Electronic supplementary information

The challenge of an EU Light-Duty Road Passenger Transport Sector within Planetary Boundaries

Fabian Lechtenberg[a,*], Jorge Jaime Gata-Cuesta[a,*], Ángel Galán-Martín[b], Richard Cabrera-Jiménez[a], Gonzalo Guillén-Gosálbez[a,**]

[a]Institute for Chemical and Bioengineering, Department of Chemistry and Applied Biosciences, ETH Zurich, Vladimir-Prelog-Weg 1, 8093 Zurich, Switzerland.

[b]Department of Chemical, Environmental and Materials Engineering; Institute of Biorefineries Research (I3B), Universidad de Jaén, Campus Las Lagunillas s/n, Jaén 23071, Spain

*These authors have contributed equally to this work and share first authorship

**Corresponding author: Gonzalo Guillén-Gosálbez: gonzalo.guillen.gosalbez@chem.ethz.ch.

Number of Figures: 25

Number of Tables: 3

Number of Pages: 36

1. Related works summary

Table S1 lists the closely related works and summarizes their scope, AESA, and downscaling methods used. The insights are presented in the main text of the manuscript.

Table S1. List of works applying AESA methods to the transport sector.

Study	Scope	AESA Method	Downscaling
Cabrera-Jiménez *et al*.[1] (2023)	Heavy-duty transport (global) Microalgae fuels	Ryberg et al.[2] Galán-Martín *et al*.[3]	None
Charalambous *et al*.[4] (2023)	Heavy-duty transport (global) Dimethyl ether fuel	Ryberg et al.[2] Galán-Martín *et al*.[3]	None
Valente *et al*.[5] (2021)	Heavy-duty transport (global) Hydrogen fuel	Ryberg et al.[2] Galán-Martín *et al*.[3]	None
Ali *et al*.[6] (2025)	NMC811 battery pack production in Germany; Climate change	Bjørn and Hauschild[7] Ohms *et al*.[8]	Egalitarian German population
Ali and Ryberg[9] (2023a)	Electricity and road transport in Tonga	Ryberg *et al*.[2]	Egalitarian Tonga population
Ali *et al.*[10] (2023b)	German LRPT demand	Ryberg *et al*.[2]	Egalitarian German population + Emission based
Sanye Mengual *et al.*[11] (2025)	Consumer footprint EU, including mobility	Sala *et al*.[12]	Egalitarian EU population (per capita)
This work	Prospective EU LRPT demand scenarios	Sala *et al*.[12]	Egalitarian EU population (total)

2. PB-LCIA thresholds

The planetary boundary life cycle impact assessment (PB-LCIA) thresholds, based on Sala et al.,[12] define environmental limits for key LCA impact categories within the planetary boundaries (PBs) framework. Each category includes a threshold, quality level, and links to relevant Sustainable Development Goals (SDGs). Provided by the European Commission's Joint Research Centre, this data helps assess whether human activities stay within safe environmental limits while supporting progress toward global sustainability goals. The PB values given in Table S2 for category i correspond to the SOS_i^{GLO} variable in the main manuscript.

Table S2. PB-LCIA thresholds, quality levels, and SDG mapping based on Sala *et al.*[12]

Impact Category	Abbreviation	Unit	PB	Quality level[13,14]	SDG
Climate change	CC	kg CO_2-eq	6.81×10^{12}	I	13
Ozone depletion	ODP	kg CFC-11-eq	5.39×10^{8}	I	13
Eutrophication, marine	MEU	kg N-eq	2.01×10^{11}	II	14
Eutrophication, freshwater	FEU	kg P-eq	5.81×10^{9}	II	14
Eutrophication, terrestrial	TEU	molc N-eq	6.13×10^{12}	II	15
Acidification	AC	molc H^+-eq	1.00×10^{12}	II	15
Land use	LU	kg soil loss	1.27×10^{13}	III	15
Particulate matter	PM	Disease incidence	5.16×10^{5}	I	3
Water use	WU	m^3 world-eq	1.82×10^{14}	III	14
Photochemical ozone formation, human health	POF	kg NMVOC-eq	4.07×10^{11}	II	3
Human toxicity, cancer	HTOX_c	CTUh	9.62×10^{5}	II/III	3
Human toxicity, non-cancer	HTOX_nc	CTUh	4.10×10^{6}	II/III	3
Ecotoxicity, freshwater	ECOTOX	CTUe	1.31×10^{14}	II/III	6
Ionising radiation, human health	IR	kBq U^{235}-eq	5.27×10^{14}	II	3
Resource use, fossils	FRD	MJ	2.24×10^{14}	III	13
Resource use, mineral and metals	MRD	kg Sb-eq	2.19×10^{8}	III	15

3. EU reference scenario 2020 fleet stock composition modelling

This section describes the fleet stock modelling approach used to characterize the European light-duty vehicle (LDV) fleet evolution and calculate associated environmental impacts through life cycle assessment. The modelling framework integrates fleet composition projections, age distribution dynamics, and life cycle phase transitions to quantify annual vehicle registrations, stock evolution, and end-of-life retirements.

The fleet stock model is based on the EU reference scenario 2020[15] which provides official European Commission projections for vehicle stock evolution built upon the PRIMES energy system model. The scenario data encompasses seven distinct powertrain categories representing the technological diversity of the European LDV fleet:

- **Internal combustion engine vehicles (ICEVs)**: diesel (ICEV-d), petrol (ICEV-p), natural gas (ICEV-g) variants.
- **Battery electric vehicles (BEVs)**: pure electric vehicles with no internal combustion components.
- **Fuel cell electric vehicles (FCEVs)**: hydrogen-powered electric vehicles.
- **Plug-in hybrid electric vehicles (PHEVs)**: diesel (PHEV-d) and petrol (PHEV-p) variants.

Since the original EU reference scenario does not distinguish between diesel and petrol variants for PHEVs, a constant 10% diesel and 90% petrol assumption was applied based on historical market observations.

The fleet stock model employs a forward simulation approach. The methodology consists of three key components.

3.1. Initial conditions (2005)

The simulation begins in 2005 with a uniform age distribution assumption for internal combustion engine vehicles. This approach assumes that the existing ICE fleet in 2005 was evenly distributed across all ages from 0 to 15 years, representing a steady-state condition. Electric vehicles (BEVs, FCEVs) and plug-in hybrids (PHEVs) are initialized at zero stock, reflecting their negligible market presence in 2005.

For each ICEV powertrain p and age a, the initial stock $S_{p,a,2005}$ is calculated as:

$$S_{p,a,2005}=\frac{S_{p,total,2005}}{L_{vehicle}} \qquad (1)$$

where $L_{vehicle}$=16 years is the assumed vehicle lifetime.

3.2. Annual fleet evolution (2006-2050)

The forward simulation proceeds year-by-year, implementing the following sequence of operations for each powertrain and year:

1. Vehicle aging: All vehicles age by one year, with the age structure advancing according to Equation (2).

$$S_{p,a+1,t+1}=S_{p,a,t} \qquad \forall\ p,\ t,\ a=0,\ 1,\ \ldots,\ L_{vehicle}\text{-}2 \qquad (2)$$

2. End-of-life retirements: Vehicles reaching the maximum lifetime are retired from the fleet according to Equation (3), where $R_{p,t}$ is the number of retired vehicles by powertrain p and year t.

$$R_{p,t}=S_{p,L_{vehicle}-1,t} \qquad \forall\ p,\ t \qquad (3)$$

3. Target fleet reconciliation: The model calculates the fleet size after aging and retirement, then determines the required new registration to meet the EU reference scenario projections according to Equation (4).

$$N_{p,t}=\max\left(0,S_{p,target,t}-\sum_{a=1}^{L_{vehicle}-1} S_{p,a,t}\right) \qquad \forall\ p,\ t \qquad (4)$$

4. New vehicle integration: New registrations are added to the zero-age group according to Equation (5).

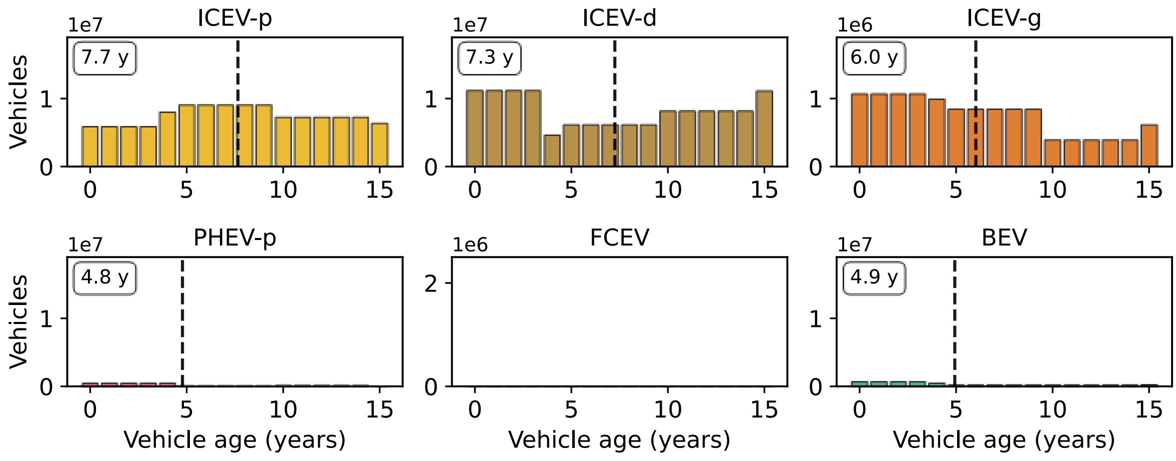
$$S_{p,0,t}=N_{p,t} \qquad \forall\ p,\ t \qquad (5)$$

3.3. Fleet dynamics outputs

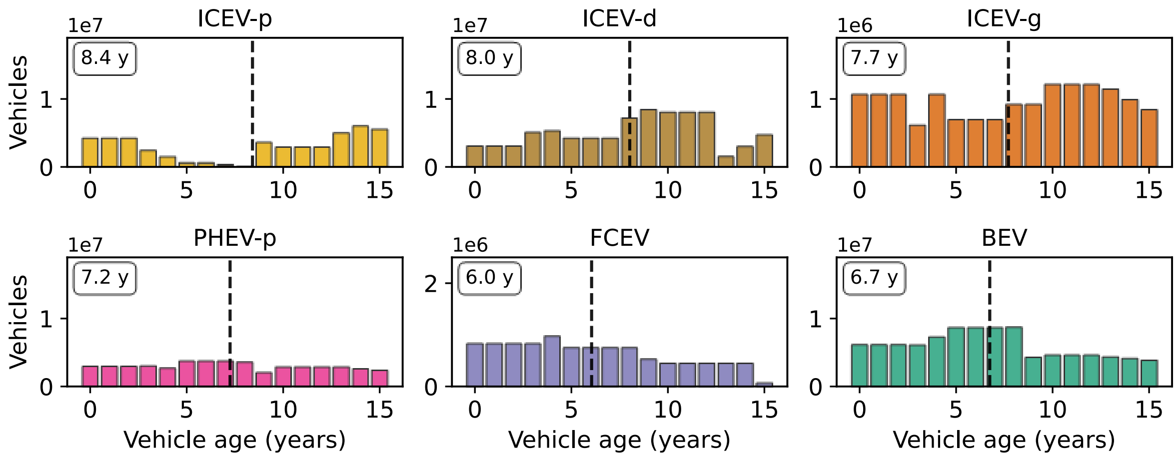
The age distribution model generates three primary time series for each powertrain from 2025 to 2050:

- Annual stock ($S_{p,t}$): Total number of vehicles in stock by powertrain and year
- Annual registrations ($N_{p,t}$): New vehicle sales requiring production-phase LCA
- Annual retirements ($R_{p,t}$): End-of-life vehicles requiring disposal LCA

This data and the corresponding impacts are represented in Figure 5 of the main manuscript. Figure S1 shows the resulting age distributions from this algorithm at years 2025 and 2050. It can be seen how the average fleet age increases, especially for powertrains that are just starting to rollout like BEVs which increase from 4.9 years to 6.7 years. In 2025 no FCEVs are recorded, while in 2050 a certain stock exists with an average age of 6.0 years.



(a) Age distribution 2025

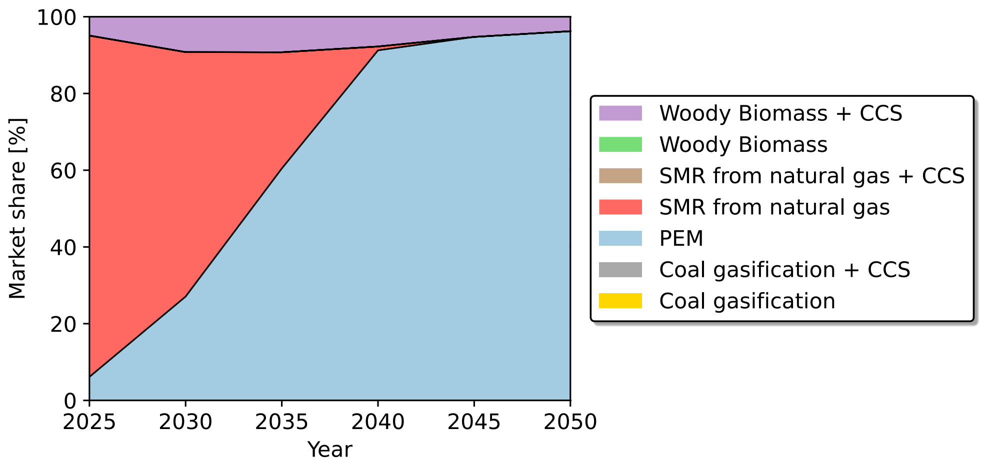


(b) Age distribution 2050

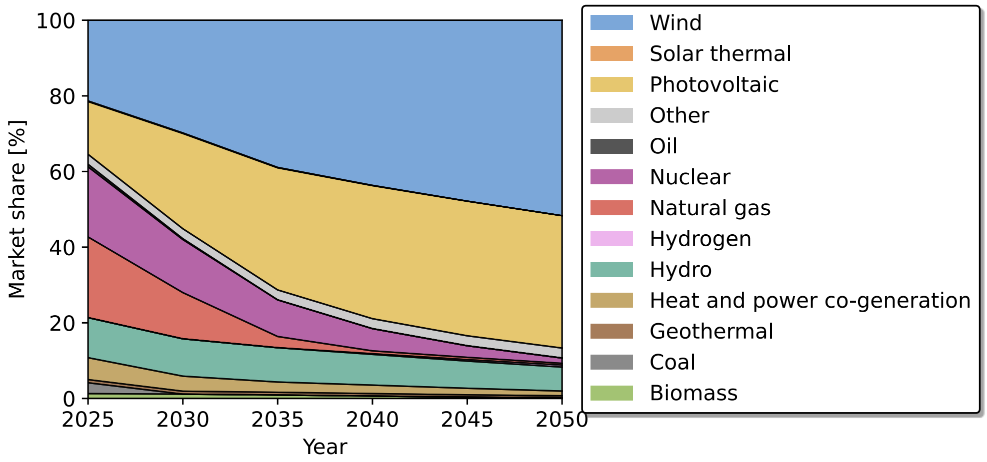
Figure S1. Age distributions for the years 2025 and 2050 based on fleet stock modelling tailing historical and projected transportation demand.

