FVV Fuels Study IV – Transformation of European Mobility to the GHG Neutral Post Fossil Age

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Abstract

On the basis of the FVV Fuels Study IV [1], different technology (energy/fuel – powertrain) pathways (100% scenarios) are investigated that all lead to carbon neutral mobility in 2050. They are compared with regard to energy demand, total costs, cumulative greenhouse gas emissions and other environmental impacts by means of a holistic cradle-to-grave approach, that considers all relevant costs and emissions from vehicle production and the setup of a complete sustainable energy supply system. For this purpose, the emissions caused by the construction of the infrastructure, such as wind turbines, electrolysers or charging stations, are also included. Only such an analysis of the entire energy system delivers valid insights into efficient defossilisation strategies.

Regardless of which of the technology pathways Europe chooses, the 1.5 °C greenhouse gas budget discussed for Europe will already be exceeded by 2032 due to transport emissions alone, when the ramp-up of carbon neutral technology is determined by the vehicle fleet exchange rate of new carbon neutral vehicle technology. The reason for this is the dominant share of the existing fleet still using fossil fuels, phasing out by 2050. Irrespective of the scenario, the GHG emissions of the existing fleet amount to around 70 % at an identical rate of introduction of new vehicle technologies and accordingly replacing fossil energy in transportation at the same rate. Without technology options that reduce emissions in the existing fleet and an efficient combination of defossilisation measures, it will not be possible to achieve the ambitious European climate targets.

Therefore, a follow-up study has been started to thoroughly investigate the constraining ramp-up bottlenecks (“FVV Fuels Study IVb”).

First potential technical bottlenecks could be identified which are likely to decelerate the ramp-up of renewable mobility, sticking to exclusive 100%-scenarios, even under absolute ideal legal boundary conditions and investment attractiveness. These bottlenecks may involve the achievable ramp-up speed of key technologies as electrolysis, direct air capturing, reverse water gas shift reaction, charging infrastructure, electrical grid extension or build capacity of solar and wind power generation. To what extent these bottlenecks are limiting the required fast ramp-up of complete sustainable transportation pathways has not been finally investigated yet. Final results are expected by autumn 2022.

However, interim results turn more and more out to confirm, that concentration on a single energy-technology pathway is limiting the achievable ramp-up speed significantly. Most efficient GHG reduction requires intelligent technology mixes that enable the fastest possible exit out of fossil energy use for the lowest costs.

Kurzfassung

Auf der Grundlage der FVV-Kraftstoffstudie IV werden verschiedene Technologiepfade (Energie/Kraftstoff - Antriebsstrang) (100%-Szenarien) untersucht, die alle zu einer klimaneutralen Mobilität im Jahr 2050 führen. Sie werden hinsichtlich des Energiebedarfs, der Gesamtkosten, der kumulierten Treibhausgasemissionen und anderer Umweltauswirkungen mit Hilfe eines ganzheitlichen Cradle-to-Grave-Ansatzes verglichen, der alle relevanten Kosten und Emissionen aus der Fahrzeugproduktion und dem Aufbau eines vollständigen nachhaltigen Energieversorgungssystems berücksichtigt. Dabei werden auch die Emissionen einbezogen, die durch den Aufbau der Infrastruktur, wie Windkraftanlagen, Elektrolyseure oder Ladestationen, entstehen. Nur eine solche Analyse des gesamten Energiesystems liefert valide Erkenntnisse über effiziente Defossilisierungsstrategien.

Unabhängig davon, für welchen der Technologiepfade sich Europa entscheidet, wird das für Europa diskutierte 1,5 °C-Treibhausgasbudget bereits im Jahr 2032 allein durch die Emissionen des Verkehrs überschritten. Der Grund dafür ist der dominierende Anteil der bestehenden Flotte, die noch fossile Kraftstoffe verwendet und bis 2050 ausläuft. Unabhängig vom Szenario belaufen sich die THG-Emissionen der bestehenden Flotte auf etwa 70 %, wenn die Einführung neuer Fahrzeugtechnologien gleich schnell erfolgt und dementsprechend fossile Energie im Verkehr in gleichem Maße ersetzt wird. Ohne Technologieoptionen, die die Emissionen der bestehenden Flotte reduzieren, und eine effiziente Kombination von Defossilisierungsmaßnahmen werden die ehrgeizigen europäischen Klimaziele nicht erreicht werden können.

