Alternative electrification pathways for light-duty vehicles in the European transport sector

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List of acronyms

BEV Battery Electric Vehicle

CES Constant Elasticity of Substitution

EDGE-T Energy Demand GEnerator-Transport

FCEV Fuel Cell Electric Vehicle

GDP Gross Domestic Product

IAM Integrated Assessment Model

IAMC Integrated Assessment Modelling Consortium

ICE Internal Combustion Engine

H_2 Hydrogen

LDV Light-Duty Vehicle

NDCs Nationally Determined Contributions

PHEV Plug-in Hybrid Electric Vehicle

PtL Power-to-Liquid

REMIND REgional Model of INvestments and Development

TCO Total Cost of Ownership

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Highlights

- Electrification is an attractive option to reduce CO_2 emissions from transport
- Alternative electrification options differ in terms of impact on the energy system
- Indirect electrification might result in a critical burden on the supply sector
- Policies addressing consumer preferences are crucial to trigger mobility shift

Abstract

There is a wide consensus that a fundamental technology shift within the light duty vehicles (LDVs) sector is necessary to achieve the emissions reductions required for the Paris Agreement's targets, but substantial controversy prevails about the most suitable strategy. While some decision makers

favor a transition to battery electric vehicles, others advocate for fuel cell vehicles and e-fuels. These strategies differ markedly in terms of consumer acceptance and implications for the energy system. We explore a range of electrification pathways in Europe until 2050. Direct electrification leads to a strong reduction in direct CO_2 emissions of LDVs, with electric vehicles reaching 90% of sales in 2050. Indirect electrification places substantially higher pressure on the supply sector, with almost double the primary energy demand relative to direct electricity use. In addition, the implementation of complementary policies addressing perceived inconvenience markups for alternative mobility is crucial to initiate the mobility transformation.

1. Introduction

The transport sector is generally considered one of the greatest decarbonization bottlenecks on the road to emissions neutrality (Creutzig et al., 2015a; Luderer et al., 2018). To halt global warming and transition to CO_2 neutrality in the coming decades, the sector needs to undergo a deep transformation to greatly reduce its reliance on fossil fuels (Roelfsema et al., 2020).

Previous studies highlighted that a massive deployment of low carbon resources in the power sector (such as renewables - photovoltaics, wind, biofuels - or via carbon capture and sequestration) offers a large and cost effective decarbonization potential (Luderer et al., 2018). By contrast, some demand sectors, among which transportation, proved to be difficult to decarbonize, due to the technical limitations linked to replacing oil-based fuels (de Blas et al., 2020). In this framework, a transition to an electricity-based transport sector would co-benefit from the power sector electrification and is therefore considered an attractive option to reduce sectoral CO_2 emissions. In this study, we aim at contributing to this debate, exploring a range of alternative decarbonization pathways of light-duty vehicles (LDVs) via electrification.

Electricity can be stored onboard in batteries in Battery Electric Vehicles (BEVs), converted into hydrogen and supplied to Fuel Cell Electric Vehicles (FCEVs), or used to produce synthetic e-fuels for internal combustion engines. E-fuels are synthetic hydrocarbons obtained by combining hydrogen from electrolysis with a carbon source. If the carbon is extracted from air or from exhaust streams, e-fuels can have almost net zero emissions in case renewable electricity is used for all processes, most importantly hydrogen provision and carbon extraction.

The availability of alternative technology options has led to fierce debates about the most suitable transformation strategy for the transport sector. A strong decrease of battery costs makes BEVs increasingly competitive (Muratori et al., 2021), but long charging times and range limitations hinder their adoption (Huang and Kockelman, 2020). Fuel cell vehicles currently have high costs and the production chain of H_2 is expensive and less efficient than direct electricity usage. On the other hand, the longer driving range of FCEVs likely is not subject to the consumer's perception of range anxiety (Noussan et al., 2020). Alternatively, producing e-fuels is costly and even more energy intensive. Due to the ease of handling, e-fuels are nevertheless considered a promising alternative in sectors such as long distance road freight, aviation and shipping, where long hauls, and volume and weight of the drivetrain pose serious challenges (Goldmann et al., 2018; IRENA, 2019; T&E, 2018).

Technologies for the direct or indirect electrification of transport differ with regard to specific requirements and enabling conditions. Structural changes to the infrastructure system are prerequisites to the adoption of battery electric and hydrogen vehicles (Noussan et al., 2020; Sierzchula et al., 2014). Due to the initially high purchase costs, financial incentives and improvements on the technology performances are required to promote alternative vehicles. A shift in consumer preferences and driving patterns is another prerequisite for the consumer adoption of BEVs. A transition to e-fuels, on the other hand, would require extensive investments in the energy supply sector, but on the other hand reduces transformation requirements on the demand side (Brynolf et al., 2018; Runge et al., 2019). A transition to a low-emissions transport sector is

particularly relevant in the context of the post-2020 European emissions standards (CABUZEL, 2020), the impacts of which has been analyzed, e.g. in Krause et al. (2020).

Transport electrification scenarios have been studied previously in Integrated Assessment Models (IAMs) (Edelenbosch et al., 2016; Girod et al., 2013; Karkatsoulis et al., 2017; Pietzcker et al., 2014). Deep electrification[1] of transport via BEVs has been analyzed with the IAM IMAGE (Edelenbosch et al., 2018), and Blanco et al. (2019) explore hydrogen based electrification scenarios with the IAM TIMES. A comparative analysis of the electricity and hydrogen decarbonization potential for transport is provided in Anandarajah et al. (2013) and van der Zwaan et al. (2013). To the best of our knowledge, no comparison of all three different deep electrification options has been performed in integrated assessment models.

For our analysis of different electrification strategies for the transport sector, we use a coupled system consisting of the Integrated Assessment Model REMIND (Luderer et al., 2020) and the transport model EDGE-T (Rottoli et al., 2021) with a focus on light-duty vehicles. The newly developed EDGE-T not only features a fine-grained transportation sector, it also considers non-monetary aspects of mobility consumption and is therefore suited to study sector specific policies.

We compare the results across a range of transport electrification scenarios with an economy-wide carbon pricing associated with a temperature increase well below the 2°C-limit until 2100 and within a Nationally Determined Contributions (NDC) policy context.

2. Modeling transport decarbonization in the energy system context

[1] We describe as “deep electrification” scenario pathways representing fast electrification of end-use sectors, leading to a high share of electricity in final energy demand.

The modelling framework we use comprehends REMIND (Baumstark et al., 2021; Luderer et al., 2020) and the novel EDGE-T (Rottoli et al., 2021), a detailed and easily extensible environment to evaluate transport sector scenarios. REMIND provides a coherent framework of the full energy-economy system, which ensures the consistency of transportation with economic drivers, the energy supply system, and competing demands from other energy end uses. Further information on the REMIND model is provided in the Appendix, section A. For the purpose of this study, we extend the representation of consumer choice in EDGE-T as described in Rottoli et al. (2021) by a detailed representation of cost markups due to inconvenience costs. The main characteristics of the modelling framework and the scenario assumptions are described in sections 2.1 to 2.5.

