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FINAL REPORT

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Zukünftige Kraftstoffe: FVV-Kraftstoffstudie IV

Future Fuels: FVV Fuels Study IV

Transformation der Mobilität im klimaneutralen und postfossilen Zeitalter

Transformation of Mobility to the GHG-neutral Post-fossil Age

Future Fuels: FVV Fuels Study IV

Project no. 1378

The Transformation of Mobility to the GHG-neutral Post-fossil Age

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Final report

Abstract:

The new, fourth fuel study published by FVV expands the framework of the previous studies in a number of ways: alongside societal costs and various environmental factors, it also compares the cumulative CO2 emissions for various energy sources and powertrains and demonstrates how these emissions stack up against the CO2 budget set for Europe.

Whether or not CO2 neutrality is achieved in the year 2050 has no bearing on whether the goals set out in the Paris Agreement are met; what matters is the absolute volume of greenhouse gases emitted up to that point. The aim of the study is to develop technology pathways (powertrains / energy sorcues) that will enable the European transport sector to meet the Paris climate objective.

The analyses show that it will not be possible to meet the 1.5-degree target without taking existing vehicles into account.

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Related reports: R586 (2018), H1086 (2016)

Note

The FVV Fuels Study IV »Transformation of mobility to the GHG-neutral post-fossil age« has been prepared for general guidance only. The reader should not act on any information provided in this study without receiving specific professional advice. FVV does not guarantee the correctness, accuracy and completeness of the information and shall not be liable for any damage resulting from the use of information contained in this study.

A briefing paper summarises the most important results of the study:

»Six theories about the climate neutrality of the European transport sector - Findings from the study ›Transformation of mobility to the greenhouse gas neutral post-fossil age‹.

Both publications are available for download from the FVV website or the THEMIS database.

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1 Executive summary

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 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 are 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 ("H2-Comb");
- 4 pathways: Producing so-called Power-to-X (PtX) fuels by again producing hydrogen via electrolysis, capturing CO2 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. 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. For 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 new vehicles operated with Fischer-Tropsch gasoline/diesel for comparability reasons, even if this fuel is compatible to the 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 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).

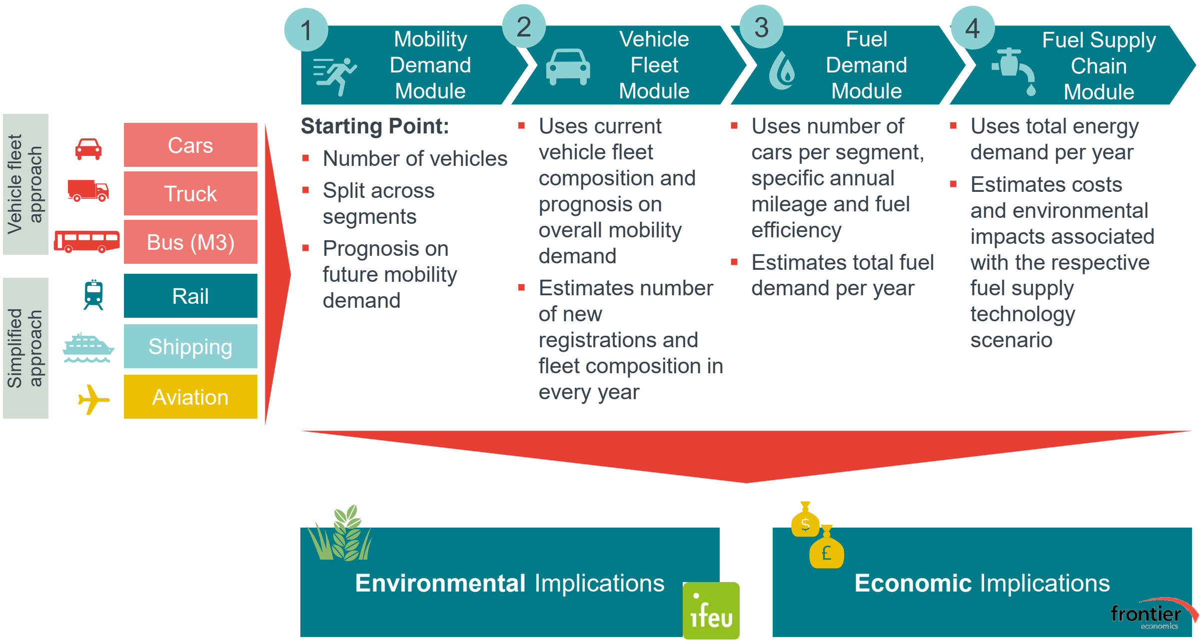

Figure 1: Schematic overview of our modelling approach [Source: Frontier Economics, ifeu].

All required steps of the supply chain including generation, transport and storage are considered (see Figure 2 for an exemplarily 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.

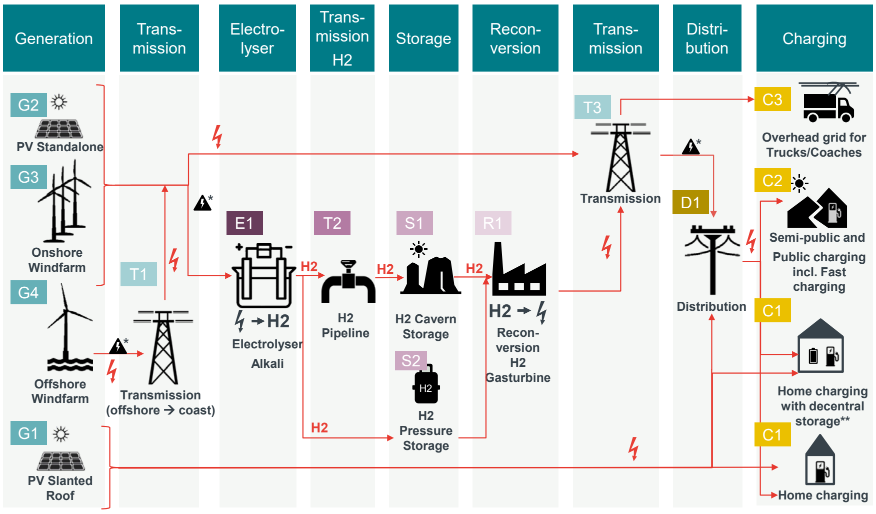

Figure 2: Overview of level of detail of supply chain model (here shown for BEV) [Source: Frontier Economics].

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.

Compared to the previous fuel study of FVV[1] (FVV Fuels Study III, 2018), 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.

Key results

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 summarises 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 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.

[1] (Forschungsvereinigung Verbrennungskraftmaschinen, 2018).

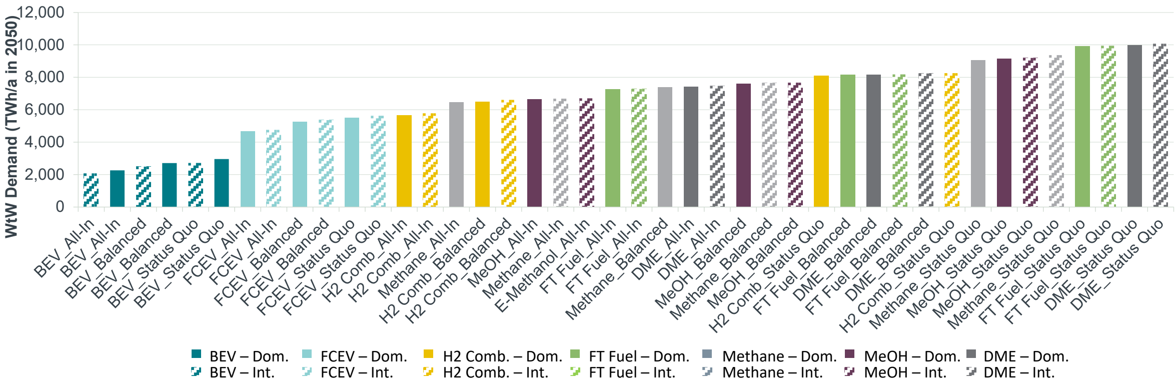

Figure 3: WtW Demand in TWh/a in 2050 for 42 scenarios [Source: Frontier Economics].

