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Life-cycle impacts from different decarbonization pathways for the European car fleet

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Abstract

For light-duty vehicles (LDVs), alternative powertrains and liquid fuels based on renewable electricity are competing options considered by policymakers and stakeholders for achieving necessary CO_2 emission reductions in the transport sector. While the urgency of climate change and the need to reach mitigation targets are well understood, system-wide implications along other sustainability dimensions need further exploration. We integrate a detailed transport system model into an integrated assessment framework and couple it with prospective life cycle impact analysis. This allows to assess different technological pathways of the European LDV fleet until 2050 for a comprehensive set of environmental and resource depletion indicators. Results indicate that greenhouse gas emissions drop significantly in all mitigation scenarios. However, impacts increase in several non-climate change impact categories even with fully renewable electricity supply. Additional impacts arise from the production of battery and fuel-cell components, and from a significant rise in electricity demand, most prominently for synthetic fuels. We consequently find that changes in mobility life-styles and in the relevant industrial processes are paramount to reduce environmental impacts from a climate-friendly LDV fleet across all categories.

1. Introduction

With the ever increasing emissions of greenhouse gases (GHGs) related to road transportation globally—rising from 5.2 Gt of direct CO_2 emissions in 2010 to 6.1 Gt in 2018 (IEA 2021)—, the idea of a future carbon-sober economy may not be attainable without combining stringent policies with a dramatic technological shift. While this statement seems to gather general agreement among the studies carried out by various intergovernmental organizations and academics alike (Intergovernmental Panel on Climate Change 2015, Axsen *et al* 2020, International Council on Clean Transportation 2020), the direction of this shift is debated. The alternatives are *battery-electric vehicles* (BEVs), fuel-cell electric vehicles (FCEVs), and internal combustion engine vehicles (ICEVs) powered by synthetic fuel made from renewable electricity (efuels). BEVs are most efficient with a 'powerplant-to-wheel' (P2W) efficiency of ∼70%, FCEVs achieve around 25%–30%, and ICEVs with efuels 10%–15% (Yazdanie *et al* 2014).

In the public discourse, life-cycle environmental footprints of conventional vehicles are usually compared with footprints from BEVs fuelled by the current regional electricity mix, e.g. in the EU (Hawkins *et al* 2013), or in the US (Onat *et al* 2015). An extensive review is given by Requia *et al* (2018). More in-depth studies use prospective life cycle assessment (P-LCA) to evaluate the impacts—mostly focussing on life-cycle GHG emissions—of future BEVs linked to scenarios of electricity markets (Spielmann *et al* 2005, Bauer *et al* 2015, Elgowainy *et al* 2018, Ambrose *et al* 2020, Beltran *et al* 2020, Cox *et al* 2020). While such studies are very helpful in comparing the performance of different powertrain technologies in the

future, they do not explore the implications the penetration of a given technology may have on the energy system and economy because of changes in demand for energy and resources. Such feedback is studied in integrated assessment models (IAMs) with varying detail on the transportation sector (Anandarajah *et al* 2013, McCollum *et al* 2014, Pietzcker *et al* 2014, Rottoli *et al* 2021b). To date however, the impact assessment in these models is mostly limited to use-phase GHG emissions and the integration of P-LCA with IAMs is still impeded by the complexity of the resulting systems. Exceptions include the derivation of prospective life-cycle coefficients for the electricity sector (Arvesen *et al* 2018, Luderer *et al* 2019).

In the present work, we for the first time incorporate the state of an energy system that is sensitive to the future light-duty vehicle (LDV) fleet into life-cycle inventories of this fleet. We are thus able to provide consistent per-vehicle and total fleet life cycle impacts of LDVs in Europe for an extended number of environmental and resource depletion indicators. A complete picture of the possible implications of different transport sector policies is necessary to make informed decisions. This complete, consistent picture is especially important when considering the significant time scales and investments required for R&D and infrastructure deployment by some of the strategies.
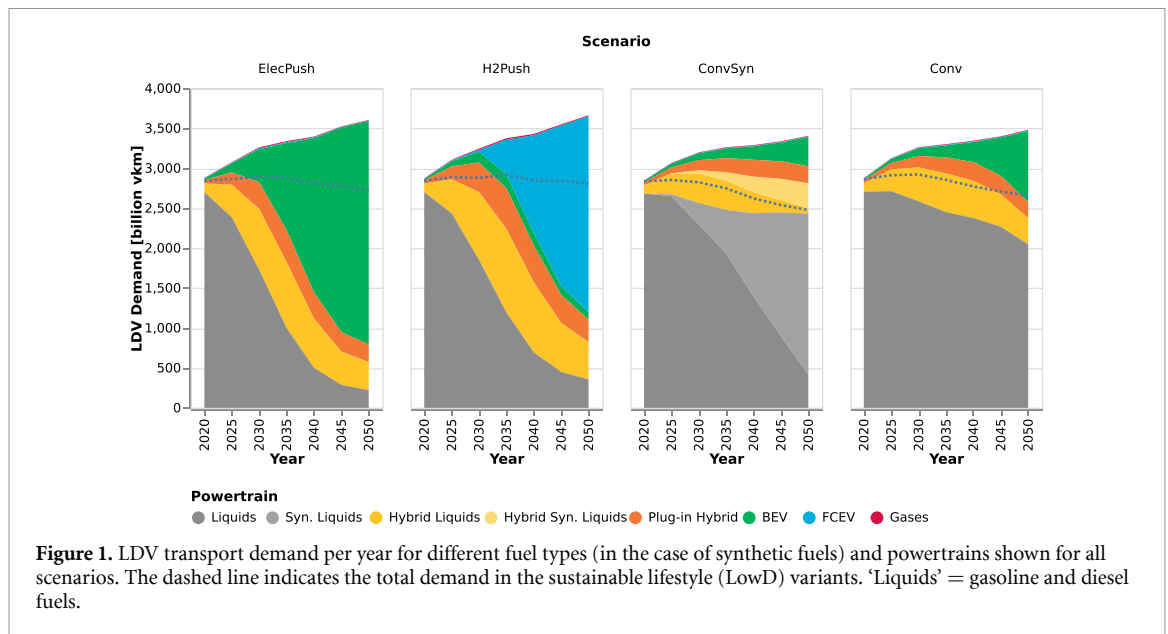
2. Methods