2.1 Coupling REMIND/EDGE-T

The REMIND model time frame spans from 2005 to 2100 and it represents the world divided into a set of aggregated regions. The spatial aggregation adopted for this study comprises twelve regions and is reported in the Appendix, section A. The EDGE-T model features a country-level spatial aggregation. The last calibration year for the models are 2005 for REMIND and 2010 for EDGE-T.

The detailed transport model EDGE-T runs in between two REMIND iterations. During each iteration, REMIND performs an intertemporal optimization over the full time period. It provides a complete set of fuel prices that are subsequently used by EDGE-T to calculate the resulting market shares of the different vehicle classes and technologies. In turn, EDGE-T provides REMIND with the mix of service demand[2] required by the transport sector, its energy intensity and costs per km, calculated on the basis of a detailed nested structure. REMIND then updates the total service demand, balancing the required investments in transport capital and fuel provisions on the one side against the associated utility from the aggregated transport. Convergence is reached after a number of iterations between

2 In this study, “service demand” refers to the demand for services, such as transportation, measured in passenger- and ton-km for passenger and freight transport respectively. This definition is conventionally adopted in IAMs (Edelenbosch et al., 2017, 2016).

REMIND and EDGE-T runs, when an equilibrium point is reached and the exchanged prices and demands no longer change. A representation of the coupled system REMIND/EDGE-T is provided in Fig. 1. For a detailed description of the model system, the reader is refered to Rottoli et al. (2021).

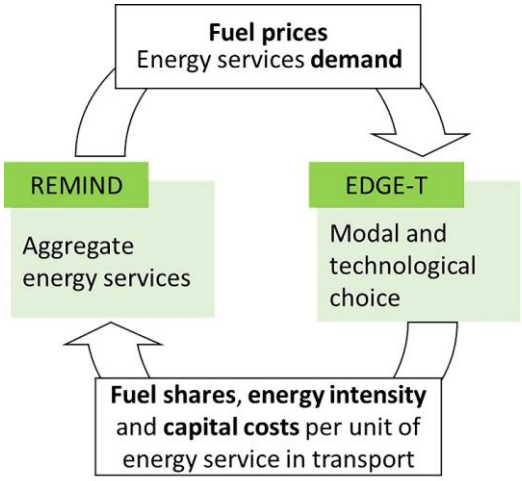

Figure 1: The working principle of EDGE-T and REMIND. EDGE-T runs in between REMIND iterations: REMIND informs EDGE-T about fuel prices and total transport service demand; EDGE-T provides REMIND with the mix of energy carriers required by the transport sector, its energy efficiency and costs per service unit.

2.2 Transport choice working principle

Decisions related to transport modes and fuel type are represented in the EDGE-T model via a nested function, see Fig. 2. Different powertrains for various vehicle types are represented by the lowest level of the tree. The nodes in Fig. 2 are aggregated hierarchically up to the top-level, where only short-to-medium and long distance as well as freight and passenger modes are distinguished. For the purpose of this study, we extend the tree as described in Rottoli et al (2021) including the powertrain option of plug-in electric cars (PHEV) based on Cox et al. (2018). In addition, we extend the learning-by-doing implementation to fuel cell cars, assuming a learning rate of 18% applied to fuel cells and H_2 tanks (Ruffini and Wei, 2018). All alternatives with internal combustion engines run on liquids. Gasoline, diesel and other blends are not distinguished. Passenger inland navigation is not

included due to their small share in total travel. The EDGE-T model provides information to the REMIND Constant Elasticity of Substitution (CES) function that represents how the demand for capital, labor and the most energy intensive economic sectors (buildings, industry and transport) concur in producing Gross Domestic Product (GDP) (Fig. A.2, see Appendix). The part of the CES integrated with the results from EDGE-Transport is highlighted with a striped pattern in Fig. 2.

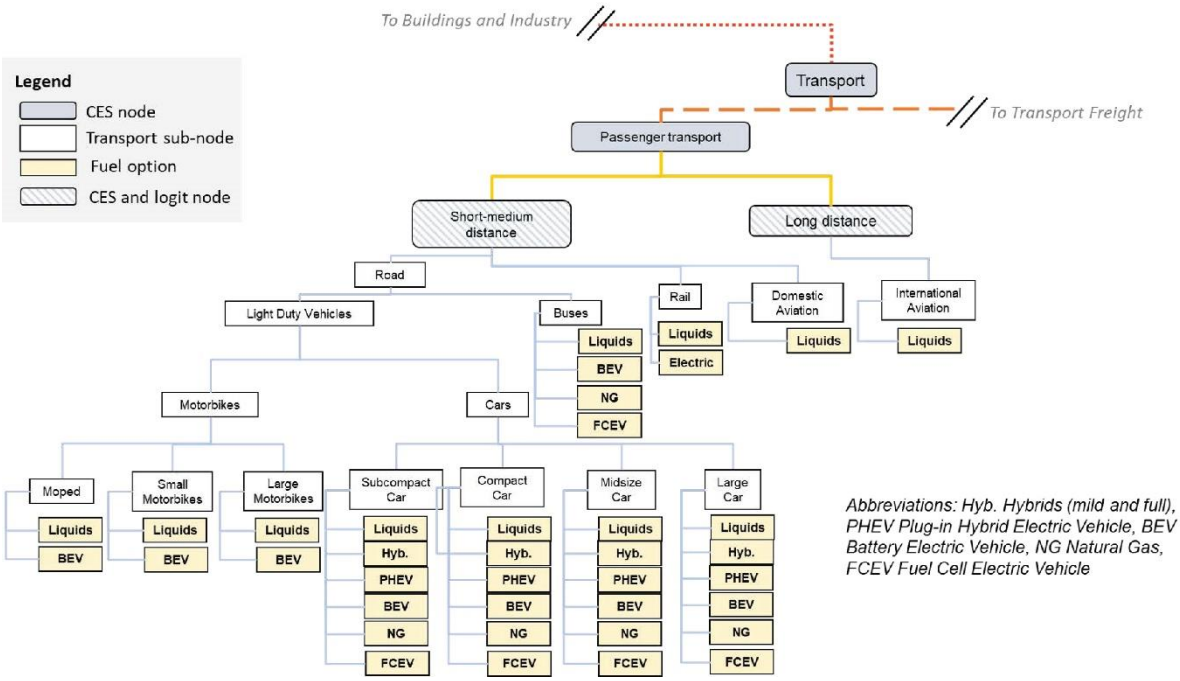

Figure 2: Overview of the passenger transport branch of EDGE-T's nested decision tree. Grey boxes are part of the REMIND Constant Elasticity of Substitution (CES) tree. The boxes with a striped pattern are shared between EDGE-T and REMIND.

