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# Well-to-wheels scenarios for 2050 carbon-neutral road transport in the EU

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ABSTRACT

The present study explores net carbon-neutral road transport options in the EU27 in 2050 from a well-to-wheel (WtW) perspective. To this aim, three scenarios have been developed regarding the evolution of the road vehicle fleet composition in terms of the degree of electrification of powertrains, and technical measures such as vehicle efficiency improvements, transport flow, and transport volumes have been considered. The fleet scenarios are further combined with four scenarios deploying different mixes of alternative fuels in 2050, including electricity, e-fuels, liquid/gaseous advanced biofuels and remaining fossil fuel components. Two different electricity production pathways are considered, as well, one of them assuming fully renewable electricity production, and an alternative one including residual shares of nuclear and natural gas power plants plus carbon capture and storage. The Joint Research Centre's DIONE model was used for the scenario calculations. From a tank-to-wheel (TtW) perspective, each scenario reduces energy consumption, mainly due to powertrain electrification, with EU27 TtW road vehicle energy consumption in 2050 ranging from roughly 650 to 1650 TWh, which is 20%–53% of that of 2019. For the most strongly electrified fleet scenario with optimistic assumptions on measures to improve vehicle efficiency, transport flow and transport volumes and renewable electricity production, well-to-tank (WtT) energy consumption is around 110–160 TWh, depending on the fuel scenario. If a moderately electrified fleet is propelled with e-fuels, even when assuming fully renewable electricity and optimistic measures, the WtT energy consumption increases ten times or more, to 1300 TWh (2150 TWh with pessimistic measures). The results show that fleet electrification is the strongest lever for WtW transport energy consumption reduction among the options considered. Other efficiency measures contribute significantly to energy savings, but their benefit decreases with increasing fleet electrification. The production pathways of fuels make a substantial difference for WtW fleet energy requirement if the fleet is moderately electrified, in which case e-fuels require significant amounts of additional renewable electricity. Nevertheless, fuel production pathways become irrelevant from an energetic point of view under very ambitious electrification scenarios since fuel volumes become marginal. The economic feasibility and the societal acceptability of different pathways towards WtW carbon-neutrality of road transport is out of scope of this paper and requires further investigation.

## 1. Introduction

The European Union (EU) introduced its Climate Law (EU, 2021) in June 2021, which requires the Union to achieve climate neutrality by 2050. The Climate law also foresees intermediate binding targets for 2030, which stipulate a domestic reduction of net greenhouse gas emissions (emissions after deduction of carbon sinks) by at least 55% compared to 1990 levels. Road transport is responsible for about 20% of total EU greenhouse gas (GHG) emissions while transport, in general, is the only sector exhibiting substantial emissions increases since 1990. $CO_2$ emission standards for new light-duty (LDV) and heavy-duty vehicles (HDV) are key policy initiatives for reducing transport $CO_2$ emissions (EC, 2020).

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**Abbreviations**

| | |
|---|---|
| (BE)CCS | (Bioenergy) Carbon Capture and Storage |
| BAU | Business As Usual |
| BEV | Battery Electric Vehicles |
| DAC | Direct Air Capture |
| ERTRAC | European Road Transport Advisory Council (ERTRAC) |
| FCHEV | Fuel Cell Hybrid Electric Vehicles |
| GHG | Greenhouse Gas |
| HDV | Heavy-Duty Vehicle (Truck, Bus) |
| HEV | Hybrid Electric Vehicles |
| HVO | Hydrotreated Vegetable Oil |
| IMO | International Maritime Organization |
| LCA | Life-cycle Assessment |
| LDV | Light-Duty Vehicle (Passenger Car, Van) |
| LBM | Liquefied Bio-methane |
| (L)NG | (Liqui(fie)d) Natural Gas |
| LSM | Liquid Synthetic Methane |
| PHEV | Plug-In Hybrid Electric Vehicles |
| RED | Renewable Energy Directive |
| RES | Renewable Energy Supply (or System) |
| SMR | Steam Methane Reforming |
| SOEC | Solid Oxide Electrolyser Cell |
| TtW | Tank-to-wheel |
| WtT | Well-to-tank |
| WtW | Well-to-wheel |
| xEV | Advanced Electrified Vehicles, comprising BEV, PHEV and FCHEV |

*Fleet Scenarios*

| | |
|---|---|
| HE&ERS | High Electrification & Electrified Road System |
| HEH | High Electrification plus Hydrogen |
| HYB | Hybrids scenario |

*Vehicle Measure Settings*

| | |
|---|---|
| Opt | Optimistic reduction potential of a measure, upper boundary according to expert assessment |
| Pess | Pessimistic reduction potential of a measure, lower boundary according to expert assessment |

*Fuel Mix Scenarios*

| | |
|---|---|
| Advanced Biofuels | Advanced biofuels dominate in liquid fuels, with a small share of e-fuel |
| Mixed | 50/50 balance between advanced biofuels and e-fuels |
| E-fuels | E-fuels dominate in liquid fuels, with a small share of advanced biofuels |
| Limited fossil | Advanced biofuels dominate in liquid fuels, with small shares of fossil fuels and e-fuel |

*Electricity Scenarios*

| | |
|---|---|
| RES | 100% renewable electricity scenario with no residual $CO_{2eq}$ emissions in the generation phase |
| 1.5 TECH | Electricity Scenario from the EU long-term strategy for climate neutrality, combining a high share of renewable energy with residual nuclear, natural gas and carbon capture and storage |

Low and zero tailpipe emission LDV sales have recently picked up in the EU. In 2020, battery electric and plug-in hybrid cars surpassed a share of 10% of new sales in the EU27 for the first time, up from below 3% in 2019, and rose further to more than 20% in 2022.[1] In the light of technological development and decarbonisation policies, and declining user costs (Weiss et al., 2019), further growth of the electrified vehicle share in the fleet is expected (Edelenbosch, 2018). Recent studies show that diverse electrified powertrains, including battery electric vehicles (BEV), plug-in hybrid electric vehicles, and fuel cell hybrid electric vehicles (FCHEV) can contribute to the decarbonisation of road transport, depending on the energy mix (Kucukvar et al., 2022), powertrain configurations (Álvarez Fernández and Pérez-Dávila, 2022) and operation modes (Tansini et al., 2022). Fleet studies have also demonstrated that ambitious transport electrification is essential for reaching climate neutrality. For example, the analysis underpinning the 2018 EC communication "A clean planet for all" (EC, 2018a) includes two scenarios compatible with net-zero GHG emissions by 2050 (1.5 TECH and 1.5LIFE). In these scenarios, the conventional car stock share is around 5% of the 2050 fleet, with BEV making up for approximately 80% of the stock. A similar pattern arises for LCVs. However, for HDV, combustion engine vehicles using liquid and gaseous fuels remain dominant, and fully electric vehicles (BEV and FCHEV) reach just above 10% by 2050 (EC, 2018b). In a study by Ricardo commissioned by Concawe (2018), different European light-duty vehicle fleet and fuel options are considered, similar to the approach taken in the present study. For passenger cars, the High EV scenario assumes a 90% share of BEV in the 2050 vehicle fleet, whereas the low carbon fuels scenario proposes biofuels and e-fuels as a primary means of emission reduction, and the fleet contains 47% of PHEV, BEV and FCHEV by 2050.