For this assessment, scenarios for the transport sector are created using the IAM REMIND (Luderer *et al* 2020, Baumstark *et al* 2021) and its newly developed transport sector model EDGE-T (Rottoli *et al* 2021a). REMIND is a multi-regional energy-climate-economy model used in previous studies on climate mitigation pathways, e.g. the IPCC special report on the 1.5 °C target (Rogelj *et al* 2018). In simple terms, REMIND tries to satisfy the projected demand in energy for the main sectors of the economy by deploying a number of energy production and transformation technologies under economic constraints and with perfect foresight in the model time frame 2005–2100. Taxation of carbon dioxide and other GHG emission is iteratively adjusted to limit cumulative budgets in line with climate targets. EDGE-T is a price-driven consumer's-choice model. Given the REMIND energy price inputs, it provides a fine-grained mix of transportation demands for the passenger and freight sectors. Among other factors, non-fuel price incentives that are known to influence users' preferences are considered such as the value of travel time and the availability of attractive models and of refueling infrastructures. As a result, EDGE-T calculates the energy intensity of (aggregated) energy services, the fuel mix and the costs for transportation. The models operate iteratively until REMIND reaches a steady state. For details on the coupling, see Rottoli *et al* (2021a). The environmental

impacts related to the LDV fleet are assessed using the passenger car LCA model *carculator* (Sacchi *et al* n.db) feeding on a time- and scenario-specific variant of the LCA database ecoinvent (Wernet *et al* 2016). The technology specific vehicle parameters used in carculator are listed in the supplementary material, section 6.2, tables 4–8 (available online at stacks.iop.org/ERL/17/044009/mmedia). These parameters have associated uncertainty distributions that are used in sensitivity analysis, as described in section 6.4 in the supplementary material. Efficiencies, emissions and market shares for hydrogen and electricity production and car fuel markets are harmonized between REMIND and ecoinvent using the *premise* library (Sacchi *et al* In Review), while air-pollution emission factors for selected heavily-polluting processes in ecoinvent are adjusted according to the GAINS project (Amann *et al* 2011); see section 5 in the supplementary material. For the evaluation of the LCA impacts we apply the ReCiPe mid-, and end-point methods (Goedkoop *et al* 2013), using average (i.e. non-local) damage factors. For climate footprints we apply the IPCC 2013 GWP 100a method (Intergovernmental Panel on Climate Change 2014) to calculate the global warming potential for a 100-year time horizon. Details on the methods can be found in the supplementary material, section 1, together with an introductory showcase of the LCA method (section 1.4). For a general introduction to the LCA method, please refer to Hauschild (2018).

2.1. Scenario design
In our framework, REMIND covers the energy supply side and the non-transportation demand sectors. All parameters in REMIND are left unaltered across the scenarios, with the single exception of the ConvSyn scenario and its LowD variant, see below. In this scenario, the synfuel share in the diesel and gasoline blend has been adjusted exogenously to reach 80% in 2050. All other scenario specific modifications are applied to the EDGE-T model. EDGE-T, being a price-driven choice model, has its most important levers in the implementation of the technological focus scenario projections for vehicle costs and for perceived costs, such as model availability and range anxiety. Vehicle costs are modified to support the focus technology (rebates) and de-incentivize the purchase of other drivetrains (feebates) if needed. The perceived costs are calibrated to reflect historical shares of the different technologies and for the future follow expectations on the uptake of alternative technologies. Note that these costs are essentially free parameters for future timesteps and allow for a wide range of fleet compositions. More detail on the assumptions for these parameters is given in Rottoli *et al* (2021b) for the same set of scenarios. The intrinsic parameters for the LCA model *carculator* are left unaltered across scenarios.

Figure 1. LDV transport demand per year for different fuel types (in the case of synthetic fuels) and powertrains shown for all scenarios. The dashed line indicates the total demand in the sustainable lifestyle (LowD) variants. 'Liquids' = gasoline and diesel fuels.