In einer schon begonnenen Folgestudie werden daher Engpässe von Hochläufen zurzeit gründlich untersucht.

Erste potenzielle technische Engpässe konnten identifiziert werden, die den Hochlauf erneuerbarer Mobilität bei einem Festhalten an ausschließlichen 100%-Szenarien auch unter absolut idealen rechtlichen Rahmenbedingungen und gesicherter Investitionsattraktivität weiter verlangsamen dürften. Diese Engpässe können die erreichbare Hochlaufgeschwindigkeit von Schlüsseltechnologien wie Elektrolyse, CO_2-Abscheidung aus der Umgebungsluft, inverse Wasser-Gas-Shift-Reaktion, Ladeinfrastruktur, Stromnetzerweiterung oder Kapazitätsaufbau bei der Solar- und Windenergieerzeugung betreffen. Inwieweit diese Engpässe den notwendigen schnellen Hochlauf vollständig nachhaltiger Transportwege einschränken, ist noch nicht abschließend untersucht. Endgültige Ergebnisse werden bis Herbst 2022 erwartet.

Zwischenergebnisse bestätigen jedoch mehr und mehr, dass die Konzentration auf einen einzigen energietechnischen Pfad die erreichbare Hochlaufgeschwindigkeit erheblich begrenzt. Eine möglichst effiziente THG-Reduktion erfordert intelligente Technologie-Mixe, die den schnellstmöglichen Ausstieg aus der Nutzung fossiler Energien zu den niedrigsten Kosten ermöglichen.

1. Aim and Method

The EU plans to reach full climate neutrality across all sectors by 2050. For the transport sector in Europe, this aim cannot be achieved with combustion engine powered vehicles using fossil fuels. To reach a carbon neutral transport sector and meet both, national and European CO_2 targets, appropriate concepts for the defossilisation of the transport sector are required.

To investigate how this goal can be reached, the FVV working group “Fuels” has compared and evaluated different mobility scenarios which will allow fully carbon neutral mobility in 2050 (including the whole fuel supply chain as well as vehicle production) and for which energy demand will solely be supplied by renewable wind and solar energy.

This study illustrates various “energy and drivetrain technology pathways”, all of which have the potential to defossilise the transport sector by 2050. All of the fuel / drivetrain pathways are evaluated in so called “100% scenarios”, where every segment of the transport sector is assumed to be powered by the respective technology if technically feasible. Interaction of the transport with other sectors is not part of the study. These extreme scenarios are theoretical and not meant to be a realistic forecast of future developments. However, they allow for a comprehensive comparison across different fuel / drivetrain pathways and illustrate potential challenges arising from industry level scale up. The considered fuel / drivetrain pathways are not based on any fossil sources. Local CO_2 emissions are allowed if they are fully compensated during the production process (e.g., capturing CO_2 directly from the air, closed CO_2 circle).

The focus of the study is a quantitative and qualitative comparison of mobility costs (including the costs for the energy/fuel production and distribution facilities as well as vehicle costs), primary energy demand (including losses along the complete energy/fuel supply chain), environmental impacts (especially greenhouse gases) and critical raw materials (e.g., lithium). Thereby, all relevant phases of the lifecycle are taken into account, including the production of vehicles as well as the required incremental build-up of the necessary energy/fuel supply infrastructure (energy provision and distribution).

