Master Thesis

Comparison of Environmental Impacts of Global Rail and Road Freight Transport Under Prospective Scenarios

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Abstract

More than 6% of global carbon dioxide emissions are caused by freight transport by road dominating emissions from the freight transport sector. To keep climate targets in reach, a rapid decarbonisation is necessary, while holistically considering trade-offs with other environmental impacts. This study compares the environmental impact profiles of road freight transport to the alternative via rail, under different prospective scenarios for the transport fleets and the socio-economic landscape in 2050, using prospective Life Cycle Assessment (pLCA). To do so the database ecoinvent v3.9.1 is systematically modified according to scenarios of the Integrated Assessment Model (IAM) REMIND, using the Python library premise. The Life Cycle Impact Assessment (LCIA) is performed in ActivityBrowser (AB) using the impact assessment method Environmental Footprint (EF) v3.1. Results show that all environmental impacts categories across scenarios are significantly lower for rail than for road freight transport, due to the higher energy and material efficiencies of trains. Depending on the scenario and year, relative climate change impacts per tonne kilometre (tkm) by rail freight transport only make up between 15-26% of the impacts from road freight transport. Absolute climate change impacts can be reduced with a higher share of freight transport by rail, decreased absolute freight transport growth, and increased electrification of the vehicle fleets, while the later increases most impact category results if applied to lorries.

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1. Introduction

The transport sector is responsible for about 22% (8 Gt carbon dioxide (CO_2) in 2022) of global CO_2 emissions from energy combustion and industrial processes, with most emissions being caused by transport over land (IEA, 2023a). Almost 75% of global transport CO_2 emissions are caused by road transport (over 45% by passenger and over 29% by freight transport). Emissions from freight and passenger transport by rail only account for 1% of transport emissions (Ritchie & Roser, 2023), although 7% of global passenger kilometres (pkm) and 6% of global tkm are being transported via rail (IEA, 2023b). Globalised supply chains and increasing international trade push the demand of freight transport services (Ortiz-Ospina et al., 2023), while there is the simultaneous need to reduce emissions to limit global warming to 2°C, ideally 1.5°C. Therefore, the freight transport sector (especially land based transport) has to undergo a transition to reduce greenhouse gas (GHG) emissions (Shukla et al., 2022).

Such transition pathways are outlined by Shared Socioeconomic Pathways (SSP) presenting underlying scenario narratives. These transition pathways are dominated by a focus on GHG emissions, which is also reflected in IAMs which specify the energy-economy interactions for given scenarios. Additional environmental impact categories such as air pollution, land use or water use, were added to IAMs but they do still lack other important environmental indicators (Luderer et al., 2019). Furthermore, these models lack granularity to encompass full life cycle impacts, as they only focus on energy supply and demand, as well as agriculture and land use (Baumstark et al., 2021; Stehfest et al., 2014). This is problematic as a decarbonisation of transport technology shifts emissions to the supply chain processes of energy and material production (Sacchi et al., 2021). Additionally environmental impacts of transport vehicles can shift to non-climate change impact categories, as findings from the road passenger transport sector suggest (Dirnaichner et al., 2022).

Such shortcomings of IAMs can be addressed by introducing a Life Cycle Assessment (LCA) (Guinée et al., 2002; Heijungs et al., 1992) perspective. By nature, static and micro-orientated, LCA can be combined with IAMs to assess dynamic changes for a multitude of impact categories over time. This has been successfully demonstrated by numerous studies (Arvesen et al., 2018; Luderer et al., 2019; Mendoza Beltran et al., 2020; Tokimatsu et al., 2020). The combination of IAM and LCA allows for a standardised approach to pLCA to assess possible future environmental impacts (Van Der Giesen et al., 2020). Multiple projects aimed at creating prospective Life Cycle Inventories (pLCI) for pLCA applications, with premise currently presenting the state of the art model, that streamlines the generation of pLCIs (Sacchi et al., 2022), combining IAMs like IMAGE (PBL, 2021) and REMIND (Tino et al., 2023) with the LCI database ecoinvent (Wernet et al., 2016). This modification of databases to create pLCI databases is of high relevance as the background in LCA modelling majorly influences results (Mendoza Beltran et al., 2020).

From a comparative LCA perspective, rail freight transport has been proven to have lower environmental impacts than road freight transport (Nahlik et al., 2016; Negri et al., 2022; Spielmann & Scholz, 2005; Stodolsky et al., 1998), presenting an alternative to inland road freight transport. With new powertrains and traction options on the rise to decarbonise the sectors (Jaramillo et al., 2022), and environmental impacts likely shifting to upstream supply chains and non-climate change impact categories (Bauer et al., 2015; Hawkins et al., 2013; Kurada et al., 2023; Schulte & Ny, 2018), the need for a pLCA perspective comparing the transport modes is substantiated. Road transport (passenger and freight) has been subject to LCA using prospective scenarios in previous studies (Dirnaichner et al., 2022; Sacchi et al., 2021) although for freight transport technology specific comparisons were made without taking market process and vehicle fleet compositions into account. pLCAs of this type for rail are lacking entirely. Recent studies compared different freight railway traction types representing future technologies, assessing GHG emissions and energy requirements for a Tank-to-Wheel (TTW) scope (Aredah et al., 2024). Building on this, Kapetanović et al. (2024) conducted a Well-to-Wheel (WTW) assessment, for GHG emissions and energy use, with simple assumptions about future energy intensity of electricity mixes. A study by Logan et al. (2021) conducted a first prospective, comparative assessment of electric and hydrogen trains until 2050, but neglected other traction types, while also only focussing on energy and GHG, and a limited scope of the life-cycle. Therefore, this work will fill this knowledge gap, considering multiple technology types for rail and road, as well as their shares in the market for future scenarios, considering relevant scenario specific changes on the scale of the economy, and comparing road and rail freight along the full environmental profile also considering non-climate change impacts. The research aims at answering the following research question: What are the prospective environmental impacts and hotspots across the full life cycle of global rail freight transport in comparison to road freight transport in 2050? To answer this question, future rail freight transport LCIs are identified and implemented to the library premise. The streamlined generation of a pLCI is used to conduct a comparative, prospective assessment of road and rail freight transport under different prospective scenarios. The assessment is carried out in the open source LCA software Activity Browser (AB) (Steubing et al., 2020).

2. Methods

Figure 1 gives an overview of the research approach and the different research step numbers, each representing one of the following sub-chapters.

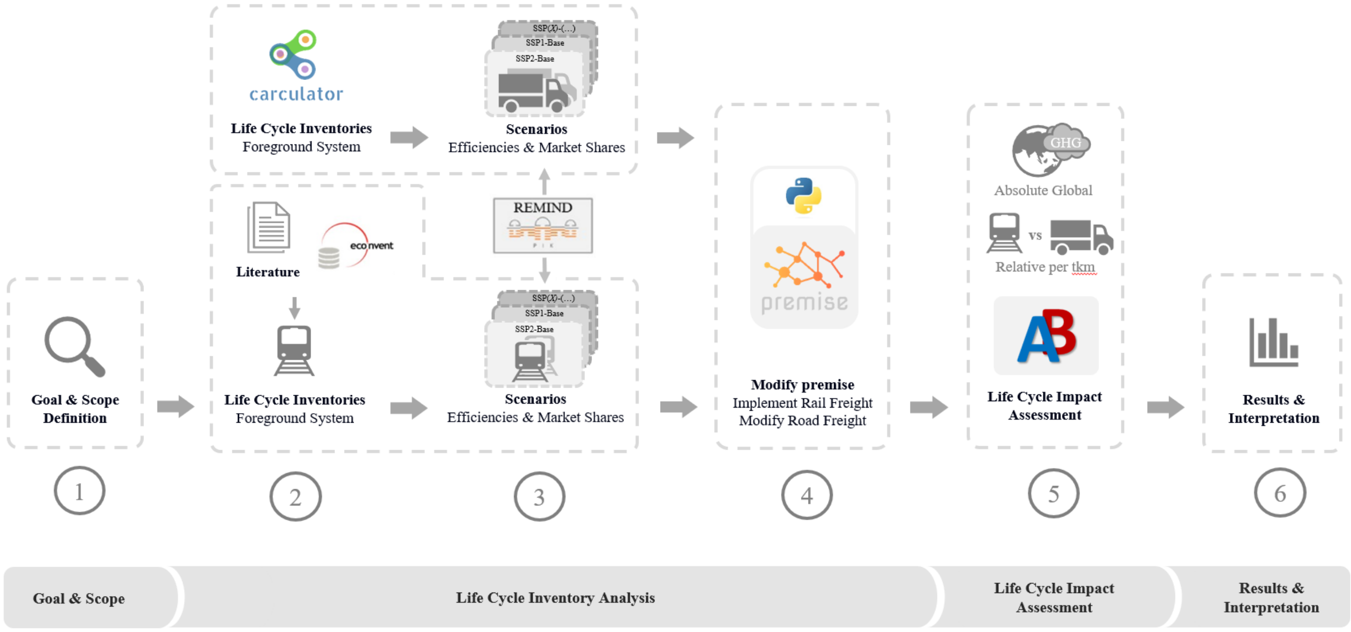

Figure 1: Overview of the research approach and steps taken to produce the results, categorised by the four LCA phases.

In the following the modes are referred to as both road freight transport for transport by *lorry*, and rail freight transport for transport by *train*, i.e., locomotives and goods wagons.

2.1. Goal & Scope Definition

This study compares prospective environmental impacts, hotspots, and shifts across impact categories of global freight transport for the modes of transportation via rail versus road. The attributional LCA takes a prospective approach with the reference year of 2050 under different selected scenarios, based on the projections of the IAM REMIND. The geographical coverage includes the 12 world regions (see supplementary material B) represented in the IAM REMIND (Baumstark et al., 2021). The applied economic system boundary is cradle-to-grave. The impact assessment method EF v3.1 alongside its characterisation methods (Andreasi et al., 2023) is chosen. Table 1 shows the function, functional unit (FU), alternatives, and reference flow definitions.

Table 1: Overview of the function, functional unit, as well as alternatives and their reference flow of the product systems.[1]

Function	Transportation of freight goods
Functional Unit	Transportation of one tonne of freight goods over the distance of one kilometre (1 tkm)
Alternatives	Freight goods transportation via road and rail
Reference Flow Alternative 1	Transportation of one tonne of freight goods over the distance of one kilometre (1 tkm) via train, i.e., locomotive and goods wagons on rail
Reference Flow Alternative 2	Transportation of one tonne of freight goods over the distance of one kilometre (1 tkm) via lorry on road

[1] The study acknowledges that constraints on comparability of the FU like costs, access to infrastructure between start and end point of the transport route and loading infrastructure and equipment, are not considered. Further information on limitations can be found in chapter 4.3.

The comparison of the two alternatives is based on global averages (world markets), while regional and technological differences in markets and their comparison are part of the further analysis of results. The technological coverage is interfered from the coverage of the IAM output of REMIND. It entails locomotives of the types diesel-electric internal combustion engine (ICE-de), catenary electric (CE), and hydrogen fuel cell electric (FCE) for rail transport, and lorries in the size 3.5t, 7.5t, 18t, 26t, and 40t for the technology type battery electric (BE), diesel internal combustion engine (ICE-d), hydrogen FCE, and compressed natural gas internal combustion engine (ICE-g) for road transport (Rottoli et al., 2021). The traction and powertrain types together make up a market process (technology mix per region per transport mode), which is determined by the scenario variables of REMIND. These markets form the basis of the LCA comparison. Impact results of these markets of current environmental impact profiles (year 2020) and prospective profiles in the reference year 2050 for different scenarios are compared to identify hotspots and development trends. The year 2050 is chosen as the Paris Agreement (PA) as well as multiple national polices specify climate targets in this time horizon (European Commission, Directorate-General for Climate Action, 2019; UNFCCC, 2015).

2.2. Life Cycle Inventories

This section 2.2 and the following section 2.3 represent the Life Cycle Inventory Analysis. For this study, inventories for rail freight transport are built using ecoinvent and literature. Inventories for road freight transport and component inventories for rail freight transport are imported from the tool carculator (Sacchi & Mutel, 2019), a Python based application to generate (prospective) life cycle inventories and assessments of road vehicles.

2.2.1. Inventory Modelling

For rail freight transport three traction types of locomotives are considered, based on the technological coverage of the REMIND scenarios. The three locomotives form transport processes which serve as an input to a market process, forming a rail freight transport market (for a specific region). The regional markets for all 12 REMIND regions make up the world market process, which serves as the basis for the comparison. Chapter 2.4 gives a detailed explanation of how market processes are built, as they are created through the modification of premise. The technology specific transport process LCIs on the other hand are created based on literature and ecoinvent, and then imported to premise to be modified and used for market processes. The same approach applies to road freight transport with the difference that technology and size specific inventories are directly imported from carculator to be used in premise. Figure 2 gives an overview of how the inventories for rail are built.