Within the transport sector, the allocation of market share for alternative technologies is included by employing a modified logit formulation which assumes Weibull probability distributions following Clarke and Edmonds (1993). We employ this formulation in two variants to account for preferences and dispreferences other than the direct technology costs.

In the first variant, market shares of technology alternative i are a polynomial function of generalized prices:

$$s_{i,c,t} = \frac{\left(p_{i,c,t} + \tilde{p}_{i,c,t} + p_{i,c,t}^{time}\right)^{\lambda}}{\sum_{i=1}^{n}\left(p_{i,c,t} + \tilde{p}_{i,c,t} + p_{i,c,t}^{time}\right)^{\lambda}}, \tag{1}$$

where λ is the (typically negative) exponent, $s_{i,c,t}$ is the obtained market share, c denotes a country, t indicates the time step, n is the total number of choices, $\tilde{p}_{i,c,t}$ the inconvenience cost (detailed in Section 2.3), $p_{i,c,t}^{time}$ represents the intangible cost of the time invested in traveling and $p_{i,c,t}$ the total cost of ownership (TCO) per km. The latter consists of two parts:

$$p_{i,c,t} = P_{i,c,t}^{fuel} + P_{i,c,t}^{non\ fuel}, \tag{2}$$

where $P_{i,c,t}^{fuel}$ represents the price of fuel per traveled km and $P_{i,c,t}^{non\ fuel}$ accounts for all ownership costs (purchase cost, operation and maintenance -O&M- costs, registration and insurance taxes, annualized and discounted) $P_{i,c,t}^{time}$.

In the second variant, the function is modified using so called weights w:

$$s_{i,c,t} = \frac{\left[w_{i,c,t}\,(p_{i,c,t} + p_{i,c,t}^{time})\right]^{\lambda}}{\sum_{i=1}^{n}\left[w_{i,c,t}\,(p_{i,c,t} + p_{i,c,t}^{time})\right]^{\lambda}}, \tag{3}$$

where the weight $w_{i,c,t}$ is a calibration parameter representing the non-monetary decisions associated with the adoption of a mode, e.g. the status of infrastructure systems or the consumer preferences.

We choose Eq. 1 to model the choice between different LDV drivetrains. Expressing the inconvenience cost explicitly allows for the comparison to real costs, i.e., purchase, operation and maintenance, and fuel costs. On the other hand, Eq. 1 is more difficult to calibrate due to the non-linear dependency on the calibration parameter $\tilde{p}$. This formulation requires initial estimates of the

inconvenience costs, which are not available to us for transport modes other than LDVs. Therefore, we resort to Eq. 3 for the choice at every other transport mode.

2.3 Inconvenience costs formulation

In this study, we aim at comparing LDVs powertrain technologies potential considering the generalized costs of transport, comprising monetary and non-monetary components. As McCollum (2018) argues, IAMs struggle to represent the non-pecuniary decision criteria of consumers' choice. Inconvenience costs, i.e. soft costs, have been shown to be extremely important in passenger transport (Compostella et al., 2020; Fulton et al., 2020; Mashhoodi and Blij, 2021). In particular, there are important systemic feedbacks between market penetration and intangible costs, especially when it comes to the market introduction of new technologies. In Greene (2001), the author provides a detailed methodology to estimate inconvenience costs associated with private vehicle usage, applied in the MA^{3}T model. The author presents functional forms to convert relevant sources of inconvenience into monetary values. The same methodology provides the basis for other studies (Levinson and West, 2018; Liu and Lin, 2017; McCollum et al., 2017; Pfaffenbichler et al., 2011; Yang et al., 2016). McCollum et al. (2017) update the estimates provided in Greene (2001) to represent the takeover of alternative vehicles (natural gas-, battery electric-, fuel cell-, plug-in hybrid-, hybrid-vehicles), reporting a set of inconvenience costs specific for these technologies across various consumer groups. In addition, Pettifor et al. (2017) analyze the effect of risk aversion on the adoption of new drivetrains.

The previously mentioned studies also analyze the feedback between market share and inconvenience cost. The MA^{3}T model features time-dependent signals that affect preferences and risk perception of consumers of the following year (Liu and Lin, 2017). In Pettifor et al. (2017) a linear decrease of risk aversion with market shares is applied to the IMAGE model, applying different slopes depending on the consumer group.

In this context, we refine the representation of intangible costs with respect to the previous formulation reported in Rottoli et al. (2021), which relied on exogenously-assumed trends to modulate the adoption of alternative vehicles adapted from Mishra et al. (2013). We extend the formulation of the non-monetary costs and introduce modifications based on current values for selected European countries. For the purpose of this study, we implement market-share dependent inconvenience costs for 4-wheelers in the EDGE-T model. We account for the dependence of consumer preferences on the market share of technologies via the variation of intangible costs and divide the inconvenience cost into a set of sub-components, on the basis of the work by Greene (2001), McCollum et al. (2017) and Pettifor et al. (2017) and our own calculations. The inconvenience cost components that we model are refuel station availability, range anxiety, EV charger installation costs, model availability and risk aversion. All inconvenience cost components (with the exception of charger installation costs, which are relatively small compared to the other components) are modelled following endogenous trends of the market share of each technology option. Please note that the body of literature we refer to adopts quantifiable proxies (such as the market share or the availability of refueling stations) to represent a cluster of intangible drivers such as consumer's awareness, familiarity with the alternative technology, or neighbourhood effects.

A detailed description of our assumptions on inconvenience costs is provided in the Appendix, section B.

2.4 Electrification potential of LDVs

As of today, transport mostly uses liquid fossil hydrocarbons as final energy carriers, due to their very high energy density and ease of handling. Liquid fuels obtained from biomass (biofuels) have characteristics similar to fossil hydrocarbons and thus represent a low-carbon alternative to fossil fuels. However, intensive biomass cultivation for energy supply would be very land intensive and could have substantial side effects due to indirect land use change (Creutzig et al., 2015b;

Humpenöder et al., 2018). It is therefore increasingly considered unlikely that the bulk of the energy demand of the transport sector can be switched to biofuels.

Concerning electrification, the prospects of application vary across transportation sub-sectors. Electrification of LDVs via batteries is widely considered the most promising decarbonization option. A notable co-benefit of BEVs is the reduced direct air pollution. However, only an extensive expansion of the recharging infrastructure system and a transition to a low-carbon power sector would enable an effective reduction in carbon emissions (Kavianipour et al., 2021; Noussan et al., 2020). High upfront costs, comparatively long charging times and range anxiety are currently hindering the adoption of BEVs. However, sales underwent an impressive rise in the last years, reaching more than 3 million globally in 2020 (IEA, 2021a). In terms of the BEV market share in sales, Norway was the global leader with 54% market sales in 2020 (Klesty, 2021).