4. Energy market projections

This section presents European market projections for hydrogen and electricity (Figure S2) and petrol and diesel (Figure S3). These markets are obtained via premise 2.2.7 using the SSP2-PkBudg1150 scenario, which is aligned with a 2.0 °C temperature increase by 2100. The electricity market shown in Figure S2 is the European average obtained from premise, while Figure S4 shows the regional markets used for the regionalized assessment in Figure 3 of the main manuscript. These projections have been obtained from ENTSO-E.[16] The compressed gas market is not represented.

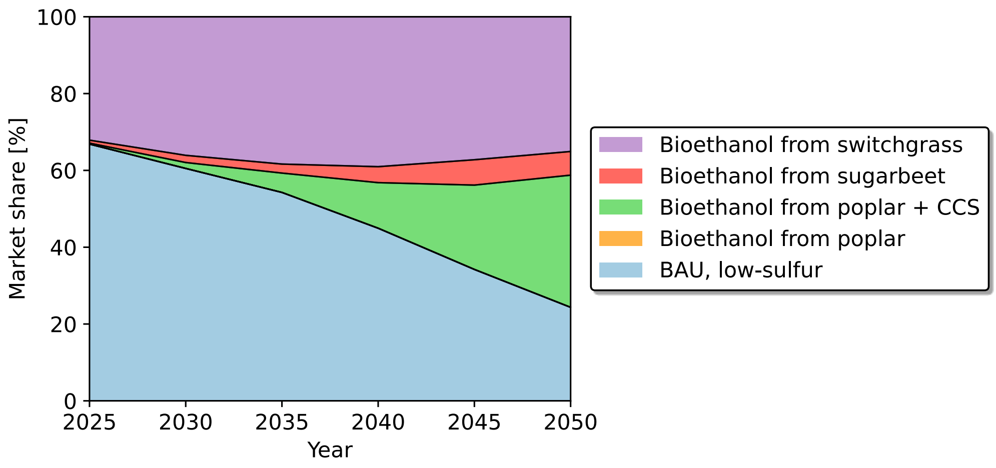


(a) Hydrogen market

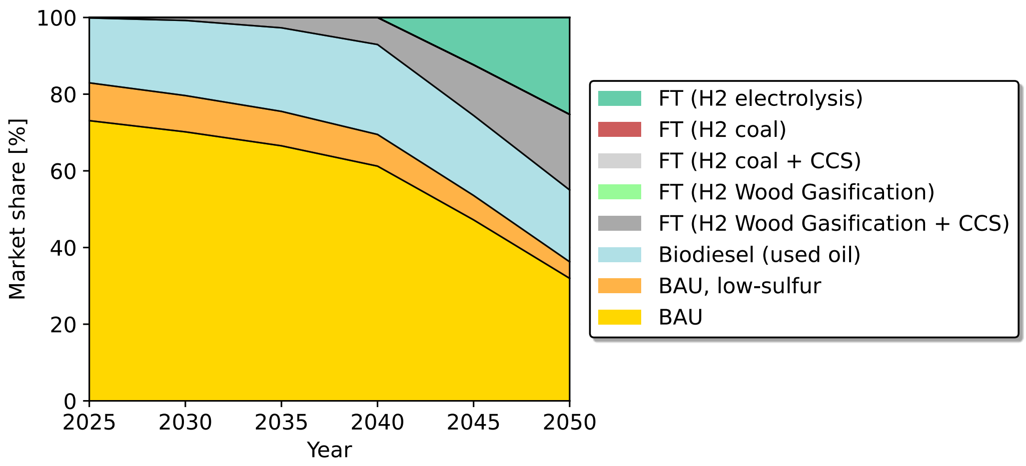


(b) Electricity market

Figure S2. Electric engine vehicle (FCEV, BEV, PHEV) energy market projections. Obtained from premise v2.2.7 PkBudg1150 scenario.



(a) Petrol market



(b) Diesel market

Figure S3. Internal combustion engine vehicle (ICEV, PHEV) energy market projections. Obtained from premise v2.2.7 PkBudg1150 scenario.

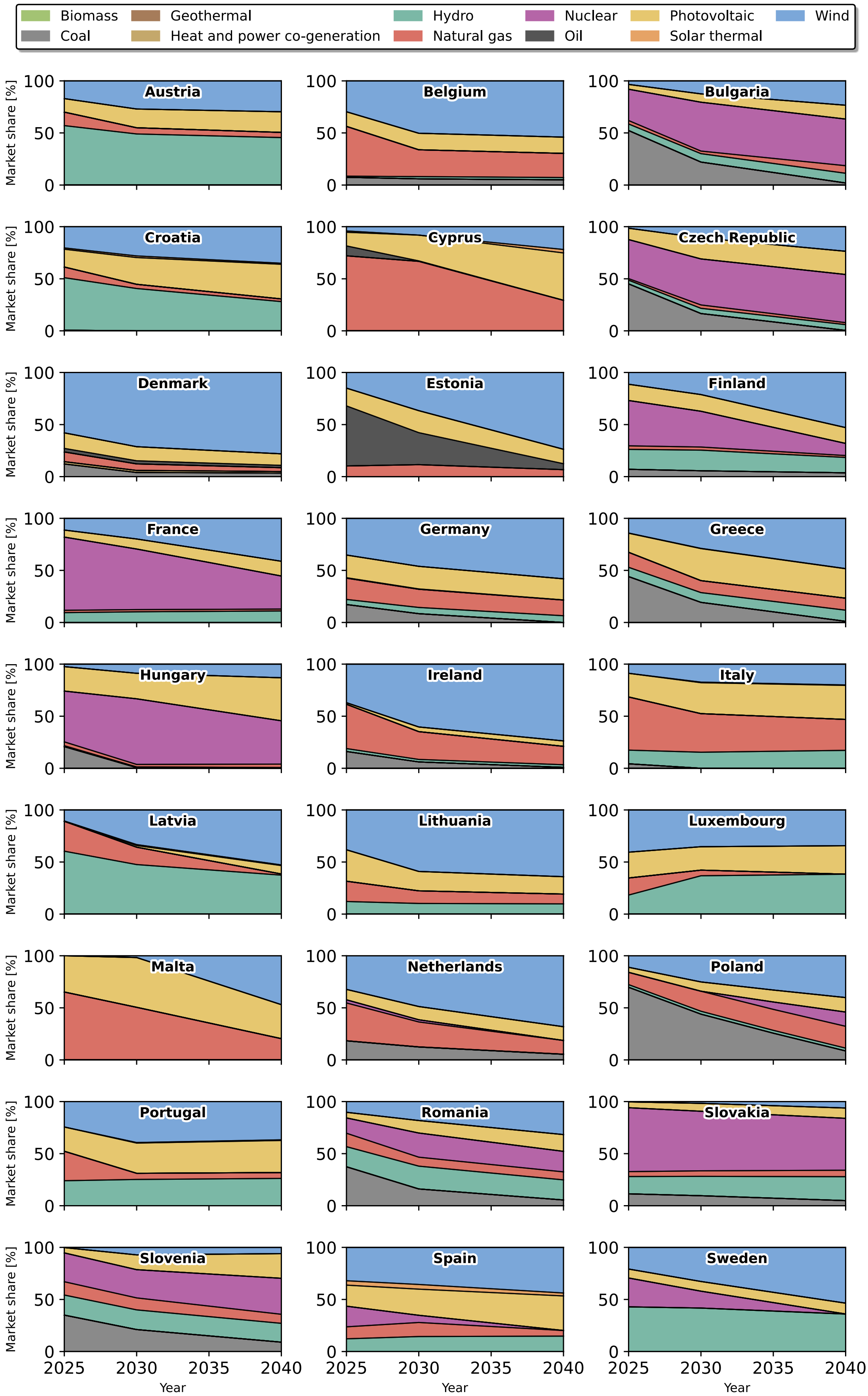


Figure S4. Regional EU-27 electricity market evolutions obtained from ENTSO-E.[16]

5. Powertrain supply chain contribution analysis

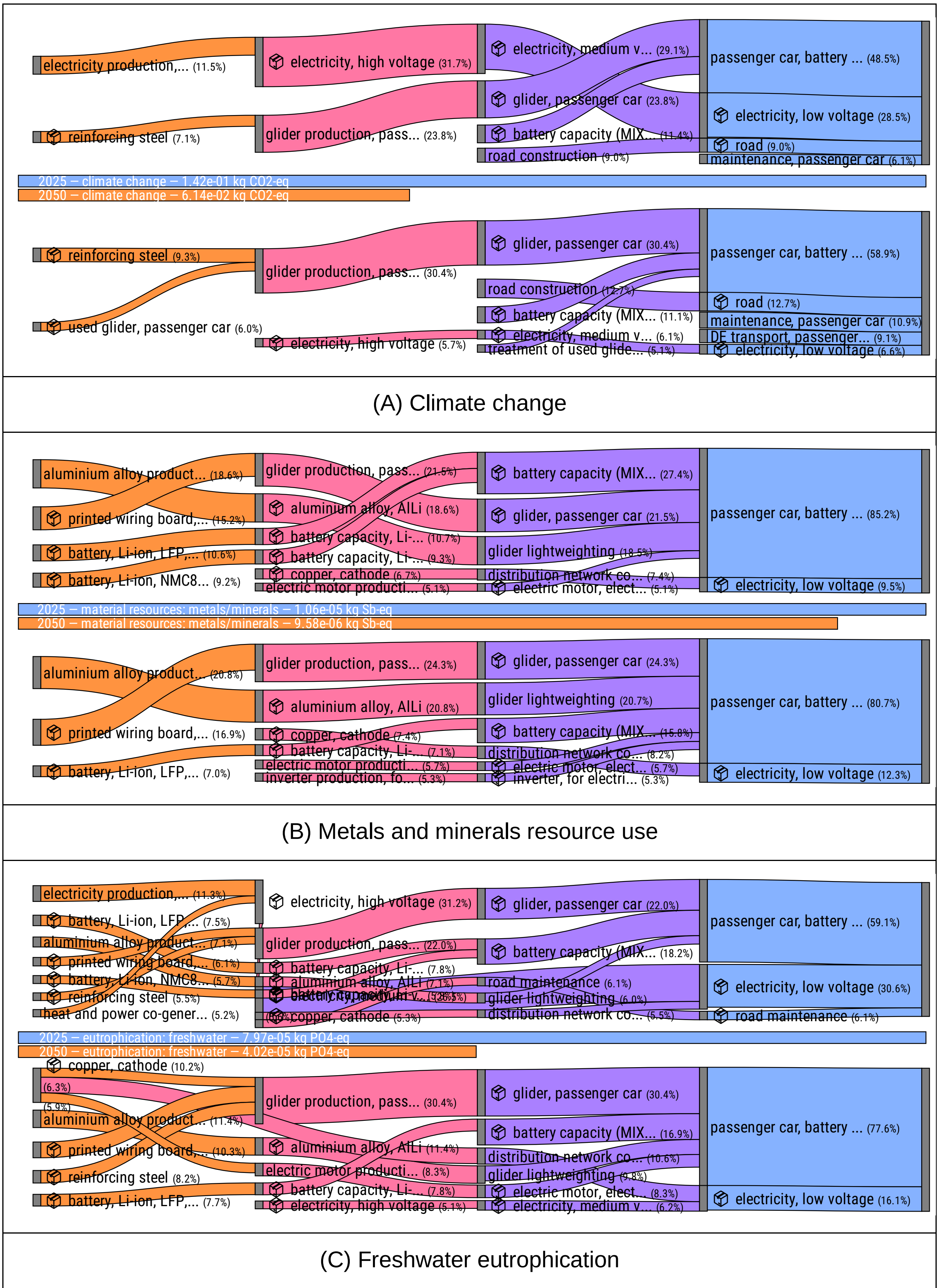


Figure S5. Supply chain contributions for battery electric vehicles (BEV) in 2025 and 2050. (**A**) climate change (**B**) metals and minerals resource use (**C**) freshwater eutrophication.