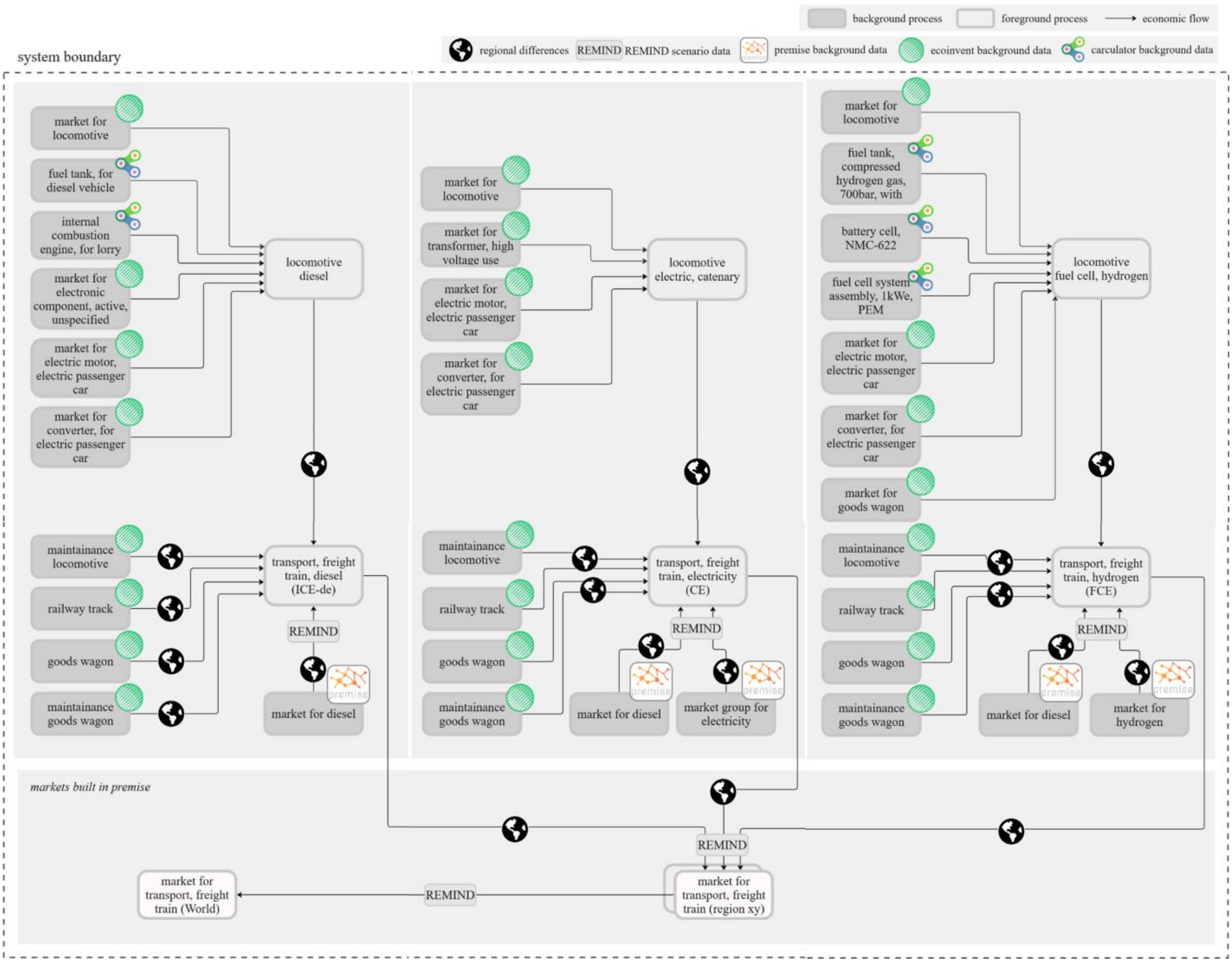

Figure 2: Simplified process flow charts of different locomotive traction types considered in the analysis and markets are built with these LCIs. Only economic flows are displayed. LCI data sources from ecoinvent (slightly modified by premise), carculator and premise (stark modification of once ecoinvent processes) are marked with icons. Whenever data differs per region, this is marked by the globe icon. Where flow quantities are determined by REMIND variables, this is marked by the REMIND icon.

CE and FCE locomotive inventories contain diesel consumption due to shunting processes. It is assumed that ICE-de locomotives will remain the main locomotive types used for shunting. Nevertheless, the market for diesel is subject to the scenario specific background modifications by premise and represents the fuel mix of diesel, biodiesel, and synthetic diesel. Some background inventory data is approximated using electrical components from passenger cars, as data availability on locomotive specific parts is low. Inventories are built for a selected year and scenario. To accomplish this, REMIND data quantifies the energy consumption and market shares for the year and scenario as marked with the REMIND icons in Figure 2 and further explained in chapter 2.4.

Road freight transport inventories are built with the same logic. Powertrain technology (BE, ICE-d, FCE, ICE-g) and lorry size (3.5t, 7.5t, 18t, 26t, and 40t) specific inventories are generated using carculator. These inventories then make up regional market processes which themselves are part of the global market process.

Unit process tables quantifying the economic and environmental flows of the LCI for the technology specific transport processes for newly created rail and via carculator produced road freight transport can be found in supplementary material A.

2.2.2. Data

Multiple data sources have been used to generate the rail freight transport inventories (see Figure 2). Locomotive inventories are built with the help of the locomotive LCI from ecoinvent. As material demand of locomotives in ecoinvent rely on the incomplete (without electronics) inventory of the CE locomotive Re460 (Frischknecht, Suter, et al., 1996), the inventory was adapted to represent material demand differences for the different traction types.

Traction equipment types and quantities were taken from product information of the supplier ABB, responsible for the traction in the Re460 locomotive (ABB, 2020). The corresponding traction equipment inventories are based on ecoinvent inventory and inventories from carculator. Freight transport inventory input quantities for ICE-de and CE traction types were based on ecoinvent inventories, whereas FCE powered rail transport inventories were built using a combination of ecoinvent and literature data. An exception to this is the quantification of the energy consumption as it relies on ecoinvent for inventories in 2020 but is modified using REMIND output data to account for efficiency adjustments in future scenarios. All background processes in darker grey (see Figure 2) are available in premise as a result of the combination of the ecoinvent database (version 3.9.1, allocation cut-off by classification), additional inventory datasets from literature and inventories from carculator. Those inventories representing the background are adjusted according to IAM projections if those sectors are covered by premise. Market shares that determine market process inventories are calculated using IAM data. Regional differences are based on regional ecoinvent datasets, as well as IAM data, e.g., for market shares per region.

Road freight transport inventories are based on the inventories built with carculator. Inventories for the technology and sizes of lorries mentioned are imported for the year 2020, using the long-haul driving cycle, representing a range autonomy of 800 km. Only EURO-VI emission standard lorries are used for fossil fuelled transport. Inventories for lorries (i.e., material used for manufacturing) are imported for the years 2020 until 2050 in 5 year steps, to account for material efficiency adjustments. See the documentation of Sacchi & Mutel (2024) for an overview of available modelling choices in carculator. For more detailed information on the respective LCIs and data sources used in this study refer to supplementary material A.

2.2.3. Cut-Offs

Table 2 gives an overview of cut-offs and indicates if they apply for rail or road inventories. If the mode is marked the cut-offs apply to all its different technology LCIs.

Table 2: Overview of process cut-offs for both rail and road inventories. (EoL = End-of-Life)

cut-off …	… for rail inventories	… for road inventories
auxiliar electronic equipment such as cooling units and other equipment nor directly used for traction	x	
small-sized electronic equipment such as cables, control units, displays, etc. [2]	x	
direct up-stream transportation (transport processes in-between background process to foreground process)	x	x
maintenance of electronic equipment and power electronics	x	x
energy required to replace components that reach their EoL before the vehicles EoL	x	x
logistic infrastructure (e.g., loading, storage, and distribution facilities)	x	x
energy and material consumption of supporting infrastructure like streetlights, sound barriers, traffic control rooms/buildings	x	x

The product systems do not produce co-products to other systems. The processes of the product systems are non-multifunctional, therefore no allocation or other method of dealing with multifunctionality is applicable.

2.3. Scenarios

The analysis is performed for a selection of scenarios. When conducting a pLCA it is important to take into consideration the scenarios of foreground and background systems (Arvidsson et al., 2018). The background is modelled with premise in accordance with the selected scenarios from the IAM REMIND. The foreground system is adjusted accordingly to adhere to these scenario consistent storylines as presented in the following.

[2] This is accounted for in road freight transport inventories only as an approximation, and not based on detailed data. As quantities are minor compared to overall material consumption of locomotives it is assumed that the exclusion of small electronic equipment will not affect the results in a major way.

2.3.1. Scenario selection

To cover a diverse range of prospective scenarios, five scenarios are applied to the foreground and background system. All of the scenarios are based on the SSP2 pathway, as it represents a middle-of -the-road development with intermediate socioeconomic challenges for adaptation and mitigation, based on the assumption that past trends and developments are likely to continue in the future (O'Neill et al., 2014; Riahi et al., 2017). The selected scenario differ in policy assumptions (Hilaire & Bertram, 2020) as presented in Table 3. The scenario policy assumptions applied to the SSP2 lead to a variety of technology mixes used to generate electricity or to satisfy the freight transport demand, while still being comparable based on common SSP2 assumptions (e.g., population and GDP growth). Differences in results using the SSP1 and SSP5 are discussed at the end of chapter 3.1.2.

Table 3: Qualitative description of SSP2 scenarios of the REMIND model used in the analysis. All global warming temperature increases refer to the end of the century.

SSP2-Base	**SSP2-NPi**	**SSP2-NDC**	**SSP2-PkBudg1150**	**SSP2-PkBudg500**
No specific climate policies are implemented, i.e., nations fail to address climate change. Resulting in approx. 3.3°C of global warming.	Intended Nationally Determined Contributions (INDC), i.e., national policies w/o the Paris Agreement, cut-off 2015, are met until 2030 and continuous efforts equivalent to the INDCs are made after 2030. Resulting in approx. 3.0°C of global warming.	National Determined Contributions (NDCs) are met until 2030 and continuous efforts equivalent to the NDCs are made after 2030. Resulting in approx. 2.2°C of global warming.	The climate target of limiting global warming to < 2.0°C is reached. Ambitious policies are implemented to stay within the carbon budget of 1150 Gt CO_2.	The climate target of limiting global warming to < 1.5°C is reached. Ambitious policies are implemented to stay within the carbon budget of 500 Gt CO_2.

2.3.2. Influence on Foreground System

The foreground system is affected by scenario specific data in two ways. First, the energy efficiency of the vehicles is influenced, decreasing the input energy consumed per tkm in the vehicle specific LCIs. Second, the market inventories are influenced, as the scenarios specify the market shares of technologies and regions. Material efficiency adjustments are not given by the IAM and therefore rely on scenario unspecific assumptions of carculator in the case of lorry inventories. Material usage of locomotive and goods wagon inventories is static for future scenarios as data availability for efficiency adjustments is low and material contributions to impact results is relatively low (see chapter 3). LCI inputs like material or energy demand quantities for manufacturing, maintenance, and end-of-life (EoL) are not subject to scenario specific adaptations. For more detailed information on foreground scenarios refer to supplementary material B.

2.3.3. Influence on Background System

The background system, representing energy, material, products, and services, is influenced by the IAM projections in multiple ways, adjusting efficiencies, market shares, emissions and introducing new technologies. The adaptation of the background system in line with the respective scenarios is streamlined in premise.

2.4. Modification of premise

The Python library premise transforms the LCI database ecoinvent based on projections by IAMs and generates pLCIs used as background data in pLCAs. For this study, the library was modified and extended to cover the land-based transport via road and rail, integrating this studies foreground system into the library. The created LCIs for rail (see chapter 2.2) are imported to be added to the ecoinvent database, alongside with road inventories from the application carculator. The final energy (FE) and energy service (ES) variable determine efficiencies of the transport technologies and allow market shares to be calculated. The LCIs are adjusted with the efficiencies taken from the IAM REMIND and additional market process are created. All process inventories are then added to a newly created pLCI database which allows for Life Cycle Impact Assessment (LCIA). Figure 3 shows the workflow of modifying LCIs with IAM outputs.