FCEVs are zero tailpipe emissions vehicles with short refueling times. The high upfront costs and the scarce availability of hydrogen refueling stations result in a limited presence of FCEVs in the market today. The number of hydrogen cars in the fleet is currently orders of magnitude lower than the number of BEVs, with above 25,000 in 2020 globally (IEA, 2021b). Large amounts of energy are required to produce, transport and store hydrogen, and the related emissions depend on the energy mix (Moro and Lonza, 2018; Noussan et al., 2020). FCEVs, like BEVs, share the additional benefit of a significant reduction in local air pollutant emissions.

A significant increase in electricity-based alternative liquid fuels (e-fuels) could also contribute to reducing CO_2 emissions, shifting the burden of the transition to the supply sector. This supply-side transition would imply 1) a significant scale-up and integration of renewable electricity sources (Solomon et al., 2016) and 2) major investments in the development of a large-scale carbon-neutral PtL (Power-to-Liquid) supply chain to increase the competitiveness of e-fuels (Dieterich et al., 2020). In addition, a transition to e-fuels would be very energy-intensive due to the efficiency losses associated with the production of renewable-based e-fuels (for a comparison with BEVs and FCEVs,

see Fig. 3). Lastly, the adoption of e-fuels would not tackle the issue of local air pollution (Brynolf et al., 2018). Assumptions on the e-fuels production adopted for this study are reported in the Appendix, section E.

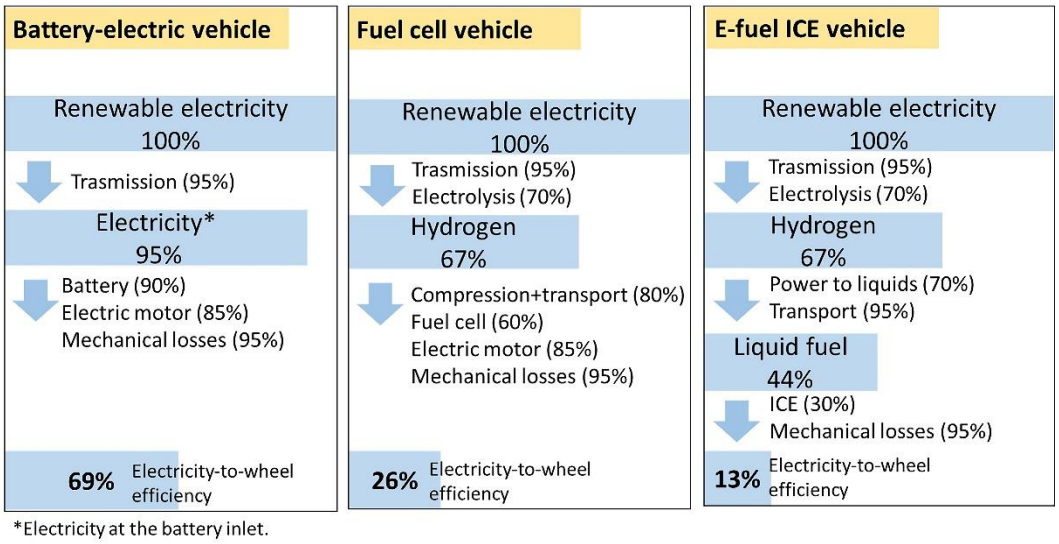

Figure 3: Loss of efficiency in light-duty vehicles, based on Deutsch (2018).

Assumptions for technology costs, efficiency parameters and preference factors adopted for the different transport modes are reported in the Appendix, section C.

2.5 Scenario description

We analyze a set of scenarios that span a range of assumptions along the transport technology dimension and the climate policy dimension. For the transport technology dimension, we discretize the option space for simplicity and implement bundles of policies that feature one technological option at a time. Due to sustainability concerns, we analyze scenarios with limited biofuels adoption. The climate policy dimension distinguishes between a business-as-usual climate policy environment and the introduction of policy packages aimed at limiting the temperature increase to below 2 degrees. An additional dimension concerning lifestyle choices of consumers is also examined. A scenario matrix summarizing the dimensions is given in Table 1.

		Lifestyle	Transport technology dimension			
			Conventional	**Electricity push**	**H_2 push**	**Conventional Synfuel**
Climate policy dimension	**ConsB (Conservative Baseline)** European countries do not embrace the shift towards alternative vehicles of the latest years due to political opposition. A pre-2020 policy environment is established.	**Default**	**ConsB_Conv**	-	-	-
	WB2C (Well Below 2 degrees °C) Cumulative CO_2 emissions from 2011 to 2100 limited to 1100 $GtCO_2$	**Default**	**WB2C_Conv**	**WB2C_ElecPush**	**WB2C_H2Push**	**WB2C_ConvSyn**
		Adoption of Sustainable lifestyles	**WB2C_Conv-Sust**	**WB2C_ElecPush-Sust**	-	-

Table 1: Matrix with an overview of the scenarios in this study. The rows illustrate the climate policy and lifestyle dimensions and the columns the technology dimension.

Following the table along the transport technology dimension, the available options are:

Conventional: due to political opposition, a pre-2020 policy environment is established concerning market introduction programs for alternative vehicles, resulting in a continued dominance of

conventional internal-combustion engine cars along with full and mild hybrid vehicles. Pessimistic assumptions on consumer acceptance of battery electric vehicles are adopted.

Electricity Push explores an accelerated transition toward battery-electric vehicles, achieved via infrastructure policies (build-up of charging stations), market introduction policies (a rebate system of subsidies for BEVs) and increasingly stringent regulation of conventional vehicles, in line with the 2020 emissions standards (ICCT, 2021). The support policies lead to increasing consumer acceptance of BEVs. Subsides applied to BEVs favor their initial takeover, starting at 5,000€[3] in 2020 and phasing out by 2035[4]. The same trend is applied to all European countries. Feebates on ICEs and announcements of future bans on LDVs discourage consumers from purchasing conventional vehicles, by means of a policy-induced inconvenience cost (see Appendix, Section B – Model Availability). The deployment of electric buses and trucks follows an optimistic trend.

H_2 Push: There is policy support towards fuel cell electric vehicles via rebates for FCEVs, and an increasingly stringent regulation of conventional vehicles, in line with the 2020 emissions standards (ICCT, 2021). These support policies lead to an increasing consumer acceptance of FCEVs. By contrast, pessimistic assumptions on the technology evolution, infrastructure build-up and consumer acceptance of battery electric vehicles ensure competitiveness. Buyer's premiums for FCEVs favor their initial takeover, starting at 5,000€ in 2020 and phasing out by 2035. Hydrogen from electrolysis is set to have a share of above 95% of the total hydrogen[5] (the remaining 5% is produced via fossil fuels methanation - either with or without carbon capture). Feebates on ICEs and announcements of future bans on LDVs discourage consumers to purchase conventional vehicles, by means of a policy-

[3] For comparison, as of June 2020 Germany grants a purchase subsidy of up to 9,000€ for purely electric and fuel cell vehicles (EAFO, 2020). By contrast, many other European countries do not provide purchase subsidies (ACEA, 2019).