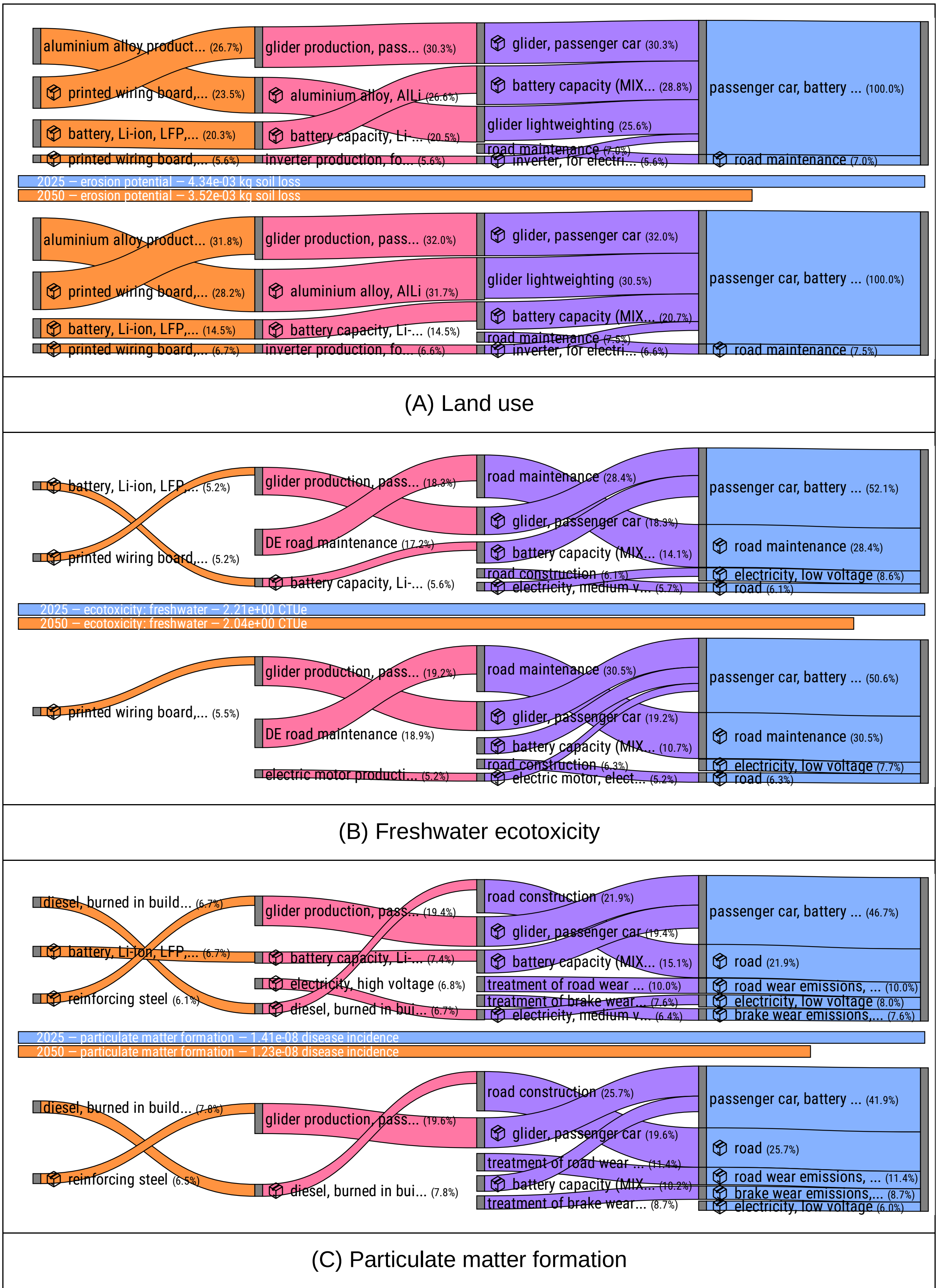


Figure S6. Supply chain contributions for battery electric vehicles (BEV) in 2025 and 2050. (**A**) land use (**B**) freshwater ecotoxicity (**C**) particulate matter formation.

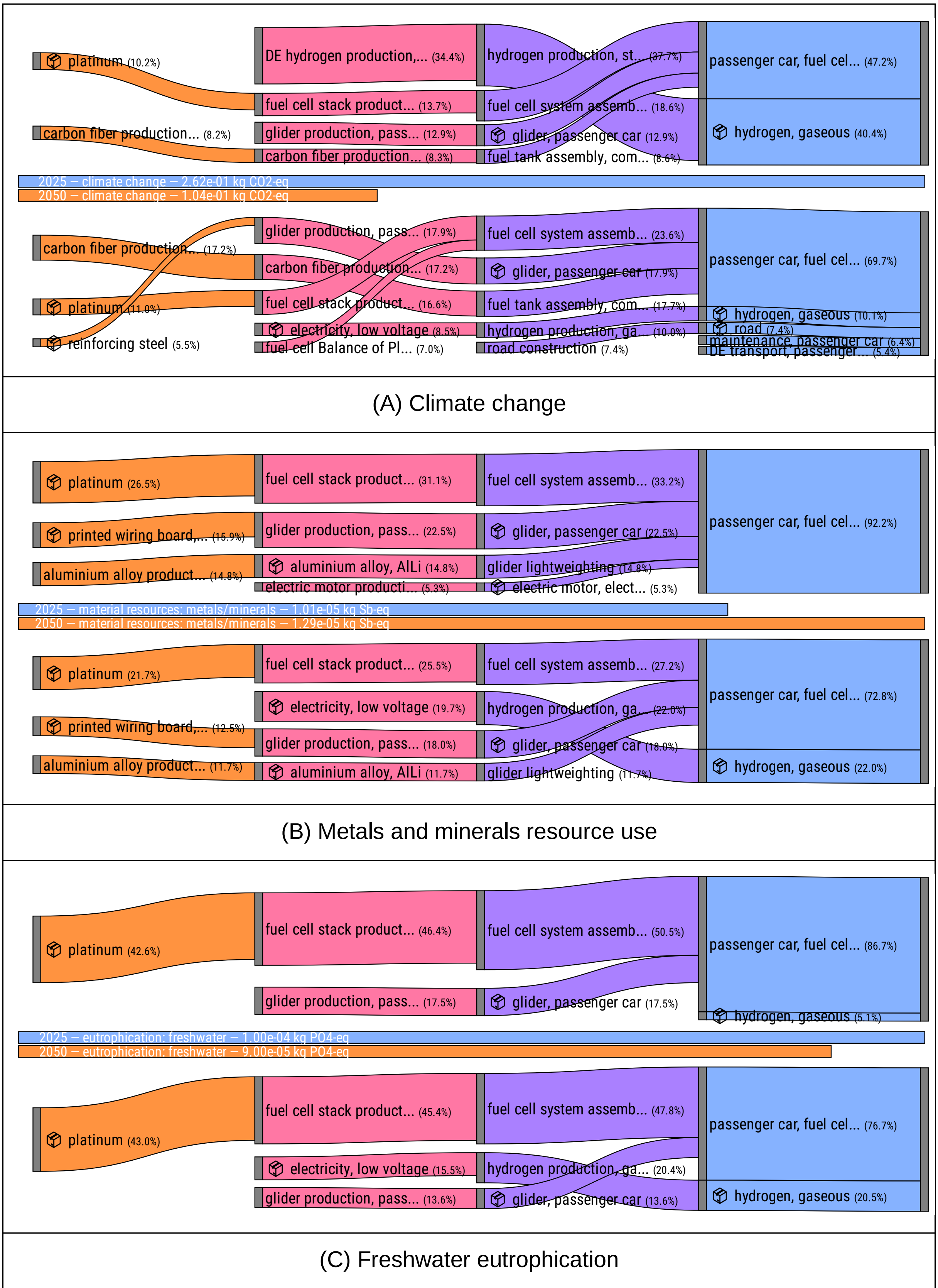
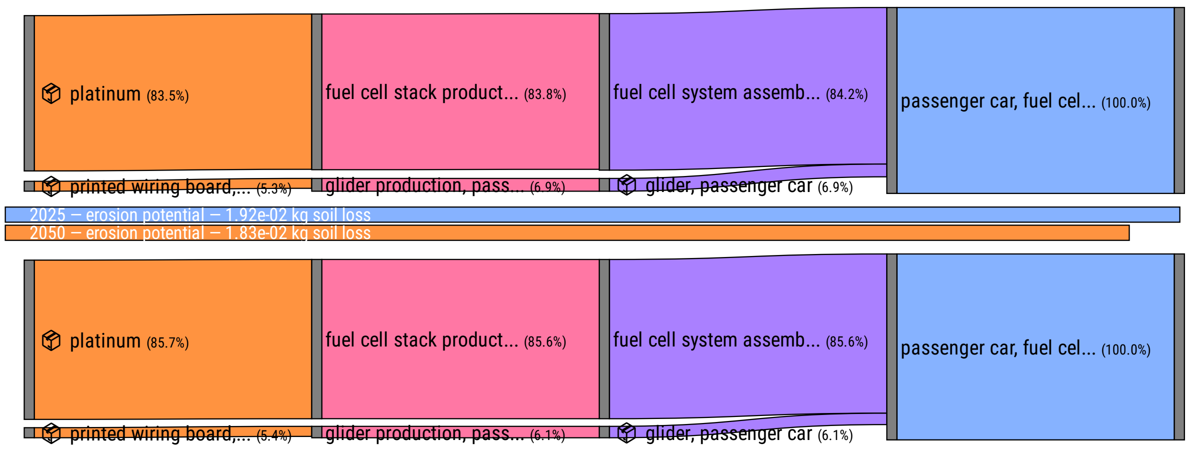
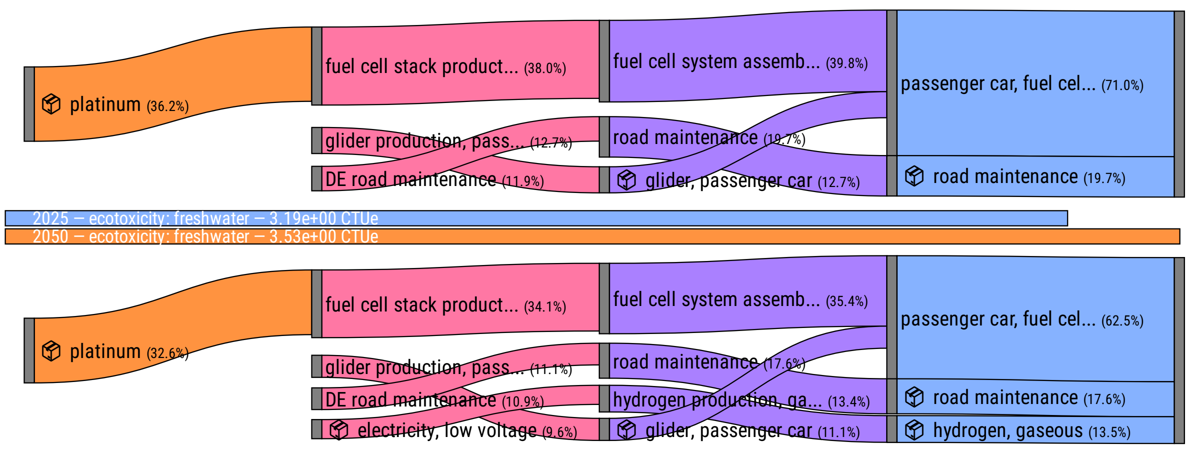


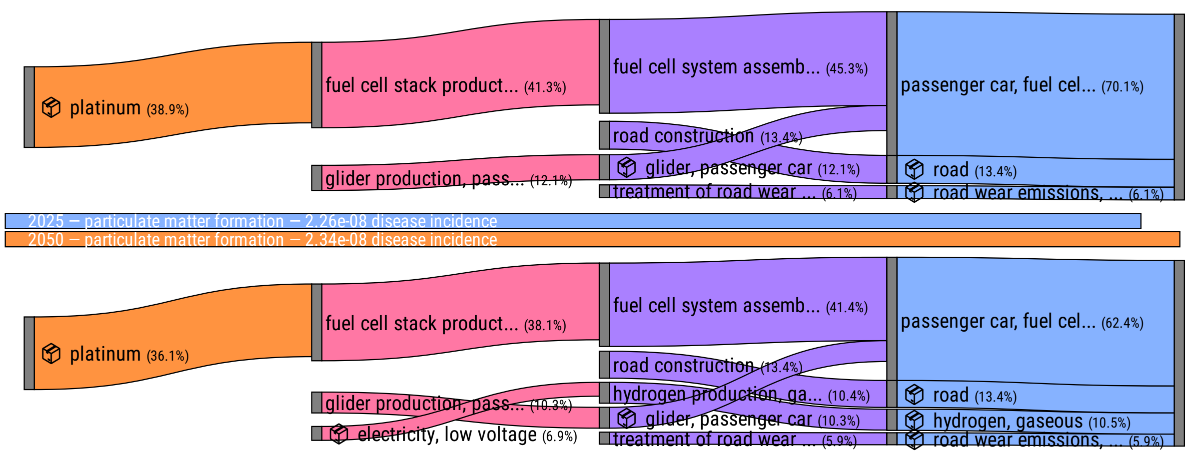
Figure S7. Supply chain contributions for fuel cell electric vehicles (FCEV) in 2025 and 2050. (**A**) climate change (**B**) metals and minerals resource use (**C**) freshwater eutrophication.



(A) Land use



(B) Freshwater ecotoxicity



(C) Particulate matter formation

Figure S8. Supply chain contributions for fuel cell electric vehicles (FCEV) in 2025 and 2050. (**A**) land use (**B**) freshwater ecotoxicity (**C**) particulate matter formation.

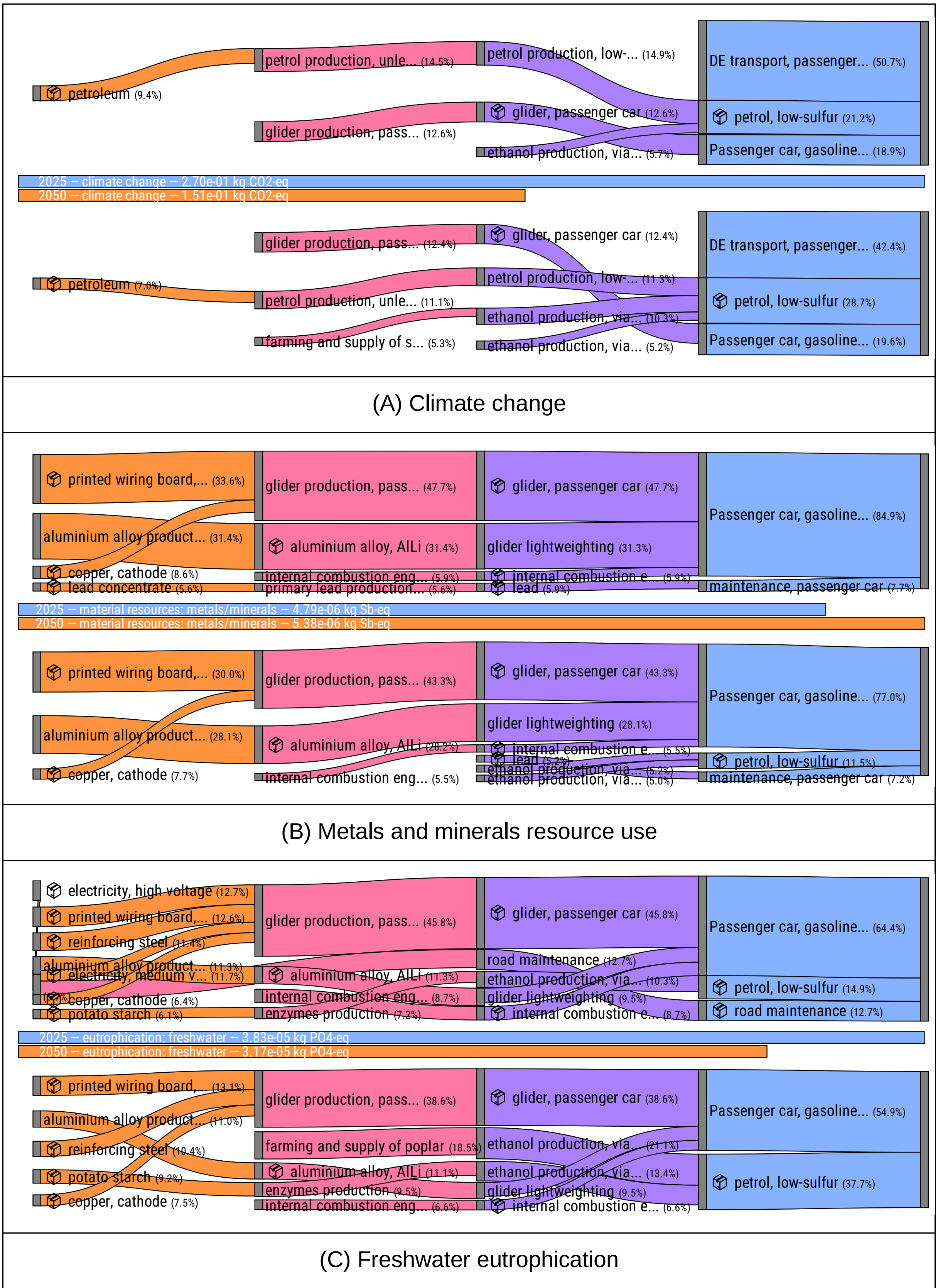


Figure S9. Supply chain contributions for petrol powered internal combustion engine vehicle (ICEV-p) in 2025 and 2050. (**A**) climate change (**B**) metals and minerals resource use (**C**) freshwater eutrophication.