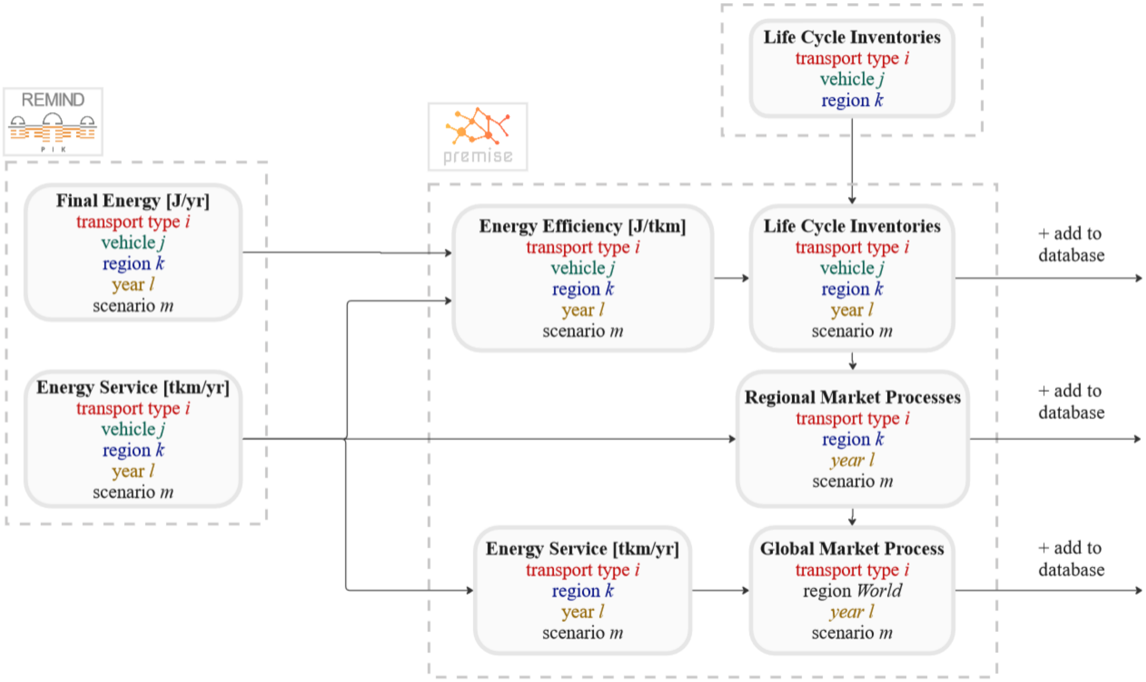

Figure 3: REMIND output and life cycle inventory utilisation and modification in premise. The REMIND output variables are imported and used to modify the imported inventories. The coloured variables show for which variable combination the new inventories are created.

For a detailed documentation of the code implementation refer to supplementary material C and the GitHub repository.

2.5. Life Cycle Impact Assessment

The LCIA is conducted for the current status quo with the reference year of 2020, as well as for the year 2050 for the selected scenarios. The SSP2-NPi case is used as the main reference scenario in 2050 as it represents a storyline in which states fall behind their NDC climate pledges but manage to achieve less ambitious national goals as the threat of climate change is acknowledged by governments around the world. To perform the LCIA, a superstructure database (Steubing & de Koning, 2021) containing multiple scenario LCI databases is exported to AB, a state-of-the-art LCA software capable of handling multi scenario analysis. The first part of the assessment compares relative impacts per tkm for both modes across the full environmental impact profiles and the selected scenario space. Additionally, implications of a 100% electrified lorry fleet in a scenario consistent with limiting global warming to 1.5°C are analysed and impact results compared to train options. The second part assesses the total global and regional climate change impacts by multiplying LCIA results from AB with variables of total tkm from REMIND, while taking into account the remaining carbon budget (Forster et al., 2024). LCA results can be found in step 6 “Results & Interpretation” in the next section 3.

3. Results

3.1. Relative Impacts

3.1.1. Status Quo and Future Impacts in the SSP2-NPi Scenario

The results show that impacts from rail freight transport are significantly lower than those of road freight, across all impact categories. Figure 4 gives an overview of the relative impact results, comparing road and rail freight transport for the current status quo in 2020 and a SSP2-NPi scenario in 2050.

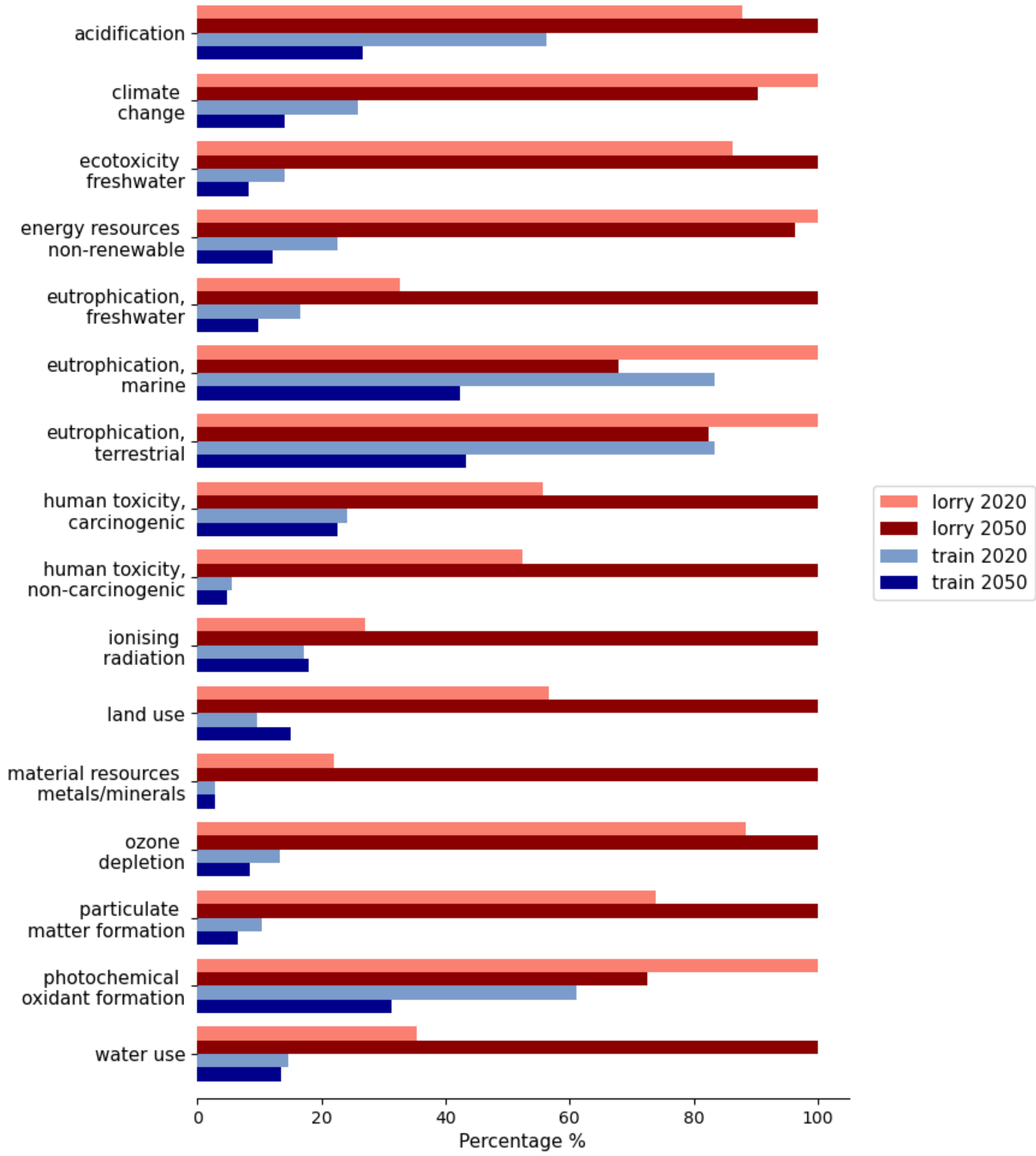

Figure 4: Environmental impact profile (EF v3.1) of the global average freight transport by lorry and by train, each for the year 2020 and 2050 under a SSP2-NPi scenario. Impacts per category are scaled to reference flow with the highest impact category result.

For freight transport by lorry, climate change impacts reduce from 2020 to 2050, with most other impacts increasing due to two reasons. First, the lorry fleet increases its share of BE vehicles from 0.2% to 26.1% which leads to higher impacts because of the significant higher material consumption, especially copper and gold in BE lorries compared to ICE-d lorries, due to the battery and the battery management system. This applies for the impact categories material resources (metals/minerals), human toxicity non-carcinogenic due to emissions from copper production and human toxicity carcinogenic due to emissions from waste treatment processes associated with material production. Furthermore, ozone depletion increases due to material production for power electronics, as well as acidification due to sulphur dioxide (SO_2) emissions from copper smelting using sulphide ore, and freshwater ecotoxicity due to sulfidic tailings from metal/mineral mining. Second, as the lorry fleet increases its share of BE vehicles, this leads to an increase in electricity consumption leading to higher impact results for water use due to cooling for nuclear power plants and water use in hydropower plants, land use due to biomass used for electricity generation, and ionising radiation due to nuclear power, as shares of nuclear, hydro, and biomass-based power increase in the electricity mix. Apart from climate change impacts, only four other impact categories show reduction for freight transport by lorry. Non-renewable energy resources because of reduced petroleum consumption for diesel production, terrestrial and marine eutrophication because of reduced nitrogen oxide (NO_x) emissions from diesel combustion, and photochemical oxidant formation impacts on human health mainly because of reduced NO_x and non-methane volatile organic compounds (NMVOC) from diesel combustion.

In contrast, impacts from freight transport by train tend to decrease as high efficiencies of CE locomotives only lead to small increases of electricity consumption per tkm in 2050. Electrification rates increase for the locomotive fleet from 39.6% to 57.0%. Therefore, impact categories associated with electricity consumption like ionising radiation impacts on human health, water use, and land use impacts only increase slightly. A switch from ICE-de to CE locomotives does not require more materials as CE locomotives do not rely on onboard energy storage, like the lorry counterpart, but use a catenary system for direct energy supply.[3] Furthermore, the usage of one or multiple locomotives in combination with multiple goods wagons, makes the train more material efficient per tkm, than the road alternative. Therefore, impact category results for human toxicity (carcinogenic and non-carcinogenic), ozone depletion and freshwater ecotoxicity are lower than 2020 levels, except for material resources (metals/minerals) as the decarbonisation of the energy supply advances and increasingly relies on metals and minerals for photovoltaic (PV) and wind power systems. With low contribution of material extraction and processing to impact categories like acidification, freshwater ecotoxicity or ozone depletion, these category results decrease because of lower petroleum extraction, processing, and consumption as well as less coal-based electricity in the grid. In contrast, in the case of transport by lorry decreased contributions from water discharge from petroleum, do not lead to decreased freshwater ecotoxicity impacts as impacts from sulfidic tailings from copper, gold, silver, and zinc-lead mines increase. Other impact categories that have previously been identified to be directly influenced by diesel consumption like marine and terrestrial eutrophication, and energy resources, decrease for trains because of the reduced diesel consumption due to the fleet electrification. This is also true for the impact category of acidification where main contributors are NO_x emissions from diesel combustion in the case of train transport in 2050, whereas impacts for lorries are dominated by sulphur dioxide (SO_2) emissions from copper mining and production, leading to NO_x only playing a minor role, while still emitting more NO_x than trains in absolute terms.

3.1.2. Climate Change Impacts Across Different SSP2 Scenarios

Looking at environmental impacts across different scenarios shows how foreground and background interact and how this influences results. Figure 5 and Figure 6 show a contribution analysis (summarised by reference products causing the impacts) for the impact category climate change for the global warming potential with a 100 year time horizon (GWP100) and how the fleet evolves under different scenarios, for lorries and trains.

[3] The catenary system is accounted for in the railway track construction, which is the same dataset used for ICE-de and CE trains. The catenary system showed to have minor contributions to impact results, therefore differences in railway tracks with and without catenary system have not been considered.