[4] This assumption is adopted under the expectation that as alternative technologies become more wide-spread, their lobby groups will also increase in relevance, likely leading to a slow phaseout of subsidies.

[5] For the remaining 5% the model selects the cost-optimal technology mix. This brings in a small fraction of hydrogen via steam methane reforming of natural gas with or without carbon capture (blue or grey H_2) depending on the carbon price.

induced inconvenience cost (see Appendix, Section B – Model Availability). The deployment of hydrogen buses and trucks follows an optimistic trend.

Conventional Synfuels: due to political opposition, a pre-2020 policy environment is established concerning market introduction programs for alternative vehicles, resulting in a continued dominance of conventional internal-combustion engine cars along with full and mild hybrid vehicles. Pessimistic assumptions on the technology evolution and consumer acceptance of battery electric vehicles are adopted. A blending mandate of 20% synthetic electricity-based fuels by 2035 is established. Hydrogen from electricity (green hydrogen) is set to be above 95% of the total hydrogen used (the remaining 5% is produced via fossil fuels methanation - either with or without carbon capture).

Note the following caveat: In our model, internal combustion engines are the only powertrain technology available for aviation and shipping. As a consequence, since in Conventional Synfuels the technological progress focuses on internal combustion engines, the decarbonization potential for aviation and shipping might be enhanced with respect to the other scenarios as the e-fuel quota mandate is affecting all transport modes. By contrast, in Electricity Push and H2Push we assume that no disruptive technological changes happen in aviation and shipping (electric vessels, hydrogen- and synthetic fuels-based vessels are absent). In these scenarios, emissions from the sectors can only be reduced by a decrease in demand.

The scenarios assumptions are synthesized in Table 2.

Scenario	**Technology-focus**	**Main assumptions on LDVs development**
Conv and ConvSyn	ICE	Recharging stations: suboptimal installation[1] (1:2000 instead of 1:1000). Continued dominance of conventional internal-combustion engine. In ConvSyn: Presence of a blending mandate of 20% synthetic electricity-based fuels by 2035.

ElecPush	BEV	From 2020 onwards, the model linearly introduces inconvenience costs on ICEs so that they reach 0.2$/km in 2030. For BEVs, subsidies on purchase cost (5,000€ incentives in 2020 linearly phasing out by 2035) and registration and insurance O&M costs reduction of 2/3 the historical value in 2020 phasing out after 2035 due to favourable policies for electric vehicles users. Electric buses and trucks deployment follows an optimistic trend.
H2Push	FCEV	From 2020 onwards, the model linearly introduces inconvenience costs on ICEs so that they reach 0.2$/km in 2030. Recharging stations: strongly decreased installation (1:10000 instead of 1:1000). For FCEVs, subsidies on purchase cost (5,000€ incentives in 2020 linearly phasing out by 2035) and registration and insurance O&M costs reduction of 2/3 the historical value in 2020 phasing out after 2035 due to favourable policies for hydrogen vehicles users. H_2 from electrolysis is set to have a share of above 95% of the total hydrogen. Hydrogen buses and trucks deployment follows an optimistic trend.

[1]Optimal number of stations: 1:1000, from (Peterson et al., 2014; Yeh, 2007)

Table 2: Modelling assumptions for the different scenarios, considering the technological dimension.

Please note that the scenario assumptions as reported in Table 2 influence the LDV mix composition and scale-up of new technologies, but 1) the feasibility of achieving the climate target, 2) the optimal demand for LDVs and 3)) the supply sector transformation required to support the LDVs market transformation represent an output of the coupled system REMIND/EDGE-T. Therefore, the final

structure of the transport demand (i.e. total fleet volume, fleet and mode composition) are the result of the optimization routine and are not prescribed by the modeler. The convergence of the system is achieved when the the feedback loop across the two models stabilizes and exchanged information no longer changes from iteration to iteration – thus the two models are in equilibrium. The contribution of the energy demand sectors (buildings, industry and transport, as reported in Fig. A.2), as well as the energy supply composition, are therefore optimized endogenously in each scenario.

Along the climate policy dimension, we consider one baseline and one mitigation scenario, see Tab. 1:

Conservative Baseline (ConsB): European countries do not embrace the shift towards electric vehicles of the latest years due to political opposition. A pre-2020 policy environment is established. Different instruments including very modest carbon prices are projected to persist with continued ambition level, without explicit strengthening (Roelfsema et al., 2020).

Well Below 2 degrees °C (WB2C) features economy wide carbon pricing leading to a temperature increase well below the 2°C-limit until 2100, in a policy context compatible with the NDCs. Since the budget is calculated on a global level, the cumulated sum of emissions from all regions have to comply with the emissions constraint. Trade is allowed for primary energy (coal, gas, oil, biomass), yet as all regions face the same carbon price to reach the global budget, carbon leakage to regions outside the EU is suppressed.

Finally, for the lifestyle dimension we consider two variants:

Default: A continuation of current transport service demand trends and modes and vehicles preferences. The price and income elasticity leading the demand trend follow the parametrization provided in Rottoli et al. (2021), considered the reference baseline, while the mode preferences

($w_{i,c,t}$ in Eq. 3) are considered constant in time and equal to the calibration values (for details on the demand calibration and the preferences calibration, see the Appendix, section D).

Sustainable lifestyles: Policies aimed at reducing and shifting demands are effectuated to ease the burden of transport sector decarbonization. Rising concern for air quality, noise emissions and spatial constraints lead to driving bans for LDVs in urban environments. The bans, backed by infrastructure investments, mediate a change in mobility lifestyles: Non-motorized mode shares increase as well as the acceptance of public transport. A more efficient railway system and logistics in the delivery of goods lead to an increased preference for rail over road-based transport for freight. Rail travel is popular, inducing a decreasing demand for short-distance flights. In addition, the total transport demand increases only moderately with respect to 2020 values. A more detailed description of the adopted assumptions for Sustainable lifestyles as compared to Default are provided in the Appendix (section D.2).