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 summarises 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.[2] 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.

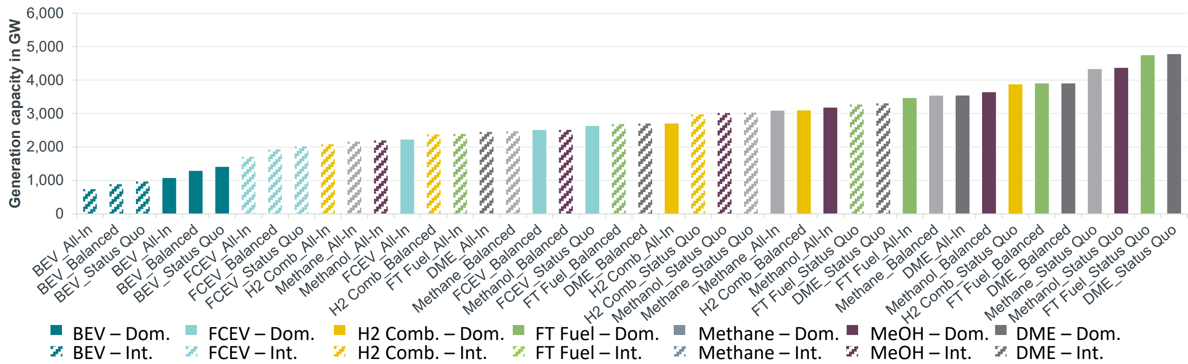

Figure 4: Generation capacity in GW in 2050 for all 42 scenarios.

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

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[2] (IRENA, 2020), (Euopean Commission, 2020) and (SolarPower Europe, 2020).

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, H2 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 maximise the utilisation of all renewable power generated. The ramp-up of electrolysis capacity is therefore likely to become a temporary bottleneck.

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% backcasting 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.

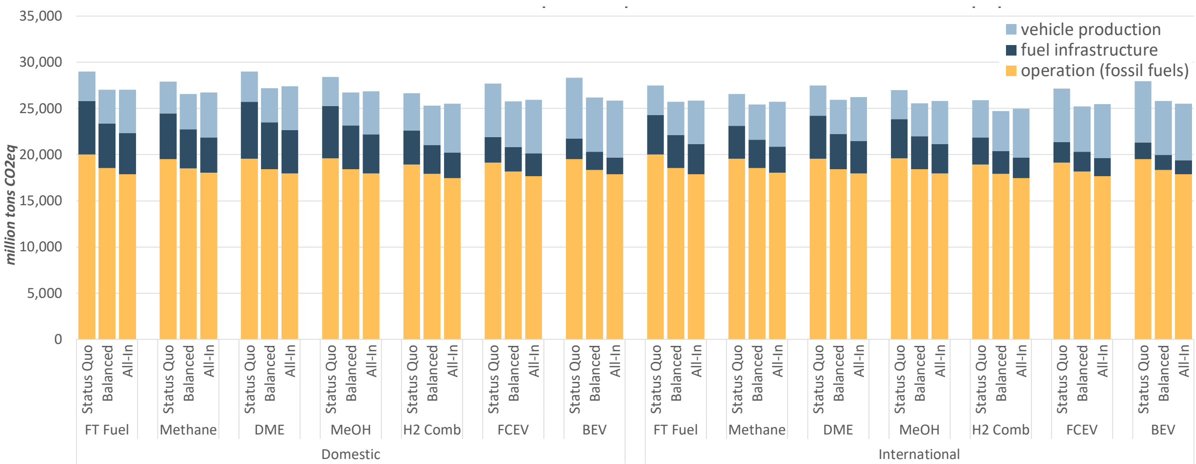

Figure 5: Cumulative GHG emissions in all 100% scenarios with identical ramp-up speed of defossilisation [Source: ifeu].

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. For passenger cars and light duty vehicles 100% sales share is required in 2033, for heavy duty trucks it is later due to shorter lifetimes (e.g. in 2042 for long haul). Complete market penetration with new vehicle technology and associated build-up of energy/fuel supply chain infrastructure until 100% is achieved in 2050 ("backcasting" approach). 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.

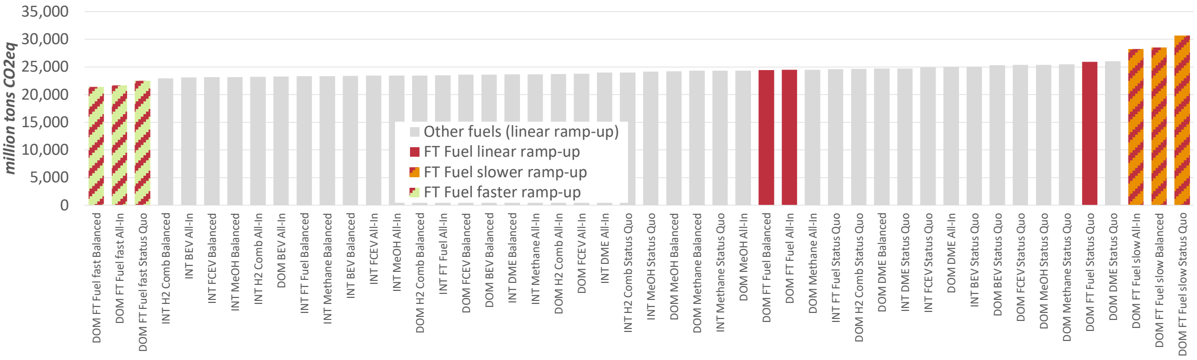

Figure 6: Sensitivity analysis for the impact of different market ramp-up speeds for FT fuels in road transport on cumulative GHG emissions 2021-2050 associated with the EU27+UK road transport [Source: ifeu].

For the FCEV and all ICE pathways the “Balanced” technology scenarios offer lower cumulative GHG emissions than “All-in” scenarios. The additional GHG from vehicle production with aluminium lightweighting outweighs GHG savings from efficiency improvements. Thus, segregated energy efficiency optimisation 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 are 1% - 2% for BEV, 2% - 3% for H2 pathways (FCEV, H2 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 analysed and applied urgently.

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 H2-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 can 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.

Rare materials

In all pathways for the defossilisation of the transport sector, availability of selected raw materials can be a limiting factor for a fast market ramp-up and for achieving 100% in 2050, if a fair share of Europe on the raw material demand for a worldwide defossilisation is assumed. Identified bottlenecks result mainly by specific vehicle configurations in the 100% scenarios and by the assumed strong future motorisation increase in non-European countries.