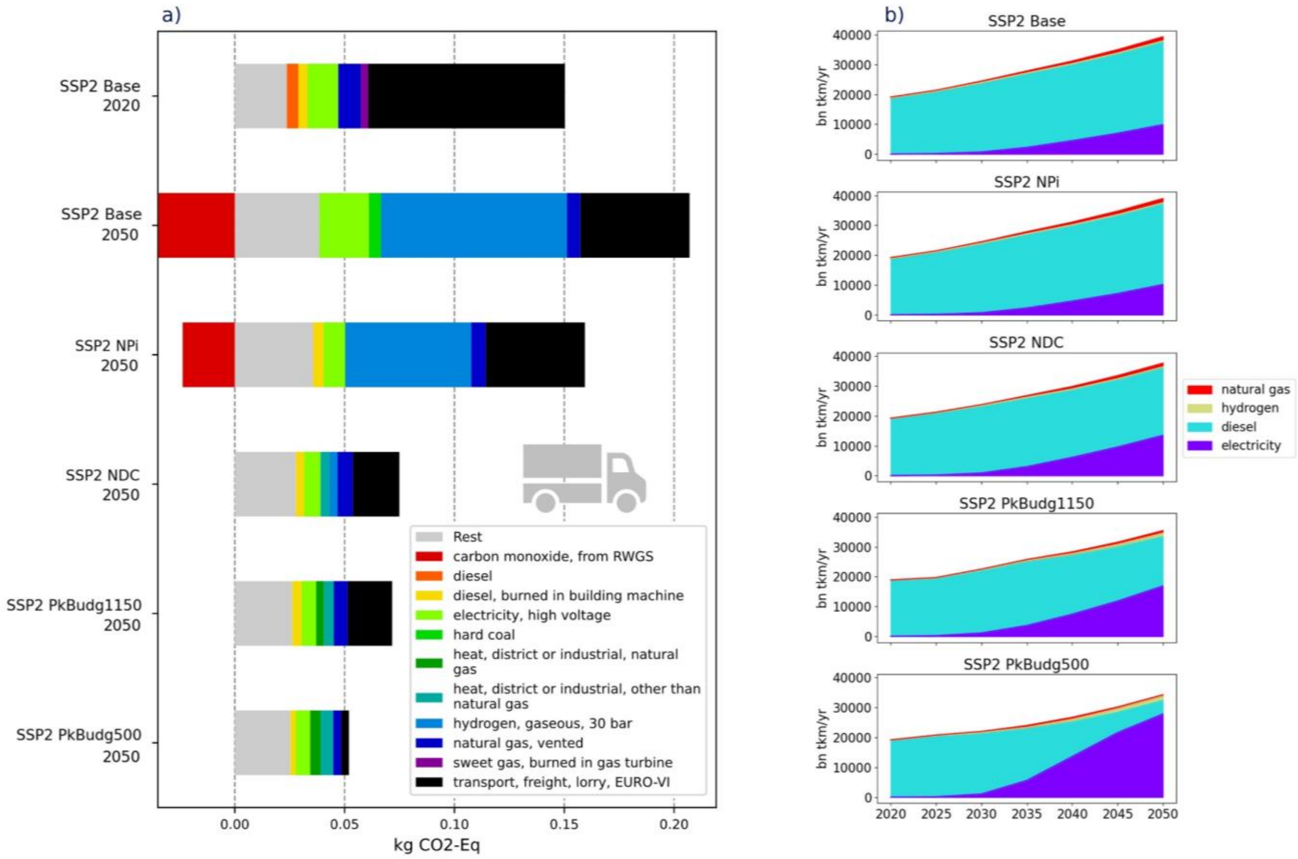

Figure 5: Results for the global average freight transport lorry fleet. a) Climate change impact (GWP100) results per one tkm in 2020 versus 2050, for selected SSP2 scenarios. Contributions are aggregated by the reference product. b) Fleet composition by fuel/energy carrier type from 2020 to 2050 for selected SSP2 scenarios, with the assumption of energy carrier to technology mapping of: natural gas = ICE-g, hydrogen = FCE, diesel = ICE-d, electricity = BE. Fleet tkm data is directly taken from REMIND (Tino et al., 2023).

As Figure 5 shows, positive climate change impact contributions for freight transport by lorry, increase in the SSP2-Base and -NPi scenario as the ICE-d lorry share in the fleet is still around 70% in both scenarios. The diesel market is composed of diesel from fossil oil based, biomass based, and synthetically produced diesel. Synthetic diesel is produced via Fischer-Tropsch (FT) process which uses hydrogen, gaseous, 30 bar, which in the case of SSP2-Base and -NPi is produced via coal gasification. This technology is primarily used by India, Sub-Saharan African states, and other Asian states (i.e., w/o China and Japan). The technology also has negative climate change impacts (in red in Figure 5) from the production of carbon monoxide, from reversed water-gas-shift reaction (RWGS), as CO_2 emissions from the coal gasification are used with hydrogen produced by coal gasification to produce syngas for the FT process. In the case of a SSP2-Base scenario this even leads to higher climate change impacts in 2050 compared to impacts in 2020. In other scenarios, climate change impacts drop as the vehicle fleet shows higher electrification rates, electricity production is less carbon intensive as renewable energy sources dominate the energy mix, and carbon capture and storage (CCS) technology is applied when producing diesel synthetically or from biomass sources. The fuel and electricity mix over time and per scenario can be found in supplementary material G.

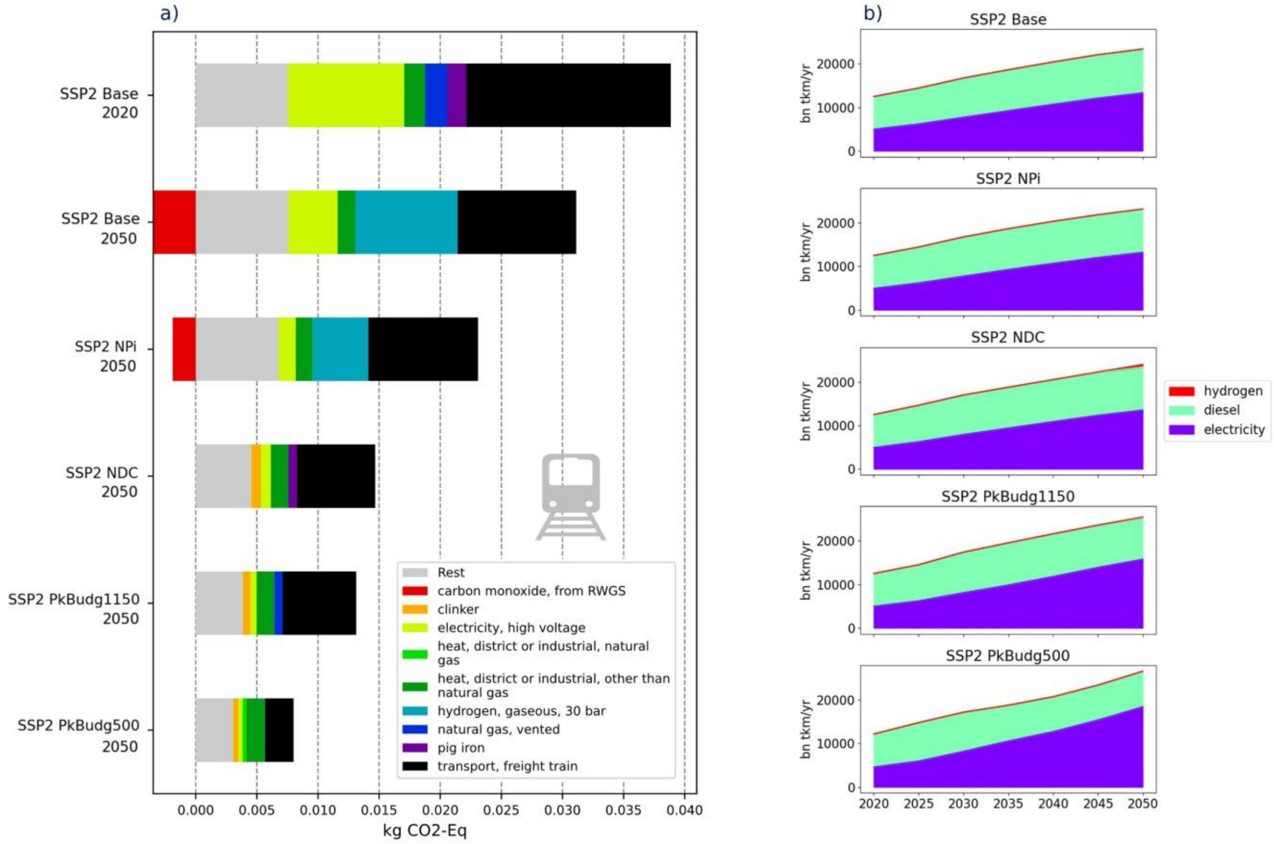

Figure 6: Results for the global average freight transport train fleet. a) Climate change impact (GWP100) results per one tkm in 2020 versus 2050, for selected SSP2 scenarios. Contributions are aggregated by the reference product. b) Fleet composition by fuel/energy carrier type from 2020 to 2050 for selected SSP2 scenarios, with the assumption of energy carrier to technology mapping of hydrogen = FCE, diesel = ICE-de, electric = CE. Fleet tkm data is directly taken from REMIND (Tino et al., 2023).

Figure 6 draws a similar picture for rail freight transport reducing impacts for more ambitious scenarios while showing similar contributions. A major difference to the lorry fleet is that the train fleet is electrified by almost 40% in 2020 already, with shares of CE locomotives rising for future scenarios. This reduces the dependence on diesel which reduces impact contributions associated with the production and combustion of diesel, especially synthetic diesel. In combination with a decarbonising electricity mix also under a SSP2-Base scenario with solar, wind, and hydro power being the main electricity generators, rail freight transport shows lower climate change impact results across all SSP2 scenarios.

No matter the scenario, freight transport by lorry shows significantly higher climate change impacts in the range of 0.05 to 0.20 kgCO_2-Eq per tkm, compared to those of freight transport by train in the range of 0.005 to 0.04 kg CO_2-Eq. The differences can be explained by the different efficiencies for lorries and trains. While the average ICE-de train only consume 52% of the diesel consumption of an ICE-d lorry (for the size of 40t, as this is the most energy efficient lorry size) required for one tkm, the CE train is even more efficient compared to its counterpart on the road, only using 41% of the electricity a BE lorry (40t) requires for one tkm. Please refer to supplementary material E for a detailed overview of efficiencies and energy consumption per mode.

This also leads to different direct contributions in vehicle specific inventories. For the average BE lorry in 2050 for a SSP2-PkBudg500 scenario electricity only contributes 5% (0.003 kg CO_2-Eq per tkm) of the climate change impact. Main contributors are the materials and energy used for the vehicle construction (50%), road construction and maintenance (22%), and charging infrastructure (16%) which make up a total contribution of 0.046 kg CO_2-Eq per tkm freight transport by lorry. On the other hand, main contributors of an exemplary CE train in 2050 in a SSP2-PkBudg500 are the railway track construction and maintenance (30%), maintenance of goods wagons (27%), construction of goods wagons (20%), and construction of locomotive (5%), which make up 0.006 kg CO_2-Eq per tkm, while energy makes up 18% (0.001 kg CO_2-Eq per tkm) of the climate change impact results. Comparable results show for diesel powered vehicles with slightly higher contributions from diesel combustion, lower contributions from materials in the case of transport by lorry, and higher overall impacts.

What has been previously analysed in chapter 3.1.1 for non-climate change impact categories, holds true for other scenarios as well. Figure 7 gives an overview of selected impact category results for each scenario. The full results in absolute terms can be found in supplementary material D.1.

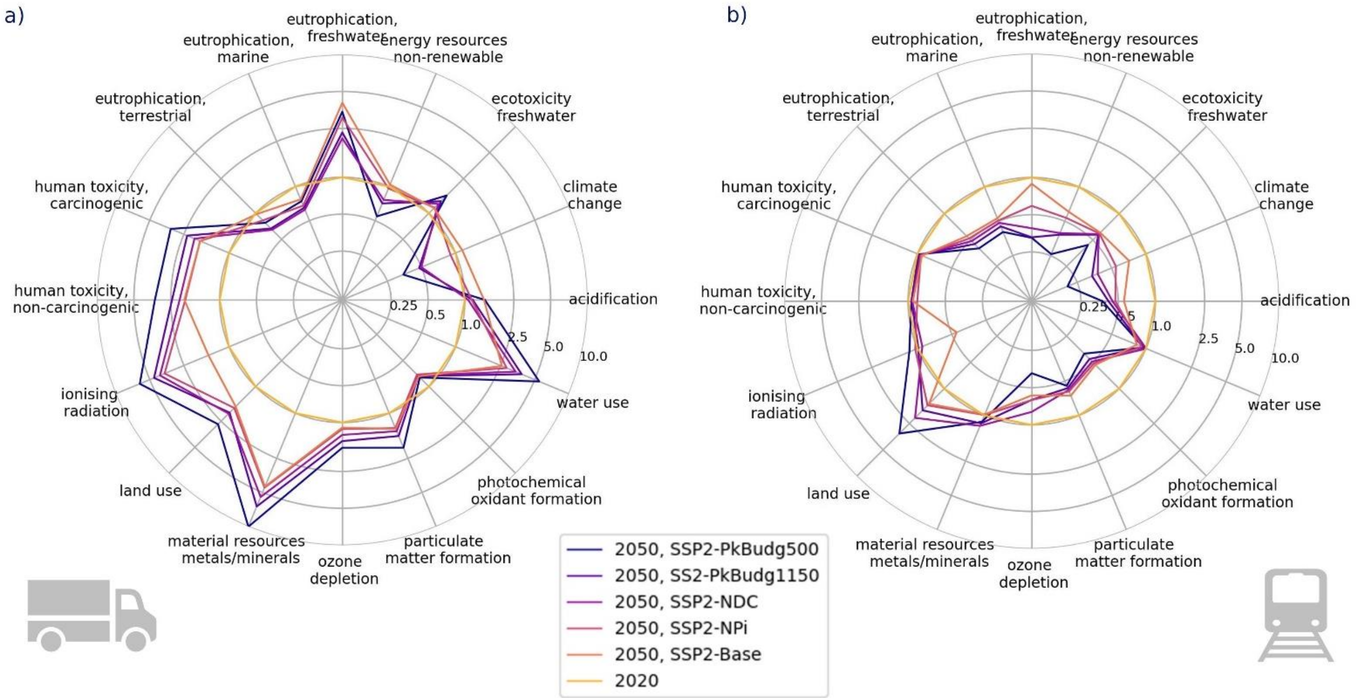

Figure 7: Selected impact category results from the environmental impact profile of EF v3.1, for global average freight transport by a) lorry and b) train for one tkm. All impact results are normalised to the status quo with the base year of 2020 for each mode respectively and represented on a base-10 logarithmic scale.