3. Results

3.1 Light-duty vehicles fleet

The total number of cars increases modestly in all scenarios with default demand projections, see Fig. 4. The fleet increases slightly in ConsB_Conv, from around 240 to around 270 million vehicles between 2020 and 2050. In the same time span, the increase in WB2C_ElecPush and WB2C_H2Push is more pronounced, reaching over 300 million vehicles by 2050: inexpensive, renewable electricity and initial technology support policies inducing technological progress result in a considerable decrease of LDV travel costs in WB2C_ElecPush and WB2C_H2Push compared to the reference developments. Furthermore, the introduction of the carbon tax combined with the availability of cheap zero emission cars induces a substitution effect of aviation with LDVs. The combined effect of generalized cost of transport, fuel price, value of time and calibration parameters (resulting from historical preferences, see Eq. 3), leads to a shift of the demand from aviation to road (mainly

composed by LDVs). As a consequence, overall vehicle demand increases with respect to ConsB_Conv. The limited improvements on ICEs and the moderate shift to alternative vehicles instead lead to a milder substitution of short-distance aviation with LDVs in WB2C_Conv and WB2C_ConvSyn. PHEVs and BEVs are short-term technology options in WB2C_H2Push, since the higher costs associated with FCEVs delay their adoption. The number of cars decreases mildly in WB2C_Conv-Sust in the time range 2020-2050, while WB2C_ElecPush-Sust shows constant demand trends.

The WB2C_ElecPush scenario leads in 2050 to almost 90% electric vehicles sales, a result in line with Krause et al. (2020).

The market share obtained by NG and PHEVs is quite limited in all scenarios, as a consequence of the combined effect of generalized costs of transport and assumptions on the inconvenience costs adopted (see Appendix, section B, subsection Model Availability).

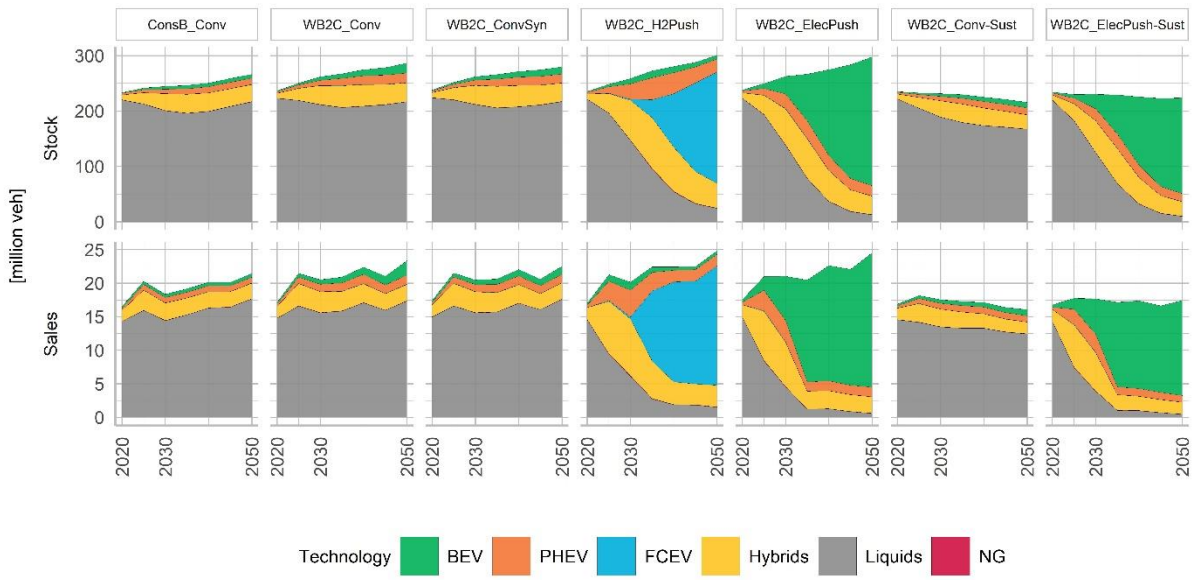

Figure 4: Evolution of the composition of the light-duty vehicles fleet in Europe with time, for all scenarios, by technology (different colors). Upper panel: vehicle stock. Lower panel: vehicle sales.

The fleet composition is driven by the scenario set-up and the combination of generalized transport cost and the inconvenience costs (see Sections 2.3 and 2.5). A representation the monetary and non-monetary costs associated with the adoption of each light-duty vehicle alternative is reported in Fig. 5, for selected scenarios and time steps. In the upper panel, monetary and non-monetary components are reported together. In the lower panel, the inconvenience cost bar is divided into its subcomponents.

Considering first the upper panel, the values for 2020 highlight higher purchase and O&M costs for BEVs and FCEVs among all technologies. Fuel costs (including taxes) are lower for BEVs and FCEVs with respect to the fossil-based alternatives. The inconvenience cost component is very prominent in the case of all technologies, with the exception of conventional ICEs. The policies promoting alternative vehicles lead to BEVs and FCEVs inconvenience costs dwindling in WB2C_ElecPush and WB2C_H2Push respectively. The purchase cost of BEVs and FCEVs decreases as well due to learning-by-doing. Fuel costs related to conventional and hybrid vehicles increase with time in all budget scenarios due to the introduction of the carbon tax. The policies to phase out conventional ICEs, e.g. driving bans - represented via a policy-induced inconvenience cost - combined with the policies to promote alternative vehicles lead to increasing inconvenience costs for conventional vehicles.

The lower panel highlights that the most important components of the inconvenience costs are model availability, range anxiety and refuel station availability. The policy-induced inconvenience cost of conventional ICE is quite prominent in 2050 in both WB2C_ElecPush and WB2C_H2Push and contributes to the phase-out of conventional vehicles. In the Appendix, a table with the different fuel prices for selected scenarios and time steps is provided (section F.3).