Current EU road vehicle $CO_2$ standards, as well as the above fleet studies, address emissions from a tank-to-wheel (TtW) perspective, focusing exclusively on measurement, certification, and monitoring of tailpipe emissions. In order to meet the target of EU climate neutrality, the attention needs to be broadened. Life-cycle assessment (LCA) is a versatile tool to determine the impacts of products in an encompassing way. Numerous studies have been published in the recent past addressing, from a life-cycle perspective, the impact of passenger car fuel blending (Puricelli et al., 2022), the use of alternative fuels such as renewable diesel (Van den Oever et al., 2023), ammonia (Boero et al., 2023), electricity, hydrogen, or biofuels (see Liu et al. (2023) for a review of alternative fuels LCA studies), comparing propulsion system alternatives such as internal combustion engines and electric vehicles (Kalverkamp et al., 2020), or internal combustion engines, electric vehicles and fuel cell electric vehicles (Joshi et al., 2022), or combining fuels and vehicle types (Hill et al., 2020). Such studies are very detailed on the vehicle or fuel side, but typically take a product-based and often static perspective and cannot quantify system-level impacts of fleet and fuel trajectories towards carbon-neutrality. This gap has previously been identified. Field et al. (2008) make the case for the need of a fleet-based LCA. Garcia and Freire (2017) review fleet-based life-cycle approaches for vehicles focusing on energy and environmental impacts. They evaluate roughly 40 studies, based on a wide LCA definition including anything that goes beyond tailpipe. Most of these studies still focus on single or few powertrains or vehicle types, on distinct vehicle-side measures or selected fuels, and are limited to light-duty vehicles, with a focus on the US. None of these studies integrates diverse vehicle technology and fuel pathways. Meanwhile, important progress has been made. Oda et al. (2022) have carried out a meta-review of 332 peer-reviewed papers on automobile LCA, finding a recent strong rise in the annual number of papers, the majority (more than 80%) of which focus on either technology comparison or evaluation of specific technologies, but only 14% on fleet-based approaches. Oda et al. (2022) highlight that fleet-based LCA remains the core upcoming challenge in automobile LCA, to enable policy-makers and consumers to support

[1] https://alternative-fuels-observatory.ec.europa.eu/transport-mode/road/european-union-eu27/vehicles-and-fleet.

environmental policy.

The present study makes several steps towards a fleet-based LCA for EU decarbonisation policy support. On the fleet side, it covers the complete road vehicle fleet in the EU27 in 2050, including light and heavy-duty vehicles, and proposes scenarios for fleet composition by powertrain technologies and segments, along with technical measures to improve vehicle efficiency, activity, or the transport system. The study builds on fleet composition scenarios, TtW energy consumption and emissions calculations developed in a previous TtW study (see Krause et al., 2020). On the way towards life-cycle assessment, it adds a well-to-tank assessment of different fuel pathways, maximising the use of renewable energy across the whole fuel production and transport phase as a novel element. When combined, the full well-to-wheel (WtW) analysis portrays an integrated fuel and powertrain picture of different 2050 carbon-neutral EU fleet scenarios, thus presenting advances over the comparison of single technology or fuel options. Both the fleet and fuel scenarios have been set up via back-casting, to shed light on options to reach carbon-neutral road transport by 2050, which can inform policy-making. However, no complete LCA is presented in this study, as vehicle production and end-of-life, as well as infrastructure development and impact factors other than energy consumption and $CO_2$ emissions are out of the scope of this work. This paper is therefore an intermediate step towards a dynamic full life-cycle approach.

The scenarios were developed within a working group of the European Road Transport Advisory Council (ERTRAC), and documented and subsequently used to evaluate future European research needs related to road transport in the ERTRAC Sustainable Energies and Powertrains Mapping (Dauphin et al., 2022). The calculation of WtW fuel and energy consumption and emissions is original research presented in this paper.

The paper is structured as follows: Section 2 explains the methods and data employed and the modelling approach, covering a model overview and the TtW and WtT calculations. Section 3 presents the results regarding 2050 fleet energy consumption and fuel mix, resource use, residual $CO_2$ emissions and compensation in different scenarios. The summary, discussion, policy implications, and needs for further research are included in Section 4.

## 2. Material and methods

### 2.1. Model framework: A two-step approach

The present analysis consists of two steps, TtW and WtT calculation of energy consumption and emissions. A schematic overview of the modelling process is given in Fig. 1.

The 2050 TtW energy consumption and emissions calculations are based on three fleet composition scenarios. For each vehicle type, base vehicle efficiency is combined with assumptions on technical improvement measures for vehicles, combined with optimistic and pessimistic ranges for each measure's impact. Details are described in section 2.2.

WtT calculations are based on four fuel mix scenarios, combined with representative fuel pathways developed in this study, and with two electricity production pathways, see section 2.3. The upstream fuel parameters are applied to the TtW quantities of the different fuels required per scenario to generate scenario outcomes in terms of WtW energy consumption and carbon compensation. The fuel (WtT) and powertrain (TtW) elements are integrated into the overall WtW picture following the approach described in JEC, 2020. Fig. 2 illustrates the boundaries of the WtT and TtW energy expended or used for different types of fuels applied in this study (using JEC WTW v5 (JEC, 2020) as a reference).

*Well-to-tank* reflects the extra energy required (*expended*) for the production of 1 MJ of final fuel (biofuel, electricity, e-fuel, $H_2$ or fossil fuel) at the point of consumption (pump at the filling station or at the charging point). This includes, e.g., generation and transmission losses in the case of electricity, or production and transport losses in the case of e-fuels. The energy content of the fuels themselves is not included in the WtT part (Lower Heating Value expressed as MJ per ton of fuel used to power the vehicle in the TtW part as described in Fig. 2).

*Tank-to-wheel* relates to the energy use of the vehicle. It reflects the fact that, depending on the powertrain, part of the energy content in the fuel will be lost and only a fraction will be effectively transformed into work to move the wheels. For example, in the case of electricity, charging losses occur, but electric propulsion is more efficient compared to the losses that occur in internal combustion engine powertrains.

These energy flows are particularly relevant when presenting the results for e-fuels or hydrogen, the latter also considered as an e-fuel when produced from electrolysis. This is also true for the electricity flow and, in order to avoid any double-counting, the WtT part only reflects the additional electricity expended in the production of these fuels (electricity required to produce $H_2$ and combine it with $CO_2$ to end up with gaseous or liquid fuel and transport this to the filling station). When reporting the total electricity that needs to be generated to power the vehicles, all the elements of the WtW energy flow (total energy expended plus total energy use including losses) are considered and reported in the results section.

### 2.2. Tank-to-Wheel scenarios

European road vehicle TtW energy consumption and emissions in 2050 are calculated based on the three road vehicle fleet composition scenarios, estimates of vehicle activities, and assumptions on improvement measures, which are detailed below.

#### 2.2.1. Fleet scenarios and vehicle activities

Three road vehicle fleet composition scenarios for 2050 were developed, based on ERTRAC's expert view, varying in their degrees of uptake of electrified powertrains. Scenarios were developed though expert discussion and agreed within ERTRAC's $CO_2$ working group. The group members who have contributed to this study are listed in Appendix A. The scenarios are by no means a projection of the market evolution; they should be seen as corner-point cases to explore the different implications of some extreme considerations. The scenarios were described in more detail in Dauphin et al. (2022). A figure presenting 2050 powertrain shares in the three scenarios can be found in the same source (Fig. 1), as well as in Appendix H of this paper.

i) **High Electrification + Electrified Road System** (HE + ERS) scenario: High market uptake of battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV); Catenary system present on for heavy-duty trucks on highways
ii) **High Electrification plus Hydrogen** (HEH) scenario: Hydrogen fuel cell hybrid electric vehicles (FCHEV) on top of the options in i)
iii) **Hybrids** (HYB) scenario: Lower direct fleet electrification, higher shares of PHEV and conventional hybridised vehicles[2]

The fleet composition scenarios are primarily based on inputs and model calculations described in Krause et al. (2020). Some core input parameters were updated to reflect recent developments and new knowledge. In particular, recent improvements in battery technology suggested an update of the specifications of advanced electric vehicle efficiencies and electric drive ranges, and increased policy ambition concerning (transport) greenhouse gas emissions triggered a review of fleet scenarios. Passenger car, van and city bus fleet composition has not been changed, but for medium and heavy-duty trucks and coaches, shares have been shifted from conventional and PHEV into BEV and FCHEV respectively in the HE + ERS and the HEH scenarios to allow maximum fleet electrification. In the HE + ERS scenario, it is assumed that a catenary (panthograph) electrified road system is present on

[2] The Hybrids scenario was developed based on the previous "MIX" scenario in Krause et al. (2020).