The modelled energy provision is CO_2 neutral and solely provided by wind and solar energy. The renewable energy is then used in seven different energy pathways:

- 1 pathway: Direct use in battery electric vehicles and catenary grid supplied long haul trucks (“BEV”)
- 2 pathways: Producing hydrogen via electrolysis which then is used in vehicles that either are equipped with a fuel cell (fuel cell electric vehicles, “FCEV”) or with an internal combustion engine optimized to combust hydrogen (“H_2-Comb”)

- 4 pathways: Producing so-called Power-to-X (PtX) fuels by again producing hydrogen via electrolysis, capturing CO_2 directly from the air (DAC) and then finally the synthesis of Methane, Methanol (“MeOH”), Dimethylether (“DME”) or Fischer-Tropsch-fuels (“FT-gasoline/diesel”)

The starting point of the analysis is the total mobility demand and its development until 2050, based on an EU Reference scenario. We then proceed to derive the required future development of the vehicle fleet (for the road sector) and new registrations for different vehicle segments to achieve 100% fleet penetration with the respective defossilised drivetrain concept in 2050. The so modelled fleet development enables combinations with annual mileages and specific energy efficiencies and thus allows us to determine the energy/fuel demand for the road sector in all scenario years. For inner European Rail, Aviation and Shipping, we use a simplified approach, as their relevance is subordinate.

In all of our scenarios, we assume that all new vehicles with alternative powertrains are fully operated with additionally generated renewable energy. This is also assumed for identical shares of new vehicles operated with Fischer-Tropsch gasoline/diesel for comparability reasons, even if this fuel is compatible to the whole existing vehicle fleet. The total renewable energy/fuel demand (or Tank to Wheel (TtW) demand) is then the starting point for our energy/fuel supply chain modelling. Following a bottom-up approach, we trace the energy demand across the different steps of each supply chain to determine the required build-up of capacities of each element (such as electrolysis or power generation) over the course of time. We focus our analysis solely on the renewable energy supply for transport, without any interactions with other sectors. A global transformation of energy supply and industrial processes to fossil-free alternatives is also assumed for the technologies used to build the infrastructure. The resulting greenhouse gas emissions of these processes are assumed to be reduced to a minimum in 2050 (transformation of the “background system” of material supply and production processes to become “quasi GHG free” from 2021 to 2050).

All required steps of the supply chain including generation, transport and storage are considered (see Figure 2 for an exemplary illustration of a modelled supply chain). Once the infrastructure and energy/fuel requirements have been assessed, they are evaluated across the different dimensions outlined above – environmental impacts, material demand and costs.

Several aspects of future development, particularly with respect to future vehicle technologies and the future sourcing of the required energy, are currently uncertain and subject to various factors, particularly technical, political and regulatory decisions. To reflect this uncertainty, we assess three levels of future technological development of vehicles (labelled “Status Quo”, “Balanced” and “All-In”) and two places of energy sourcing (Europe and Worldwide) in our analysis of the seven different energy / drivetrain pathways. This results in a total of 42 different scenarios assessed.

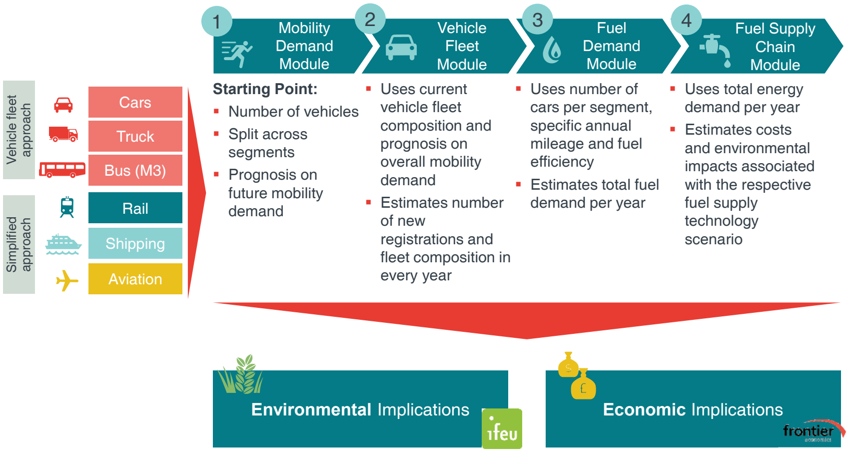

Fig. 1: Schematic overview of our modelling approach [Source: Frontier Economics, ifeu]