A worldwide ramp-up of electric mobility can be affected by absolute and temporary lithium or cobalt bottlenecks. With the specific battery configurations assumed in our scenarios (Li-NMC battery technology, as state of the art in Europe), extrapolated worldwide material demand is on the upper end impeding 100% worldwide electric mobility. A future mix of different battery technologies, with lower lithium and cobalt content could reduce raw material demand. Furthermore, global lithium and cobalt resources and reserves have developed very dynamically in the last few years. Therefore, a considerable future increase of primary material supply can be expected.

Platinum is a clear bottleneck in the FCEV scenarios. Global platinum supply could only fulfil the demand of Europe’s transport sector for 100% FCEV. Assuming similar developments of FCEV fleets in the rest of the world, global demand will clearly exceed currently known reserves and lead to absolute bottlenecks. In all other fuel / drivetrain pathways currently known reserves of platinum group metals (PGM) are sufficient to fulfil cumulative demand for primary PGM for the global mobility sector in all scenarios.

Further materials such as copper, silver, nickel and neodymium are required in vehicle production and / or the energy/fuel supply chain infrastructure and could therefore cause bottlenecks in all energy/fuel pathways. However, proactive demand and supply strategies can prevent future bottlenecks of these materials: Primary material demand can be reduced in transport and other demand sectors by increase of recycling, substitution with less critical materials or use of existing alternative technologies. At the same time, supply has to be increased based on sustainable mining and supply systems.

Costs

While costs do not constitute a binding constraint, it is of common interest for consumers, manufacturers and governments to proceed with an economical pathway to transform the transport sector. Identifying core cost drivers and dependencies can also aid in determining which technological measures might have a particularly good cost benefit ratio.

We have looked into vehicle and energy/fuel supply chain costs. The results are expressed in terms of incremental costs – so additional investments that need to be made compared to today. This approach focuses on the differences between various fuel / drivetrain pathways and thereby provides a clearer picture of the cost effects of choosing different drivetrain technologies. Total incremental costs are expressed in 2020 Euros and as Net Present Values. The total incremental costs to defossilise the complete European (EU27+UK) road transport sector by 2050 range from 2,600 billion € to 5,300 billion €, which corresponds to 17% to 34% of the annual European (EU27+UK) GDP in 2020 (15,600 billion € in 2020). Figure 7 compares the total incremental costs for all 42 scenarios.

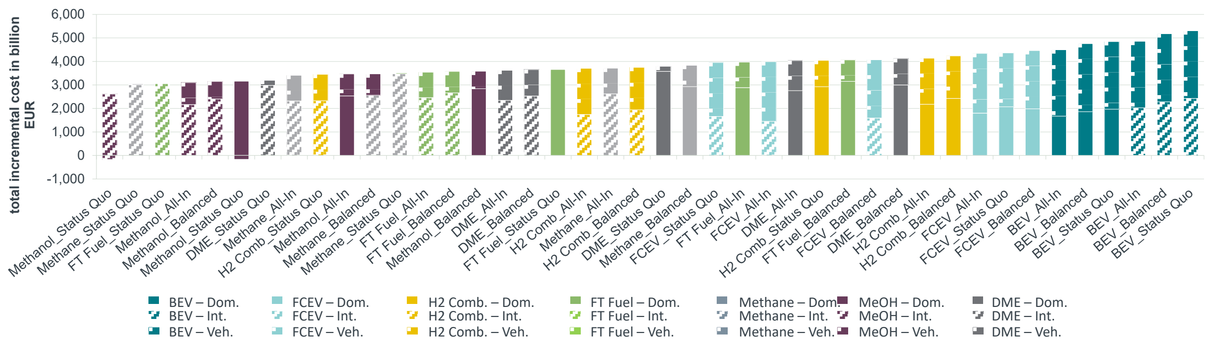

Figure 7: Total incremental costs – energy/fuel supply chain and vehicles – until 2050 in billion € [Source: Frontier Economics].

The highest total incremental costs (in NPV) for total road transport are found in the BEV scenarios (4,500-5,300 billion €) followed by FCEV (3,900-4,500 billion €), where costs for passenger vehicles dominate overall costs. BEV vehicle costs are driven by the battery costs, determined by range assumptions (as e.g. 300 – 500 km passenger car/LDV range) and resulting battery sizes, as well as assumed specific battery costs (160 €/kWh for 2020, 120 €/kWh for 2030, 80 €/kWh for 2050). The BEV vehicle costs are modelled to decrease over time with assumed progress in battery technology development. The incremental vehicle costs dominate the total costs for the BEV and FCEV pathways and contribute to 50% of the total costs. The lowest total incremental costs for road transport are found for synthetic fuels, particularly due to lower incremental vehicle costs.

Energy generation costs are the main driver of energy/fuel supply chain costs. The total energy/fuel supply chain costs are lower in the international than in the domestic scenario for most fuels, driven by a decrease in total generation costs. Not only are the costs per unit of generation assumed to be lower outside than within Europe, but at the same time, fewer generation capacities are required overall due to better conditions for wind and/or solar generation. Only the international BEV scenario is expected to be more expensive than the domestic scenario because of expensive import power lines. When assessing pathways using international energy sourcing, significant political uncertainties have to be considered affecting the general feasibility as well as cost levels.

The lowest total incremental costs for total road transport are found for “E-Fuel-ICE international sourcing pathways” with continued 2020 vehicle technology (“Status-Quo” pathway: without hybridisation or light-weight measures), starting from Methanol-ICE (2,600 billion €) over FT-gasoline/diesel-ICE (3,000 billion €) up to H2-Comb (3,500 billion €).

The cumulated incremental costs for the road sector of the “Status Quo vehicle technology scenarios” are lower than those for the “Balanced scenarios” and “All-In scenarios” for all fuel/drivetrain pathways, except for BEV. Vehicle cost increases from hybridisation or light-weight measures outweigh cost savings from reduced energy/fuel supply infrastructure requirements. From an economic perspective, it is more cost efficient to build additional power generation and energy/fuel distribution infrastructure than to maximise efficiency measures (at high cost) on the vehicle level. Neither hybridisation, nor light weight measures are pay off. Therefore, stringent sector limits, such as TtW GHG targets for vehicles, lead to increased societal costs. Energy efficiency optimisation per sector does not necessarily lead to the most cost-efficient solution for GHG reduction.

Main Conclusions

The defossilisation of the complete European (EU27 + UK) transport sector is possible and affordable. The total costs are in a range of 1% of the European GDP per year over 30 years, with incremental vehicle costs dominating the total defossilisation costs for BEV and FCEV pathways and costs for energy/fuel supply chain infrastructure dominating the total defossilisation costs for synthetic fuels. Therefore, vehicle costs as well as energy/fuel supply chain infrastructure costs must be considered in any economic system optimization and GHG reduction strategy. The lowest total incremental costs for passenger cars (incl. LDV) are achieved with e-fuel operated ICEV with continued 2020 vehicle technology (without hybridization or light-weight measures). Total costs are lower for international energy sourcing than for domestic energy sourcing for all ICEV and FCEV pathways, while domestic costs are lower for the BEV scenario. Therefore, mixed scenarios with domestic BEV and international FCEV/ICEV energy sourcing appear to be the most cost efficient.

The introduction of alternative vehicle technology pathways is limited by the vehicle fleet exchange rate. In all investigated 100% scenarios - with assumed defossilisation ramp-ups determined by the fleet exchange rate - the GHG emissions associated with the transport sector (including vehicle production and defossilised energy supply) will exceed the total 1.5°C GHG budget (67% probability) for Europe (EU27+UK, all sectors) already by 2031/32.