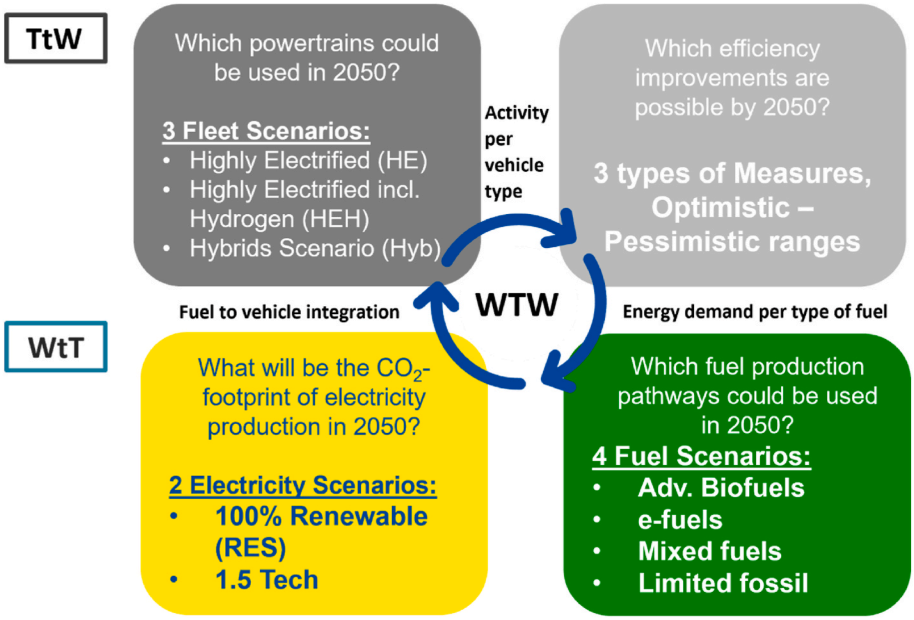



**Fig. 1.** Building blocks of the overall well-to-wheel approach adopted in the present study.

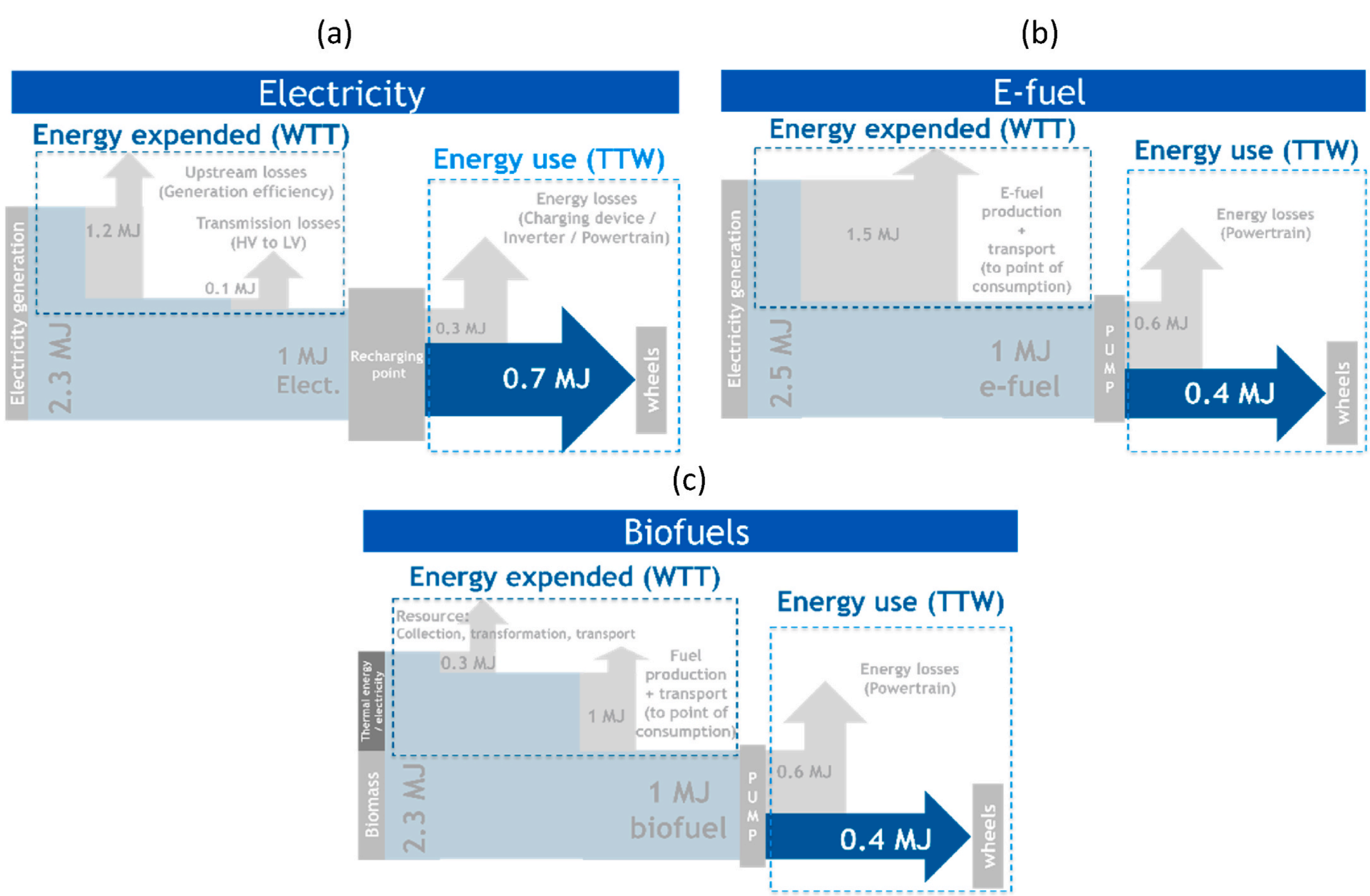



**Fig. 2.** Energy flows for different illustrative examples of fuel families. (Note that the term "fuels" refers here to electricity (a), e-fuels (100% RES electricity case) (b) and other liquid/gaseous biofuels (c)).

highways and used by heavy-duty vehicles, to reduce their need for battery capacity and to increase their range. No inductive charging is assumed. The combination of these fleet scenarios and the level of activity defines the total energy demand per type of fuel that needs to be satisfied in the WtT part of the analysis.

The 2050 total road vehicle fleet activity and the stock was calibrated with the EU Reference Scenario 2016; EC, 2016) which implies an increase of roughly 15% by 2050 compared to today's road vehicle activity, with a much stronger increase in freight transport than in passenger transport. Total 2050 EU27 road vehicle activity is split by propulsion mode, i.e., distance travelled in battery-electric, fuel cell electric, or combustion engine mode, depending on the scenarios. The share of electrified mileage varies between 55% and 98% (for details see Appendix C).

#### 2.2.2. Baseline vehicle parameters

Baseline efficiencies of different vehicles segments and powertrains were strongly based on (Krause et al., 2020). Electric shares of PHEV were revised for this study to take recent battery trends into account. Further details on the parameters used and changes made can be found in the Appendices (Appendix C and K).

#### 2.2.3. Technical measures

Three types of measures for improving TtW transport efficiency were considered, that are expected to have a positive impact on the baseline vehicle efficiency, namely.

A) Measures for vehicle improvement, e.g., improving engine efficiency, reducing vehicle weight, improving aerodynamics or rolling resistance. Ten measures of this type were included.
B) Measures for improving transport flow, e.g., speed smoothening, platooning; two measures were considered.
C) Measures reducing transport activity, e.g., by reducing parking search or increasing truck capacity. Four measures of this type were defined.