2.2. The scenarios

The geographical scope of REMIND is global, but for this study we focus on the 'EUR' region, which is equivalent to the EU-27 plus the United Kingdom[4]. All scenarios are subject to a worldwide carbon budget equivalent to the cumulative release of 700–800 Gt of CO_2 in the timeframe 2011–2100. This is consistent with a high likelihood of limiting the global temperature increase to 1.5 °C. In contrast to current EU and UK legislation we implemented no regional or sectoral emission reduction targets to allow our model to freely select low-mitigation policies for the LDV sector. Apart from the budget constraint, the goal and scope of our scenarios is thus of explorative nature ('possible future, what can happen?') (Börjeson *et al* 2006). Six scenarios with four different technological foci are considered. These scenarios do not necessarily present equally likely projections but are rather designed to span the spectrum of possible future technology deployments. The level of LDV mobility in each of these scenarios is displayed in figure 1. Effects of the COVID-19 pandemic are not considered since short term adjustments are small on a 5 year background and long-term trends are yet to emerge. For more information on the age structure and the vehicle size distributions in the fleet, please refer to figure 4 in the supplementary material. The scenarios are documented in detail in Rottoli *et al* (2021b) and available at Zenodo (Dirnaichner *et al* 2021).
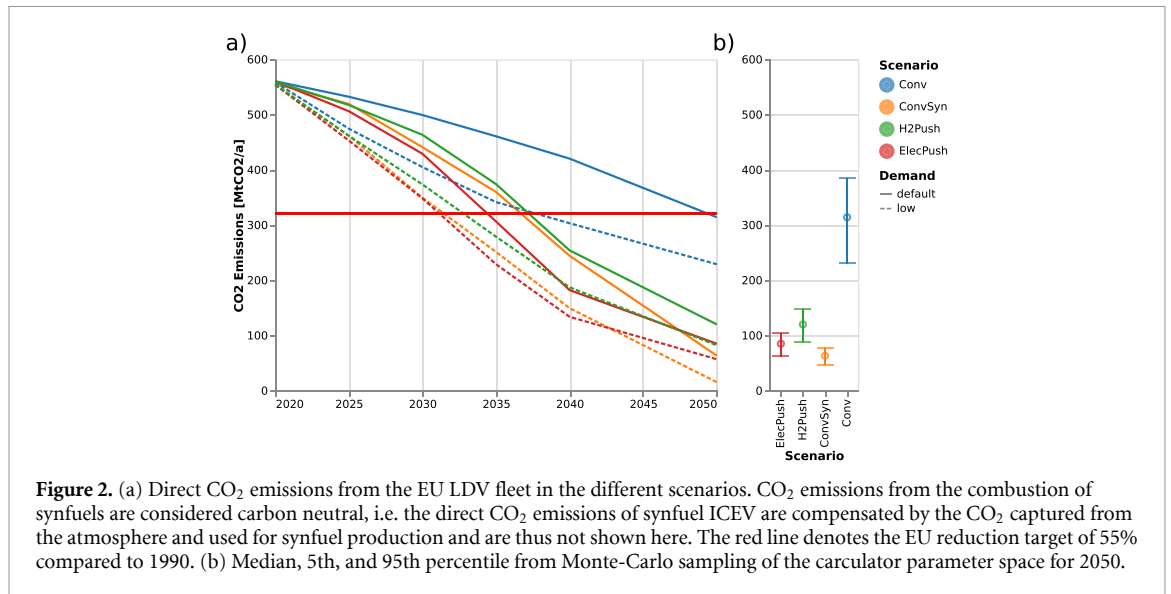
Conv and **ConvSyn** feature the most conservative assumptions regarding the vehicle markets: In both scenarios the markets remain dominated by cars with internal combustion engines. The ∼10% market

share of BEVs remains at the lower end of available projections (Muratori *et al* 2021). In the **Conv** scenario, it is assumed that no transportation-sector specific policies are in place beyond economy-wide carbon pricing. On the other hand, for the **ConvSyn** scenario, a gradual transition toward mostly synthetic fuels supply (80%) for gasoline and diesel by 2050 is mandated. At least 95% of the hydrogen for the synthetic fuels is supplied by electrolysis from 2025 on; the remaining share originates from natural gas reforming. As a carbon source for synthetic fuel production, we assume atmospheric carbon dioxide removal from low-temperature direct air capture. Note that the demand for LDV mobility is affected by comparably high fuel prices in ConvSyn, leading to a difference of 10% by 2050 compared to ElecPush.

In a third scenario, entitled **H2Push**, a global hydrogen economy emerges which makes fuel-cell vehicles a viable option: being not yet established in the market, FCEVs do not cover all LDV demands in 2050. We reach a penetration rate of 67% in 2050—see bottom left panel in figure 1—below the target of 80% considered in the EU's HyWays scenario (European Commission. Directorate-General for Research 2008). This scenario assumes high subsidies to reduce the financial burden and broad societal acceptance of hydrogen-based technologies. It is assumed here that 95% of the hydrogen is produced via electrolysis using the electricity mix as defined by REMIND under this energy scenario for each future time step. In 2020, hydrogen is obtained mainly via steam reforming of natural gas.

Finally, the **ElecPush** scenario promotes a fast and thorough acceptance of (battery) electric vehicle technologies. Under this storyline, a progressive majority of consumers embraces the new technology and policymakers guide the transformation by subsidies and infrastructure build-up. Here, the share of LDV

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[4] The scenario specific decarbonization strategies for the LDV fleet are applied globally, but the implications are only discussed for Europe. The low level of detail available on the LDV fleets in some world regions proscribe a global scope of the study.

Figure 2. (a) Direct CO_2 emissions from the EU LDV fleet in the different scenarios. CO_2 emissions from the combustion of synfuels are considered carbon neutral, i.e. the direct CO_2 emissions of synfuel ICEV are compensated by the CO_2 captured from the atmosphere and used for synfuel production and are thus not shown here. The red line denotes the EU reduction target of 55% compared to 1990. (b) Median, 5th, and 95th percentile from Monte-Carlo sampling of the carculator parameter space for 2050.

demand supplied by BEVs reaches 76% in 2050 and BEVs constitute 95% of new sales. This is well in line with projections from 'High' scenario of the NREL Electrification Futures Study (Mai *et al* 2018), or the Shell Sky scenario.

In all these scenarios, LDVs are assumed to remain the major pillar of individual mobility, with growth rates based on historical trends. In additions, we consider low-demand variants (**LowD**) for all scenarios, in which new mobility patterns emerge and LDVs are partially replaced by other modes of transport (see supplementary material, figure 5). The lifestyle changes in our scenarios reduce the total LDV demand by almost 25% compared to the default trajectories in the scenarios in 2050, as shown in figure 1. The scenario data is published at (Dirnaichner *et al* 2021).

3. Results

The main purpose of the different strategies portrayed here in the form of the three fuel-shift scenarios is the reduction in GHG emissions for the LDV fleet. The direct CO_2 emissions from the fleet are shown in figure 2 for the four scenarios with baseline demand patterns (solid lines) and low demand for LDV-based mobility (dashed lines). In this figure, direct emissions from synthetic liquids are considered climate-neutral for simplicity. Notably, none of the scenarios in our ensemble succeeds in meeting the EU transport-sector reduction target of 55% by 2030 (322 $MtCO_2$). The LowD variant of ElecPush and ConvSyn come closest to the target, reaching it by 2031.