Since the cumulative GHG emissions 2021-2050 of all pathways are dominated by emissions of vehicle operation with fossil fuels (remaining vehicle fleet), a quick ramp-down of fossil fuel usage is most important to meet the climate targets. The ramp-up speed of complete sustainable transportation pathways, and thus the quickest ramp-down of fossil fuel usage, is “the crucial factor” for cumulative GHG emissions minimisation. The faster carbon neutral energy can penetrate the existing market, the lower the cumulative GHG emissions.

Even with the assumed ramp-up of a new powertrain technology (passenger car 2033: 100% sales of new PT technology), keeping up the pace with the ramp-up of sustainable energy supply is a considerable challenge. Technically feasible ramp-ups of powertrain and energy/fuels supply are planned to be defined in a follow up study.

Defossilised drop-in fuels (carbon free on a WtW basis) are an option to eliminate GHG emissions of existing ICE powered vehicles and therefore could be an option to enable a faster introduction of GHG neutral energy supply to road transport. Therefore, significant efforts are required to defossilise gasoline and diesel fuel, which can be used in the existing vehicle fleet and non-electrifiable sectors. Electrolysis is a key element for a carbon neutral mobility sector. All pathways require significant electrolysis capacity, including BEV, since BEV in a fully renewable energy system requires a chemical buffer for dark doldrums. Ramp-up of electrolysis capacity is likely to become a temporary bottleneck.

Availability of critical raw materials is a key factor for enabling 100% BEV or 100% FCEV pathways. Potential bottlenecks have to be assessed in the global context. Lithium and cobalt demands are likely to become temporary bottlenecks in all 100% BEV scenarios with assumed battery technology assumptions (NMC 622, NMC 881 and solid state Li-ion), 300 km / 500 km LDV range and future global transport increase. A mix of potential future battery technologies with lower specific Li and Co content, combined with slower increase of worldwide motorization and reduced battery sizes can reduce lithium and cobalt demand, That does not exceed today known global resources. Furthermore, global lithium and cobalt resources and reserves have developed very dynamically in the last few years. Therefore, a considerable future increase of primary material supply can be expected.

Platinum demand will become a severe bottleneck in all 100% FCEV scenarios.

None of the investigated 100% pathways is restricted by land use bottlenecks or by other environmental impacts as eutrophication, PM formation and acidification.

Since ramp-ups of all pathways are likely to face temporary bottlenecks, a mix of technologies seems more robust to overcome those restrictions and is required to allow for quickest possible defossilisation and lowest cumulative GHG emissions.

While the analysed theoretical 100% scenarios, where a single drivetrain technology and energy/fuel pathways is modelled to provide all of Europe's (road) transport demand allow for a comprehensive comparison of technologies, the most effective transformation will without doubt include a mix of technologies (which is recommended to be analysed in a follow-up study). This expectation is supported by the results of this study, as depending on the applied metric, different technologies come out on top:

- With regard to minimum cumulative GHG emissions, identical ramp-up speeds would lead to very similar cumulative GHG emissions for hydrocarbon synthetic fuels, H_2 (both for combustion engines as well as for fuel cells) and electric mobility. Any change of assumed ramp-up speed is likely to change the ranking of technologies.
- Regarding the lowest energy requirements, direct electrification (BEV) has the greatest advantage.
- Looking at total incremental costs, (short chain) synthetic hydrocarbon fuels, as methanol or methane are the least expensive options.

Considering the possibility of faster introduction than determined by the fleet exchange rate, legacy fleet compatible fuels, such as FT-gasoline/diesel could have a significant advantage, but only if the complete energy/fuel supply chain infrastructure (inclusive significantly large capacities of renewable power generation) can be built considerably quicker than the vehicle exchange rate allows. This is a major challenge, as the assumed scenarios already contain 28 % defossilised energy/fuel share in 2030.

Increasing vehicle efficiency is not always leading to an increase of overall efficiency. For FCEV and all ICE pathways e. g. light weight measures can increase the cumulative GHG emissions, if additional GHG from vehicle production outweighs GHG savings from efficiency improvements. Furthermore, the lowest total incremental costs, are achieved with state-of-the-art ICEV (no hybridization, no light-weight measures etc.) operated with synthetic fuels, since total costs of sustainable energy/fuel supply are lower than the vehicle on-costs for efficiency measures. Therefore, any efficient GHG avoidance policy requires a Life Cycle GHG reduction approach. If sector targets at set, they need to be well aligned with the life cycle approach.

2 Motivation and objective of the Study

As part of the European Green Deal, the EU is striving to reach full climate neutrality across all sectors by 2050.

For the transport sector in Europe and Germany, this aim cannot be achieved with combustion engine-powered vehicles using fossil fuels. Therefore, appropriate concepts for the transport sector are required to achieve both national as well as European CO_2 emission targets and lead the transport sector into carbon neutrality.

Looking at recent trends in sectored greenhouse gas (GHG) emissions, the challenge to be faced by the transport sector becomes obvious: while many other sectors (e.g. power sector, industry) show significantly reduced emissions, emissions from the transport sector have increased in recent years due to growing transport demands, which have overcompensated for the efficiency gains in engine technology and technological progress. Challenges occur not only in the long, but also in the medium term. With the "Fit for 55" package, the EU has recently set an ambitious intermediate goal. By way of example: To meet its targets, Germany will need to reduce its emissions in the transport sector by more than 40 % within the coming 10 years. [3]

This study aims to explore various technology/fuel (energy) pathways ("fuels"), all of which are exclusively based on wind and solar power and have the potential to defossilise the transport sector by 2050. All of the fuels are evaluated in so called "100% scenarios", where every segment of the transport sector is powered by the respective technology (if technologically feasible). These extreme scenarios are not meant to be a realistic forecast of future developments. However, they allow for a fair comparison across different fuels and illustrate potential challenges arising from industry level scale up. In a follow-up study these results will be used to inform a realistic transformation scenario, bringing the transport sector to carbon neutrality while avoiding technical or economic bottlenecks.

The study has been developed in close cooperation with the FVV Working Group "Fuels". More than 50 experts from over 40 organisations spanning both the transport and the energy industry have contributed their expertise, knowledge and industry insights to our modelling. Across several expert groups, all crucial assumptions and deciding methodological questions were discussed and agreed. The underlying assumptions and parameters thus reflect the shared views of all participants who were involved. Based on the experts' input, Frontier Economics and ifeu carried out the modelling as laid out in this study, with Frontier Economics developing the 100% scenarios and ramp-up speeds and focussing on the economic implications, ifeu analysing environmental impacts and material demands based on the scenarios . We are therefore confident to reflect the current state of industry knowledge in our analysis.

In a previous study, (FVV Fuels Study III, 2018), the Working Group "Fuels" of the FVV has already evaluated and compared several different 100 %-mobility scenarios for road transport in Germany for the "photo year" 2050, which has been used as starting point for further analysis. In that previous study complete "transportation systems" have been compared on a well-to-wheel basis (including the GHG emissions of the energy supply system).The results already challenged the strong sector focus of currently applied GHG reduction legislation and identified sector emission targets have only very limited potential to lead to an ecologically and economically optimized GHG reduction.

[3] BMU Referentenentwurf eines Ersten Gesetzes zur Änderung des Bundes-Klimaschutzgesetzes und Bundes-Klimaschutzgesetz (KSG), Anlage 2.