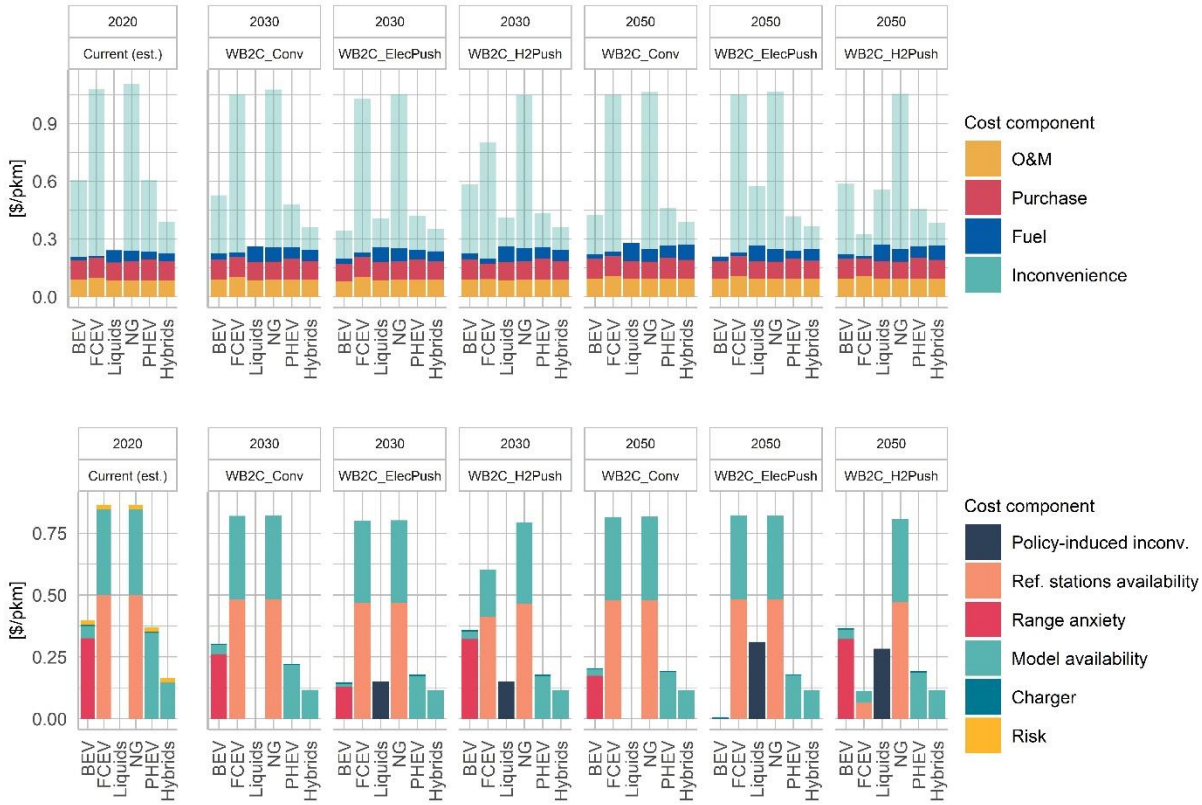

Figure 5: Total costs (monetary and non-monetary) (upper panel) and inconvenience costs by sub-components (lower panel) for the average light-duty vehicle in Europe, across selected scenarios and time steps.

3.2 Service demand for passenger transport

As highlighted in Fig. 4 and 5, the total demand for LDVs varies across scenarios due to the combined effect of monetary and non-monetary costs of the preferred technology mix. Due to the nested transport representation (Fig. 2), the LDVs composition impacts on the rest of the transport system, influencing the mode composition. Fig. 6 shows the service demand for passenger transport in Europe as a function of time. In ConsB_Conv, we observe an increase in total transport demand, mainly driven by aviation. WB2C_ElecPush and WB2C_H2Push show increases similar to those in ConsB_Conv. In these cases, the demand growth is driven by alternative LDVs, while aviation growth is constrained by fossil fuels price increases under mitigation scenarios. The Sust- scenarios are

characterized by a slight shift towards non-motorized and public ground transport, in line with the narrative of the scenarios.

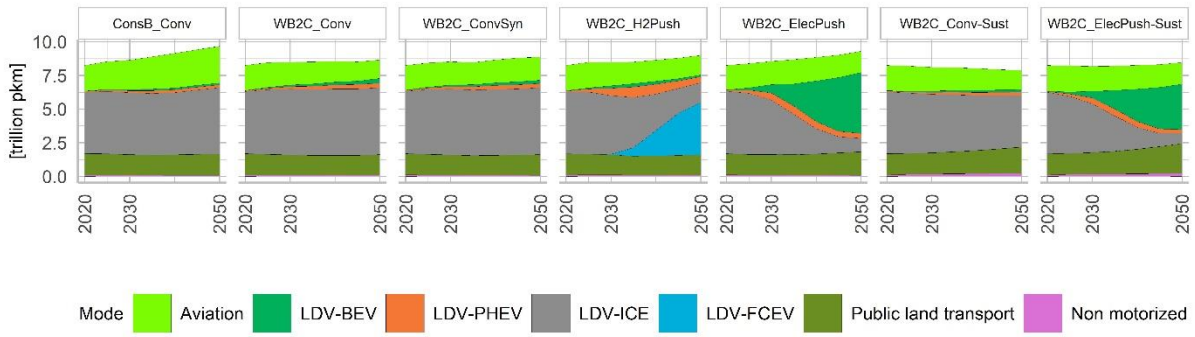

Figure 6: Passenger service demand for by transport mode as a function of time.

3.3 Energy demand and emissions for light-duty vehicles

The final energy demand for LDVs for Europe in time is shown in Fig. 7. All scenarios show decreasing trends of total final energy because of the improvements in efficiency of ICEs and the switch to alternative vehicles. Synfuel demand grows in WB2C_ConvSyn, while hydrogen and electricity demand increase in WB2C_H2Push and WB2C_ElecPush, respectively.

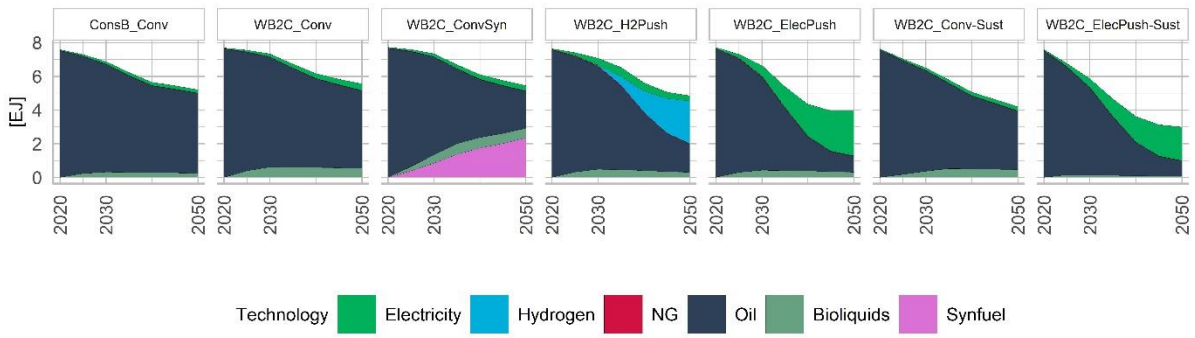

Figure 7: Final energy demand for light-duty vehicles in Europe as a function of time, across scenarios, broken down by fuel type.

The alternative electrification strategies differ markedly in terms of final energy demand due to the variations in energy intensity associated with the technologies and in the demand absolute values. In

addition, each electrification strategy results in significantly divergent demand trends for primary energy due to the supply-side impact of electricity direct and indirect use. Fig. 8 represents the primary energy demand by supply technology for the set of scenarios, in time. Due to the improvements in energy efficiency of conventional vehicles, demand decreases between 2020 and 2050 in ConsB_Conv, with service demand mildly increasing for LDVs (as reported in Fig. 4). Primary energy demand from intermittent renewables (solar PV and wind) is significantly higher in the whole-time frame for WB2C_ConvSyn, followed by WB2C_H2Push and WB2C_ElecPush. The efficiency of the direct use of electricity leads to a strongly decreasing total primary energy demand with time in WB2C_ElecPush, even with the highest number of LDVs across all scenarios (as seen in Fig. 4).