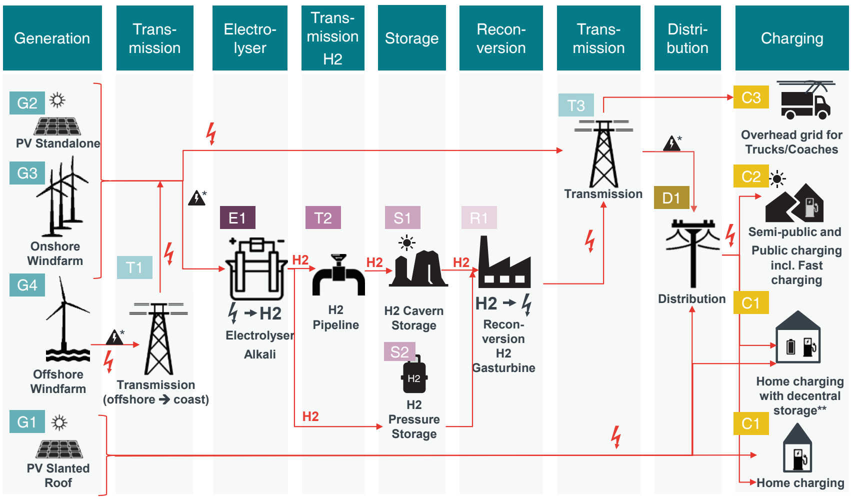

Fig. 2: Overview of level of detail of supply chain model (here shown for BEV) [Source: Frontier Economics, ifeu]

Compared to the previous fuel study of FVV (FVV Fuels Study III, 2018) [2], which modelled 100% scenarios for various energy / drivetrain pathways for the road mobility in Germany for the “photo year 2050”, this study expands the geographic scope to

EU27+UK and focuses on all transport sectors, while at the same time including a more detailed breakdown for the road sector. All scenarios are simulated for the "photo years" 2020, 2030 and 2050, in order to describe the ramp-up from today into a defossilised future 2050. The analysis is further complemented by an economic and environmental assessment, covering all phases of a vehicle life and the provision of final energy carriers, including the required infrastructure (e.g., for energy/fuel generation, transport, storage, and distribution). The focus is solely on the transport sector – potential interactions with other sectors (i.e. sector coupling) are not taken into account.

2. Energy Demand and required capacities in 2050

The required total energy in the mobility sector (on a Well-to-Wheel basis, taking into account the losses along the energy/fuel supply chain) determines the requirements for initial generation capacities (PV and wind plants), as well as any infrastructure requirements further down the supply chains. Relative comparisons of the WtW energy demand across the different energy / drivetrain pathways are therefore a valuable indication for further assessments. Figure 3 summarizes the results for the 42 different fuel / drivetrain pathways: BEV by far requires the lowest WtW energy demand (starting from 2,000 TWh, which is around 68% of EU27+UK electricity demand in 2019), due to its low TtW demand. The highest WtW demand is required for synthetic fuels (up to 10,000 TWh), due to higher TtW demands and high losses along the energy/fuel supply chain. These are particularly driven by the fuel synthesis and electrolysis.
Hydrogen powered fuel cell vehicles (H_2-FCEV) require approximately twice as much WtW energy as BEV, while H_2 powered vehicles equipped with combustion engines (H_2 Comb) consume approximately 2.5 to 3 times as much energy as BEV. Sufficient amounts of legacy fleet compatible, defossilised Fischer-Tropsch diesel/gasoline require 3.5 to 4 times as much WtW energy as BEV.