As the lorry fleet increases its share of BE vehicles in 2050 per scenario (from 25.1% in a SSP2-Base to 81.3% in a SSP2-PkBudg500 scenario) the impact categories for water use, land use and ionising radiation show higher results the higher the share of BE vehicles in the scenario. This is due to a decarbonisation of the electricity supply using more biomass, nuclear, solar, wind and hydropower. The increasing electrification also impacts the categories material resources (metals/minerals), human toxicity (non-carcinogenic and carcinogenic), ozone depletion, and freshwater ecotoxicity, because of increased material consumption as already mentioned in chapter 3.1.1. An exception to this is freshwater eutrophication as impacts are higher for an SSP2-Base and -NPi scenario compared to 2020 levels, due to the phosphate emissions from coal mining, as more than 1.2% of the electricity still comes from coal. As impacts from coal mining drop due to less coal-based electricity generation, total impacts start to rise again for the scenarios SSP2-NDC, -PkBudg1150 and -PkBudg500 due to higher mine tailing emissions from copper, gold, and silver.

In contrast, impacts from freight transport by train tend to decrease as an increase in electrification of the locomotive fleet does not come with an increase in material consumption of the foreground system. Therefore, impacts are increasingly dependent on the impacts of the electricity grid while the contribution of fossil fuel production and consumption decreases. Significant impact category result increases can only be observed for land use as biomass products from forestry are used for electricity production as well as biodiesel and synthetic diesel production. This is relevant across all scenarios as the electrification rate is 56.9% in a SSP2-Base case and only increases to 69.3% for a SSP2-PkBudg500 case.

Scenarios under different SSPs show equivalent results. SSP1 scenarios have higher electrification rates, while fleets for SSP5 scenarios rely primarily on diesel, except for the SSP5-PkBudg500. This influences impact category results similar to what has been described in this chapter, as electric vehicles are only deployed on large scale when the electricity supply shows advanced decarbonisation. Shares of trains or lorries powered by hydrogen are slightly higher in SSP5 scenarios compared to SSP1 and SSP2, but still insignificant. Exemplary LCIA results for SSP1 and SSP5 scenarios can be found in supplementary material D.3.

3.1.3. Implications of a Push for Road Electrification

To increase robustness of the results, a fictive case of a fully electrified lorry fleet in 2050 with a background system consistent with limiting global warming to 1.5°C (SSP2-PkBudg500 scenario) is compared against global average freight transport by train for the most pessimistic scenario of the SSP2 storyline, the SSP2-Base in 2050 taking the average fleet composition. Furthermore, a fictive 100% electrification of the train fleet in a SSP2-PkBudg500 scenario is compared against the electrified lorry fleet.

Climate change impacts for a fully electrified lorry fleet decrease to 0.052 kg CO_2-Eq per tkm in 2050 under a SSP2-PkBudg500 scenario, which is still 33.3% higher than impacts from train of 0.039 kg CO_2-Eq per tkm in 2020, while impacts decrease for the average train to 0.028 kg CO_2-Eq per tkm in 2050 in a SSP2-Base scenario. A fully electrified train fleet in a SSP2-PkBudg500 scenario would further decrease those impacts to 0.007 kgCO_2-Eq per tkm. These results also apply to other impact categories as every category result for the EF v3.1 impact method is higher for freight transport by lorry in 2050 (SSP2-PkBudg500), compared to freight transport by train in 2050 (SSP2-Base and SSP2-PkBudg500). A visualisation of the environmental profile comparison can be found in supplementary material F, with absolute numbers being displayed in supplementary material D.2.

3.2. Absolute Impacts

3.2.1. Global Climate Change Impact

As relative GHG emissions decrease across modes and scenarios (except for lorry in a SSP2-Base scenario), this is not the case for absolute impacts. Absolute climate change impacts increase in a SSP2-Base and -NPi scenario for both modes and increase for freight transport by lorry in a SSP2-NDC scenario. This is due to the background and the fleets still relying on fossil fuels for energy supply, as well as an almost doubling of freight transport demand. Figure 8 gives an overview of the development of yearly GHG emission and relative climate change impacts per tkm, as well as total tkm developments per mode and traction/powertrain type. For absolute numbers on yearly emissions per scenario and transport mode refer to supplementary material D.7.

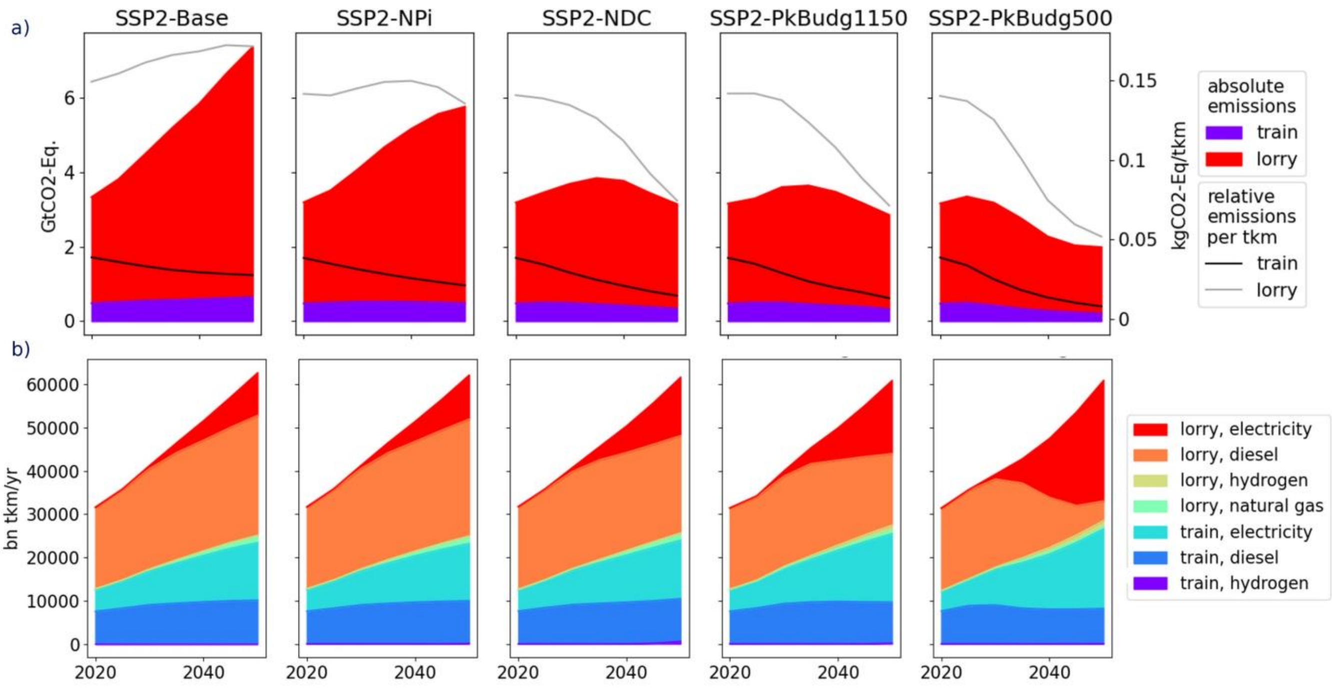

Figure 8: a) Development (2020-2050) of absolute global life cycle GHG emissions (primary y-axis) and relative global life cycle GHG emissions (secondary- y-axis) by freight transport by lorry and train for different SSP2 scenarios. b) Development of the total freight transport service (tkm) by lorry and train for different SSP2 scenarios. Fleet tkm data is directly taken from REMIND (Tino et al., 2023).

Table 4 shows the quantification of the changes in relative terms as emission reductions and freight transport tkm development for the different modes of transport.

Table 4: a) Development of global GHG emissions and global freight transport service in relative terms, comparing 2050 to 2020 across different SSP2 scenarios. b) Split between transport service (tonne kilometres) supplied by lorry and train in 2050 for different scenarios.

a) relative difference 2050 to 2020	**SSP2-Base**	**SSP2-NPi**	**SSP2-NDC**	**SSP2-PkBudg1150**	**SSP2-PkBudg500**
GHG emissions lorry & train	+121%	+80%	-2%	-10%	-37%
tonne kilometres lorry & train	+98%	+96%	+92%	+93%	+94%
GHG emissions lorry	+136%	+94%	+4%	-6%	-34%
tonne kilometres lorry	+106%	+103%	+96%	+87%	+79%
GHG emissions train	+33%	+2%	-29%	-31%	-55%
tonne kilometres train	+87%	+85%	+87%	+102%	+118%
b) shares in tonne kilometres in 2050					
lorry	63%	63%	62%	58%	56%
train	37%	37%	38%	42%	44%

In scenarios consistent with PA climate pledges (SSP2-NDC) and staying below 2°C (SSP2-PkBudg1150) and 1.5°C (SSP2-PkBudg500) of global warming, absolute GHG emissions drop for three reasons: 1) Relative GHG emissions per tkm decrease for both modes due to continuous electrification of the transport fleets and decarbonisation of the energy sector. 2) Total freight transport tkm amounts in 2050 are slightly lower than in the SSP2-Base and -NPi scenarios. 3) The share of freight transport by train increases. The shifting from road to rail freight transport effectively translates into absolute GHG emission reduction. This also show the results of a sensitivity analysis changing 10% of road freight transport to rail by 2050 for the SSP2-NPi scenario. This leads to climate change impact result reductions of -7.7% of emissions from both road and rail freight transport.

In a SSP2-NPi scenario, yearly cumulative emissions from 2020 until 2050 would use up 9.7% (lorry) and 1.2% (train) of the remaining global carbon budget identified by Forster et al. (2024), to limit warming to under 2°C. This could be reduced if countries fulfil their NDCs pledged under the PA to 7.4% (lorry) and 1.1% (train). These numbers are likely an overestimate as not all processes in the background are transformed by the IAM data. For a detailed overview with absolute numbers please refer to supplementary material H.

Trends and reasons for decreasing total climate change impacts hold true across other SSP storyline scenarios as well. Faster emission reductions occur in SSP1 scenarios where shares of rail freight and electrification rates are higher, and GHG emission intensity of electricity supply is lower. This is true vice versa for the SSP5 scenarios.

3.2.2. Regional Climate Change Impact

The following chapter presents regionalised climate change impact results for combined road and rail freight transport with direct, upstream, and downstream life cycle GHG emissions accounted for the region where the transport service is delivered. Figure 9 visualises the impact results for the current status quo in 2020 and exemplary for the year 2050 for the scenario SSP2-NPi and SSP2-PkBudg500. A quantification of GHG emissions development for all regions and all scenarios can be found in supplementary material D.8.

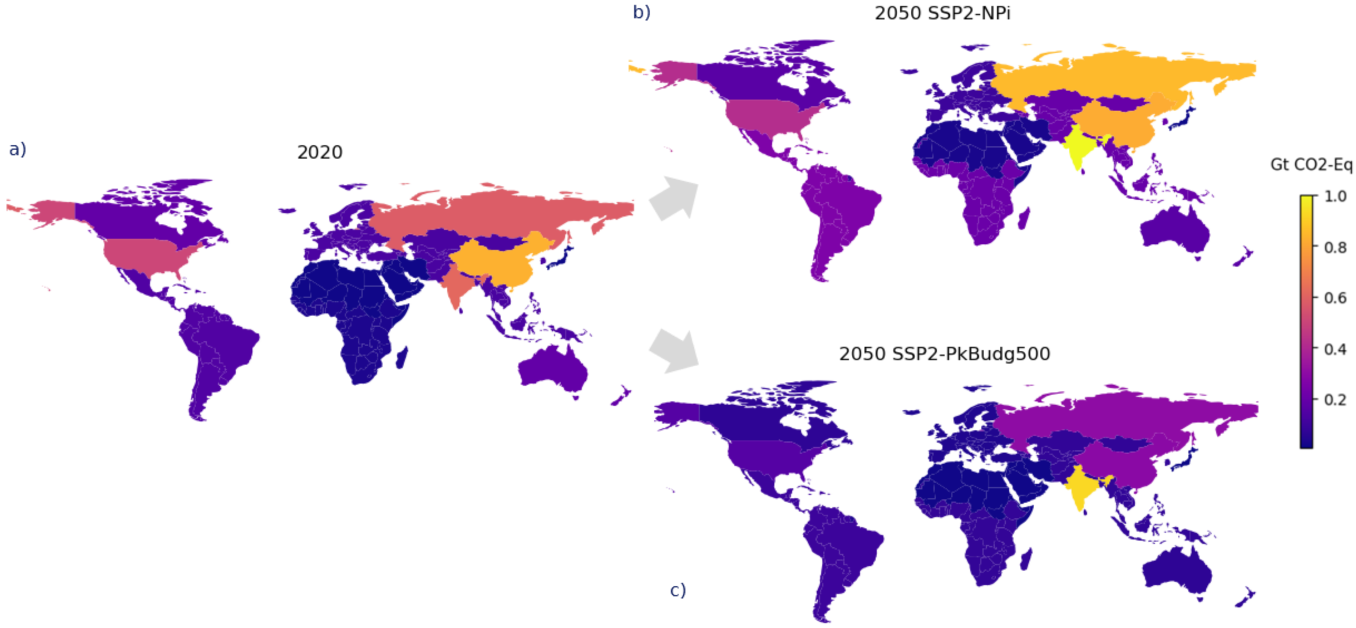

Figure 9: Regional distribution of total climate change impacts from freight transport by lorry, for the year 2020 (a) and 2050 under a SSP2-NPi (b) and -PkBudg500 (c) scenario. All GHG emissions, direct and upstream, are accounted to the region in which the transport service is demanded.