Figure 3(a) shows yearly life-cycle global warming potentials for the full fleet. The range of different emission trajectories is spanned by the Conv scenario on the upper end and the low-demand variant of the ElecPush scenario on the lower end. On the global level, all scenarios stay within the 800

$GtCO_2$ budget, including the Conv scenarios where (mild) hybridization is the only measure taken to reduce emissions. In these scenarios, negative emissions in other regions are used to offset the surplus fleet emissions in the EU. For details on the resulting global CO_2 balance, please refer to the supplementary material, figure 3.

In figure 3(c), we show GHG emissions per vehicle-kilometre for different life cycle process categories in 2020 and 2050. We can clearly observe the reduction in emissions from the energy chain for BEVs and FCEVs in their respective focus scenarios which make up for the largest part of emissions in 2020. The carbon intensity of the electricity mix in 2020 is 305 gCO_2-eq kWh^{-1} (full life cycle emissions) and 10–12 gCO_2-eq kWh^{-1} in 2050. We also observe a decrease in emissions for ICEVs, mainly due to a mild hybridization of their powertrain (i.e. an auxiliary electric motor operates alongside the main combustion engine). Please refer to the supplementary material, tables 6 and 7, for details on these assumptions. In the ConvSyn scenario in 2050, one third of direct GHG emissions are offset by direct air-capture in the energy supply chain, serving as the carbon supply for the synthetic fuels. The synthetic liquids which make up 80% of the fuel supply for a 2050 ICEV in the ConvSyn scenario are far from carbon neutral, with significant emission from processing and remaining fossil energy carriers in the heat supply. Emissions from vehicle production, maintenance and disposal decrease in all scenarios due to improvements in industrial processes and in the energy supply. Remaining emissions from glider production in 2050 can be traced back mainly to the production of aluminium (30%) and steel (10%), and in particular to coal-fired heat supply and pig iron production. The GHG emissions from ICEV vehicle production (excluding energy storage) are slightly lower due to their lighter powertrain.
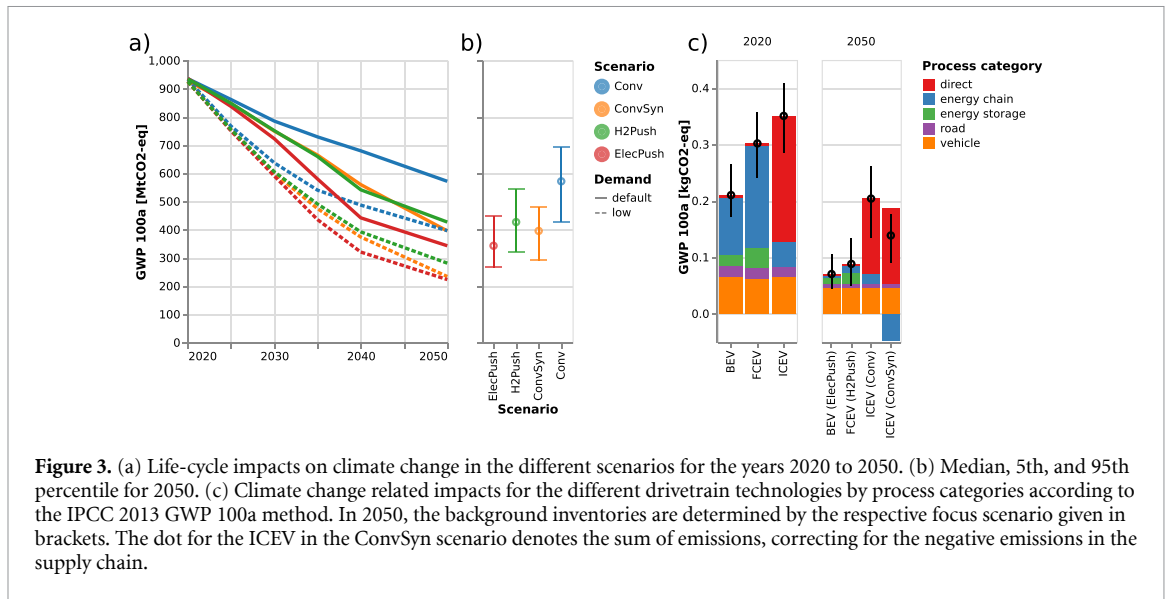
Figure 3. (a) Life-cycle impacts on climate change in the different scenarios for the years 2020 to 2050. (b) Median, 5th, and 95th percentile for 2050. (c) Climate change related impacts for the different drivetrain technologies by process categories according to the IPCC 2013 GWP 100a method. In 2050, the background inventories are determined by the respective focus scenario given in brackets. The dot for the ICEV in the ConvSyn scenario denotes the sum of emissions, correcting for the negative emissions in the supply chain.
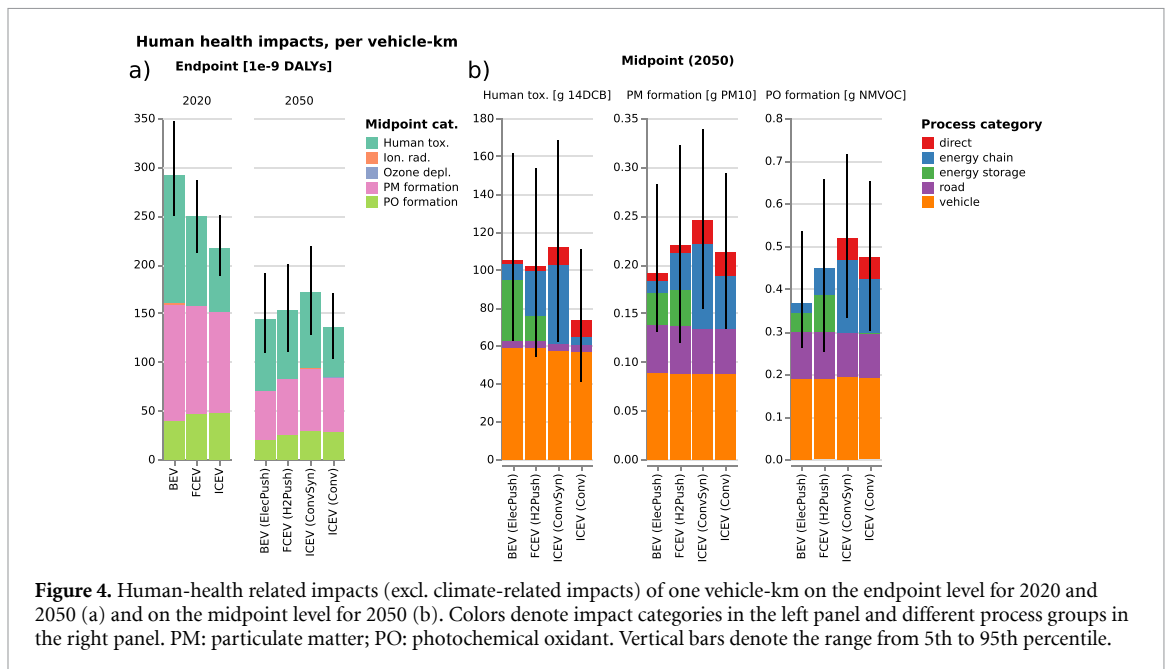