To cover for the present uncertainty on the order of magnitude of improvements that can be reached by these measures, optimistic and pessimistic reduction potentials by 2050, compared to the present, were defined for each measure. The optimistic reduction potential of a measure is the upper boundary this measure could achieve, and the pessimistic potential is the lower boundary, according to consensus expert assessment within ERTRAC's $CO_2$ working group (see Appendix A). To cover the maximum range of measure impact, the optimistic and the pessimistic potentials for all measures were combined in the scenarios.

Measure settings are taken mainly from Krause et al. (2020), with a few updates. The complete list of measures with quantified efficiency improvement potentials is given in the appendices (Appendix B).

#### 2.2.4. TtW fleet calculations

TtW vehicle fleet energy consumption, residual $CO_2$ emissions and respective compensation needs are calculated with the JRC's DIONE model (see Thiel et al., 2016; Harrison et al., 2016; Gómez Vilchez et al., 2019). The DIONE fleet impact model is a road transport fleet projection tool developed and run at the European Commission's Joint Research Centre (JRC) that allows analysing scenarios of road vehicle stock, activity, energy consumption and $CO_2$ as well as air pollutant emissions up to 2050. Emission calculation is carried out based on the methodology described in the EMEP/EEA air pollutant emission inventory guidebook.[3] Present new conventional vehicle fuel consumption for this study was taken from DIONE and is based on the COPERT[4] road transport emission inventory software. For the 2050 scenarios, baseline data was combined with expert assessment on vehicle measures and fleet composition specified in Appendices B and C to this paper. Calculations follow the methods established in Krause et al. (2020).

### 2.3. Well-to-Tank scenarios

Following the JEC WTT v5 methodology (JEC, 2020), the WtT section of the analysis explores both the energy requirements as well as the GHG emission intensity associated with the production of 1 MJ of final fuel. The steps modelled start at the point where the feedstocks/resources are available and progress with the transport and production stages until the point where the final fuel is ready for use (expressed as $MJ_{energy\ expended}/MJ_{final\ fuel}$ and $tCO_{2eq}/MJ_{final\ fuel}$).

When looking into the 2050 timeframe, many combinations of feedstocks and conversion technology pathways could be envisaged, some of them not fully deployed at a commercial scale yet. In this context, some selected routes have been used for this analysis as examples of future carbon intensities of different drop-in road fuels which could become available in the market. For the selected fuel routes, the expert group has extrapolated the JEC WTT v5 values (2030 timeframe) to a 2050 world in which upstream improvements are implemented together with the use of low GHG intensity energy sources in the conversion processes.

Table 1 presents the selected fuel families and their pathways, described in more detail in the subsequent sections.

#### 2.3.1. Electricity scenarios

Two different electricity production scenarios for 2050 have been considered in this study. Firstly, the "1.5 TECH"[5] scenario aligned with the European Commission's long-term vision (EC, 2018a) is used as the reference case. The power generation mix for this scenario has been taken from the homonymous scenario developed in the EU long-term strategy for climate neutrality (EC, 2018a). It assumes an 83% share of renewable energy sources (RES) in the 2050 power generation mix, 12% nuclear, 4% natural gas with carbon capture and storage (CCS), and 1% others. The approach to calculating this scenario's parameter values is detailed in the appendices (Appendix D). Secondly, a 100% renewable scenario ("100% RES") with no residual $CO_{2eq}$ emissions in the generation phase is used as a sensitivity. These parameters are applied to calculate the TtW GHG intensity of electricity used in advanced electrified vehicles' (xEVs) powertrains and the WtT fuel production processes. The assumptions for the two electricity scenarios considered in our 2050 scenarios are detailed in Dauphin et al. (2022, Fig. 1), and included in Appendix I to this paper.

#### 2.3.2. Liquid/gaseous fuel scenarios

In an attempt to capture the complexity and uncertainty on the 2050 future fuel mix, four scenarios for the production of liquid and gaseous fuels have been explored, weighting the individual pathways. The "**Advanced biofuels**" scenario assumes that 90% of fuel production in 2050 will be advanced biofuels, sourced from lignocellulosic material, residues or waste. The remaining demand (10%) will be fulfilled by e-fuels. No food nor crop-based fuels have been included in the assessment. Bioenergy carbon capture and storage (BECCS) is used to create negative emissions. It replaces advanced biofuel production to the extent needed to reach carbon-neutrality. Assumed BECCS parameters are emissions savings of 119.4 $gCO_{2eq}$ per MJ, at an energy consumption of 1.26 MJ of energy expended per MJ of final fuel corresponding to a waste wood gasification and Fischer-Tropsch pathway coupled with CCS.

[3] https://www.eea.europa.eu/themes/air/air-pollution-sources-1/emep-eea-air-pollutant-emission-inventory-guidebook.

[4] See http://emisia.com/products/copert.

[5] The 1.5 TECH scenario was designed having in mind the Paris Agreement goal of pursuing efforts to limit to a 1.5 °C temperature change, translated to a target of −100% GHG (including sinks), i.e. net zero GHG emissions in 2050. These are achieved by compensating with negative emissions for the "harder to abate" emissions sectors such as transport. The scenario assumed advancements in technology compared to today, including as a key complementary action negative $CO_2$ emissions as of 2050 (in significant amounts). It increases carbon capturing and storage (CCS) to lower the remaining emissions. It also applies more use of e-gases and fuels based on air captured or biogenic $CO_2$ to reduce remaining emissions. It applies negative emission technologies via biomass coupled with CCS and the storage of biogenic $CO_2$ in material.

**Table 1**
Summary of selected WtT fuel pathways.

| Fuel family | Electricity | Biofuel | E-fuel | Hydrogen | Fossil fuels |
|---|---|---|---|---|---|
| **Fuel/ Feedstock/ Source/ Conversion Process** | 100% RES (wind) | **Synthetic diesel** Waste wood to gasification (a) Fischer Tropsch (b) Black liquor | **e-diesel/e-methane** Renewable $H_2$ from high temperature water electrolysis based on Solid Oxide Electrolyser Cell + $CO_2$ from flue gases ((a) industrial site; (b) biomass upgrading)) or Direct Air Capture (c) + Fischer-Tropsch (liquid)/ methanation (gaseous). Electricity sources depending on the scenario considered. | (a) Water electrolysis with low GHG electricity (renewable) | Gasoline/Diesel from crude oil |
| | Mix as in 1.5 TECH scenario | **Hydrotreated Vegetable Oil** Waste cooking oil/ Hydrotreatment | | (b) Steam reforming (SMR) of natural gas with $CO_2$ capture and storage (CCS) | Natural gas/LNG |
| **Basis for 2050 WtT values** | JEC WTT v5 [JEC 2020] for Wind offshore (WDEL). ERTRAC internal elaboration for the 1.5 TECH generation mix [EC 2018a] | 2050 ERTRAC elaboration based on 2030 JEC WTT v5 [JEC 2020] related pathways (Codes: WWSD1a, BLSD1a, WOH1a) | 2050 ERTRAC elaboration based on 2030 JEC WTT v5 [JEC 2020] related pathways (Codes: RESD2a/ b/c – RELG1a) | 2050 ERTRAC elaboration based on 2030 JEC WTT v5 [JEC 2020] related pathways (Codes: (a) WDEL1/$CH_2$; (b) GPC$H_2$C) | 2050 ERTRAC elaboration based on 2030 JEC WTT v5 [JEC 2020] related pathways (Code: GRLG1) |

At the other extreme, the **"e-fuels"** scenario sets e-fuel deployment in transport to 100%. For this scenario, as no biofuels are used, direct air capture (DAC) will be employed to create negative emissions. Due to the early stage of the development of the technology, there is a big uncertainty around the energy consumption when deployed at scale. Different sources show a range between 0.5 and 2.7 MWh electricity/t$CO_2$ (Viebahn et al., 2019). For this study, a mid-range estimate of energy expended of 1.6 MWh/t$CO_2$ was used.

As a combination of the above, the "**Mixed"** scenario examines a case with equal shares of e-fuels and advanced biofuels. Finally, the "**Limited fossil"** scenario is derived from the Advanced Biofuels scenario, adding some remaining fossil fuels in the fuel mix (10%).

