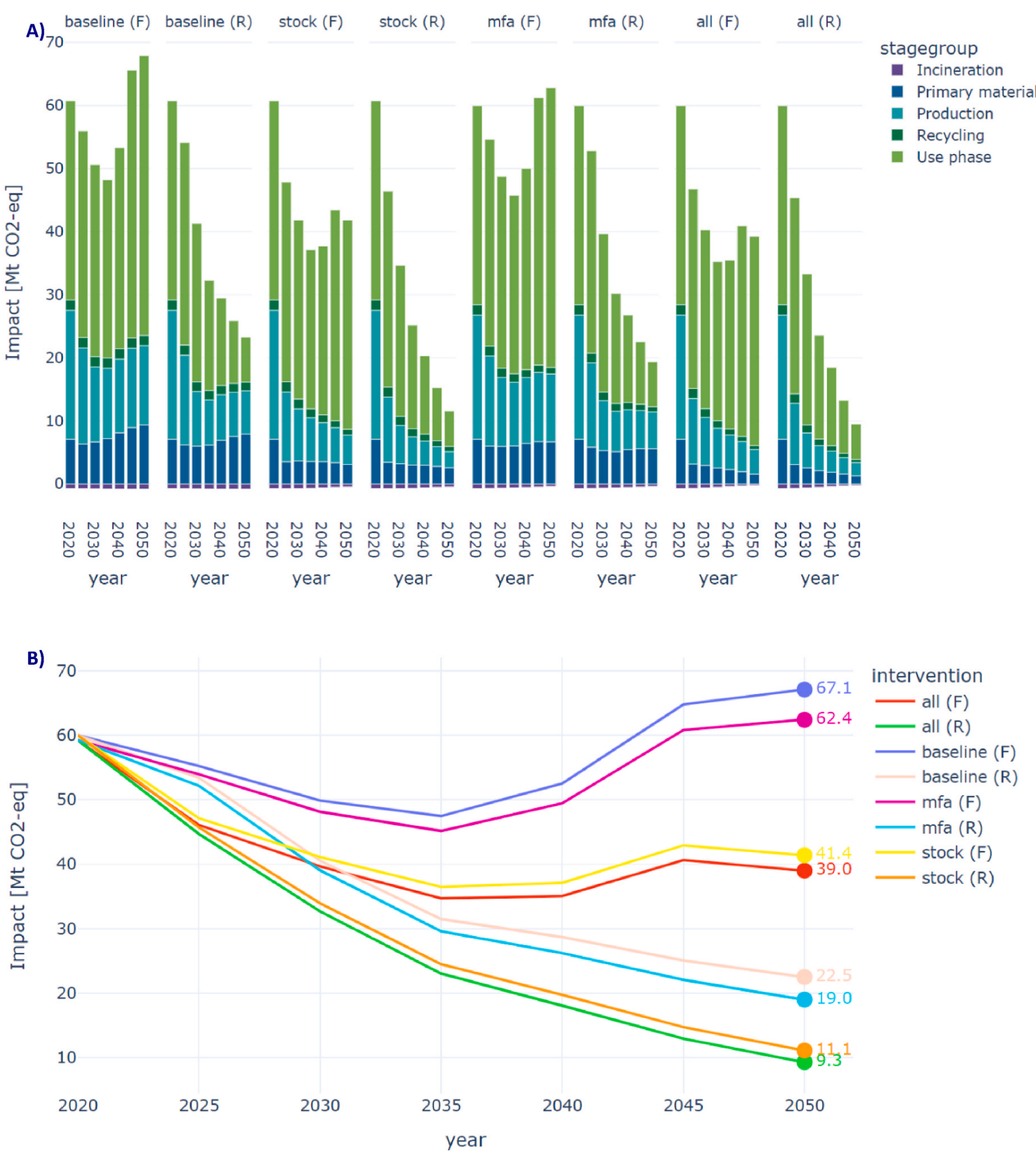

Fig. 5. CO_2-eq. emissions of the entire automotive sector in Germany, with the transition towards electric passenger vehicles in 2030. F depicts the prospective LCA scenario without climate policy interventions (SSP2-base), the R depicts the SSP2-RCP19 scenario. MFA interventions include collection, sorting, recycling, dismantling, manufacturing and Stock interventions include lifetime extension, demand, sharing. A) CO_2-eq. emissions per life cycle stage. B) total sector CO_2-eq. emissions over time.

emphasizes that a synergy between transformative climate policies and CE strategies is required to limit global warming. Most environmental impact is reduced when climate policies are aligned with circularity. From a system perspective, CE interventions affecting the stock (car fleet) are shown to be most effective in impact reduction in the short-term. Governments should increase the efforts to foster circular strategies such as demand reduction, e.g., via incentivizing shifts to public transport, whilst the industry could enhance car sharing models. Also, the importance of dismantling is a key strategy for primary material demand reduction. Through various dismantling practices, the quality of the material output from the system increases as materials are separated for reuse. To avoid an impact on virgin raw material, policies that encourage proper dismantling, are recommended.