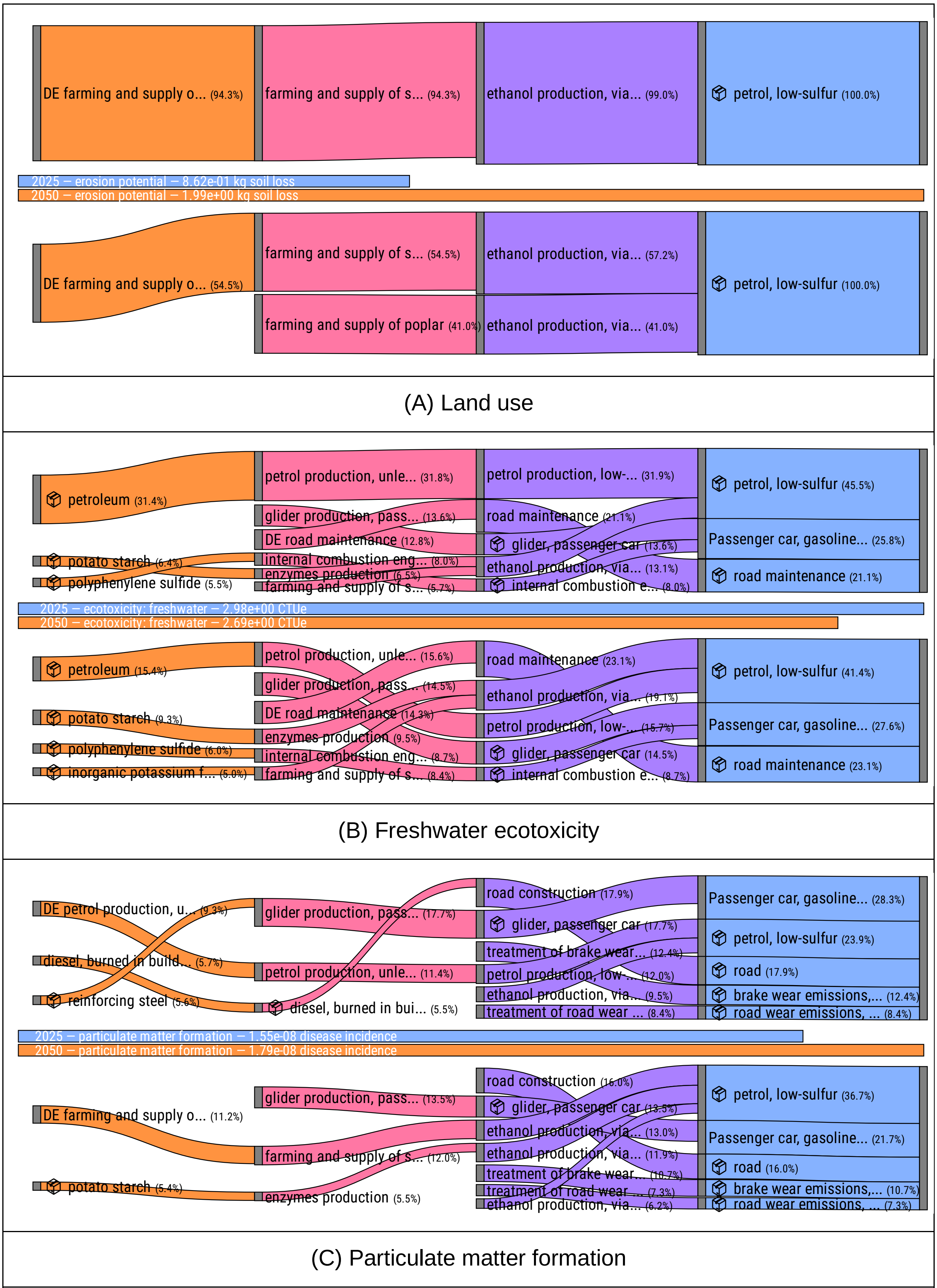


Figure S10. Supply chain contributions for petrol powered internal combustion engine vehicle (ICEV-p) in 2025 and 2050. (**A**) land use (**B**) freshwater ecotoxicity (**C**) particulate matter formation.

Figure S5 to Figure S10 show supply chain contribution of the impact of driving one vkm. Here, BEVs, FCEVs, and ICEVs-p are shown focusing on climate change, material and resource depletion, and freshwater eutrophication for the years 2025 and 2050, analyzing contributions up to 4 levels deep, applying a cutoff of 5%. This means that shares with less than 5% contribution to the final impact are not shown in the Sankey diagrams.

We can see how supply chain impacts are projected to change. For example, the first-tier contribution for **climate change** has revealed already that the electricity contributions lower in 2050, leaving manufacturing and end-of-life impacts as hotspots. Figure S5 (A) shows that those impacts mainly stem from the glider production (30.4% in 2050) and the corresponding steel production and use of recycled materials. The battery also contributes significantly (11.4%). Similarly, for FCEVs the manufacturing impacts stems from the glider (17.9%), the fuel tank (17.7%), and the fuel cell itself (23.6%). The fuel tank impacts are driven by carbon fiber production and fuel cell impacts come from platinum production. ICEVs-p show a 1.79 times reduction in overall impacts related to efficiency gains and changes in the petrol market adopting biofuels. Also, a significant contribution comes from the glider (12.4%) but the largest share is still direct combustion (42.4%).

In 2050, **metals and minerals resource use** in BEVs and ICEVs-p is driven by aluminum for lightweight gliders (20.8% and 28.1%) and printed wiring boards (16.9% and 30.0%). This is in contrast to FCEVs whose higher material resource depletion comes from the platinum used in the fuel cell construction (21.7% contribution).

For **freshwater eutrophication**, impact reductions are achieved for BEVs due to changes in the electricity production, lowering its share from 30.6% to 16.1%. Minor improvements also stem from road maintenance, linked again to electricity production as shown in level 3 of the Sankey. No further improvements are projected, but vehicle manufacturing remains a major impact source, especially platinum production in FCEVs, contributing 43.0%.

6. Additional prospective assessment results

6.1. Remaining indicator results (main scenario)

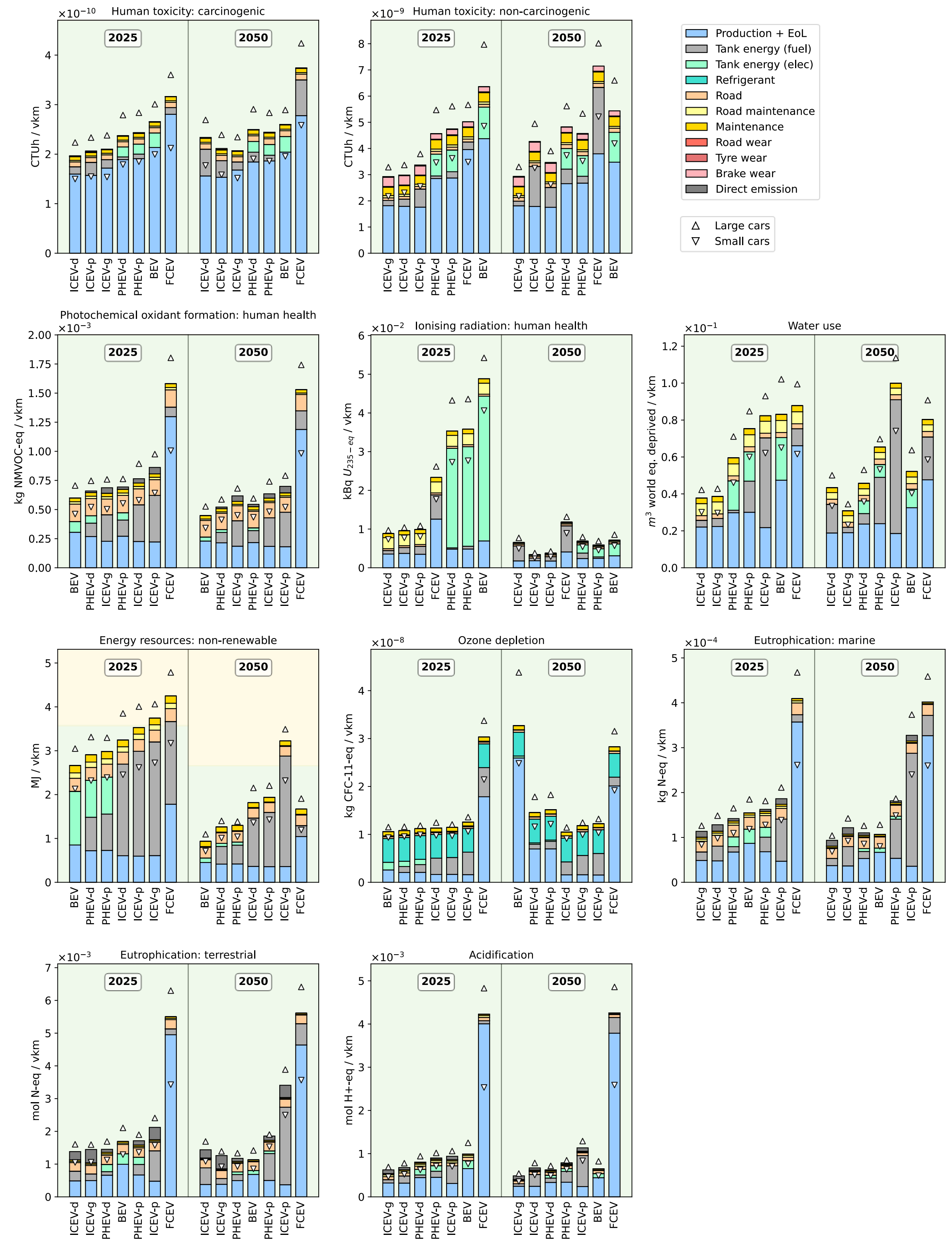


Figure S11. Prospective assessment of non-transgression impact categories in 2025 and 2050. EU reference scenario 2020 demand and SSP2-PkBudg1150 background scenario. Complements results of Figure 2 in main manuscript.

6.2. Indicator results adhering to a 1.5 °C scenario

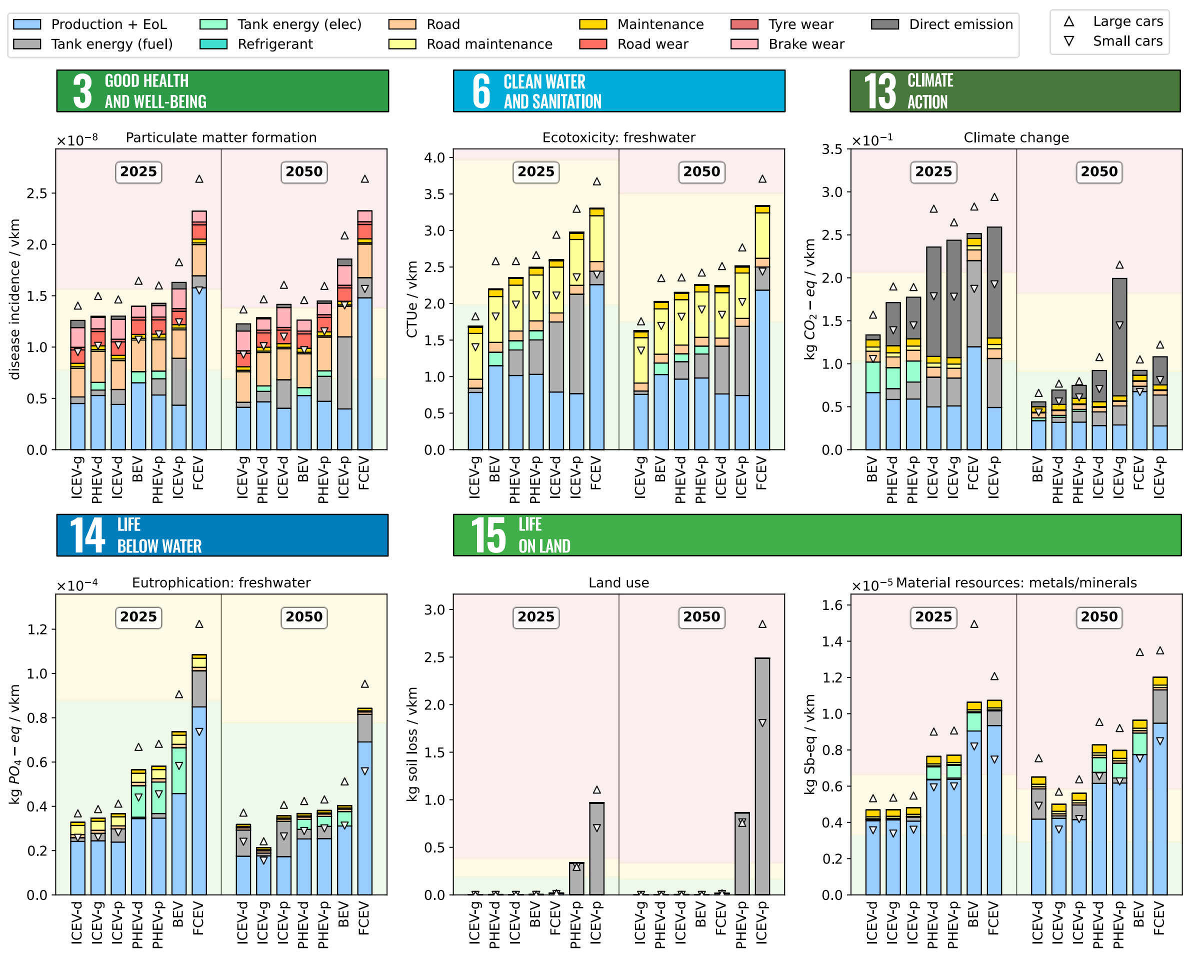


Figure S12. Per vkm breakdown of critical impacts associated to selected powertrain options in the PkBudg500 (1.5 °C increase) scenario. Complementary results to the PkBudg1150 scenario from Figure 2 presented in the main manuscript.