Figure 4. Human-health related impacts (excl. climate-related impacts) of one vehicle-km on the endpoint level for 2020 and 2050 (a) and on the midpoint level for 2050 (b). Colors denote impact categories in the left panel and different process groups in the right panel. PM: particulate matter; PO: photochemical oxidant. Vertical bars denote the range from 5th to 95th percentile.

3.1. Health impacts (excl. climate-related impacts)

Health impacts per vehicle-km are shown in figure 4 at the endpoint level (unit: DALY, disability adjusted life years) in (a) and for the three most prominent midpoint categories that make up the endpoint impacts in (b), i.e. human toxicity impacts (mainly causing cancer), particulate matter (PM) (respiratory issues, lung cancer) and photochemical oxidants (POs) (asthma, COPD, lung damage). Climate related contributions to the human health endpoint are excluded. From figure 4(a) it is evident that average BEVs with the current European electricity mix have comparably high adverse health impacts caused by the remaining coal power plants in the European electricity mix. In 2050, health related impacts decrease considerably in all scenarios, with

the highest number of DALYs reported for the synfuel driven ICE car.

The detailed split of the dominant midpoint impact categories in figure 4(b) sheds some light on the origin of the differences among the technologies in 2050. Higher direct impacts still arise from ICEVs. Emissions from the energy chain are proportional to the P2W efficiencies of the respective drivetrains for all technologies except the fossil-fuelled ICE. Human toxicity related impacts are comparably low across the fossil fuel supply chain. This category is dominated by impacts linked to glider production, namely heavy metals from tailings from mining operations which can diffuse into ground water. In the realm of air-pollution related health impacts we examine 'PM formation' and 'POs formation'.
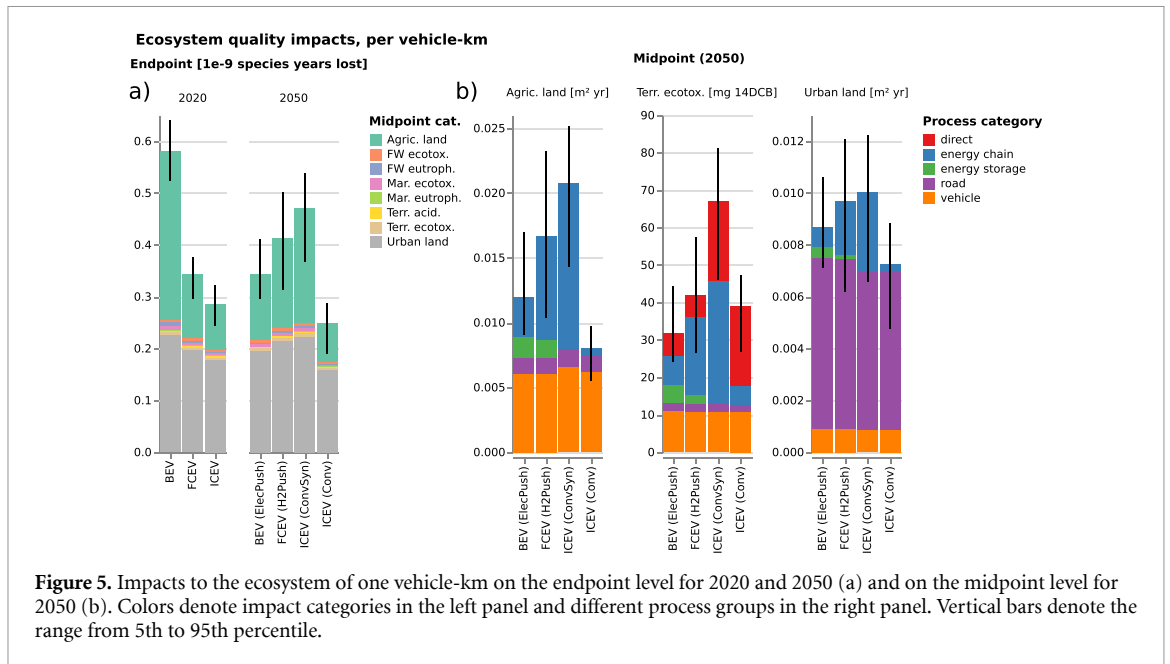
Figure 5. Impacts to the ecosystem of one vehicle-km on the endpoint level for 2020 and 2050 (a) and on the midpoint level for 2050 (b). Colors denote impact categories in the left panel and different process groups in the right panel. Vertical bars denote the range from 5th to 95th percentile.

The impact pathways for both categories are similar. Vehicle production is quite prominent, with impacts distributed equally across electricity supply, steel and aluminium production, provision of fiber-reinforced plastics and manufacturing of electronics. Abrasion emissions from brake, tire and road wear remain a local source of particulate air pollution across all powertrain types, with reductions in electrified powertrains thanks to electro-braking.