Major contributors are the region of India and China due to high absolute freight transport tkm numbers because of high population numbers, while being among the lowest freight transport tkm per capita consumers. This holds true across all scenarios and timeframes. Their absolute GHG emissions are higher for, e.g., the SSP2-NPi scenario with some decarbonisation of the background and electrification of the fleet, and lower for more optimistic scenarios like the SSP2-PkBudg500 for which the decarbonisation of the background is advanced and most of the fleet runs on electricity. Figure 10 shows the combined fleet development for the modes of road and rail for different powertrains and traction types, for the scenario SSP2-NPi and -PkBudg500.

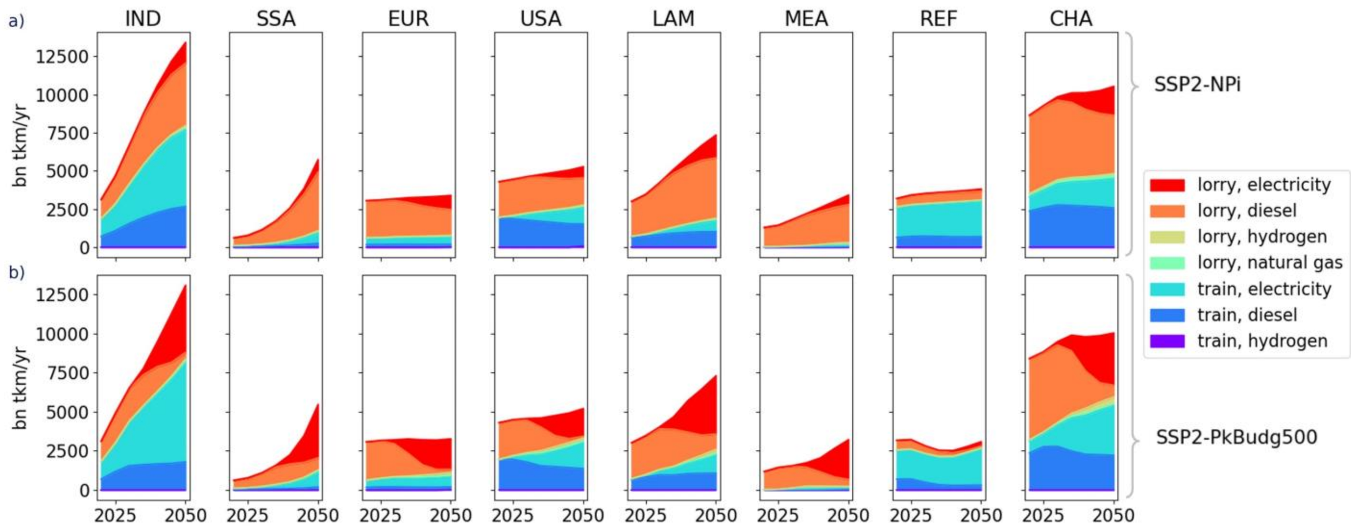

Figure 10: Development of total freight transport service in tkm, for freight transport by road and rail, differentiated by powertrain type, for multiple selected regions, a) for the scenario SSP2-NPi, b) and for the scenario SSP2-PkBudg500. (IND = India, SSA = Sub-Saharan Africa, EUR = Europe, USA = United States of America, LAM = Latin America, MEA = Middle East and Africa, REF = Russia, Eastern Europe, Former Soviet Union, CHA = China). Fleet tkm data is directly taken from REMIND (Tino et al., 2023).

India does not achieve absolute GHG emission reduction in nether of the scenarios as the mere increase in freight transport is too high to be counterbalanced by emission intensity reduction of the fleet or the background system. This even applies to the SSP2-PkBudg500 scenario where most freight tkm is delivered by train and both train and lorry fleets are predominantly electrified, which still leads to a 51% GHG emission increase compared to a 340% increase in the SSP2-NPi scenario. The only other region that does not manage to reduce its absolute climate change impacts across scenarios is Sub-Saharan Africa (SSA) as impacts even in a SSP2-PkBudg500 scenario increase by 106%, due to an increase in tkm mainly realised by road transport. China, the second biggest contributor in 2050 across scenarios, reduces its GHG emissions (e.g., by -2% in the SSP2-NPi and -51% in the SSP2-PkBudg500 scenario) due to the increased freight transport demand being mainly satisfied by rail freight and relatively high electrification rates of especially the lorry fleet even in the SSP2-NPi scenario. The relatively biggest climate impact result reductions occur in the region of Europe and the United States. Both manage to reduce their GHG emissions by -29% (EU) and -17% (USA) for the NPi, and -75% (EU) and -70% (USA) for the PkBudg500 scenario. This is accomplished through increasing the share of rail freight transport, while increasing absolute tkm service only slightly, as well as decreasing relative climate change impacts per tkm. Other regions like Latin America (LAM) and Middel East and Africa (MEA) only reduce absolute climate change impacts in more optimistic scenarios, as their freight transport demand increase is satisfied by road freight primarily. An exception to this is the region of Russia, Eastern Europe, and Former Soviet Union countries (REF), as its main mode of freight transport are electrified railways already in 2020. REF only manages to reduce absolute climate change impacts in optimistic scenarios as the electricity mix does not decarbonise fast enough in scenarios like the SSP2-NPi, to counterbalance the slight increase in total freight transport tkm.

4. Discussion

4.1. Key Findings

4.1.1. Relative Impact Comparison

The results show that freight transport by train is less environmentally harming than by lorry. This holds true for all impact categories, and all considered scenarios. Even a 100% electrified lorry fleet with a decarbonised electricity mix and background system (in line with limiting global warming to 1.5°C) performs worse in nearly every impact category including climate change, compared to the current global average freight transport by train. Even though relative climate change impacts reduce with increased electrification of the lorry fleet and the decarbonisation of the energy supply, impacts are still more than 500% higher than for rail freight transport across scenarios. This is due to freight train transport operating approximately with a twice as high energy efficiency, leading to lower environmental impacts for trains compared to lorries. Efficiency assumptions have been found consistent with literature with efficiency differences even higher than values used in this study (Frischknecht, Bollens, et al., 1996; Tolliver et al., 2013; Wernet et al., 2016) The stark increase of electrification and therefore electricity consumption for the lorry fleet across scenarios, leads to increased impact category results of ionising radiation, water use and land use due to more nuclear, hydro, and biomass-based power for electricity generation. The impact results for these categories are far lower for trains because of their higher efficiency and a less aggressive electrification of the fleet. Other impact categories for road freight transport also increase with higher electrification rates because of the material consumption (mainly copper, gold, and silver) of the energy onboard storage of BE lorries. This applies to the impact categories of human toxicity, freshwater eutrophication, freshwater ecotoxicity, acidification and ozone depletion. These impact categories do not increase or even decrease for trains, as CE trains rely on a catenary system instead of onboard energy storage and material efficiency per tkm is high due to the usage of locomotives with multiple goods wagons attached. Impact category results that decrease for both modes across scenarios due to less vehicles operating on fossil fuel, are those related to emissions from fossil fuel combustion like climate change, terrestrial and marine eutrophication, and those related to fossil fuel extraction like non-renewable energy resources. Absolute impact results in these categories are higher for lorries than trains due to the higher energy efficiency of the locomotives. A sensitivity analysis on energy and material efficiency parameters was conducted and showed that uncertainties in those parameters do not affect the overall conclusion from the results. Please refer to supplementary material D.5 and D.6 for sensitivity analysis results.

4.1.1. Absolute Impact Development

Relative climate change impacts per tkm can be reduced over time but this does not hold true for absolute impacts across scenarios. Because of the stark increase in driven freight transport tkm for road and rail together (+96% in the SSP2-NPi scenario), relative impact reductions are not enough to counterbalance the increase in total freight transported, increasing absolute impacts by +80%. This leads to a depletion of the current carbon budget (50% likelihood to stay under 2°C global warming) by almost 12% for a SSP2-NPi scenario considering both modes of freight transport. In scenario projections that rely on relatively higher increase of the share of freight transport by rail, higher electrification rates in the vehicle fleets and high rates of decarbonisation of the background, absolute climate change impacts form road and rail together decrease by -2% (SSP2-NDC), -10% (SSP2-PkBudg1150) and -37% (SSP2-PkBudg500). Contributions to global climate change impacts differ per region, as it was found that biggest polluters are India and China. India does not manage to reduce absolute climate change impacts because of their stark increase in total tkm, whereas China reduces absolute climate change impacts already in a SSP2-NPi scenario through moderate freight service tkm increase while simultaneously increasing rail freight transport shares, as well as electric vehicle shares in both rail and road fleets, and gradually decarbonising the energy supply. These findings are consistent across regions and scenarios suggesting that absolute climate change impacts decrease only in the combination of moderate, limited or no freight transport service tkm growth, increasing rail freight transport shares, electrification of the transport fleets and decarbonisation of the energy supply. While this is true for climate change impacts, other impact categories can increase significantly due to increase road freight electrification and a changing background. To limit all environmental impacts from road and rail freight transport it is essential to limit the growth of absolute tkm and shift to rail freight transport. A potential decrease of global road freight demand and shift to rail of 10% of road freight transport service tkm can already reduce environmental impacts by almost 8%, with multiple co-benefits for other impact categories.

It should be noted that there is an ongoing discussion if scenario assumptions of IAMs like REMIND for ambitious climate targets are feasible or even realistic, as they rely on negative carbon technology, i.e., CCS and carbon capture and usage (CCU), as well as stark energy efficiency increases for technologies, and high renewable energy deployment rates (Keyßer & Lenzen, 2021; Li et al., 2023). This further strengthens the argument that a modal shift from road to rail and a decrease in freight transport growth is essential in decreasing environmental impacts, as this reduces dependencies on economy wide efficiency increases, and renewable energy and carbon capture technology deployment.

4.2. Comparison to Literature

LCIA results of this studies for road and rail freight transport are in line with results obtained by using ecoinvent LCIs (ecoinvent, 2024) and ecoinvent's supporting literature (Frischknecht, Bollens, et al., 1996; Spielmann & Scholz, 2005) for the base year 2020. Studies comparing ICE-d and BE road vehicles suggest similar findings with environmental profiles depending on the background and/or scenario, especially for BE vehicles. They generally find relatively higher impact category results for BE compared to ICE-d vehicles, similar to those that have been identified to increase in this research (Bauer et al., 2015; Kurada et al., 2023; Schulte & Ny, 2018; van den Oever et al., 2023). Studies on prospective impacts of (freight) transport by road or rail are limited. Sacchi et al. (2021) introduced carculator in a study using the SSP2-Base scenario to calculate prospective impact results. Results are consistent with baseline levels in 2020 for long haul lorry inventories but deviate for prospective scenarios, as the study focuses on Europe as a region and adjusts efficiencies of diesel lorries by introducing hybridisation to align emission levels with European legislation requirements.

4.3. Limitations and Future Research

This section discusses limitations that stem from modelling choices and data availability. First, inventories for freight transport do not include the refrigerated transport of goods, as REMIND does not include variables on refrigerated transport. A consideration of the cooling chain might lead to higher results, especially in those categories impacted by the emissions of refrigerant gases, like ozone depletion and non-carcinogenic human toxicity. As this would apply to both modes of transport it is not expected to influence their ranking with respect to the impact categories considered. Second, material efficiency adjustments are only considered for lorry inventories without considering infrastructure for both modes, locomotives, and goods wagons. Furthermore, regional differences in infrastructure are not considered for freight transport by lorry. As materials for locomotives and goods wagons have minor contributions for most impact categories and differences between regional infrastructure are insignificant, the influence on the results is deemed minor. Third, battery types and battery EoL processes are static in the model. This means no other batteries than NMC-622 (60% nickel, 20% manganese, 20% cobalt) are considered for BE lorries and batteries are not recycled at their EoL. Making this dynamic in scenarios would impact results for the BE lorry. It should also be noted that modelling limitations from data sources such as ecoinvent and carculator also apply to this research.