The aim of (FVV Fuels Study IV) is to build on the existing tool and data suit of FVV's first CO_2 study in order to develop a more comprehensive study, going beyond the scope of the last one (FVV Fuels Study III) regarding:

- **Geography** – While the FVV study "De-fossilizing the transportation sector" has been limited to Germany, this study includes the entire European transport sector (EU27 + UK).
- **Technologies** – In addition to the LD/HD focus of the recent FVV study (FVV Fuels Study III), we also extend the range of technologies reviewed, spanning more sectors (road transport, aviation, rail and shipping), and including a wider list of technologies.
- **Scope of analysis –** The analysis includes an extended economic and environmental assessment including all phases of a vehicle life ("cradle to grave") and the provision of final energy carriers, including the required infrastructure (e.g. for fuel generation/transport/storage/distribution). The focus is solely on the transport sector – potential interactions with other sectors (i.e. sector coupling) are not taken into account.

We define the following seven potential technology pathways (also looking at the situation in 2020 and 2030) based on 100 % scenarios until 2050, all of them exclusively operated with renewable wind and solar energy, which are

- Battery Electric Vehicles ("BEV"), whereby we assume a catenary grid supply for heavy duty vehicles;
- Fuel Cell Electric Vehicles ("FCEV") supplied with hydrogen;
- Internal Combustion Engines ("ICEs") operated with synthetic fuels as follows:
  - Fischer Tropsch gasoline/diesel mix ("FT Fuel");
  - Synthetic Methane ("Methane");
  - Synthetic Dimethylether ("DME");
  - Synthetic Methanol ("MeOH");
  - H2 Combustion engine ("H2 Comb").

For the other transport segments aviation (within Europe), rail and shipping (within Europe), which contribute much less to overall emissions, we define a subset of technology options, as not all options are technologically feasible or economically sensible.

In a system-wide analysis, the different technology pathways are evaluated in terms of GHG emissions and further environmental impacts, material demand and cost. We therefore consider any alterations to the status quo which are necessary to transform the transport sector into carbon neutrality – both on the fuel and the vehicle side. Following this approach enables us to determine the most cost-efficient pathway to defossilise mobility, as well as the pathway with the lowest environmental impact.

3 Approach

We aim to ensure for a comprehensive analysis and therefore set out a detailed modelling approach to assess the technological transformation of the transport sector to carbon neutrality.

The starting point of our analysis is the total mobility demand and its development until 2050. We then proceed to derive the future development of the vehicle fleet (for the road sector) for different vehicle segments, which, in combination with annual mileages and specific fuel efficiencies, allows us to determine the fuel demand for the road sector. For Rail, Aviation and Shipping, we use a simplified approach, as their contribution to the overall emissions is subordinate.

The total final fuel demand (or "Tank to Wheel" (TtW) demand) is then the starting point for our fuel supply chain modelling. Following a bottom-up approach, we trace the energy demand across the different steps of each supply chain up to the provision of the primary energy to determine the required capacities of each element (such as electrolysis or generation). Once the infrastructure and fuel requirements have been assessed, they are evaluated across the different dimensions – environmental impacts, material demand and costs.

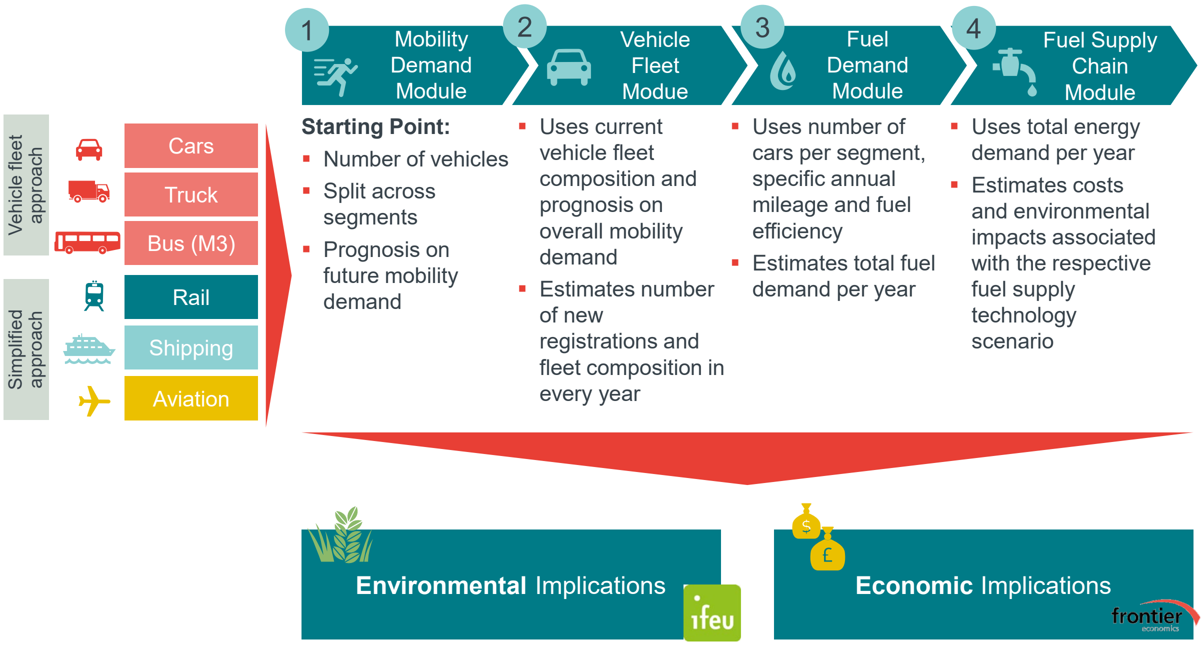

Figure 8: Schematic overview of our modelling approach [Source: Frontier Economics].

As several aspects of future development are still uncertain, we carry out our assessment across several scenarios, which enable us to determine ranges for the results and provide further understanding of their sensitivity towards certain assumptions.

The structure of this report broadly follows the logic of our modelling. First off, section 4 sets out the different scenarios which have been considered. Section 5 then provides further background on how the mobility demand and its future development is assessed. Using the mobility demand, section 6 illustrates how we model the future development of the vehicle fleet for the road sector. In section 7, we specify how the fuel demand is determined for the different sectors. Section 8 then gives a detailed insight into methodology and assumptions for one of the centrepieces of our analysis, the fuel supply chain modelling, along with initial results. The assumptions required to derive the environmental impact, material demand and cost, are laid out in sections 10, 11 and 12, along with results comparing the advantages and downfalls of the different fuels. Finally, section 13 summarizes the results of the study into concise key findings, with main conclusions being summarized in section 14.

4 Scenarios

As laid out before, the objective of the study is to assess and compare different pathway scenarios that are technically suitable to defossilise the European transport sector by 2050, in line with the EU's defossilisation targets.

To fulfil this requirement, the underlying energy for all pathways needs to be provided in a carbon-neutral manner through wind- and solar power (biogenic pathways as well as nuclear pathways have not been considered). The utilization of the electricity to power the transport sector can then broadly be divided into three main energy conversion pathways:

- direct electrification,
- conversion to hydrogen and then hydrogen usage in combustion engines or via fuel cell technology,
- further conversion from hydrogen into synthetic fuels (so called Power-to-X (PtX) fuels), feeding into combustion engines.

Thus, we assess a total of seven different drivetrain technology scenarios based on six different fuels (see section 4.1).