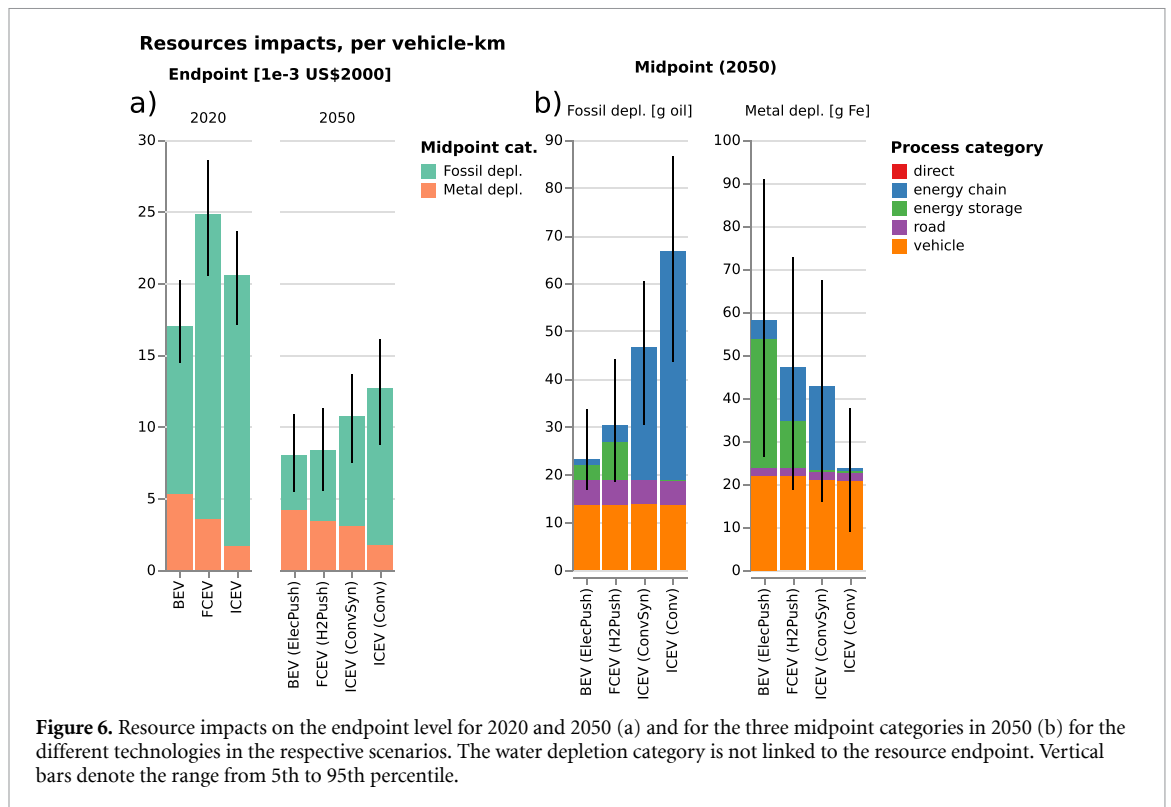### 3.2. Impacts on ecosystem quality (excl. climate-related impacts)

Land occupation impacts dominate the biodiversity endpoint category (unit: species years lost) for ecosystem health, see figure 5(a). Again, the upstream electricity demand (mainly for battery production) for 2020 BEVs has a large footprint. Land occupation resulting from the fossil ICEV and FCEV energy chain are comparably small. In 2050, the largest impacts across scenarios and technologies arise for ICEVs in the ConvSyn scenario, again due to the high electricity demand and the linked expansion of renewable energy supply, see figure 5(b). Land occupied in urban areas can be attributed mainly to roads, which are required for all technologies in all scenarios. Road wear is slightly larger for the heavier BEVs and also the need for road construction and maintenance is proportional to the vehicle mass. Terrestrial eco-toxicity impacts, shown in the central panel in figure 5(b), are governed by direct emissions and emissions along the energy chain. Consequently, synfuel-driven cars have the largest footprint, while FCEVs and ICEVs are on par with emissions from the energy chain for hydrogen production balancing direct (exhaust) emissions from ICEVs.

In the 'terrestrial eco-toxicity' category, the metals (e.g. copper) required for the provision of electricity

grid infrastructure play a major role, both when being mined and refined as well as when being recycled. Scrap copper treatment for distribution networks make up for the biggest part (37%) in the 2050 ConvSyn scenario. Other important contributions arise copper smelting (15%) and sulfidic tailings from copper mining (13%). We note, however, that copper is typically mined jointly with other metals (e.g. lead, zinc, nickel, cobalt), which requires allocating the burden of mining between these co-products. In this case, the allocation has been performed based on the respective market value of the co-products. The impacts from the energy chain in the other scenarios again reflect the P2W efficiencies. Another big share, especially for BEVs, arise from battery production (11% in 2050), where 7% of the impacts can be traced to the cathode production, namely the supply of cobalt, despite a 150% improvement of the energy density of the cells (compare table 5 in the supplementary material).

3.3. Impacts on resource demands

Resource demands on the endpoint level are quantified in ReCiPe in monetary terms for fossils and metals, see figure 6(a). For 2020, the combined demand for resources is highest for FCEVs owing to the natural gas input to the reforming process. The resource demands of a BEV during its life cycle of a BEV are lower but comparable to the ICEV. In 2050, FCEVs and BEVs clearly outperform the conventional cars. Remaining gas power plants in the system are responsible for fossil resource demands along the energy chain in the ConvSyn scenario; see figure 6(b). The remaining fossil demands for alternative technologies are governed by glider fabrication and road construction, notably coal used for the production of aluminium and petroleum for

Figure 6. Resource impacts on the endpoint level for 2020 and 2050 (a) and for the three midpoint categories in 2050 (b) for the different technologies in the respective scenarios. The water depletion category is not linked to the resource endpoint. Vertical bars denote the range from 5th to 95th percentile.

bitumen. Naturally, the fabrication of the glider is also responsible for a large share of metal demands in the form of aluminium and steel for all vehicle technologies. Steel supply chains are discussed in the supplementary material, section 6.5. In FCEVs, platinum is an important ingredient in the fuel-cell stack and in BEVs, cobalt, lithium and copper contribute to the energy chain related metal demands. For BEV batteries we assume the most common NMC-111 chemistry, see table 4 in the supplementary material. Along the energy chain, copper is required in transmission and distribution networks as well as voltage transformation, and steel and rare earths are needed for wind turbines and photovoltaic panels, leading to a prominent share of metal use linked to the energy chain in the ConvSyn scenario. The repercussions of lower recycling rates on Cobalt, Lithium and Platinum demands are discussed in the supplementary material, section 7. The water footprint, which is per the ReCiPe methodology not linked to the resource endpoint, is shown in the supplementary material, section 8.