5.2. Comparison to other studies

Multiple studies have modelled the automotive sector using LCAs without MFA contributions (Girardi et al., 2015; Kawamoto et al., 2019; Mehta et al., 2023; Wolfram et al., 2021). In these LCAs studies, it is often concluded that BEVs outperform ICE cars due to reduced CO_2 emissions during the use phase, depending mainly on electricity sources and mileage (Girardi et al., 2015; Kawamoto et al., 2019). However, on a system level the environmental impact assessment is more complex due to the transition towards BEV combined with stocks, as well as the temporal aspect regarding changes in the electricity mix. Several studies also show that the production phase highly influences the life cycle impact of BEVs (Helmers et al., 2017). Although Helmers et al. (2017) assume a renewable energy scenario for the use phase, there lacks a proper prospective assessment in the LCA for the production phase. This means that the impact from the production phase remains the same throughout the years and could therefore tremendously affect future renewable energy scenarios. In CITS, the P-LCA results in an impact reduction in production, end-of-life, and in the use phase. The difference is visible as the production phase only contributes 30% of total impacts in 2050 with climate policies in place and 20% without climate policy mitigations (Fig. 5). This highlights the importance of applying a P-LCA approach on impact results, as without, wrong conclusions can be drawn on dominant life cycle phases in the automotive value chain. Hence, the system perspective in the current study can give complementary input to individual LCA case studies.

The role of additional material efficiency strategies for passenger cars has been similarly assessed in LCA (Wolfram et al., 2021). Here, conclusions align with the CITS modelling framework where demand mitigations were an effective material efficiency strategy. Wolfram et al. calculate a reduction potential of 83% when all mitigations were applied (Wolfram et al., 2021). This result is slightly higher than the 80% reduction potential assessed with CITS in the current study.

Both Bobba et al. (2020) and Rossi et al. (2023) have combined MFA and LCA to assess the impact of batteries in the EU until 2050, which are part of BEV (Bobba et al., 2020; Rossi et al., 2023). Although the LCI scope is focused on critical raw materials in batteries, in contrast to bulk materials in CITS case study, both studies have similar findings to the current study. For example, climate mitigations will result in lower impact of electricity (Bobba et al., 2020). Additionally, recycling and manufacturing impacts decrease over time (Rossi et al., 2023). Furthermore, timing of policies is also a key element, where battery accumulation and recycling after 2044 can be a proper strategy for environmental impact reduction (Rossi et al., 2023).

A focus on single materials in multiple sectors and scenarios has been executed by Dong et al., 2022, where copper is the primary focus of the MFA and LCA integration (Dong et al., 2022). Conclusions from this study highlight the importance of waste prevention, reuse, and quality. Both Dong et al. (2022) and the current study highlight the importance of stock mitigations in impact and primary material requirement. For future comparisons and assessments, the flexibility of the CITS framework makes it applicable to critical raw materials or single material flows, or to assess other potential interventions and mitigations.

A similar system assessment of the automotive sector using both MFA and LCA has been conducted for China, albeit the study is scoped to the end of life and scrap prediction (Liu and Nowack, 2022). The study shows similar results compared to the current study in terms of material flows, now and in the future, where steel is the key material assessed. Liu and Nowack 2022 predict a peak in scrap material at end-of-life, around 2038, whereas the current study shows a peak at mechanical recycling volumes. Hence, Liu and Nowack (2022) show similar concerns for bottlenecks at end-of-life without mitigations (Liu and Nowack, 2022).

5.3. Limitations and future steps

With the modularity of the MFA and LCA, the CITS model is designed to be flexible and can be applied to specific products, materials, and to entire sectors, while covering different spatial and temporal scales. Additional to the case study on the German automotive sector in this article, CITS was applied to assess circular strategies for seven different packaging types in the Netherlands (Stegmann et al., 2024). Sectors that face high resource challenges and high emission mitigation potentials can benefit from the insights given by a modelling approach such as CITS. This includes the electronics sector, where critical raw materials are used in various components. Furthermore, sectors with long lasting products can benefit from the DSM and P-LCA modules, such as the building and construction sector. Thus, applying the CITS model to such sectors would support policy makers in guiding circular and sustainable transitions.

Unfortunately, complex models are data intensive, which means that the data availability and quality is key for reliable results of such system assessments. CITS requires data from stock, material flows and their impact which all need to be collected and assessed accordingly. Sourcing and collecting reliable data can become a bottleneck in the modelling process. Additionally, data sources that are available come with uncertainties resulting from data gaps and inconsistencies. For example, data collection methods can differ between countries, leading to inconsistencies even in, e.g., Eurostat, which is a key data source for this and other studies. Additionally, Eurostat, ACEA and ecoinvent datasets can include outdated information, which reduces the reliability of the data. Also, data uncertainties increase strongly when temporal and spatial scales are increased. For example, car types and corresponding material demand, maintenance and energy use may greatly vary, whilst the model assumed the use of an archetype car. That is why, product lifetime distribution is a key factor in stock modelling. For most products, only aggregated lifetime distribution data is available. Whereas the lifetime of products can vary substantially between regions due to varying usage patterns and maintenance practices. Variations in these data point can give additional uncertainties in the modelling results, of which the effect can be seen by the foreground scenario adaptations (e.g. longer lifetimes). Future modelling efforts will be undertaken to map these uncertainties and sensitivities as well. When specific data is missing, data gaps can be tackled by taking proxy data, such as data from similar countries or sectors for volumes, or by taking inventory data from similar processes. Using data ranges instead of data points for unknown data can also solve data issues and directly contribute sensitivity of the input data on the overall modelling results.