All pathways have advantages and disadvantages (e.g. infrastructure needs for BEV, efficiency losses for synthetic fuels), making it impossible to ex ante determine which option will be the most efficient (in terms of costs as well as environmental impact and material demand). Based on the total projected future European mobility demand and in line with the project's objective, we therefore model "100 % worlds", where the entire transport sector is solely fuelled by the respective fuel. These extreme scenarios then enable us to assess strengths and weaknesses of each pathway scenario, as well as total costs and environmental impacts and their sensitivity to certain input assumptions.

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. To reflect this uncertainty, we assess three levels of future technological development (see section 4.2) and two places of origin (see section 4.3) in our analysis, resulting in 42 different scenarios. Figure 9 provides an overview of scenarios and dimensions we assess in this study.

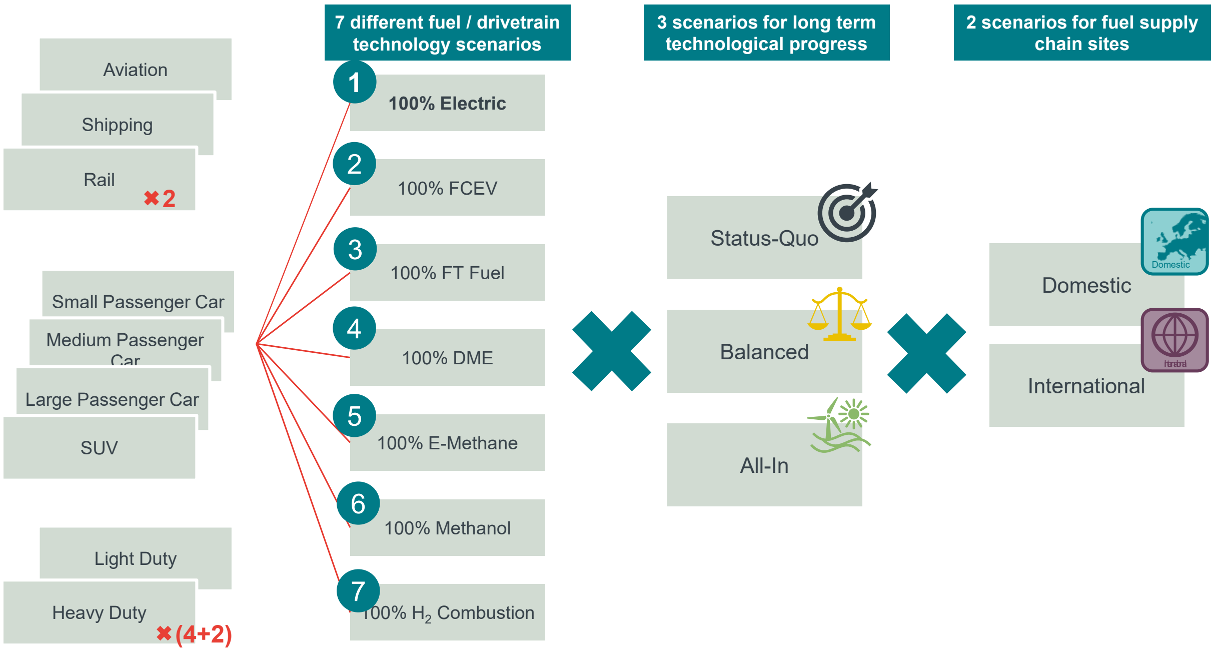

Figure 9: Schematic overview of scenarios and assumptions. Note: We consider two types of railway transportation (passenger and freight), four types of heavy-duty freight transportation and two types of busses [Source: Frontier Economics].

4.1 Fuels

The EU has set targets to fully defossilise the European transport sector by 2050[4], with an ambitious interim goal of 55 % (50 %) reduction by 2030 for passenger cars (heavy duty vehicles).[5]Therefore, all energy used in the transport sector will ultimately need to origin from exclusively from carbon neutral sources, primarily wind and solar power (nuclear power as well as bio mass based energy has been excluded from our view since they have other environmental impacts controversially discussed). There are several ways to then make the renewable energy available to the transport sector:

- Direct Electrification – In a (hypothetical) 100 % electrified world, all vehicles are directly powered by electric engines. For passenger cars and small heavy-duty vehicles (up to 16t), we assume the equipment of the vehicle with batteries. Larger heavy-duty vehicles are modelled as grid bound electrified vehicles (with a small-scale battery), as is the not-yet electrified share of the Rail sector. Shipping and Aviation are not modelled in electrified variants, because the technology is not suitable for airplanes or vessels (as batteries would be too heavy and catenaries not applicable). These sectors are defossilised in the electrification scenarios via synthetic FT Fuel (kerosene/diesel);

- Fuel Cell technology – The renewable power can alternatively be converted to hydrogen via electrolysis, which can then be used in fuel cells. Therefore, in the 100 % FCEV pathway scenario, all vehicles (light and heavy duty) are equipped with a hydrogen tank, a hydrogen fuel cell and an electric engine. This technology is also applicable to the rail, aviation and shipping sectors;

- Combustion engines fuelled by hydrogen or synthetic fuels: There is further the option to use energy from renewable sources to produce synthetic fuels, which are then utilized in combustion engines. There are multiple synthetic fuels which are worth

[4] (European Commission, 2018).
[5] https://www.consilium.europa.eu/en/policies/fit-for-55/.

considering: ranging from "simple" hydrogen, to synthetic MeOH, synthetic Methane, Dimethylether (DME) and then finally complex hydrocarbons such as synthetic diesel and gasoline produced via Fischer Tropsch synthesis (FT Fuel). Depending on the respective fuel, different alterations to the vehicles are required (more on that in section 6). Not all fuels are also suitable for the rail, aviation and shipping sectors. Figure 10 provides an overview of which fuels are applicable for these "other" sectors. As in the electrified scenario, we assume that FT Fuel is used whenever the actual technology is not applicable.

BEV	✓	⊖	⊖
FCEV	✓	✓	✓
H2 Comb.	⊖	✓	✓
FT Fuel	✓	✓	✓
Methanol	✓	✓	⊖
Methane	✓	✓	✓
DME	✓	⊖	⊖

Figure 10: Suitability of fuels to the rail, aviation and shipping sectors [Source: Frontier Economics].

4.2 Technological Advancement

In the light of this study, the future technological advancement of vehicles is particularly relevant regarding the potential to increase efficiencies and lower fuel consumption. While there are several potential measures which could possibly decrease the energy demand of vehicles, they all come at a cost, both economically (because they increase vehicle costs) and environmentally (as they often require a switch to alternative materials with higher environmental impact). Implementing these technologies is only sensible if the costs and environmental consequences prevented through energy savings outweigh the additional costs caused by the more complex vehicle production. To obtain a better understanding of the overall direction of these effects, the FVV working group suggested three scenarios of technological advancement for all road vehicles, which we implement in our modelling:

- **"Status Quo" Technology Bundle**
  As indicated by the name, all vehicle efficiencies in the "Status Quo" scenarios remain unchanged. This applies for technologies which are already at mass production, such as (non-hybridised) diesel/gasoline combustion engines, and battery electric vehicles on the level at which they are currently observed. For fuels which are currently at a niche production level, efficiencies are scaled up to levels which would currently be achievable if the respective vehicles were produced at large volume, with optimized single fuel production levels.