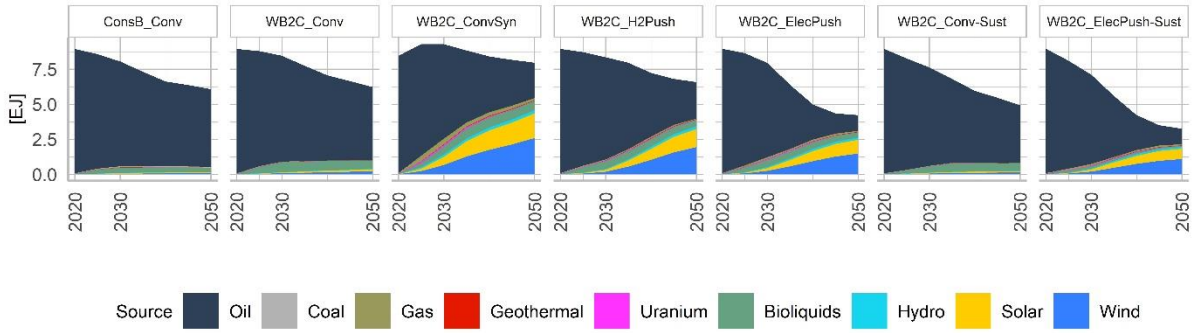

Figure 8: Primary energy required by light-duty vehicles in Europe as a function of time across all scenarios, broken down by source.

In addition to impacting on the energy demand, the alternative technology adopted and the absolute value of the demand impact on the LDVs associated emissions. Fossil tailpipe emissions from LDVs are presented in Fig. 9. In the figure, note that emissions from synthetic fuel combustion and biofuels combustion are not included, since their CO_2 flows are not accounted for on the demand-side[6]. A strong decrease in emissions accompanies the shift towards the electricity-based

[6] CO_2 for synthetic fuels either comes from carbon-neutral sources (direct air capture or biomass) or from fossil emissions from energy supply or industrial plants. Such fossil emissions are accounted for at their origin outside of the transport sector. We follow the Integrated Assessment Modelling Consortium (IAMC) convention which accounts separately the “demand emissions” (tailpipe emissions discounted for biofuels and

options: E-fuels (WB2C_ConvSyn), FCEVs (WB2C_H2Push) and BEVs (WB2C_ElecPush). The most striking decrease can be observed in WB2C_ElecPush (default and –Sust).

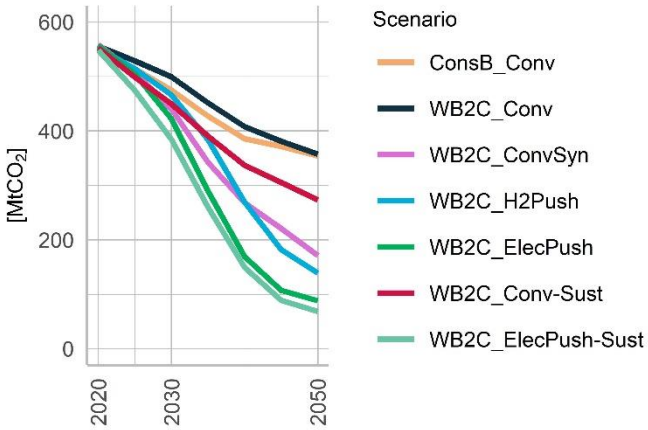

Figure 9: Fossil tailpipe emissions from light-duty vehicles in Europe with time, across scenarios.

An analysis of the CO_2 prices across scenarios and a Kaya decomposition of the demand for LDVs are provided as additional results in the Appendix, Section F. Section G provides a validation of the model results for selected historical values, highlighting that the values projected by the EDGE-T model for 2015 are quite in line with historical values in terms of absolute demand. In addition, the sales for alternative vehicles in ElecPush are slightly delayed with respect to historical numbers (historical: around 5% sales in 2020; ElecPush: around 5% sales in 2022).

4. Conclusions

We have analyzed alternative transformation pathways of the transport system with a focus on the role of electrification. Low-carbon electricity can be used for mobility either directly via batteries or indirectly via hydrogen, utilized either in fuel cell vehicles or synthesized to e-fuels for internal combustion engines.

e-fuels emissions" and the "supply emission" (emissions on the energy production side, i.e. electricity production, e-fuels and biofuels production, fossil fuels extraction and refinery) (Bertram et al., 2020).

This transformation of the transport sector also increases the interconnectedness within the energy system. Against this background, as a key innovation of this paper, we use the REMIND/EDGE-T coupled system to characterize alternative low-carbon transformation pathways within the system context. The purpose of EDGE-T is to provide a detailed and easily extensible environment to evaluate transport-specific policy analyses. REMIND on the other hand provides a coherent framework of the full energy-economy system, which ensures the consistency of transportation with economic drivers, the energy supply system, and competing demands from other energy end uses.

The following key findings emerge:

- First, we find that direct electrification has the potential for a substantial decarbonization of road-based private passenger transportation. Indirect electrification via H_2 or synthetic fuels is in principle also viable, but will be slower due to lower maturity of the required technologies and their higher cost. The tailpipe emissions decrease significantly in all electrification pathways, with direct electrification being associated with the lowest emissions.
- Second, the electrification pathways show vastly different primary energy demand and emissions implications, with indirect electrification proving to be significantly more energy intensive. The demand for hydrogen, either used directly in FCEVs or used indirectly to produce e-fuels, leads to a very high demand for electricity, which implies a massive increase in primary energy demand for solar and wind energy in mitigation scenarios. This results in a significant additional burden on the supply sector.
- Third, non-monetary consumer preferences, modelled here as intangible costs, play a crucial role for vehicle choice. Since range anxiety, fuel and model availability currently hinder the adoption of alternative vehicles, complementary policies are required in the near-term to initiate the mobility transformation. A timely build-up of recharging points and refueling stations is key, as well as a wider range of LDV models in the market. Given the strong

market build-up of battery-electric vehicles over the last years, a significantly stronger policy push would be needed for FCEVs to allow them to catch up. Eventually, we find that in all scenarios featuring alternative drivetrains, additional policies are required to increase real or perceived costs for ICEVs for a faster phase-out.

The market for alternative vehicles is rapidly and continuously evolving, due to the new legislations (CABUZEL, 2020) and the technological progress (see e.g. Muratori et al. (2021)). The authors are aware of the primary importance of keeping up-to-date input data in order to capture the market dynamics. In future work, we aim to further analyze the dynamics of infrastructure build-up and the related barriers, exploring the role of consumer preferences in influencing the infrastructure system. In parallel, future research will provide a more detailed analysis of the environmental impacts of direct and indirect electrification.

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