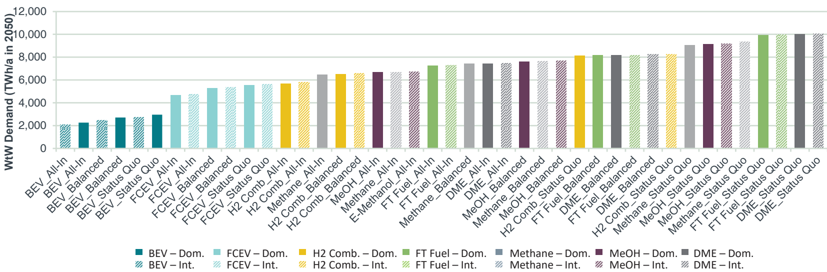

Fig. 3: WtW Demand in TWh/a in 2050 for 42 scenarios [Source: Frontier Economics]

However, for environmental impacts as well as for costs of the energy/fuel supply chain, not the WtW energy demand, but the required installed capacities are the deciding factor. Figure 4 therefore summarizes the required capacities of renewable energy generation infrastructure for all scenarios (for the road sector). Without exception, the domestic energy sourcing scenarios require much higher generation capacities than international scenarios, where energy is also sourced from regions outside of Europe such as MENA or Patagonia. This is due to the fact that regions outside of Europe have better conditions for generating renewable energy (e.g., hours of sunshine and/or wind). The highest generation capacities are required for domestically produced synthetic fuels, as FT diesel/gasoline or DME (up to 4,800 GW), while BEV scenarios require the lowest generation capacities (starting from 750 GW when energy is sourced internationally from MENA, and from 1,100 GW for domestic energy sourcing). By way of comparison, 340 GW of renewable wind and solar generation are currently installed in Europe for all sectors, which is planned to be increased to up to 690 GW by 2030. The factor of required installed power generation capacity for “FT-ICE / BEV” is in the range of 3 for domestic energy sourcing. When FT fuel is produced internationally the factor is reduced to approximately 2 to 2.5.

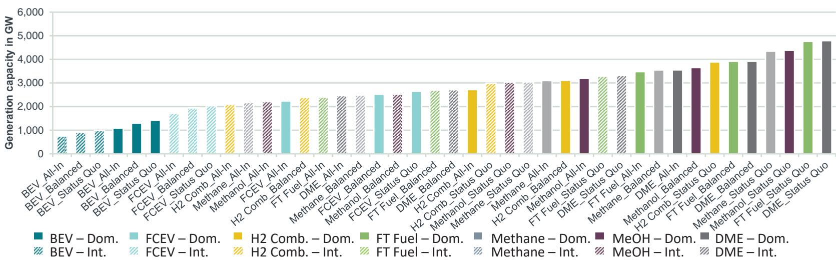

Fig. 4: Generation capacity in GW in 2050 for all 42 scenarios [Source: Frontier Economics]

Similarly, hydrogen plays a role in all scenarios, albeit in varying forms. Electrolysis is thus a key element for a carbon neutral mobility sector, independent from the selected energy pathway. All fuel / drivetrain pathways require significant electrolysis capacities, including BEV, as in a fully renewable energy system a chemical buffer (here: hydrogen) is required for dark doldrums to buffer seasonal fluctuations. In the domestic scenario for the road sector, the required installed electrolysis capacity ranges from 870 GW up to 2,200 GW in 2050, solely for transportation. Currently, only 40 GW are planned for EU27+UK until 2030. H_2-FCEV pathways finally (in 2050) require approximately 1,200 GW, H_2 Comb 1,600 GW and FT-ICE 1,900 GW of electrolysis capacity. In the BEV scenarios, approximately 600 GW (international) and 1,000 GW (domestic) of electrolysis capacities need to be built until 2050, in order to maximize the utilization of all renewable power generated. The ramp-up of electrolysis capacity is therefore likely to become a temporary bottleneck.

3. Environmental impacts

With a full defossilisation of the transport sector by 2050, annual GHG emissions are in all energy / drivetrain pathways 95-97% lower than in the baseline year 2020. Origin of the small amount of remaining unavoidable GHG emissions are primarily processes in the background system (as e.g., concrete use for wind turbine foundations, methane slip). However, the contribution of the transport sector to global warming depends on its cumulative emissions over the entire pathway towards full defossilisation. Assessing the GHG mitigation effectiveness of different defossilisation pathways must therefore include the GHG emission backpack associated with the ramp-up to a 100% defossilised transport sector. In our methodology with 100% back-casting scenarios, cumulative GHG emissions 2021 to 2050 turn out to be in a comparable order of magnitude in all scenarios (bandwidth of road transport in the range of 14%). This is mainly due to the assumed identical ramp-up speed of alternative vehicle concepts (determined by the assumed vehicle fleet exchange rate) and renewable energy/fuel supply required for achieving 100% of the respective pathway in the year 2050. Cumulative emissions in all pathways are dominated by operation of the remaining gasoline/diesel vehicle fleet with fossil fuels (already containing 7% biofuel share) with a total contribution of 66-74%, as 100% defossilised energy/fuel supply will be achieved only in 2050. The ramp-up of renewable energy/fuel supply chain infrastructure contributes 5-20% and vehicle production 11-24% to total cumulative GHG emissions.