Fourth, the impact assessment method EF v3.1 is not adapted for prospective scenarios. Impact category calculations are based on current knowledge, e.g., for currently known ultimate resources to calculate abiotic depletion potential (ADP) for the impact category material resources (metals/minerals) or currently known environmental thresholds to calculate accumulated exceedance (AE) for acidification or terrestrial eutrophication. It should also be mentioned that toxicity impact categories and indicators have high uncertainties already in non-prospective assessments (Fantke et al., 2018; Gust et al., 2016). Furthermore, premise adjusts processes' GHG emissions and energy expenditure. Other environmentally relevant process emissions often lack representation in future scenarios. For example, specific regulations concerning mining practices and the handling of tailings may arise in the future. This could reduce impacts from road freight transport as BE lorries rely heavily on mining processes to supply the material need of batteries.

Fifth, it is implicitly assumed that road and rail freight transport compete in all contexts. The analysis does not consider the existing availability of infrastructure, i.e., roads and railways for specific routes. One or the other mode might not be applicable for a specific route, thus, the alternative cannot be considered. Furthermore, the environmental assessment does not include infrastructure necessary to realise intermodal freight transport, like ports or stations that transfer goods from one mode to the other, which might be necessary to realise transport for certain routes.

These limitations should be addressed in future research for case studies for specific routes, as the selection of transport mode depends on the actual route when optimising for the lowest environmental impacts (Ingrao et al., 2021). Furthermore, the impacts of BE lorries depend on range autonomy (Sacchi et al., 2021), which might be lower in specific cases than the long haul range autonomy of 800 kilometres assumed in this work. Future studies should also consider other modes of transport, e.g., via waterways and integrate those into the intermodal comparison. Furthermore, the current approach should be applied to scenarios from different IAMs to consider a broad range of scenario-specific modelling choices and identify hotspots. Additionally, future work in premise should cover more sectors and processes to be modified for future scenarios, like mineral/metal extraction and refining processes as well as battery EoL management.

5. Conclusion

This study compared prospective environmental profiles for global road and rail freight transport using pLCA. It did so by modelling and combining LCI data, with prospective scenarios from the IAM REMIND for a SSP2 socioeconomic storyline with different policy scenarios from no climate specific policy interventions (SSP2-Base) to climate policies consistent with complying with INDCs (SSP2-NPi) or NDCs (SSP2-NDC), to those consistent with staying below 2.0°C (SSP2-PkBudg1150) and 1.5°C (SSP2-PkBudg500) of global warming. To combine both data sources the Python library premise, a tool to streamline the creation of pLCI databases consistent with IAM scenarios, was modified to reflect changes in the foreground and background system. Considering previously discussed limitations, the following tendencies could be identified:

- No matter the foreground (fleet composition and vehicle efficiencies) and the background (e.g., energy mix, material supply) development for different scenarios, rail freight transport showed climate change impacts only 10-25% of those from road freight as well as lower impact results across all other impact categories. This is due to the higher energy and material efficiency of trains compared to lorries.
- Even a fully electrified lorry fleet with an energy supply consistent with staying under 1.5°C of global warming has higher climate change impact results than the current rail freight transport with the reference year 2020.
- Relative climate change impact results per tkm for lorry and train decrease until 2050 for all scenarios (except SSP2-Base in the case of lorry) as the background decarbonises and fleets are increasingly electrified. Absolute impacts on the other hand rise for a SSP2-Base and -NPi scenario, as freight transport service tkm increase. Scenarios that show absolute climate change impact reductions achieve this via electrification of the transport fleet, decarbonisation of the energy supply, and higher shares of freight transport demand satisfied by rail transport.
- Environmental impacts shift across impact categories. As reduced diesel combustion leads to reduced carbon, NO_x and NMVOC emissions, impact category results for climate change, terrestrial and marine eutrophication, and photochemical oxidant formation decrease for both modes of transport. Impact category results of ionising radiation and land use increase for both modes, as the electricity mix uses more nuclear and biomass energy. For freight transport by lorry, impact categories of material resources depletion, human toxicity (carcinogenic and non-carcinogenic), ozone depletion, acidification and ecotoxicity (freshwater) increase due to the material consumption of BE lorries and their onboard energy storage system. Such stark increases do not hold true or are even reversed for freight transport by train, as locomotives do not rely on onboard energy storage for CE locomotives and are more material efficient due to being able to carry multiple lorries loads with one locomotive and additional goods wagons.

These findings suggest that a successful reduction of environmental impacts including non-climate change impact categories for freight transport (considering the modes of road and rail only), imply 1) a switch from road to rail wherever possible, 2) a reduction of freight transport demand increase, 3) and an increase in electric vehicles in the train fleets with an electricity supply based on renewables. Increasing electrification for the lorry fleet would decrease climate change impacts at the cost of increasing multiple other impact category results due to high material and electricity consumption of BE lorries. Future research should focus on including other modes like freight transport by water to comprehensively assess different alternatives and determine environmentally friendliest freight transport options based on case specific routes, while including impacts from ports and terminals used to transfer goods between modes.

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Supplementary Material

A – Life Cycle Inventories of Rail Freight Transport

Please refer to the document "lci-rail-freight.xlsx" and "lci-trucks_NEW.xlsx" available on the GitHub repository, for rail and for road transport. Market processes are formed in premise itself as described in chapter 2.4. Therefore, these are not part of the unit process tables.

B – Freight Transport Foreground Scenarios

To adequately represent foreground system changes in transport in accordance with the selected scenario for the background system, the technological efficiency of the traction/powertrain type is adjusted to the scenario. This is achieved through keeping the energy carrier input per tkm of transport as a variable that is calculated, as shown in equation 1:

$$consumption_i \left(\frac{MJ}{tkm}\right) = \frac{final\ energy\ consumption_i\ (\frac{MJ}{year})}{energy\ service_i\ (\frac{tkm}{year})} \tag{1}$$

Final energy consumption and energy service are common output variables of IAMs. The index (i) indicates the type of transport vehicle for either rail or road. From the IAM REMIND the following output variables of transport types were used (see **Error! Reference source not found.**).

Table 5: Output variable granularity of the IAM REMIND for land-based transport (equivalent to the index i in equation 1). Source: REMIND output file for premise (Sacchi et al., 2018/2023), to be decrypted with decryption key, available upon request.

Transport|Freight|Road|Truck (0-3.5t)|Electricity	Transport|Freight|Rail|Electricity
Transport|Freight|Road|Truck (0-3.5t)|Gases	Transport|Freight|Rail|Liquids
Transport|Freight|Road|Truck (0-3.5t)|Hydrogen	Transport|Freight|Rail|Liquids|Hydrogen
Transport|Freight|Road|Truck (0-3.5t)|Liquids	
Transport|Freight|Road|Truck (7.5t)|Electricity	
Transport|Freight|Road|Truck (7.5t)|Gases	
Transport|Freight|Road|Truck (7.5t)|Hydrogen	
Transport|Freight|Road|Truck (7.5t)|Liquids	
Transport|Freight|Road|Truck (18t)|Electricity	
Transport|Freight|Road|Truck (18t)|Gases	
Transport|Freight|Road|Truck (18t)|Hydrogen	
Transport|Freight|Road|Truck (18t)|Liquids	
Transport|Freight|Road|Truck (26t)|Electricity	
Transport|Freight|Road|Truck (26t)|Gases	
Transport|Freight|Road|Truck (26t)|Hydrogen	
Transport|Freight|Road|Truck (26t)|Liquids	
Transport|Freight|Road|Truck (40t)|Electricity	
Transport|Freight|Road|Truck (40t)|Gases	
Transport|Freight|Road|Truck (40t)|Hydrogen	
Transport|Freight|Road|Truck (40t)|Liquids	

The index i in equation 1 represents each type. Per type both final energy consumption and energy service (transported tkm) variables are available per year. The consumption is calculated per type, for a given year and scenario, and adjusted in the LCI of the respective transport type. Liquids in the case of not being further specified, refer to diesel consumption from fossil sources or biomass. As the inventories consume diesel from a market process, the share of biodiesel and fossil fuel diesel is determined by the market process already implemented in premise. The implementation into premise can be found in the script `transport_new.py` in the function `adjust_transport_efficiency()` on GitHub.

Furthermore, market processes are created representing average fleets of freight transport processes in the IAM regions. The regional coverage of the IAM REMIND is presented in **Error! Reference source not found.**.

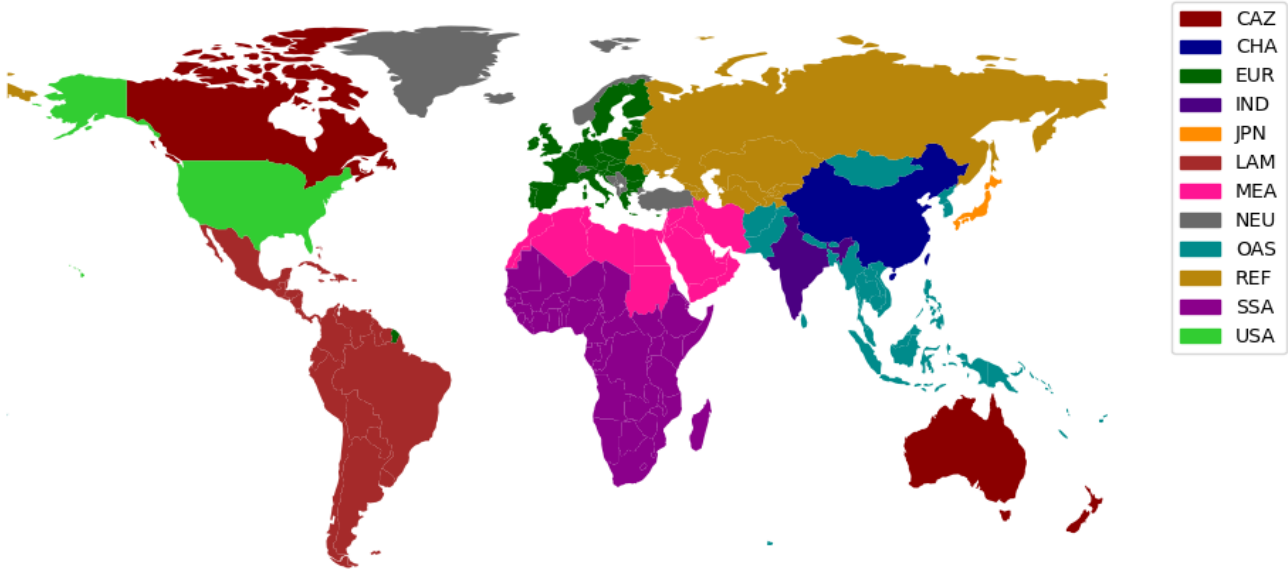

Figure 11: Regional definitions of the REMIND model. Own visualisation based on (Baumstark et al., 2021).

Per mode of transport (rail and road) and for each of the twelve world regions an average fleet market process is created. This is achieved by summing up all energy service variables for a region per mode of transport and dividing the service variable per type (i) by this sum (see equation 2).

$$(share\ of\ market\ in\ region\ X)_i = \frac{(energy\ service\ in\ region\ X)_i}{\sum(energy\ service\ in\ region\ X)_i} \qquad (2)$$

The share per type (i) is multiplied with the reference product of the market output, i.e., one tkm, to get the supply of type (i) to the regional market. Once all markets are built the world market is created using the same logic. The sum of energy service per mode of transport per region is divided by the global energy service per mode of transport, to get the share of each region of the global market process. The shares are then multiplied with the reference product amount (1 tkm) to calculate the input number of each region to the global dataset. The implementation into premise can be found in the script `transport_new.py` in the function `generate_transport_markets()` on GitHub.

C – Modification of the Library *premise*

Error! Reference source not found. gives an overview of the main modifications in *premise*. All files can be found on the GitHub repository of the author.

Table 6: Overview of the main modifications in premise

Modification	File	Description
additional LCI creation	lci-rail-freight.xlsx lci-trucks_NEW.xlsx	Newly created inventories for rail freight, and adjusted inventories from *carculator* for road freight are created.
additional LCI imports and updated update_transport function	new_database.py	Additional LCIs for rail and road freight transport are imported and added to the database. The update function for transport is added.
IAM data collection	data_collection.py	Market shares and efficiencies for rail and road freight transport variables are extracted from the REMIND output files.
IAM data collection variables	transport_roadfreight_variables.yaml transport_railfreight_variables.yaml	The .yaml files specify the variables to be retrieved from the REMIND output files.
new update function freight transport	transport_new.py	When creating a new database via *premise* the update_transport function can be called to adjust the freight transport relevant LCIs to the REMIND projection. The main purpose of this function is to… • create freight transport datasets for all IAM regions, based on additional LCI imports, • adjust energy and material efficiencies, • generate regional and global transport markets, • generate truck size specific fleet markets for road freight transport.
additional variable mapping	vehicles_map_NEW.yaml	This .yaml file contains mapping between different transport related variables to be used in the transport_new.py script.