6.3. Indicator results adhering to a 3.5 °C scenario

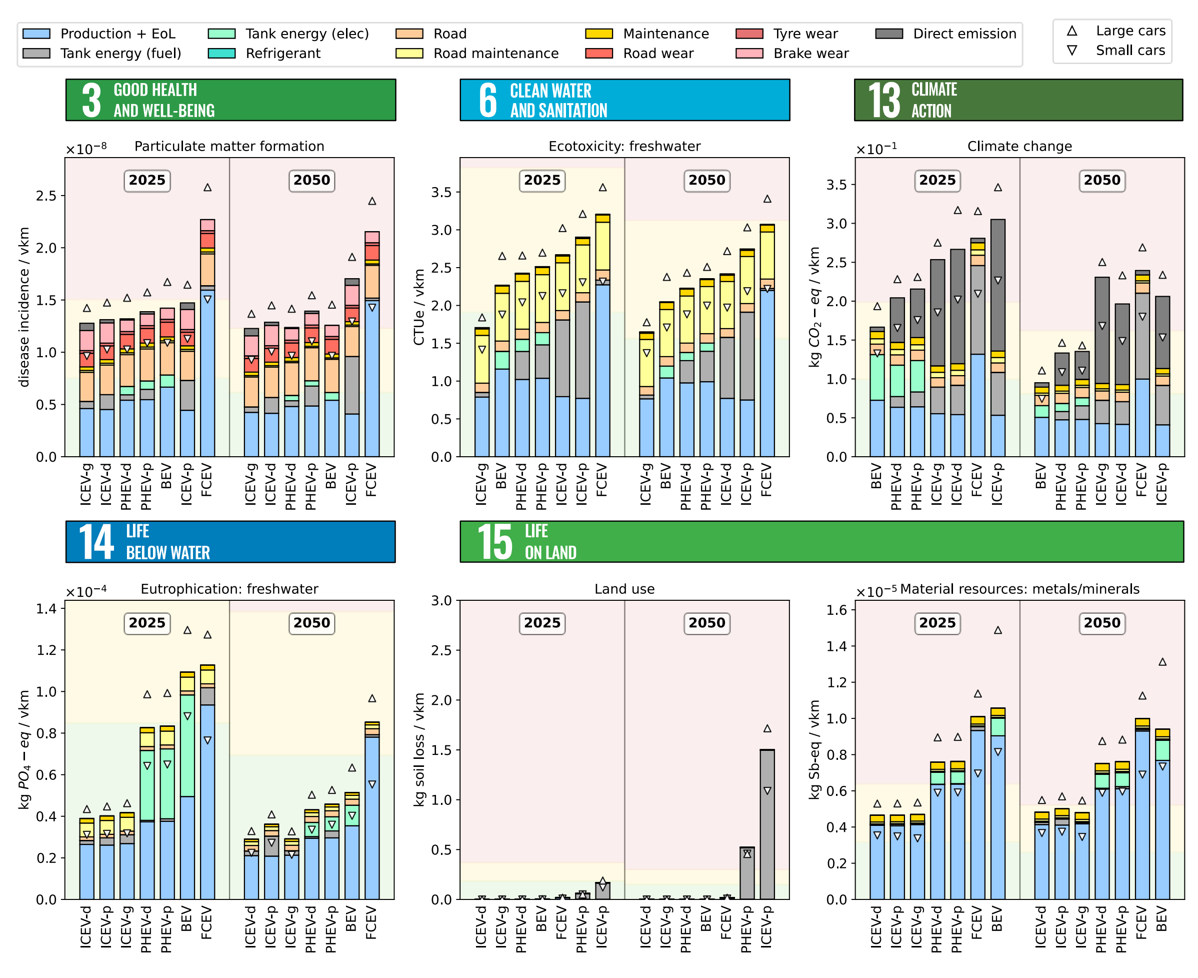


Figure S13. Per vkm breakdown of critical impacts associated to selected powertrain options in the base (3.5 °C increase) scenario. Complementary results to the PkBudg1150 scenario from Figure 2 presented in the main manuscript.

7. Sensitivity and uncertainty analysis

Since the premise inventories lack underlying uncertainty distributions (unlike the base ecoinvent inventories), a simple Monte Carlo sampling of these uncertainties cannot be performed. Instead, we conduct a sensitivity analysis on the premise foreground inputs (Figures S14 and S15), increasing each input parameter exchange by 10% and recording the resulting change in the transport activity's impact. This corresponds to the contribution breakdown shown in Figure 2 of the main manuscript. Across powertrains and categories, production and end-of-life stages consistently emerge as the most sensitive to change. For land use, sensitivities are omitted for non-petrol powertrains because negative contributions from road construction distort the results.

Beyond the LCI input sensitivity, we also performed an uncertainty assessment using the "carculator" package (v1.9.4).[17] This package is the source for the premise inventories. However, the specific version used and its mapping to the ecoinvent inventories are not clearly documented. As a result, outputs from carculator can deviate from those generated by premise.

To estimate the magnitude of parameter uncertainty, we ran 10,000 Monte Carlo iterations on all input parameters, with results shown in Figure S16. These input parameters differ from the LCI inputs: carculator starts from vehicle-level parameters (e.g., frontal area, combustion power share, battery mass), which are processed through two submodels to generate the final LCI. In premise, these characteristics are already aggregated into a specific bill of materials. For the uncertainty analysis, we sampled from the uncertainty distributions defined within carculator for each parameter.

Results show that premise values largely fall within the carculator uncertainty ranges. Notable exceptions include particulate matter formation for FCEV and ICEV-p, likely caused by different modelling settings or background inventories coupled to the vehicle foreground data. Overall, the agreement can be considered satisfactory, and the analysis provides a reasonable impression of uncertainty magnitude. Uncertainty appears smaller for more mature powertrains such as ICEVs, although the range varies by impact category.

Finally, a sensitivity analysis using the vehicle-level parameters in carculator was conducted, with results shown in Figure S17. Across powertrains and impact categories, glider base mass and lifetime kilometers were the most influential parameters, while for BEVs, battery mass showed also high sensitivity to change.

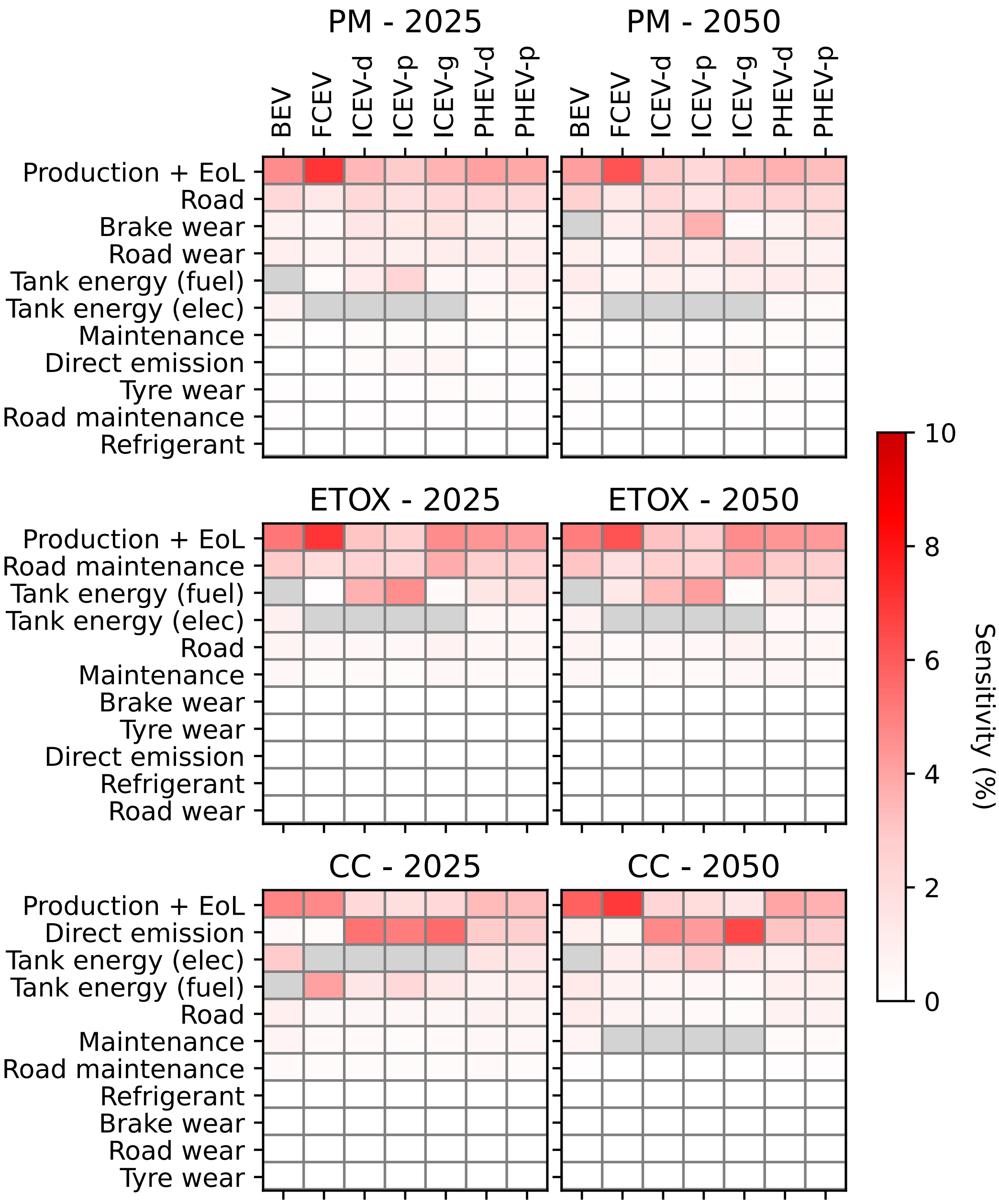


Figure S14. Sensitivity analysis of premise foreground LCI inputs for particulate matter formation (PM), freshwater ecotoxicity (ETOX), and climate change (CC) for the years 2025 and 2050. Each input parameter exchange is increased by 10%, and the resulting percentage change in the transport activity's impact is recorded. Darker red indicates higher sensitivity.

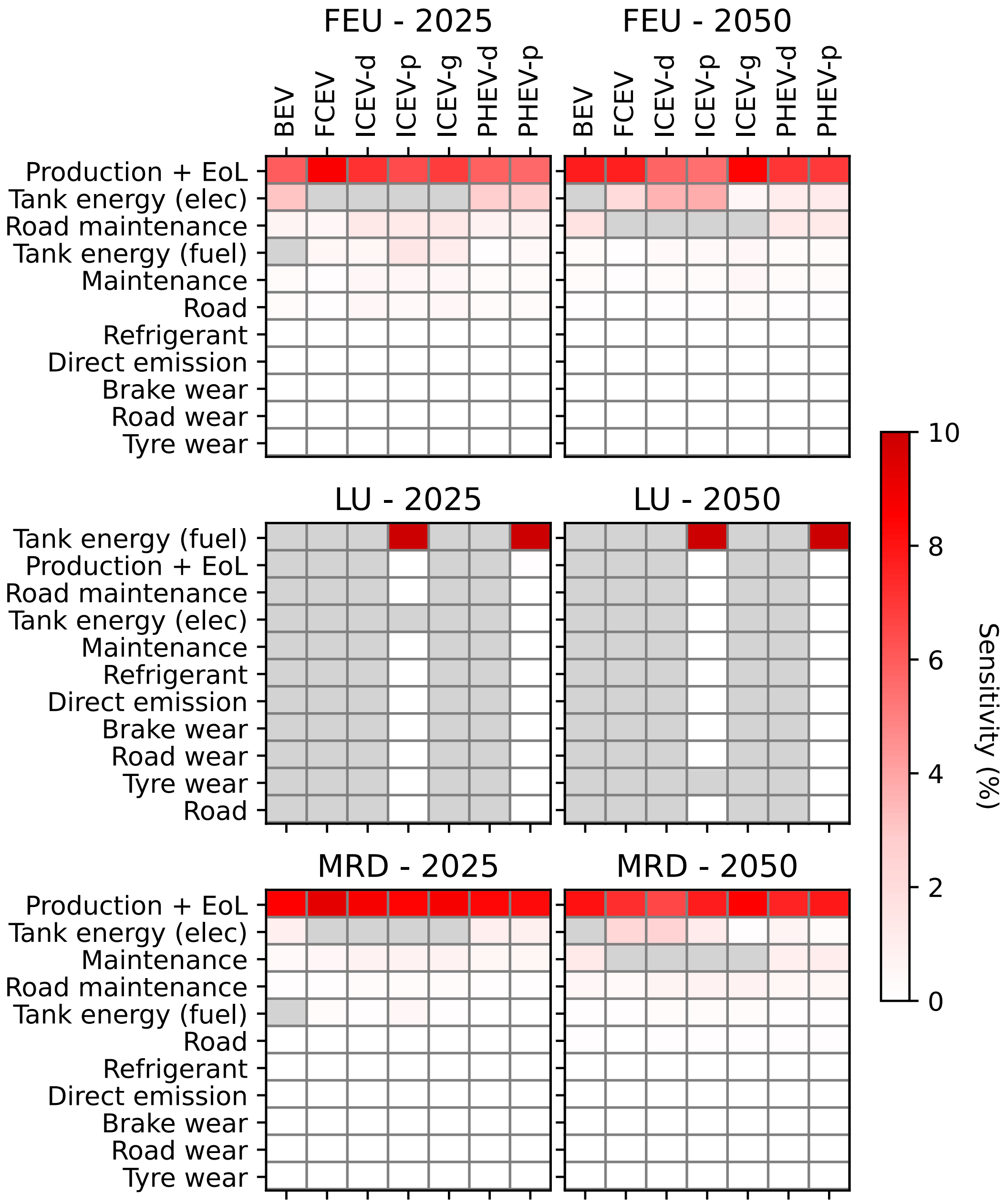


Figure S15. Sensitivity analysis of premise foreground LCI inputs for freshwater eutrophication (FEU), land use (LU), and resource use, metals and minerals (MRD) for the years 2025 and 2050. Each input parameter exchange is increased by 10%, and the resulting percentage change in the transport activity's impact is recorded. Darker red indicates higher sensitivity. Sensitivities for non-petrol powertrains in the land use category are greyed out due to negative contributions from road construction distorting results.