- **"Balanced" Technology Bundle**
  In the "Balanced" scenario, technological measures which are expected to have a positive cost-benefit balance are implemented. This is particularly relevant for all combustion engine vehicles, which are fully hybridised (i.e. equipped with a battery). For Battery and Fuel Cell electric vehicles, the underlying technology changes, as set out in section 12.

- **"All-In" Technology Bundle**

  Finally, in the "All-In" technology scenario, all available measures to decrease the fuel consumption are integrated into the vehicle. In addition to the hybridization, combustion engines are optimised to maximise powertrain efficiency (as fully variable valvetrain, VCR, lean operation, etc.). All vehicles are built with light weight technology (in particular replacing steel in chassis and body with aluminium where possible) and equipped with heat pumps instead of PTC heaters used in all vehicles in the previous scenarios. Batteries are further developed and all BEV vehicles are equipped with an entirely solid-state NMC battery with an increased energy density.

Further details on the fuel efficiencies across the different levels of technological advancement are provided in Annex 16.3.

4.3 Origin of Energy

All technology pathways require renewable energy as the starting point. In our initial approach, we assume that the energy required for all fuel pathways is sourced "locally" in Europe. This allows for short transportation distances and requires no import-specific infrastructure extension. However, the conditions to produce renewable energy in Europe are not ideal. From a global perspective, there are other locations with better conditions which are therefore at a competitive advantage to generate energy. The same capacity (at the same cost) will lead to lower costs per unit when at a higher utilization. However, producing energy outside of Europe will at the same time lead to additional efforts for the build-up of a suitable import infrastructure. We also assess the import of fuels to quantify these effects and determine if and when the import of energy for the transport sector could be beneficial.[6]

As both, the benefits from higher utilization as well as the additional import requirements depend on the exact location, we distinguish between "nearby" good locations (such as MENA) and "far off" top locations (such as Patagonia) from a European perspective.

Across all technology pathways and scenarios, we assume that the final fuel is imported, implying that all necessary synthesis steps are carried out where the energy is generated. The way in which the fuel is imported depends on both the fuel itself as well as whether it is sourced from a nearby or a far off location.

For nearby locations, we assume that electricity for the 100% electric scenario is imported via submarine cables, directly connecting generating and consuming countries. Fuels which are either liquid (Fischer Tropsch diesel and gasoline, MeOH) or can easily be liquefied (DME) are imported via ship, while gaseous fuels (Hydrogen, Methane) are imported via pipeline.

From far off locations, only import via ship is feasible. Therefore, we only consider the option of import from far off location where shipping is indeed easily feasible, which limits it to liquid or easily liquifiable hydrocarbon-fuels. For Hydrogen, import from far off locations would either require liquefaction or conversion to LOHC or Ammonia. Literature considers Ammonia to be the most viable out of these options.[7] A rough assessment of hydrogen import via that route illustrated that for the large quantities required, the Ammonia pathway is not competitive to large-scale pipeline import. Therefore, we exclude this option from our modelling. Importing electricity (as needed for the 100 % electric scenario) from a far off location necessarily requires the conversion of electricity into a chemical carrier and then the reconversion back to electricity in Europe. The most efficient option for that is hydrogen. As the import of Hydrogen in itself is not viable (see above), adding the reconversion and further lowering the efficiency

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[6] We exclusively consider the transport sector and do not take into account any potential interactions from the defossilisation of other sectors through shared infrastructure etc.

[7] See for example: IEA, The Future of Hydrogen: Seizing today's opportunities, June 2019, p. 84.

would make the option even less attractive. Therefore, we also only consider the import of Electricity via transmission lines from MENA. Figure 11 provides an overview of the import options for each fuel of the study.

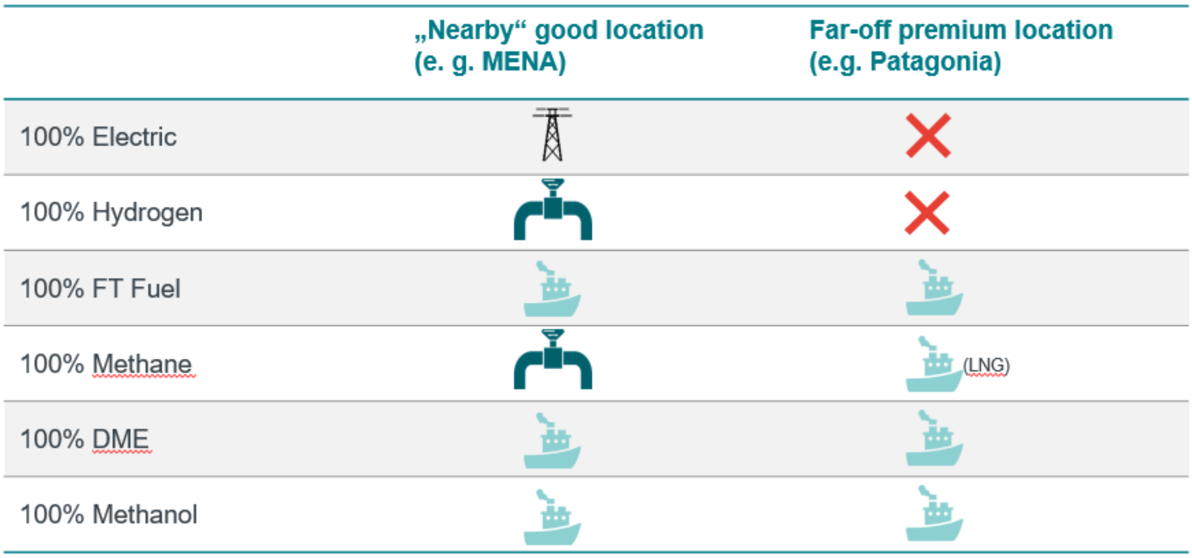


Figure 11: Overview of import options across fuels and import locations [Source: Frontier Economics].

Despite the competitive advantage of international generation, it does not seem realistic that 100% of the European fuel demand will be imported. Therefore, we assume that even in the international scenarios, 30 % of the fuel are produced locally. In 100 % electrified and 100 % H2 scenarios, the remaining 70 % are assumed to be imported from nearby good locations. For all hydrocarbons, imports are evenly split between nearby good and far off premium locations, as import from both destinations causes comparable costs and environmental impacts.

5 Mobility Demand

The total mobility demand for the EU is the starting point of our analysis, as it is one of the core drivers of the future fuel demand. We base our analysis on the projection from the EU Reference Scenarios[8], which projects the total development of the future demand for mobility for the EU27+UK for passenger transport activity (in Gpkm) and freight transport activity (in Gtkm).

For passenger transport, we split the total mobility demand between private and public road transport, rail and aviation, while for freight transport, we distinguish between heavy goods and light commercial vehicles, rail and inland navigation, all based on the EU Reference Scenarios.