D – Life Cycle Impact Analysis

Please refer to the document "LCIA_results.xlsx" with the following sheets:

- **D.1**: Absolute and relative impact results for all impact categories of the impact method EF v3.1, for freight transport by lorry and by train for the base case SSP2-Base 2020, and the scenarios SSP2-NPi, SSP2-NDC, SSP2-PkBudg1150. SSP2-PkBudg500 for the year 2050.
- **D.2**: Absolute and relative impact results for all impact categories of the impact method EF v3.1, for freight transport by a fictive 100% electrified lorry fleet in 2050 for the SSP2-PkBudg500 scenario and by train for the base case SSP2-Base 2020, and the scenario SSP2-Base for the year 2050.
- **D.3**: Absolute and relative impact results for all impact categories of the impact method EF v3.1, for freight transport by lorry and by train for the scenarios SSP1-Base, SSP2-Base, and SSP5-Base, SSP1-PkBudg500, SSP2-PkBudg500, and SSP5-PkBudg500. The scenarios represent the extreme cases of the respective storyline to analyse results under significant different assumptions.
- **D.4**: Absolute and relative impact results for all impact categories of the impact method EF v3.1, for freight transport by lorry and by train per technology type (lorry, only for size 40t: ICE-d, BE, FCE, ICE-g; train: ICE-de, CE, FCE), for the scenarios SSP2-NPi and SSP2-PkBudg500.
- **D.5**: Sensitivity analysis on energy efficiency parameters (+-10%) presenting absolute and relative impact results for all impact categories of the impact method EF v3.1, for freight transport by lorry and by train.
- **D.6**: Sensitivity analysis on material efficiency parameters (+-10%) presenting absolute and relative impact results for all impact categories of the impact method EF v3.1, for freight transport by lorry.

- **D.7**: Absolute global GHG emissions development per year for a global scope, for train and lorry freight transport, under different scenarios.
- **D.8**: Absolute regional GHG emission development considering freight transport by lorry and train together, under different scenarios.

E – Efficiency Comparison Lorry vs Train

The efficiencies are specific to the region of Europe, but the order of magnitude also applies to all other regions. Region specific efficiencies inventories can be examined by creating a database using the modified premise repository on GitHub.

Table 7: Efficiency comparison for freight transport by lorry and by train (both electric and diesel) for the current status quo and for the SSP2-NPi scenario (representative for other scenarios) and the region Europe (representative for other regions).

	2020	**2050** SSP2-NPi	relative efficiency increase	efficiency differences in 2050 train relative to lorry
l/tkm				
lorry, diesel	0.0204	0.0203	0.5%	
train, diesel	0.0107	0.0105	1.9%	51.7%
kWh/tkm				
lorry, electric	0.1570	0.1151	26.7%	
train, electric	0.0478	0.0467	2.3%	40.6%

Even though only a representative selection for one scenario and one region is displayed in the table, the order of magnitude is similar for other scenarios and regions.

F – Fictive 100% Electrified Lorry Fleet vs Average Train Fleet

Error! Reference source not found. shows the relative results of the environmental impact profiles comparing a 100% electrified lorry fleet in a SSP2-PkBudg500 scenario to the average train fleet in a SSP2-Base scenario.

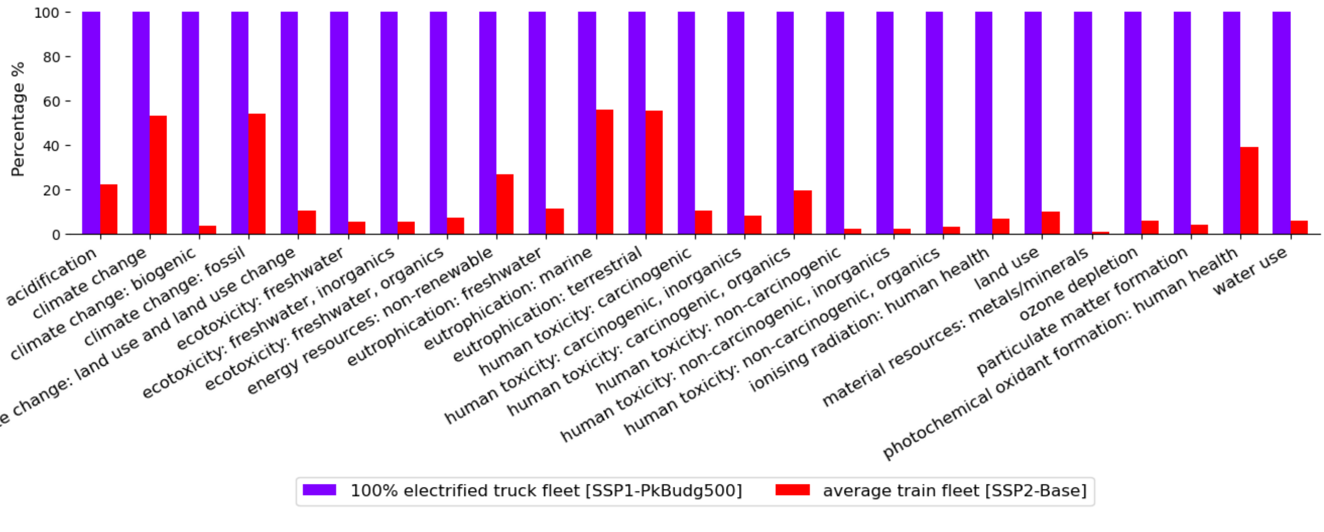

Figure 12: Comparison of selected impact category results for a fictive 100% electrified truck fleet with a SSP1-PkBudg500 background, versus an average train fleet under the SSP2-Base scenario. The global averages are compared and scaled to a 100% per impact category for the electrified truck fleet.

Detailed numbers can be found in supplementary material D.2.

G – Energy-Mixes and GHG Emissions Under Different SSP2 Scenarios

Error! Reference source not found. describes the development of the electricity mix under different SSP2 scenarios from the year 2020 until 2050.

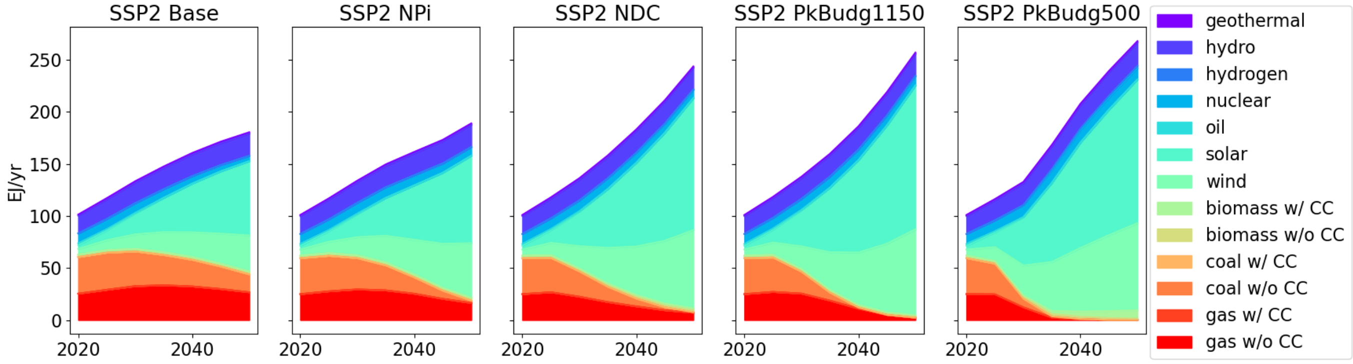

Figure 13: Secondary energy, electricity mixes under different scenarios for the years 2020 until 2050. Fleet tkm data is directly taken from REMIND (Tino et al., 2023).

Error! Reference source not found. describes the development of the diesel mix under different SSP2 scenarios from the year 2020 until 2050.

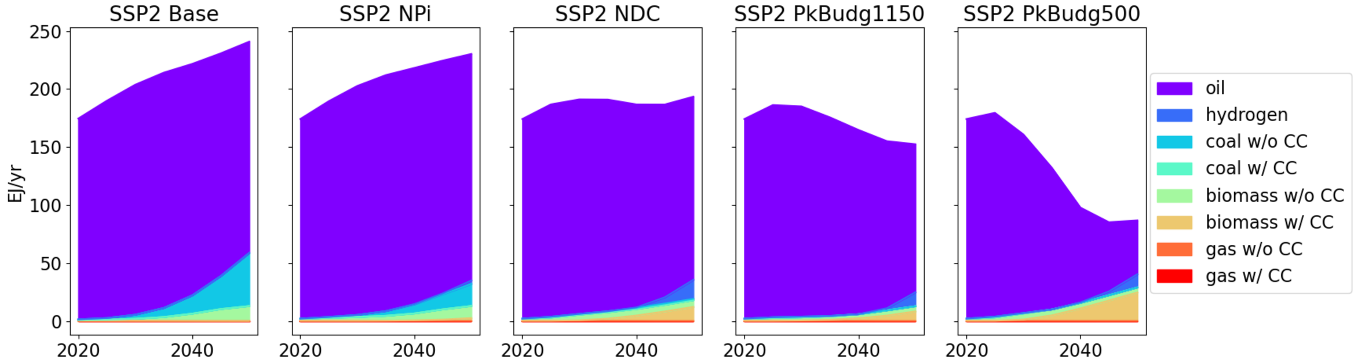

Figure 14: Secondary energy, liquids mix (i.e. diesel fuel) under different scenarios for the year 2020 until 2050. Fleet tkm data is directly taken from REMIND (Tino et al., 2023).

Error! Reference source not found. describes the development of the total global GHG emissions per sector under different SSP2 scenarios from the year 2020 until 2050.

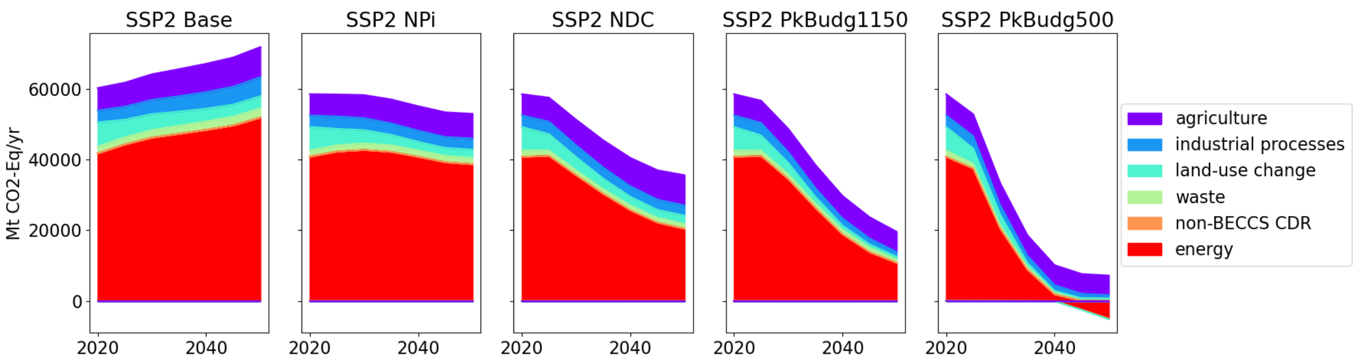

Figure 15: GHG emissions per sector, under different scenarios for the year 2020 until 2050. Fleet tkm data is directly taken from REMIND (Tino et al., 2023).

H – Carbon Budget Calculations

Error! Reference source not found. gives an overview of the cumulative life cycle GHG emissions and usage of carbon budget.

Table 8: Cumulative GHG emissions and shares of carbon budget for the global life cycle climate change impacts caused by freight transport by lorry and train.

	Cumulative GHG emissions 2024 -2050 $GtCO_2$-Eq	**% of carbon budget <1.5°C warming 2024 until 2100 50% likelihood**	**% of carbon budget <2.0°C warming 2024 until 2100 50% likelihood**
SSP2-Base lorry	144.4	36.1%	11.1%
SSP2-Base train	17.8	4.4%	1.4%
SSP2-NPi lorry	114.9	76.6 %	10.4 %
SSP2-NPi train	13.9	9.3 %	1.3 %
SSP2-NDC lorry	85.1	56.7%	7.7%
SSP2-NDC train	11.9	8.0%	1.1%
SSP2-PkBudg1150 lorry	90.2	22.6%	6.9%
SSP2-PkBudg1150 train	13.9	3.5%	1.1%
SSP2-PkBudg500 lorry	72.6	18.2%	5.6%
SSP2-PkBudg500 train	11.0	2.8%	0.8%