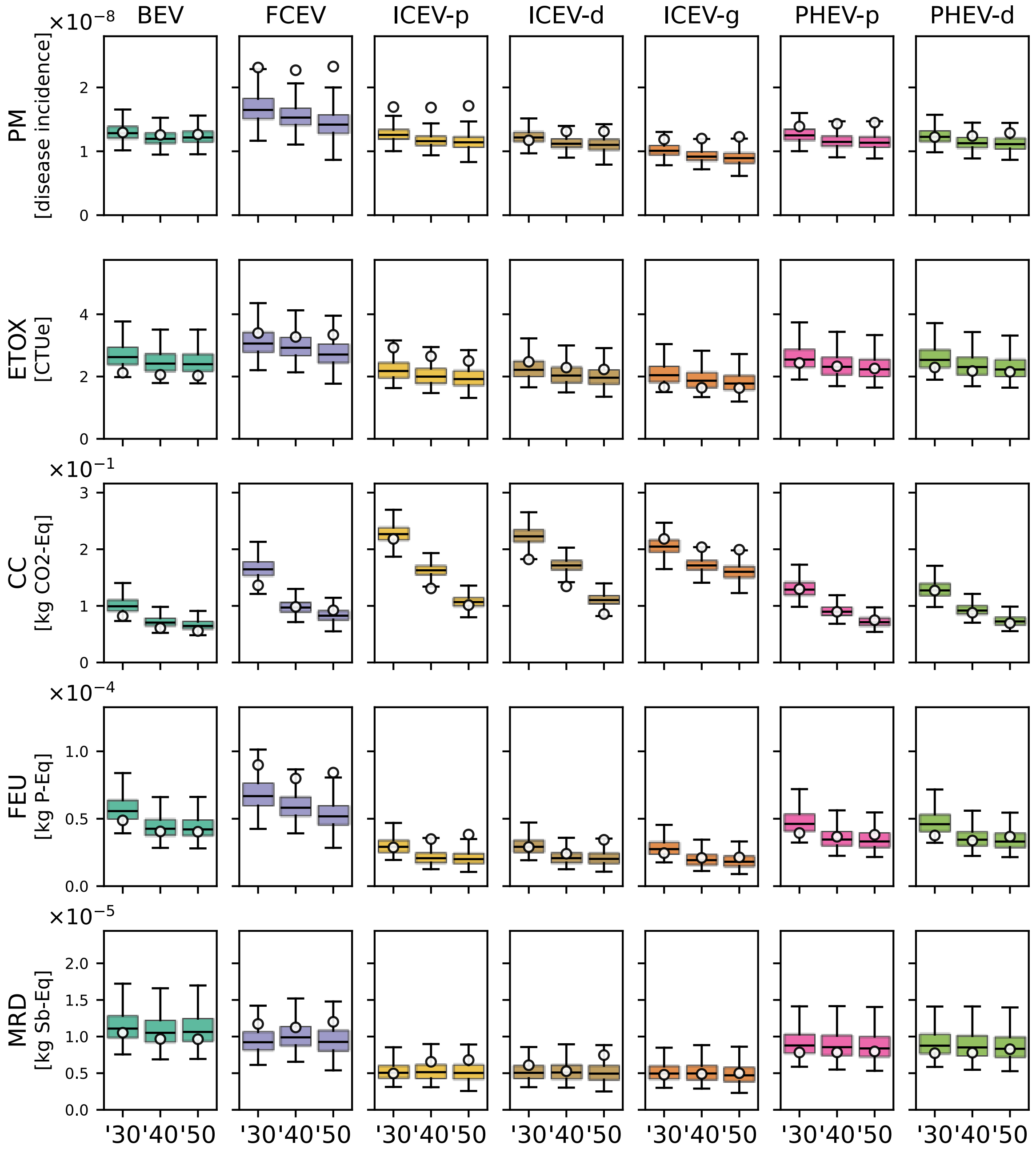


Figure S16. Uncertainty assessment using the carculator package (v1.9.4) for particulate matter formation (PM), freshwater ecotoxicity (ETOX), climate change (CC), freshwater eutrophication (FEU), and metals and minerals resource use (MRD) for the years 2030, 2040, and 2050. Results are based on 10,000 Monte Carlo iterations applied to vehicle-level input parameters, sampled from the uncertainty distributions defined in carculator. Boxplots show the distribution of results for each powertrain and year, with premise results indicated by white circles.

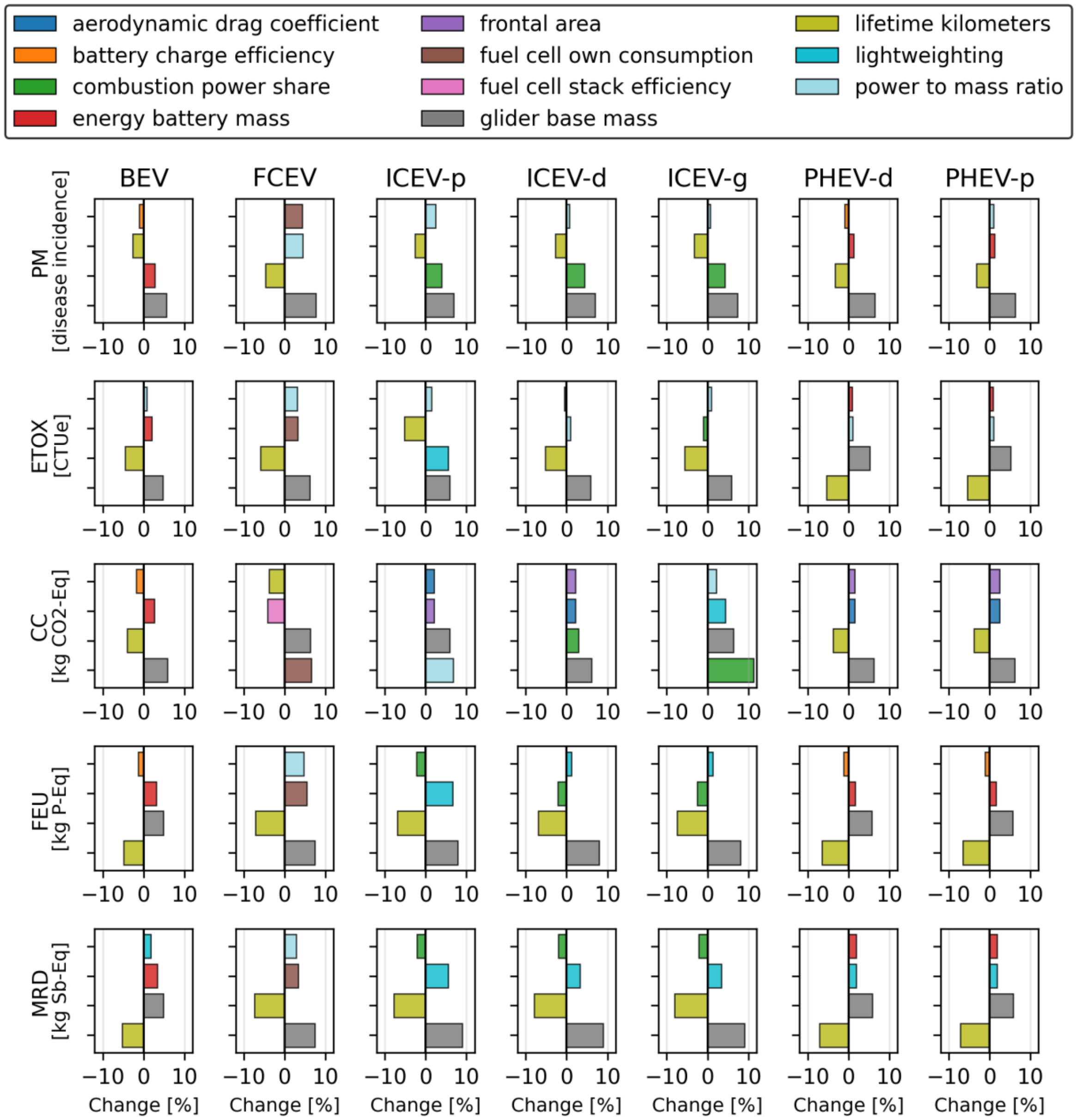


Figure S17. Sensitivity analysis of vehicle-level parameters in carculator for particulate matter formation (PM), freshwater ecotoxicity (ETOX), climate change (CC), freshwater eutrophication (FEU), and metals and minerals resource use (MRD). Results show the percentage change in each impact when the parameter value is increased or decreased by 10%, for each powertrain.

8. Additional time-explicit assessment results

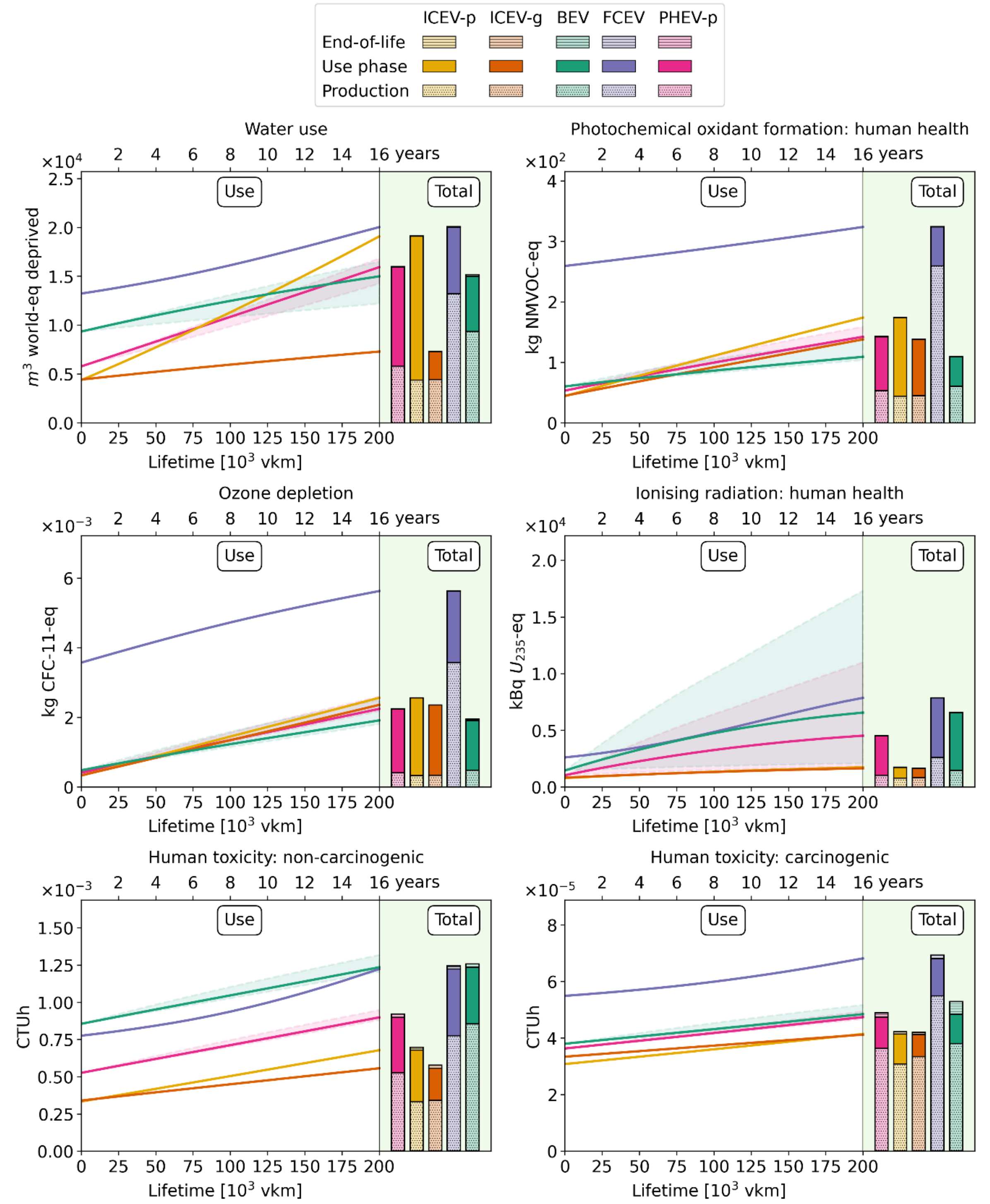


Figure S18. Time-explicit assessment of non-critical impact categories. Six out of sixteen indicators are shown, representing SDGs three, six, and thirteen. EU reference scenario 2020 demand and SSP2-PkBudg1150 background scenario. Complementary results to Figure 3 in main manuscript.