A representation of pathway shares can be found in Appendix J to this paper, and in Dauphin et al. (2022).

### 2.3.3. 2050 fuel parameters

To derive 2050 fuel parameters, the JEC WTT v5 data for 2030 (JEC, 2020) has been modified in several ways. Firstly, ambitious assumptions have been made concerning process electrification: In the conversion processes, thermal energy has been replaced by electric energy wherever possible, i.e., completely within Europe and partially when produced out of Europe. Heat and steam for process chemicals have also been replaced by electricity. Secondly, fossil fuels usage has been replaced by biofuels in some processes (e.g. collection, chopping) where limited electrification is foreseen. Thirdly, JEC present state-of-the-art technology has been assumed for the average energy consumption of fuel production plants in 2050. No additional energy efficiency improvement versus the JEC WTT v5 figures has been considered, with the only exception of the use of highly efficient turbines. As a simplification, $N_2O$ and $CH_4$ emissions linked to biofuel production processes are kept as in JEC WTT v5 (JEC, 2020).

As regards transport during fuel production, it has been assumed that $CO_{2eq}$ emissions due to transport of feedstocks from out of Europe to Europe will be significantly reduced. This is inspired by ongoing international initiatives such as the International Maritime Organization's long-term strategy[6] to reduce GHG emissions related to maritime transport by at least 50% by 2050 compared to 2008. In this paper, a 50% reduction has been assumed in the period 2030 to 2050. It has been assumed that emissions related to the domestic transport are already included within the fleet TtW emissions (road).

For electricity consumed in the fuel production process, generally, each fuel scenario has been combined with both pathways detailed in section 2.3.1, but for the e-fuel production process, 100% renewable electricity is assumed as the main case and used for both the hydrogen electrolyser and for the subsequent e-fuel conversion process.

In all fuel scenarios except the limited fossil one, Hydrogen ($H_2$) is produced through water electrolysis with Proton Exchange Membrane (PEM) electrolysis technology applied as a simplification. In the limited fossil scenario, 50% of the total $H_2$ demand will be satisfied as renewable hydrogen (as above) and the rest with Steam Methane Reforming (SMR) coupled with Carbon Capture and Storage (CCS) and transported to the retail station via pipeline. Moreover, it is assumed that the water central electrolysis process uses electricity only from wind or solar energy, whereas hydrogen pipeline transport and compression, up to 88 MPa, can use either 100% renewable or 1.5 TECH scenario electricity parameters. Natural gas from Russia is transported to the EU by pipeline from Southern Asia/Middle East (4000 km to the EU), distributed through high pressure trunk lines.

In downstream long-distance pipeline transport, more efficient gas turbines have been assumed to be in place compared to JEC WTT v5. Downstream distribution is conducted by means of electrically instead of natural gas driven compressors.

As the intention of the present scenarios is not to foresee the future but to explore potential options, a limited fossil scenario is included, where the contribution from fossil natural gas with CCS is considered. For such a case, an even share with electrolytic $H_2$ has been used.

Fig. 3 summarises the WtT energy expended and related GHG emissions for the individual pathways considered, for 2030 as well as the extrapolations to 2050 elaborated within this study. The fuel energy consumption and $CO_2$ emission parameters for liquid and gaseous fuel scenarios as well as an illustration of the procedure followed to derive the 2050 values are included the supplementary material (Appendix E).

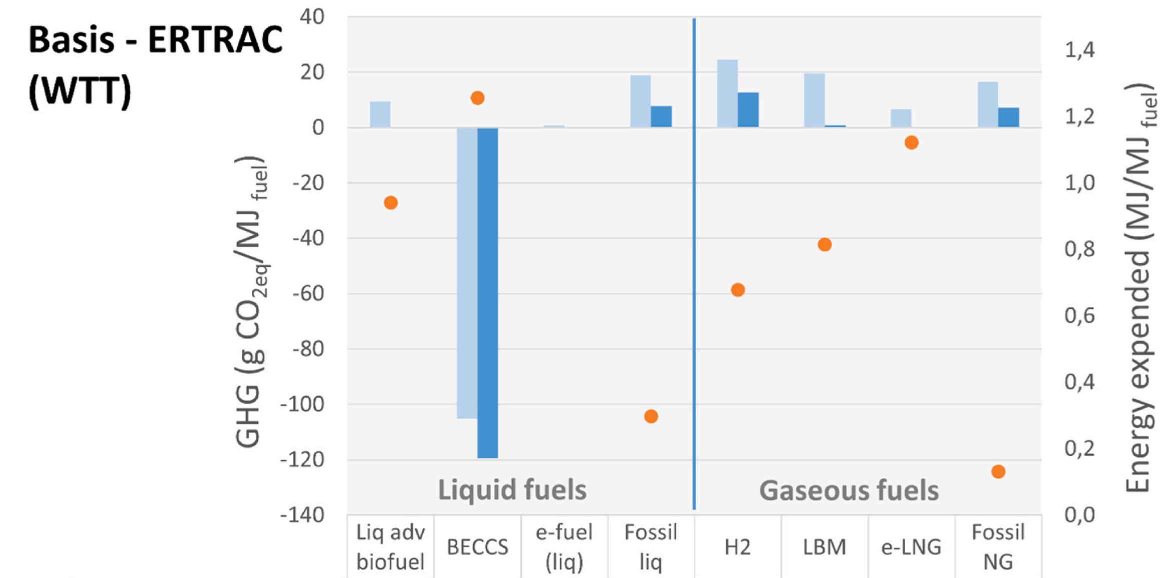
### 2.3.4. Well-to-wheel integration

Well-to-wheel energy consumption is calculated by integrating the above scenarios on vehicle fleet composition, activity and efficiencies with the well-to-tank modelling for fuels and electricity. This has been done for all six combinations of fleet scenarios (HE, HEH and HYB) and measure settings (optimistic and pessimistic), which have been complemented by the four 2050 fuel scenarios (mixed fuels, e-fuels, advanced biofuels, limited fossil) with two electricity production options (100% RES and 1.5 TECH) each, generating a total of 48 scenarios.

## 3. Results

In this section, study results are presented, starting from 2050 vehicle fleet energy consumption under the different scenarios in a TtW and WtW perspective, and then summarising findings on electricity

[6] https://www.imo.org/en/MediaCentre/PressBriefings/Pages/06GHGinitialstrategy.aspx.




| | Liq adv biofuel | BECCS | e-fuel (liq) | Fossil liq | H2 | LBM | e-LNG | Fossil NG |
|---|---|---|---|---|---|---|---|---|
| JEC, 2030, GHG | 9,4 | -105,1 | 0,73 | 18,9 | 24,6 | 19,55 | 6,7 | 16,6 |
| ERTRAC, 2050, GHG | 0,05 | -119,4 | 0,1 | 7,8 | 12,7 | 0,9 | 0,0 | 7,2 |
| ERTRAC, 2050, Energ exp | 0,94 | 1,26 | 1,68 | 0,30 | 0,68 | 0,82 | 1,12 | 0,13 |

**Fig. 3.** 2050 GHG emissions (left scale) and energy expended (right scale) per MJ of fuel, for the different fuels assumed in this study, for 100% RES electricity. (100% RES electricity assumed as 0 g $CO_{2eq}$/MJ and 100% efficiency in a WTW approach).

consumption. The study evaluates 48 scenarios in total, considering all the possible combinations of the different assumptions. Each scenario achieves net carbon-neutral road transport in 2050, using carbon emission compensation where necessary.

### *3.1. Tank-to-wheel energy*

In the tank to wheel analysis, we have calculated the final energy consumption for road vehicles in the EU in 2050, both from fuels and electricity supplied through the grid. The impact of the different fleet composition scenarios and the technical measures applied are considered. The outcomes can be seen in Fig. 4[7] which shows the total amount of final energy required and its split by liquid or gaseous fuels, hydrogen and electricity.