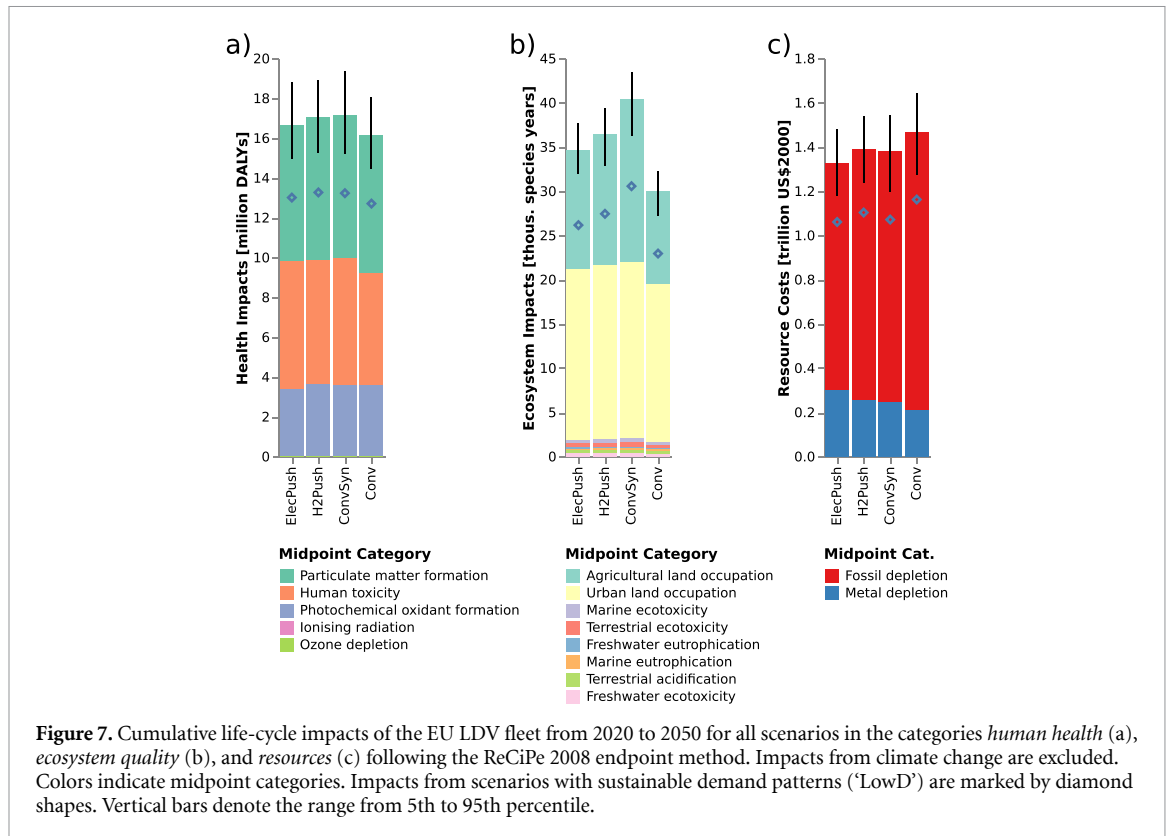**3.4. Impacts from the full LDV fleet at the endpoint level**

Finally, we compare cumulative impacts of the full LDV fleet for the three endpoint categories in figure 7. Shown are the sum of (non-climate) impacts that arise in the years 2020–2050 from the full life cycle of the European LDV fleet. In the 'Human health' category, figure 7(a), the differences among the scenarios are within the range of uncertainty and can partially be attributed to a slightly different transportation

demands, see figure 1. In the 'Ecosystem quality' category, the ConvSyn scenario causes the highest impacts due to the additional land requirements for renewable electricity production (compare figure 1 in the supplementary material). In figure 7(c) we compare expenses for resource extraction, showing small differences in the scenario uncertainty ranges in 2050. This result emerges mainly from the gradual penetration of alternative technologies with time on the one hand and remaining fossil dependencies in the industrial supply chain on the other.

The impact reductions in the variants featuring sustainable lifestyles (LowD), denoted by diamond shapes in figure 7 are mostly proportional to the reduction in cumulative LDV mobility demand. In all categories, we observe a decrease in impacts by 25% relative to the reference demand.

4. Discussion

From the life cycle analysis of the scenarios, it is evident that reductions in **GHG emissions** can be expected for the rollout of any alternative drivetrain technologies and fuels. Reductions in direct emissions with respect to 2020 range from 40% for the Conv scenario down to 85% for ElecPush. With changes in mobility lifestyles, the sector almost reaches carbon neutrality in ElecPush-LowD (97% reductions). Considering the full life-cycle emissions, even the fleet in ElecPush-LowD is far from carbon neutral (74% reductions). Globally, REMIND manages to meet the climate mitigation targets across scenarios, even in the Conv scenario, by balancing additional transport

Figure 7. Cumulative life-cycle impacts of the EU LDV fleet from 2020 to 2050 for all scenarios in the categories *human health* (a), *ecosystem quality* (b), and *resources* (c) following the ReCiPe 2008 endpoint method. Impacts from climate change are excluded. Colors indicate midpoint categories. Impacts from scenarios with sustainable demand patterns ('LowD') are marked by diamond shapes. Vertical bars denote the range from 5th to 95th percentile.

sector emissions by negative emissions using bioenergy in conjunction with carbon capture and storage (BECCS), see figure 2 in the supplement. The additional BECCS potential is acquired mainly in India and in the region of the former Soviet Union. Since this technology has adverse impacts on biodiversity and poses a challenge to land, water and food security (Fajardy *et al* 2018, Heck *et al* 2018), a no- or low-mitigation strategy in the LDV sector most likely shifts burdens to developing regions.