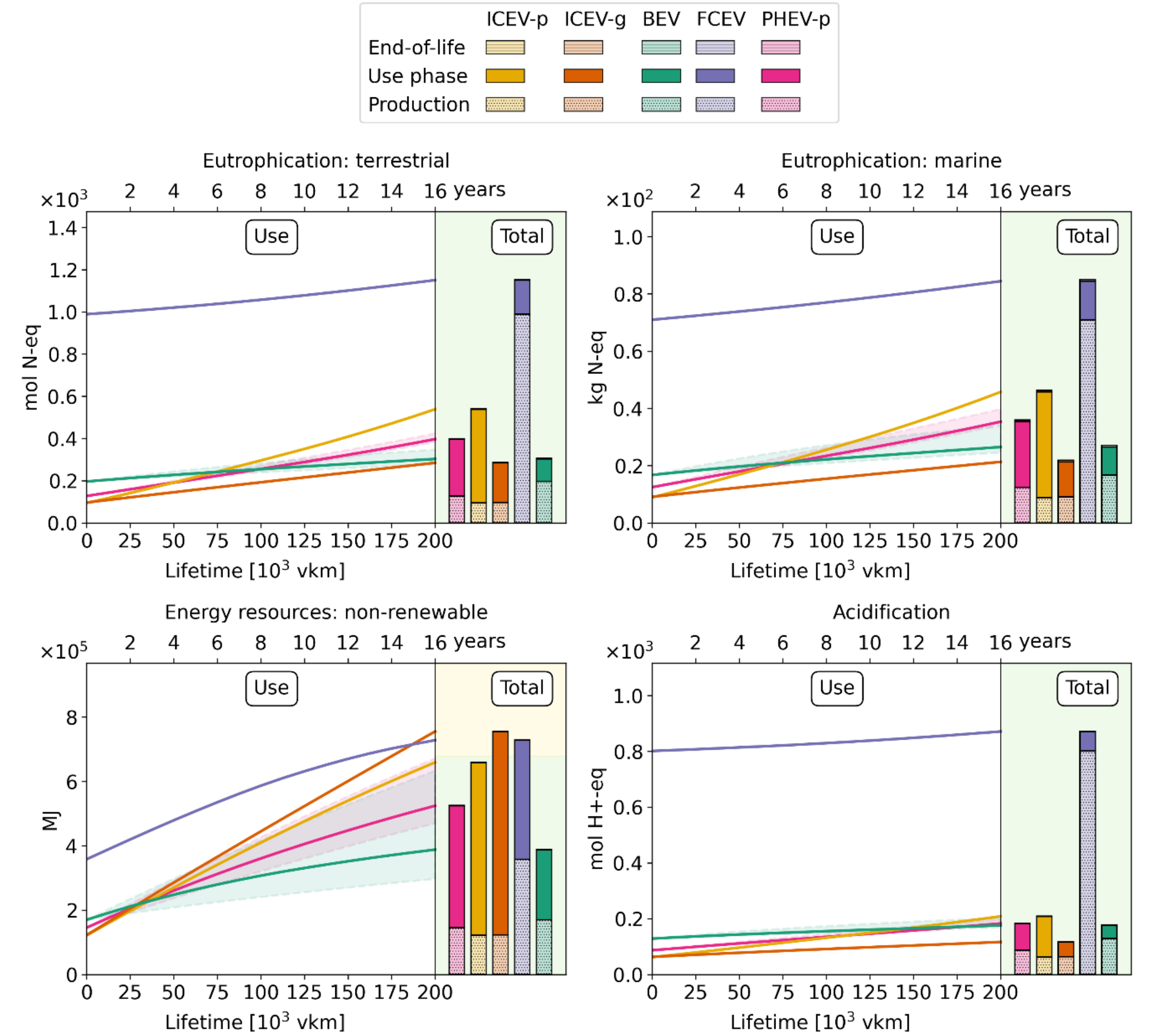
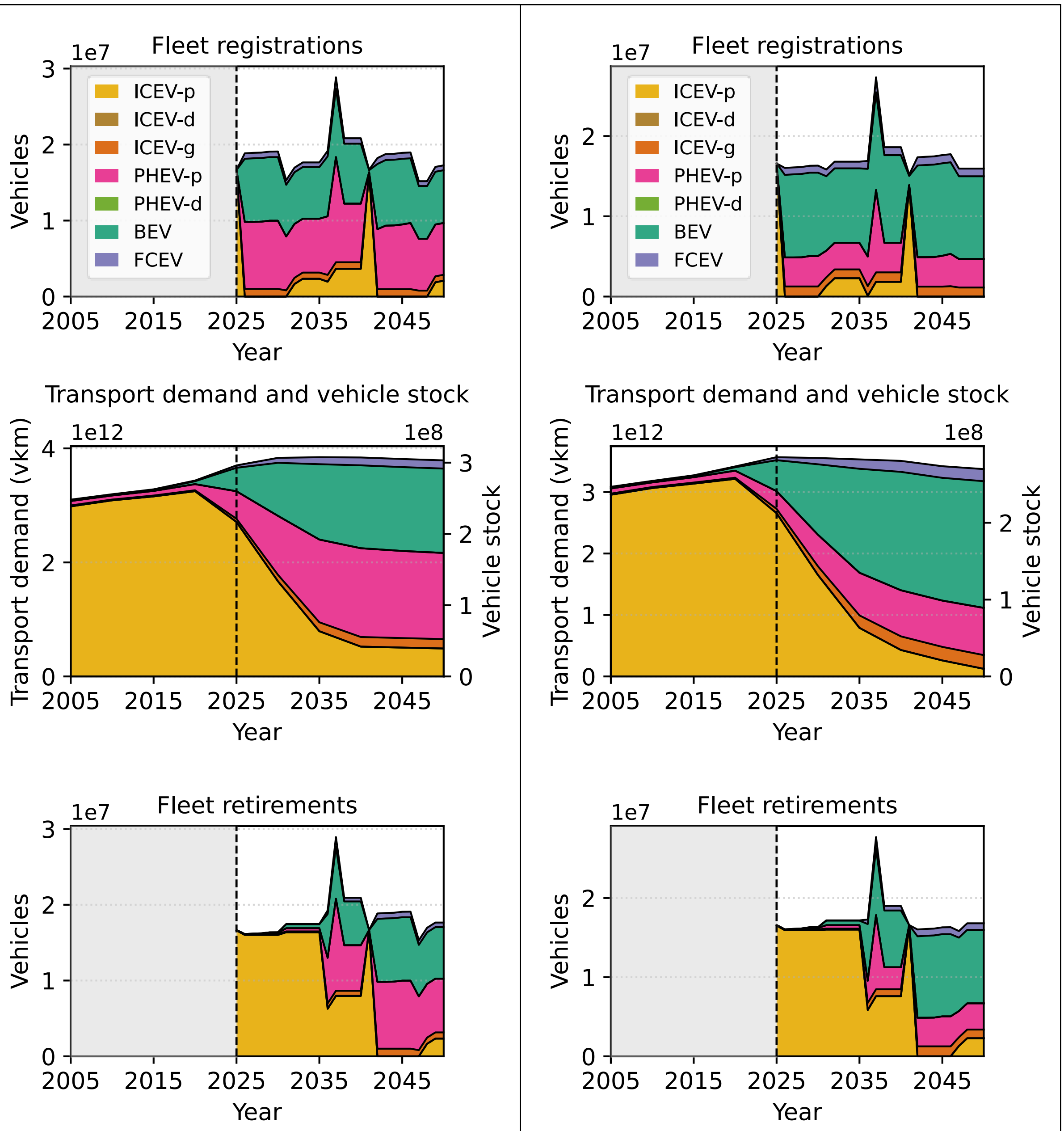


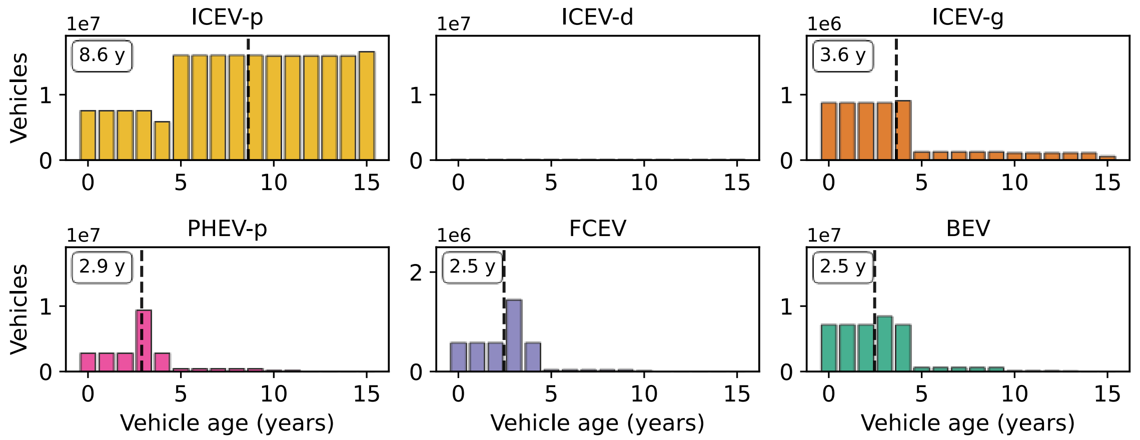
Figure S19. Time-explicit assessment of non-critical impact categories. Four out of sixteen indicators are shown, representing SDGs 13-15. EU reference scenario 2020 demand and SSP2-PkBudg1150 background scenario. Complementary results to Figure 3 in main manuscript.

9. Additional total sector assessment results

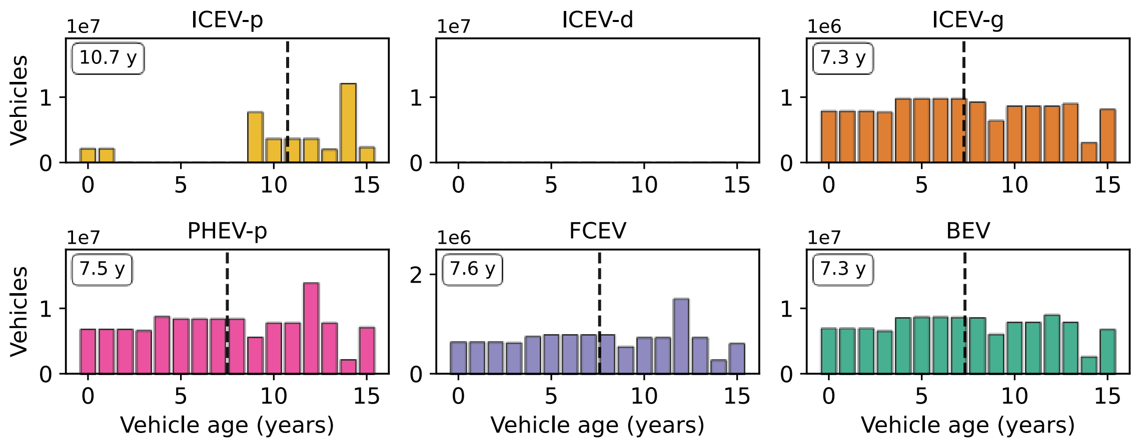


(A) Base	(B) PkBudg500

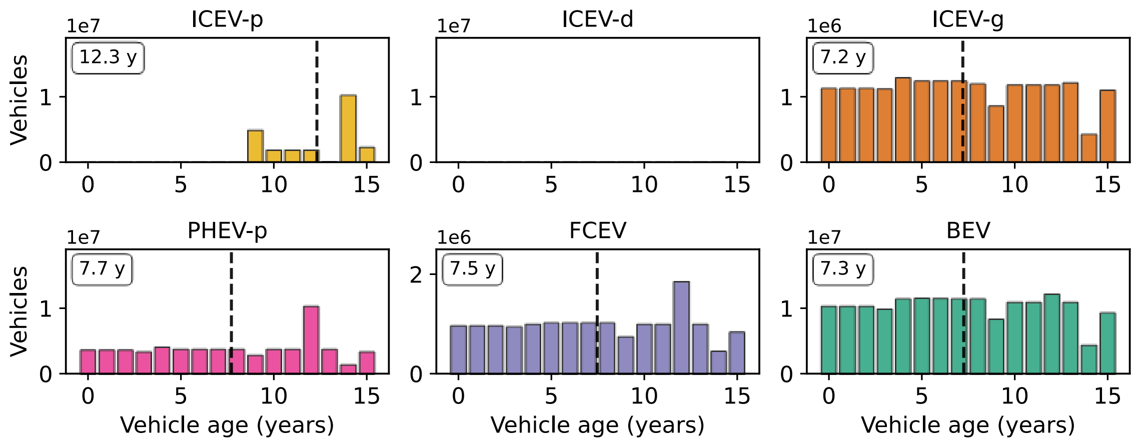
Figure S20. Transport demand and vehicle stock projections according to REMIND IAM scenarios (A) Base and (B) PkBudg500. Complementary results to Figure 5 in the main manuscript.



(A) Base and PkBudg500 in 2025



(B) Base in 2050



(C) PkBudg500 in 2050

Figure S21. Age distributions following the (A) Base and PkBudg500 scenarios in 2025 as well as (B) Base in 2050 and (C) PkBudg500 in 2050. Average values given in textboxes.

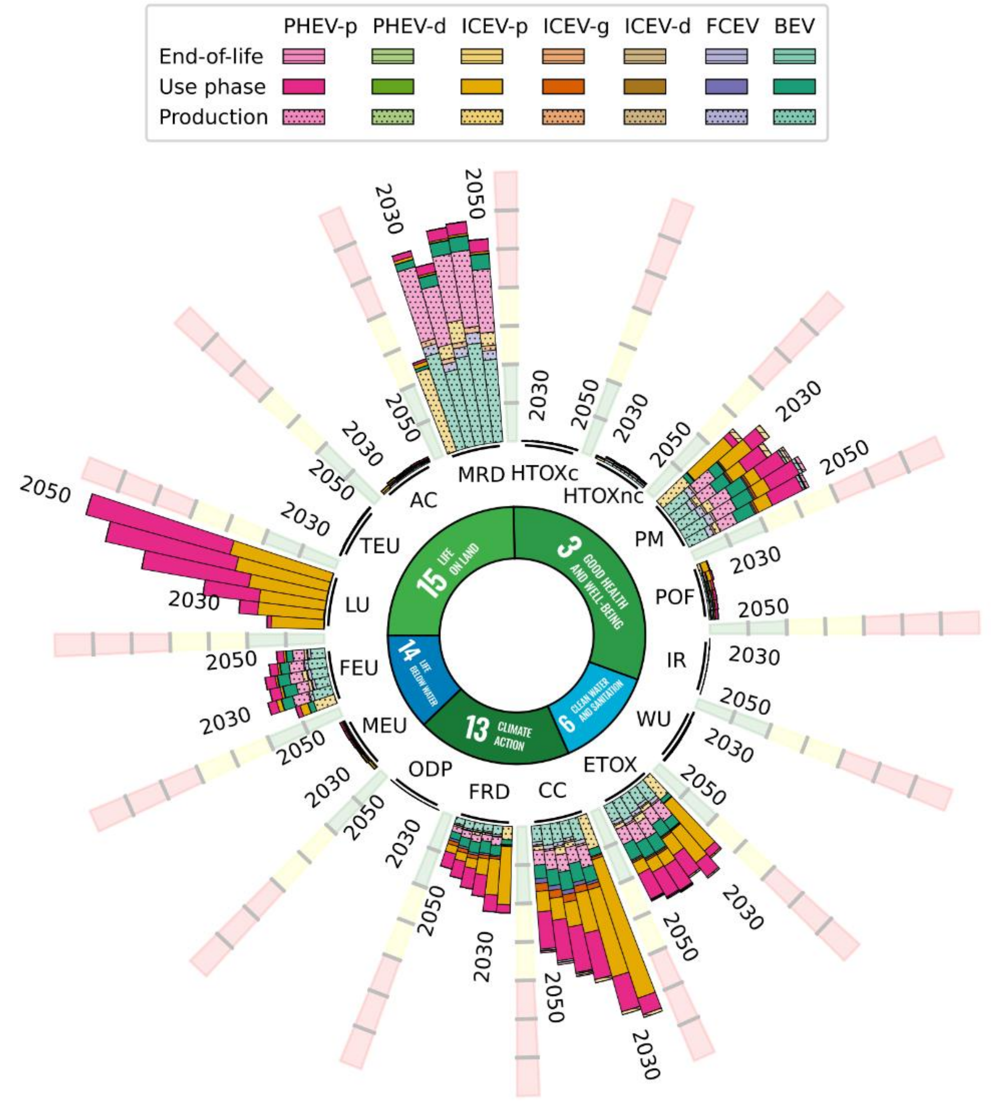


Figure S22. Total transgression levels for the Base scenario. Complementary results to the EU reference scenario 2020 results with PkBudg1150 background from Figure 6 in the main manuscript.