On the left-hand side (“References”), the 2019 EU27 road transport energy consumption is shown, as well as that of two scenarios for 2050 (Baseline and 1.5 TECH Scenario) from the analysis for the EC long-term climate strategy (EC, 2018b), labelled ACP4A (A Clean Planet for all), both for EU28, i.e., the 27 present EU member states plus the UK. In a second block (Fleet Composition Effect), the results are shown for the three fleet composition scenarios of the present analysis without applying any technical measures. The third block shows the impacts including the full set of technical measures, for the optimistic and pessimistic cases. To facilitate comparison, for each of the EU27 outcomes the total road transport energy consumption for the EU28 is included as an error bar.

The 2050 EU27 TtW road vehicle energy consumption ranges from 640 to 1660 TWh in the different scenarios, which is 20%–53% of that in 2019. As can be seen, the higher the share of battery electric vehicles, the lower TtW energy consumption. Thus, the HE + ERS scenario performs best in terms of reducing the final energy consumption, followed by the HEH scenario which includes fuel cell electric vehicles, whereas the moderately electrified HYB scenario shows the highest TtW energy consumption. This is a direct consequence of the difference in powertrains efficiencies, as electric powertrains have a much higher efficiency than internal combustion engines. Technical measures have a significant impact on further reducing energy consumption, with the optimistic version saving roughly a third of the energy consumption compared to the pessimistic version.

In the HE + ERS and HEH scenarios, a strong shift in the fuel mix towards electricity and $H_2$ is induced, making them the primary energy carriers for transport in 2050, whereas in the HYB scenario liquid and gaseous fuels remain dominant. Compared to Krause et al. (2020), total EU28 TtW transport energy consumption remains similar. But the updates of assumptions towards higher medium and heavy-duty xEV shares in the HE + ERS and HEH scenarios and the increased electric ranges of PHEV have driven a shift into electricity and $H_2$.

As explained earlier, TtW energy consumption is combined with different fuel mix scenarios for 2050. In line with EU decarbonisation objectives towards 2050, liquid and gaseous fuels are assumed to be mixes of different shares of biofuels/waste based fuels and e-fuels, with only the “limited fossil” fuel scenario retaining a small share (10%) of fossil fuels. For details, see Section 2.3 and Appendix J.

### *3.2. Well-to-wheel energy*

Well-to-wheel energy consumption for the combination of fleet scenarios, vehicle efficiency measure settings, fuel and electricity mix scenarios is presented in Fig. 5. The figure shows that for the HE optimistic scenario, the WtT energy consumption is around 20% of TtW, and 2050 EU27 WtW energy consumption is 800 TWh at most, regardless of the fuel and electricity production pathways. In contrast, if a moderately electrified fleet is propelled with e-fuels, even when assuming fully renewable electricity and optimistic measures, the WtT energy is 130% of TtW energy resulting in a WtW energy consumption of 2400 TWh. The highest WtW energy consumption of more than 5000 TWh occurs when a HYB fleet is propelled with e-fuels produced from 1.5 TECH electricity, and measures reach only their pessimistic potential, leading to a WtT energy consumption of more than twice TtW.

It can be seen that the broader pattern present in the TtW results persists: the HE (including ERS) scenario always exhibits the lowest

[7] For a decomposition by fuel type, see Appendix F.

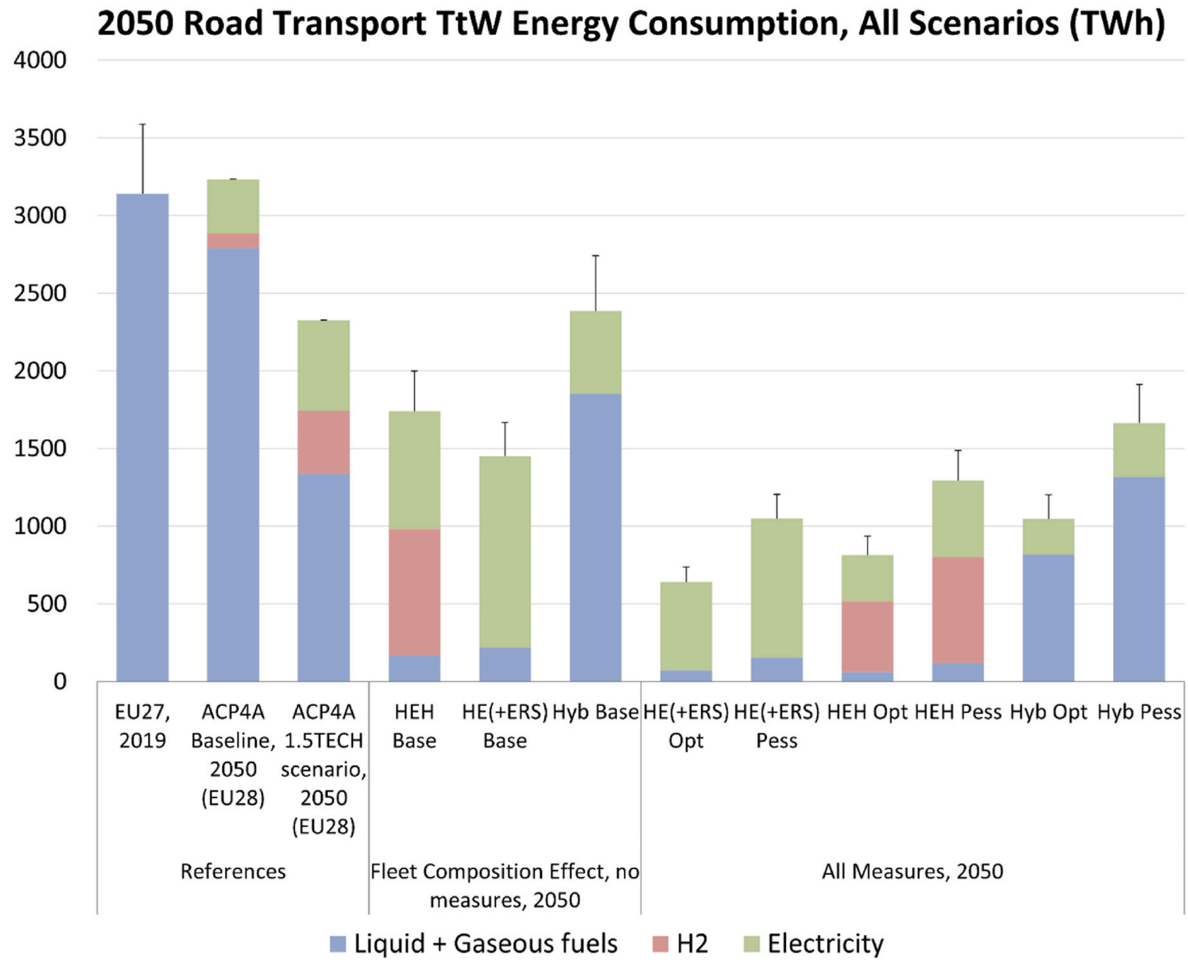



**Fig. 4.** Tank to wheel energy consumption of the 2050 road transport vehicle fleet (TWh, for selected references, the fleet composition scenarios only and including the impact of improvement measures (optimistic and pessimistic estimates), for the EU27. Error bars represent EU28 totals, i.e., adding the UK.

WtW energy consumption, followed by the HEH and HYB scenarios. The difference between the HE and HEH fleets, in terms of energy consumption, is at least 450 TWh and at least 1060 TWh between HE and HYB, all else being equal. The maximum difference caused by fleet composition can be up to 2500 TWh or almost triple total WtT energy consumption, when comparing the HE pess e-fuels (RES) and the HYB pess e-fuels (RES) scenarios, and even up to more than 3600 TWh when comparing the same two fleet and fuel scenarios for the 1.5 TECH electricity production pathway. This confirms that fleet electrification is the strongest driver for transport energy consumption reduction, from a WtW as well as a TtW perspective.