A key consideration in the future background scenarios as developed by IAMs and GDP projections is uncertainty. These models and their underlying predictions do not account for sudden geopolitical shifts or disruptive global events, such as the COVID-19 pandemic. Furthermore, changes in human behaviour, such as a shift from owning products to a sharing economy are not included in baseline projections, which could affect the projected consumption patterns, as depicted in the case study. At last, the model only includes technological improvements over time in a limited manner, which is used in the vehicle energy efficiency of BEV. However, technological developments over time can significantly affect environmental impacts (van der Hulst et al., 2020). Furthermore, technological breakthroughs can also result in complete transitions to different production systems, such as batteries with different compositions or novel recycling technologies. In further assessments, including novel chemical recycling technologies can improve end-of-life assumptions in the future (Schwarz et al., 2021). Moreover, the P-LCA module can be improved by developing scenarios that also include technological learning and industry improvements that go beyond changes in the energy mix.

Further development is required to improve the CITS model, including addressing the sensitivities and uncertainties described above. These can be tackled by running additional prospective scenarios and providing a comprehensive sensitivity analysis of the parameters involved to obtain the most impactful and uncertain variables. Fortunately, CITS allows such assessments due to its flexible and dynamic model system design. Data obtained from alternative sources, sectors and spatial scales can be used to assess different systems, such as alternative GDP projections, stocks, consumer behaviour elements and p-LCA background scenarios. However, providing the reliable data needed for such modelling requires coordinated and societal efforts. Policy can steer such efforts by enforcing open-source availability of data and providing data collection guidelines that ensure comparability between countries and regions and foster regular updates.

Finally, to make the model more applicable, its foreground scenarios can be aligned with existing policies and industry developments. This effort involves additional data collection, alignment, and key discussions with the respective government and industry experts. Next, additional indicators that are relevant for potential users of the model can be included which will allow a better basis for decision making. To obtain not only environmental but also an economic and social system perspective on transitions, such indicators can include costs and social impacts. At last, CITS will benefit from linking or exchanging information with other types of models. For example, to better include economic dynamics, the model can be linked to economic computable General Equilibrium models.

6. Conclusions

In this study, the CITS (Circular Industrial Transformation System) model was presented, which is a combination of DSM, MFA and P-LCA methods. CITS was developed to holistically assess the long-term environmental impacts of CE strategies in complex, dynamic systems. The model was applied to a case study of the German automotive sector and the transition towards BEV until 2050. The foreground scenarios included interventions to assess the effectiveness of increased circularity and climate mitigation strategies over time. The circularity of the modelled system was assessed, as well as individual product & material demand, annual production needs, material volumes along the value chain and waste generation over time. The impact assessment was used to assess the effect of circularity and climate policy interventions.

For long term impact reduction, the full electrification of the passenger vehicle fleet in combination with a renewable energy transition is the most effective strategy for reducing the global warming potential. However, CE mitigation strategies affecting vehicle stock (refuse, reduce or lifetime extension) are the most effective CO_2 emission reduction strategy in the short term (2025–2030), when the passenger fleet is still largely based on ICE cars and the energy mix dominated by fossil sources. Improving the end-of-life of vehicles through better collection, sorting, and recycling reduced emissions to a lesser extent but improved the circularity of the system. The transition to renewable electricity should be implemented in conjunction with the electrification of the automotive passenger fleet to reduce impacts. The results of the automotive case study align with traditional LCAs of automotive vehicles but highlight the importance of a prospective system perspective in the transition towards BEV and the potential of circular interventions.

The CITS model was developed as a flexible model to be applied on complex, dynamic systems, across different spatial and temporal scales. The case study results provided a holistic assessment of CE strategies for the German automotive industry, which included the development of a CE and electrification of the passenger fleet. Through that, the CITS model contributed to the integration of different scientific disciplines for addressing societal and environmental challenges. With further improvements, CITS could additionally address present uncertainties as well as indicators beyond environmental impact, such as costs and social indicators. Next to the automotive and packaging sector, the CITS model could guide the transition towards a circular, carbon neutral, and resilient industry in other sectors, such as electronics or building and construction.

CRediT authorship contribution statement

A.E. Schwarz: Writing – original draft, Data curation, Conceptualization. **S.M.C. Lensen:** Writing – original draft, Visualization, Software, Methodology. **S.D.M. Herlaar:** Writing – original draft, Software, Methodology. **T. van Harmelen:** Writing – review & editing, Supervision, Funding acquisition. **P.H. Stegmann:** Writing – original draft, Supervision, Funding acquisition, Conceptualization.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.144158.

Data availability

Data in supplementary information

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