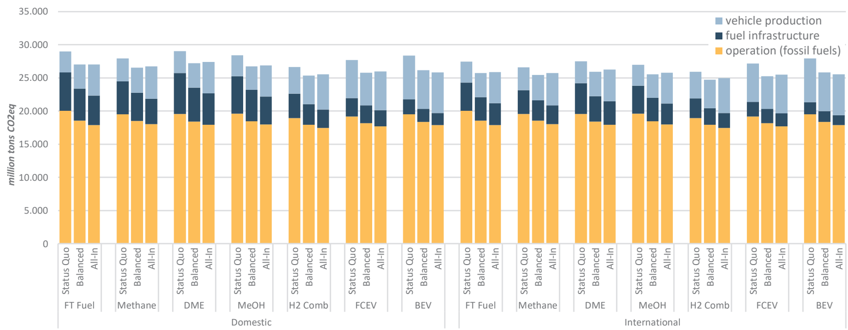

Fig. 5: Cumulative GHG emissions in all 100% scenarios with identical ramp-up speed of defossilisation [Source: ifeu]

In all 100% scenarios, we assume a linear ramp-up of new registrations of alternative drivetrain technologies up to 100% sales share at a point of time, which allows a complete fleet renewal until 2050 (“backcasting” approach). For passenger cars and light duty vehicles 100% sales share of the defossilised drivetrain technology is required in 2033, for heavy duty trucks it is later due to shorter lifetimes (e.g., in 2042 for long haul). Complete fleet turnover with new vehicle technology and associated build-up of defossilised energy/fuel supply chain infrastructure until 100% is achieved in 2050. The

same ramp-up speed is also assumed for legacy fleet compatible FT gasoline/diesel, even if this fuel could already be used in existing gasoline/diesel vehicles.
In reality, however, actually reachable ramp-up speeds will most probably differ considerably between the technology pathways. A sensitivity analysis shows that ramp-up speed of defossilised final energy supply is the crucial factor determining how fast GHG emissions of the transport can be reduced with purely technical measures (without transport-reducing and modal-shift measures) and which cumulative GHG emissions are to be expected over the entire transition period. As investigated on the example of the FT fuel pathway, the achievable ramp-up speed has a significant greater impact on cumulative GHG emissions than the choice of the pathway itself, if identical ramp-up speeds for all pathways are assumed. Quickest possible applicability of substantial quantities of renewable energy to reduce dependencies on fossil fuels is essential for minimizing GHG emissions from transport and, therefore, measures applied already in the present decade are most important for the reduction of the GHG backpack until 2050.

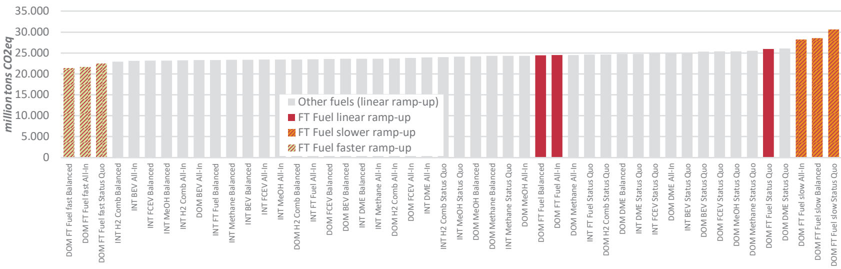

Fig. 6: Sensitivity analysis for the impact of different market ramp-up speeds for FT fuels in road transport on cumulative GHG emissions 2021-2050 associated with the EU27+UK road transport [Source: ifeu]