Secondly, the impact of technical measures to increase vehicle efficiency, smoothen or reduce transport also remains important in a WtW perspective but this decreases with increasing fleet electrification. The optimistic to pessimistic difference is around 500 to 700 TWh for the HE fleet composition, around 700 to 800 TWh with HEH fleets, and 1100 up to 2000 TWh for HYB fleet composition, all else being equal.

Thirdly, it can be seen that WtW energy consumption is very similar for all 2050 fuel production pathways for the HE and HEH scenarios but that the fuels scenario can make a substantial difference for the HYB fleet. In particular, in the e-fuels scenario, HYB fleets consume 500 to 800 TWh more energy, even under the 100% RES electricity production scenario, than they do when fuelled according to the advanced biofuel scenario. The difference for 1.5 TECH electricity production is 1300 TWh to more than 2000 TWh. However, such differences occur only where fleets retaining significant shares of conventional vehicles are fuelled by e-fuels. Under very ambitious fleet electrification scenarios, the production pathway of fuels becomes irrelevant from an energetic point of view in a WtW perspective, as their volumes become marginal. For fuels, another relevant comparison is that with benchmark 2030 fuels: for the HE and HEH fleet scenarios, the 2050 fuel scenarios all exhibit energy savings from a WtW perspective compared to the use of 2030 benchmark fuels. This is due to the uptake of RES electricity, which improves the electricity generation efficiency (hence less energy expended in the WtT part). However, the opposite is the case for HYB fleets, where the WtW energy consumption generally increases with the 2050 fuels. The latter is due to the replacement of fossil-based liquid fuels by renewable fuels which increases the WtT contribution.

Finally, analogously to the fuel pathways, the impact of the electricity production pathway also depends on the degree to which the fleet is electrified. The impact is small in the HE and HEH scenarios, though slightly more relevant in the e-fuels scenario than in the other ones. The more e-fuels are used, the more the electricity production pathway matters. Thus, in the e-fuels and HYB fleet scenario with pessimistic measures, where propulsion by combustion engine retains the highest share of all present scenarios, the sole production of liquid fuels consumes 3500 TWh of energy, more than four times the amount needed, WtW, for the most energy-efficient HE fleet in the 2050 scenarios. In conclusion, from an energetic point of view, e-fuels with a HYB fleet can be a viable option only if substantial additional amounts of fully renewable energy become available in the future to produce them.

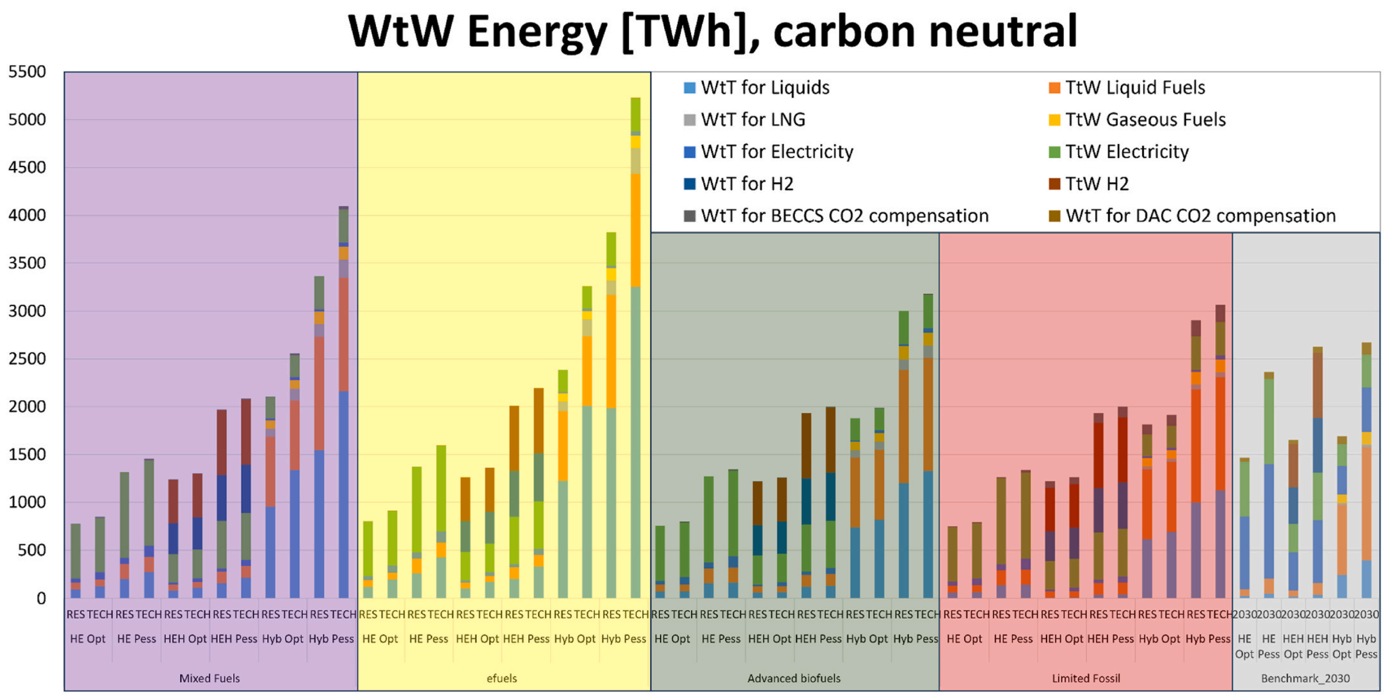



**Fig. 5.** WtW energy demand for WtW net carbon-neutral EU27 road transport in 2050 (TWh), for the different fleet scenarios (HE, HEH, HYB), measure settings (optimistic, pessimistic), fuel scenarios (Mixed Fuels, e-fuels, Advanced biofuels, Limited fossil, Benchmark, 2030), and electricity production scenarios ("RES": 100% RES, "TECH": 1.5 TECH, "2030": Benchmark, 2030 electricity). Each scenario is net carbon-neutral in a WtW frame, energy consumption for $CO_2$ compensation is included where necessary (via BECCS, or DAC).

### 3.3. Electricity demand

It is also of interest to understand to what extent different fuels will be needed for road transport under the different scenarios. In the above, the total WtT energy expended was assigned to the respective final fuel, regardless of the energy carrier. Based on the fuel production pathways described in this study, the WtT energy consumption can be split into different types of energy carrier and combined with the TtW consumption of the same energy carrier.

This has been done for electricity in Fig. 6, to show the total electricity generation needed to propel the 2050 vehicle fleet in the EU27 according to the different scenarios, for the 100% renewable electricity