Figure S23. Total transgression levels for the PkBudg500 scenario. Complementary results to the EU reference scenario 2020 results with PkBudg1150 background from Figure 6 in the main manuscript.

10. Mode shift assessment

Figure S24 and Figure S25 illustrate the environmental impacts of alternative transport modes compared to electric cars. This assessment uses a global scope, as EU-specific inventories are not available for all transport options. The selected activities are detailed in Table S3.

Overall, the results show that, under a global scope, electric cars are, with few exceptions, the most environmentally impactful option among those considered. Bicycles (both conventional and electric) consistently exhibit the lowest environmental impacts. They are followed by public transport options such as trams and trains, which also perform favourably.

In contrast, conventional petrol-based buses can be more impactful than electric cars for several impact categories, including climate change, photochemical oxidant formation, eutrophication, and acidification. Electric buses, while also dependent on battery use, generally have lower impacts per vkm due to their longer lifespans and shared passenger loads, which help offset the environmental burden associated with battery production.

These findings support the conclusion that shifting to alternative transport modes, particularly active and shared modes, can be an effective strategy to reduce pressure on planetary boundaries. These results align with broader LCA literature. For instance, Spreafico *et al*.[18] found that across the EU-28 footprint, bicycles had the lowest per-km environmental impact, with buses ranking next most sustainable, and cars dominating. Similarly, Huang *et al*.[19] reported that e-bikes substantially outperform battery electric vehicles and petrol cars across multiple impact categories in the UK context.

Table S3. List of activities selected for mode comparison.

Mode	Activity	Region
Bicycle	transport, passenger, bicycle	RoW
Electric bicycle	transport, passenger, electric bicycle	RoW
Tram	transport, tram	RoW
Train	transport, passenger train	RoW
Regular bus	transport, regular bus	RoW
Electric bus	transport, passenger bus, battery electric - overnight charging, 13m single deck urban bus	World
Electric car	transport, passenger car, electric*	GLO

* Results divided by 1.6 to convert vehicle to passenger kilometer.

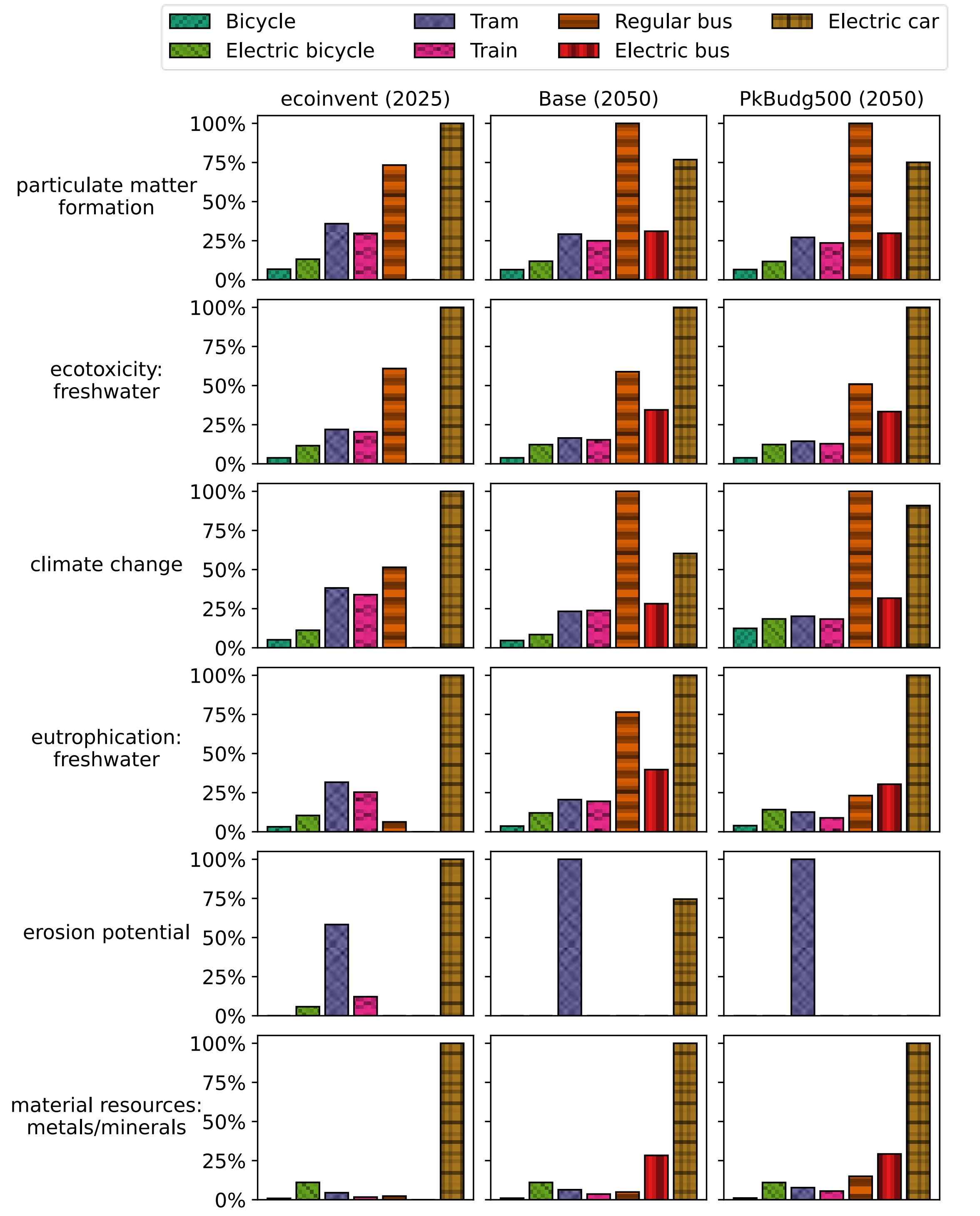


Figure S24. Transport mode impact comparison for six critical categories of main assessment. Shown are alternatives to light-duty transport modes, comparing bicycle, and public transport options with transport by electric car. Results are generated with ecoinvent v3.9.1 cutoff system model and premise v2.2.7 using the SSP2 socioeconomic pathway under the PkBudg1150 scenario.

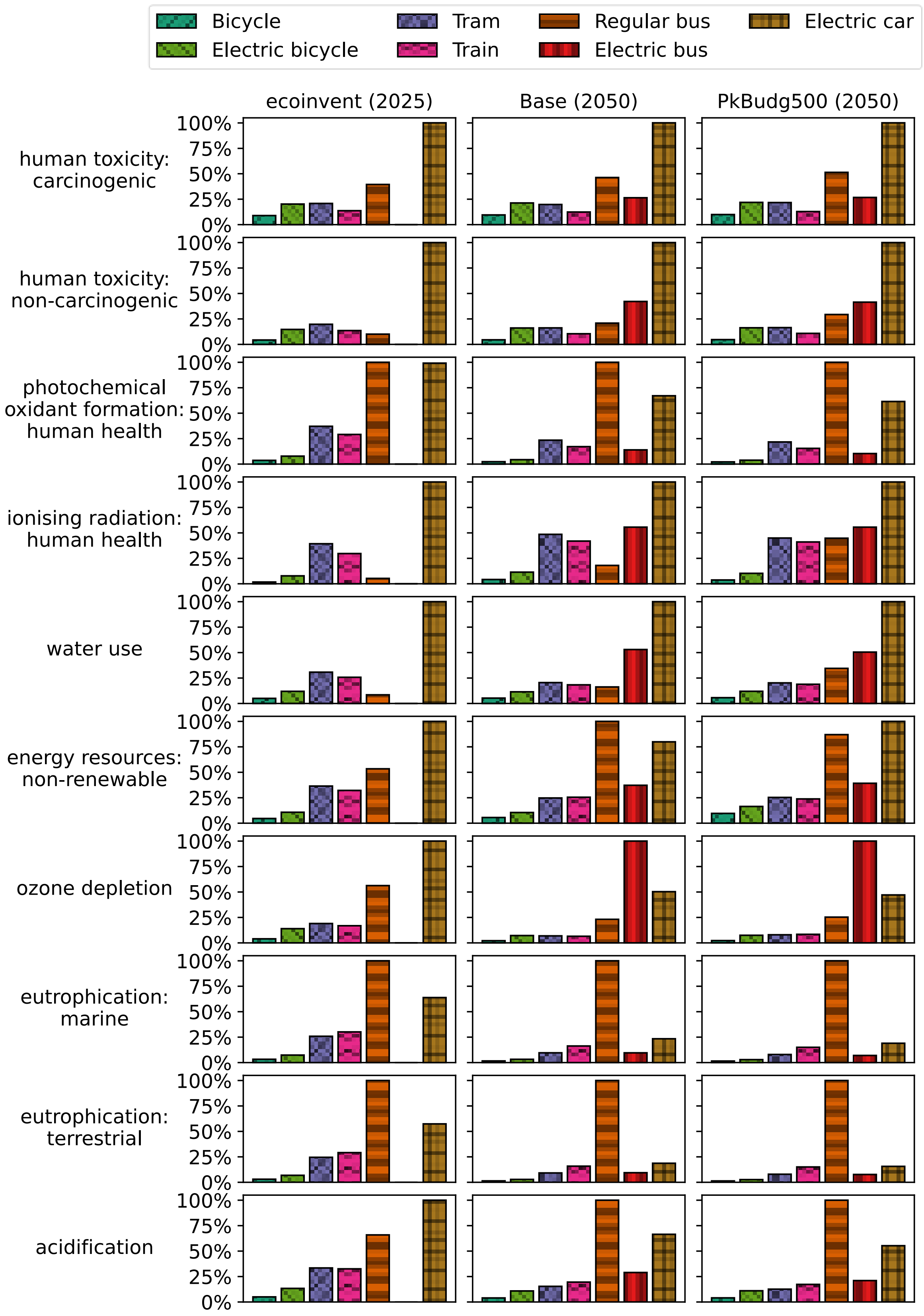


Figure S25. Transport mode impact comparison for remaining categories. Shown are alternatives to light-duty transpsort modes, comparing bicycle, and public transport options with transport by electric car. Results are generated with ecoinvent v3.9.1 cutoff system model and premise v2.2.7 using the SSP2 socioeconomic pathway under the PkBudg1150 scenario.

11. Assumptions and limitations

Assumptions

- **System boundaries**: The study adopts a cradle-to-grave perspective, encompassing all stages from raw material extraction, processing, and manufacturing of vehicle components and energy carriers, through fuel or electricity production, distribution, and vehicle operation, to the end-of-life phase covering vehicle recycling and disposal. Infrastructure such as roads, fuelling stations, and charging networks is included.
- **Demand and usage patterns**: Future LRPT demand follows the EU reference scenario 2020 (PRIMES), and EDGE-T projections in the Supplementary Material, with a constant average occupancy of 1.6 persons per vehicle, an average lifetime of 16 years (200,000 km), and representative EU-wide driving and usage patterns without behavioural changes.
- **Background data and scenarios**: Prospective life cycle inventories are generated via premise v2.2.7 using REMIND (SSP2-PkBudg1150 for the main scenario, SSP2-Base, and SSP2-PkBudg500 in Supplementary Material) and ecoinvent 3.9.1, assuming projected energy system, industrial, and supply chain changes occur as modelled.
- **Planetary boundary allocation**: The safe operating space is downscaled to the EU level using a population-based egalitarian approach, without further allocation to specific sectors. This means that, even if an impact category is calculated to be within the safe share of the operating space, the remaining share should be sufficient to allow for the other sectors of the economy to operate.

Limitations

- **Prospective data robustness**: Climate-related flows benefit from higher-quality prospective data, whereas categories such as toxicity rely on less robust projections.[20]
- **LCIA indicator quality**: The quality levels of the EF LCIA indicators vary across impact categories from I to III,[13,14] as shown in Table S2, reflecting differences in methodological robustness and data reliability, meaning that indicators with lower quality levels such as land use, water use, and resource depletion introduce higher uncertainty into the overall assessment and should be interpreted with caution.
- **PB conceptual alignment**: The PB-LCIA method[12] harmonizes planetary boundary control variables with LCA indicators, but differences in scale and metrics introduce methodological uncertainty and potential inconsistencies across impact categories.[21]

- **PB coverage and spatial scope**: The approach covers only a subset of Earth-system processes, with incomplete treatment of key processes such as biosphere integrity and novel entities, and applies globally aggregated boundaries, limiting the capture of regional environmental pressures such as land and freshwater use.[21]
- **PB threshold and data uncertainty**: Several boundary thresholds are based on best estimates rather than fixed limits, and background data were not developed for PB applications, which increases uncertainty.[12]
- **Recycling representation**: Potential advances in material recovery, especially for batteries, gliders, and electronic components, may be underrepresented.
- **Spatial and temporal resolution**: While regionalized and time-explicit analysis is applied, regionalization is limited to country-specific electricity markets for BEVs and PHEVs, excluding other electricity-dependent activities such as hydrogen electrolysis. Additionally, the origin of other fuels (petrol, diesel, gas) is assumed constant across the EU, without accounting for potential regional differences in sourcing and production pathways.
- **Technology coverage**: Unmodeled technological shifts (e.g., disruptive innovations, large-scale deployment of negative emission technologies) are not covered.

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