In all energy / drivetrain pathways, better vehicle efficiencies in the "Balanced" technology scenarios lead to lower cumulative GHG emissions compared to the "Status Quo" technology scenarios. However, the "All-in" scenarios with highest vehicle efficiencies lead to slightly increased cumulative GHG emissions compared to the "Balanced" scenarios for the FCEV and all ICE pathways. The additional GHG from vehicle production with aluminum light weighting outweighs GHG savings from efficiency improvements. Thus, segregated energy efficiency optimization per sector is not necessarily leading to the most efficient solution for overall GHG reduction.
The international energy/fuel supply scenarios deliver the lowest cumulative GHG emissions. The savings by international energy/fuel sourcing compared to local sourcing (only in Europe) are 1% - 2% for BEV, 2% - 3% for H_2 pathways (FCEV, H_2 Comb) and 4% - 6% for hydrocarbon e-fuel pathways.
In order to assess compatibility of the 100% scenarios with the Paris climate targets, we compare cumulative GHG emissions with estimates of the remaining CO_2 budget

for the European Union. In all 100% scenarios, the GHG emissions associated with the transport sector (including vehicle production and defossilised energy supply infrastructure) will exceed the total 1.5 °C GHG budget for Europe (EU27+UK, all sectors, 67% probability) in 2031 - 2032 and will require 43% - 51% of the total 1.75 °C GHG budget (50% probability) for Europe. This indicates that an exclusively technical defossilisation with one single energy / drivetrain pathway and assumed vehicle characteristics cannot meet the GHG reduction requirements on Europe's transport sector. Further GHG reduction potentials need to be analyzed and applied urgently.

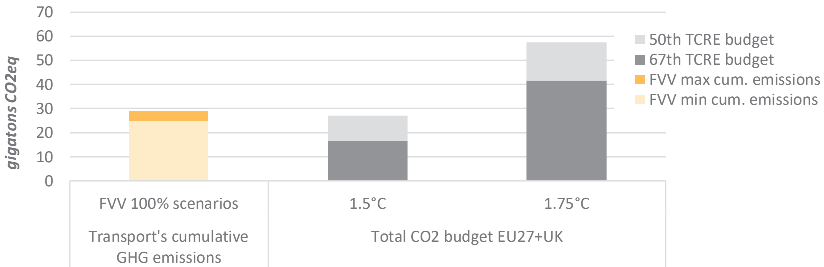

Fig. 7: Comparison of cumulative GHG emissions of EU27+UK transport 2021-2050 with total CO_2 budgets (own estimates for all sectors) of EU27+UK 2021-2050 [Source: ifeu]

Further environmental impact categories considered in this study (acidification, eutrophication, PM formation) do not show general ecological risks for any of the defossilisation pathways. Eutrophication and PM formation potentials show a strong reduction from 2020 to 2050 for all pathways. Annual acidification potential is reduced from 2020 to 2050 by 30-50 % in the H_2-FCEV and all ICE scenarios. Since contribution of land-based transport to acidification is very low, even a slight increase of acidification potential in the BEV Status quo scenario would not cause an environmental bottleneck. Furthermore, land use for renewable power generation for the defossilised transport sector does not generally pose an ecological bottleneck. For the domestic energy sourcing scenario, we assumed that Europe could become energy independent. As laid out in other studies this also depends on the development of key technologies such as "floating offshore wind". In the domestic energy sourcing scenario land use for power generation for European transportation requires 0.5% to 1.3% of EU27+UK land area, which corresponds to an area up to twice the size of Belgium. International energy sourcing requires about 1/3 less land use than energy sourcing exclusively in Europe. Land use of all other facilities in the defossilised energy/fuel supply chain (DAC, synthesis plants etc.) is negligible (e.g., DAC land use is max. 0.004% of EU27+UK land area). However, installation of renewable power generation capacities should avoid environmentally sensitive areas in order to minimize land use related environmental impacts.