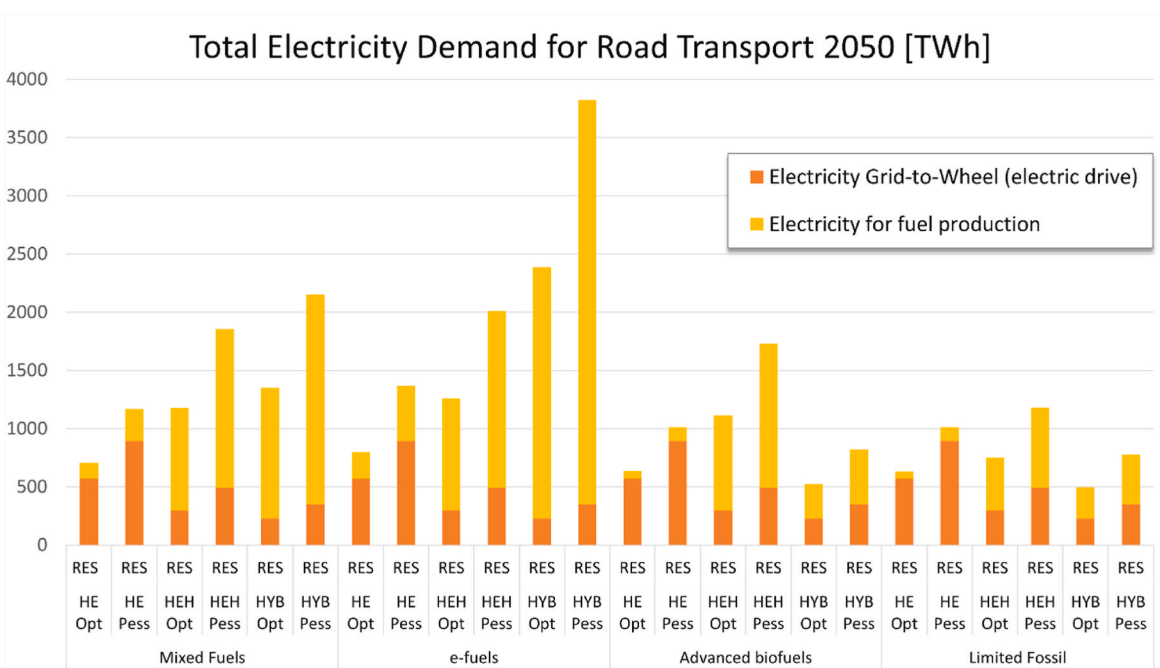



**Fig. 6.** Total Electricity Generation for EU27 road transport in 2050 (TWh), for the different Fleet scenarios (HE, HEH, HYB), measure settings (optimistic, pessimistic), and fuel scenarios (Mixed Fuels, e-fuels, advanced biofuels, limited fossil, benchmark 2030), for electricity production scenario "RES": 100% RES.

production pathway. The 1.5 TECH scenario values are not shown, as they are very similar ( ± 10% difference at most). More primary energy is needed for fuel production, but electricity needs vary only to a limited extent, e.g., for CCS to offset the remaining $CO_2$ emissions of the 1.5 TECH scenario power generation (increasing electricity demand in this instance), or for Steam Methane Reforming used instead of electrolysis for $H_2$ production (reducing electricity demand in this instance).

Compared to the WtW energy consumption shown previously in Fig. 5, electricity makes up for a significant share of the WtW energy in the 100% RES electricity scenarios and can be 100% of the energy required, which happens in the e-fuel scenario, regardless of fleet composition. As expected, minimum electricity shares of around 15% of the WtW energy occur in the HYB scenario with advanced biofuels or limited fossil fuel scenarios.

Furthermore, in absolute terms, the e-fuels scenario triggers the highest demand for electricity generation. Up to 3800 TWh of electricity is consumed in the HYB Scenario with pessimistic measures when combined with e-fuels produced according to the 100% RES electricity scenario. In this case, the EU27 transport sector alone would consume 140% of the net production of electricity in the EU27 today.[8] In the most electricity-consumption intense scenarios, e-fuel production drives electricity need (yellow part of the bars in Fig. 6)), dominating by far the quantity of electricity needed for EV.

In summary, in a WtW perspective, electricity is a significant and, in many cases, the dominant energy vector to be used in EU27 road transport in 2050, under the present fleet and fuel scenarios, either used as final energy (in batteries) or as intermediate feedstock (for fuel production). The viability of some of the pathways presented here, particularly the e-fuel scenario combined with the HYB fleet scenario, will depend on the capacity of the power sector to supply large quantities of additional, carbon-neutral electricity for use in transport without crowding out other sectors' demand. The economics of this solution, questions of production capacity within Europe and energy security are essential determinants beyond the scope of this paper, which require further investigation.

### 3.4. Further results

The discussion in this paper focusses on energy consumption and electricity needs. However, apart from electricity, substantial demand of biomass-based fuels can arise in the biofuels and limited fossil scenarios. A representation of TtW energy consumption by fuel type showcasing this and respective discussion is included in the appendices (Appendix F).

Likewise, for scenarios that are not carbon-neutral in a WtW perspective, $CO_2$ emissions prior to carbon compensation and the related energy needs are presented and discussed in Appendix G.

## 4. Conclusions and discussion

From a WtW perspective, drastic changes in many aspects of road transport are necessary to achieve carbon-neutrality in the EU by 2050. Specifically, the road vehicle stock, its efficiency and activity, together with traffic management, transport infrastructure and the production of energy carriers (electricity, renewable fuels etc.) need addressing. In this paper, different pathways towards WtW carbon-neutrality of road transport have been examined. Their economic feasibility has not been evaluated, nor have the societal acceptability or possible, e.g. environmental, side-effects: these topics require further in-depth investigation.

The present study extends the scenario-based analysis of road transport greenhouse gas emission reduction options from a TtW perspective to a WtW perspective and quantifies the energy demand for different options. As such, it should be seen as a further contribution on the path to assessing the societal benefit and impact of different options for carbon-neutral road transport. From a technical point of view and from a WtW perspective, the following conclusions can be drawn:

Firstly, road vehicle fleet electrification, focusing on battery and fuel cell electric vehicles, is the strongest single enabler for transport final energy consumption reduction. The EU27 road vehicle TtW energy demand decreases significantly in all scenarios, with 2050 energy consumption ranging from 20% to 53% of 2019. It decreases most strongly in the highly electrified scenario, which also consumes least energy WtT.

Secondly, the impact of measures to increase vehicle efficiency, smoothen or reduce transport can be similarly important as that of fleet electrification, but this importance decreases with increasing fleet electrification.

Thirdly, under very ambitious fleet electrification scenarios, the production pathways of energy carriers do not have an important impact on WtW energy consumption.

Finally, the total demand for electricity in road transport, i.e. for fuel production and for direct use in vehicles, is substantial for most of the scenarios investigated. For the combination of the e-fuels scenario with the hybrid fleet, the electricity demand for road transport alone can be similar or even higher than present total EU27 net production of electricity. The viability of transport electrification, either directly or via e-fuels, will depend on the capacity of the power sector to supply large quantities of additional, carbon-neutral electricity for use in transport without compromising its supply to other sectors. This needs further investigation.

The results offer insights into what amount of fuels and energy carriers for road transport could be needed in 2050, from a WtW perspective. However, it would be unwise to draw solid conclusions on which scenarios could be more or less feasible or desirable without also analysing the economics of the different solutions, including vehicle and fuel production and provision costs. Such an analysis should investigate infrastructure requirements (charging infrastructure, hydrogen filling stations, electrified road systems, production capacities for renewable fuels etc.), and competitiveness as well as labour market impacts of different options. Critical factors determining future developments are the availability of resources needed to deploy the options examined in the study, such as biomass, water, rare earths; potential social and environmental side effects; consumer behaviour, and the feasibility of renewable energy generation within Europe. Finally, considering the complexity and interoperability of transport systems, the interactions of the measures taken to tackle transport emissions with those adopted in other sectors inside the EU, or in transport worldwide, need to be studied. All these aspects merit further investigation, and such investigations are just now appearing in literature, see eg. Kramer et al. (2021). The study team acknowledges the need for further research on the topics mentioned, combined with information regarding the life-cycle emissions of different vehicle technologies, including also the impacts of potential shifts in vehicle production location, more stringent vehicle air pollutant emissions standards, and net zero carbon emission fuels.

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## CRediT authorship contribution statement

**Jette Krause:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marta Yugo:** Writing – original draft,

[8] According to Eurostat, total net production of electricity in the EU27 in 2019 was 2724 TWh (Source: https://ec.europa.eu/eurostat/statistics-explained/images/3/32/Electricity_Statistics%2C_EU-27_and_EA-19%2C_2017-2019_%28GWh%29.png.

Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Zissis Samaras:** Writing – review & editing, Visualization, Validation, Methodology, Data curation, Conceptualization. **Simon Edwards:** Writing – review & editing, Conceptualization. **Georgios Fontaras:** Writing – review & editing, Methodology. **Roland Dauphin:** Writing – review & editing, Validation, Methodology. **Peter Prenninger:** Writing – review & editing, Conceptualization. **Stephan Neugebauer:** Writing – review & editing, Supervision, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

I have added the data as an excel file.

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The present paper is based on the intense involvement of experts from the automotive industry, research and public authorities. The list of contributing experts is included in Appendix A.

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The scientific output expressed does not imply a policy position of the European Commission nor a position of any of the institutions to which authors are affiliated.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.141084.

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