Harmful effects to **human health** from PM and PO emissions are likely to shift from the use phase to the mining and manufacturing phases, as 'zero exhaust emission' drivetrain alternatives (i.e. BEVs and FCEVs) are introduced. Since we do not have prospective data for some high-impact activities in the manufacturing chain we likely over-estimate these future impacts.

Regarding **damage on ecosystems**, the results suggest that direct or indirect electrification of the European LDV fleet comes at the cost of increased pressure on biodiversity, both aquatic and terrestrial. This is governed by three distinct mechanisms: an increased demand for electricity production, a shift of electricity production from fossil to non-fossil technologies, and an increased demand for battery and fuel cell production. Ecosystem impacts for indirect electrification routes are greater than for direct electrification, due to lower well-to-wheel efficiency: the largest land and ecotoxicity footprints are observed in the ConvSyn scenario. Direct electrification, by

contrast, leads eventually to an increased demand for **mineral resources** for batteries despite recycling. High electricity demands also require a decent amount of mineral resources, especially when the share of supply by renewable power plants such as wind turbines and photovoltaic panels is large.

This study has many limitations. Not all technical parameters change over time. Examples include wind turbine and electrolyser efficiencies. On the other hand, we have included improved recycling rates for steel, cobalt and platinum, improved energy density of battery cells and more efficient fuel cell stacks, and efficiency improvements for photovoltaic panels. We also do not improve emissions of all economic activities; the GAINS model is used for emission factor improvements in the electricity sector and for selected industrial processes. Another important aspect is technological switch, where innovative processes fully replace existing ones, inducing drastic improvements from the life cycle perspective. For new battery technologies, it is yet unclear which technology will replace conventional NMC designs, and life cycle inventories are usually not available until there are products ready for the market. A switch to the lithium-iron-phosphate chemistry, for example, can substantially reduce resource demands, see supplementary material, section 6.6. In light of these limitations, the presented impacts are conservative and future cars are likely to outperform them.

The characterization factors from the ReCiPe2008 method provide another source of uncertainty. They

are likely to vary as a function of time and space to an extend which is difficult to quantify.

Last but not least, variations in the input parameters for the carculator car model affect the results on the vehicle and fleet level, as shown in the uncertainty estimates in figures 2–7. Since these uncertainty estimates only cover the technical input parameters of the carculator model, but not uncertainties in the background model of the global industrial economy, the estimates present a lower bound of the actual uncertainties. The derivation of the uncertainty ranges is described in section 6.4 of the supplementary material. More specifically, improvements in the battery roundtrip efficiency, in the vehicle or battery lifetime, and in the average vehicle weight can reduce impacts significantly. Please refer to section 6.3 of the supplementary material for a sensitivity analysis to a range of input parameters for multiple impact categories. Finally, variations among impacts from different regional steel supply routes are small as part of the mobility footprint, compare section 6.5 of the supplementary material.

5. Conclusions

To decarbonize the European LDV fleet different options are on the table. All of them affect the energy system and the ecosystem, and raise concerns of international burden sharing of climate change mitigation efforts. In this article we try to assess some aspects of the LDV sector transformation using integrated assessment modeling and applying a life-cycle perspective on the technological level and on the fleet level. In the background LCA inventory we mainly modify the fuel supply markets, the electricity production facilities and markets, the recycling rates of selected metals and some processes in the steel industry according to the IAM output and other sources as a function of time. Taking into account the different sources of uncertainty discussed in the previous section we identify the following tendencies:

- No- and low-mitigation strategies for the European LDV sector can lead to an expansion of controversial negative emission technologies in less developed regions in the regime of a global carbon budget.
- Direct electrification is the most effective option to eliminate direct emissions given current demand trends. However, electrification of the LDV fleet in conjunction with a decarbonization of the electricity sector is far from sufficient to reach climate neutrality for the fleet from an life cycle perspective.
- Alternative drive-train technologies and a renewable electricity supply both drive land and mineral resource demands, entailing larger nonclimate impacts on ecosystems. However, among all climate change mitigation options, direct

electrification exerts the lowest pressure on ecosystems due to high electricity-to-wheel efficiency.
- Alternative drive-train technologies will shift the pressure that conventional cars exert on human health and the ecosystem in the EU to regions which supply raw metals or host the steel industry.
- Especially in the human health category, the choice of technology does not make a big difference when excluding climate change related impacts. To mitigate impacts of individual mobility on human health, a change in mobility lifestyles is mandated.

The transformation of the steel industry toward hydrogen and electricity-based processes and technological innovations in the metal mining and refining sector can certainly invalidate some of these points. On the other hand, our analysis does not include ethically troublesome practices, e.g. the artisanal mining of cobalt which still makes up for a significant fraction of the world cobalt supply (Nkulu *et al* 2018). A reduction in LDV usage directly translate into a more sustainable mobility footprint without the reliance on yet-to-develop green technologies while mitigating other externalities such as congestion, land consumption, accidents, and noise. In the light of these findings, EU policies for a sustainable transformation of the LDV fleet should aim (1) at a reduction of the total fleet size, (2) to expand the BEV fleet share, (3) to reduce the average vehicle weight, and (4) to substitute burdensome upstream processes, especially for the provision and refinement of metals. Since these processes are mostly not under European jurisdiction, policies that address the responsibility of car manufacturers for their supply chains are an option.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: 10.5281/zenodo.4979995.

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