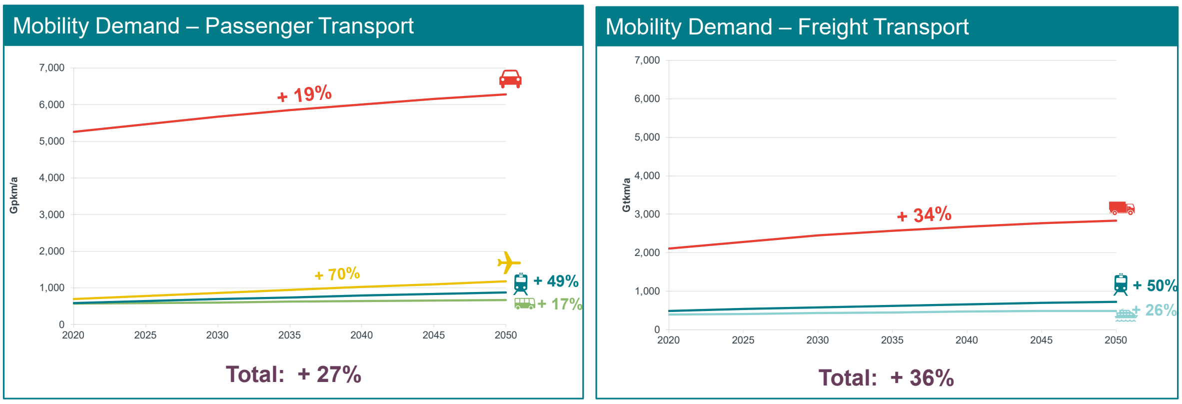


Figure 12: Share of global mobility demand by sector [Source: Frontier Economics based on EU Reference Scenarios].

The underlying data suggests that demand for mobility will increase for all sectors from now to 2050. Freight transport is assumed to increase by more than a third (36%) and passenger transport by more than a quarter (27 %).

Across all means of transportation, we only consider inter-European transportation (so no international travel from or into Europe). Therefore, we do not model freight aviation, as dedicated cargo flights only play a subordinate role in inter-European transportation.

Moreover, we assume transport demand across different means of transportation to be price inelastic, implying that there will be no modal switches between different modes of transportation. While that may be an interesting assessment, it would weaken the informative value of the analysis regarding the core question of the relative performance of the different technology pathways and could possibly lead to circularities. For the same reason, we consider global learning curves for technologies to be independent from the development we model for Europe.

Overall, it is clear that the "Road"-Sector dominates both, passenger and freight transport. Hence, we pursue a detailed modelling approach for this sector, in particular explicitly modelling the vehicle fleet on a year by year basis, while we follow a simplified approach (calculating fuel demand directly based on mobility demand) for the other sectors.

[8] (European Comission, 2016).

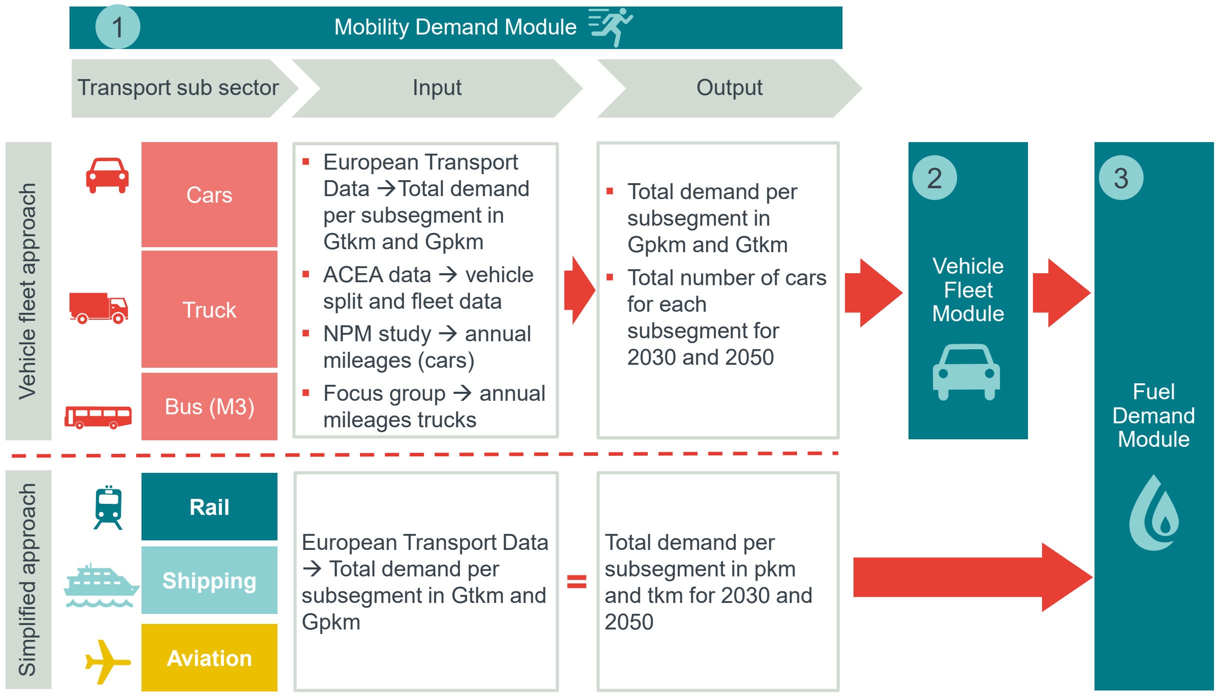


Figure 13: Overview of the Mobility Demand Module [Source: Frontier Economics].

6 Vehicle Fleet

As outlined before, the road sector dominates the total European mobility demand. Any developments in this segment are likely to be decisive for the entire sector. Therefore, we follow a granular approach for this segment, inter alia explicitly modelling the vehicle fleet. This allows us to obtain a detailed understanding of the total required new vehicle registrations as well as the exact fleet composition and therefore fuel consumption in each of the base years (2020, 2030, 2050).

As nearly all cost and environmental impacts from the transport sector can be traced back to either fuel or vehicle production, carrying out this detailed approach for the most relevant segment reinforces the overall reliability of the results of our study.

The starting point for our modelling is the present vehicle fleet, in particular the current vehicle stock and its split across different sub-segments.

For convenience purposes, we do not model all possible vehicle segments for passenger cars. Instead, we split the total number of vehicles between the five biggest vehicle segments: Small, medium, large cars, SUV and LCV as illustrated in Table 1.

Table 1: Passenger mobility demand split between vehicle segments [Source: Frontier Economics based on ACEA].

Passenger	**Share**
Small	34%
Medium	23%
Large	10%
SUV	22%
LCV	11%

For the heavy-duty segment, we differentiate between Small Rigid Trucks (<7.5t), Regional Delivery Trucks (7.5t-16t), Long Haul (<40t) and “Super long Haul” (40t-60t) Trucks. Public Road transportation is also a subgroup of this segment and split between urban transport (primarily short distance travel by city busses) and coaches (primarily long distance). The splits are displayed in Table 2.

Table 2: Freight mobility demand split between vehicle segments [Source: Frontier Economics based on EUROSTAT and LOT II].

Heavy Duty	**Share**
3.5 - 7.5t Rigid	19 %
7.5 - 16t "Regional Delivery"	13 %
16 - 40t "Long Haul"	57 %
>40t "Super Long Haul"	11 %
Buses	**Share**
Urban	80 %
Coaches	20 %

Following on from the present vehicle stock, we then project the future development of the fleet using a “cohort model” approach.

In a first step, we determine the age distribution of vehicles within the current vehicle fleet using data from the TRACCS project[9], adjusted to fit the current average age of the European fleet

[9] The “TRACCS” project was a project funded by the European Commission with the aim to collect data on transportation as the basis for quantitative analyses of measures relating to transport and climate change, https://traccs.emisia.com/ (Anon., 2020).

of 11 years. This then sets the baseline vehicle stock in the first year of the cohort modelling (2020), as depicted in Figure 14.

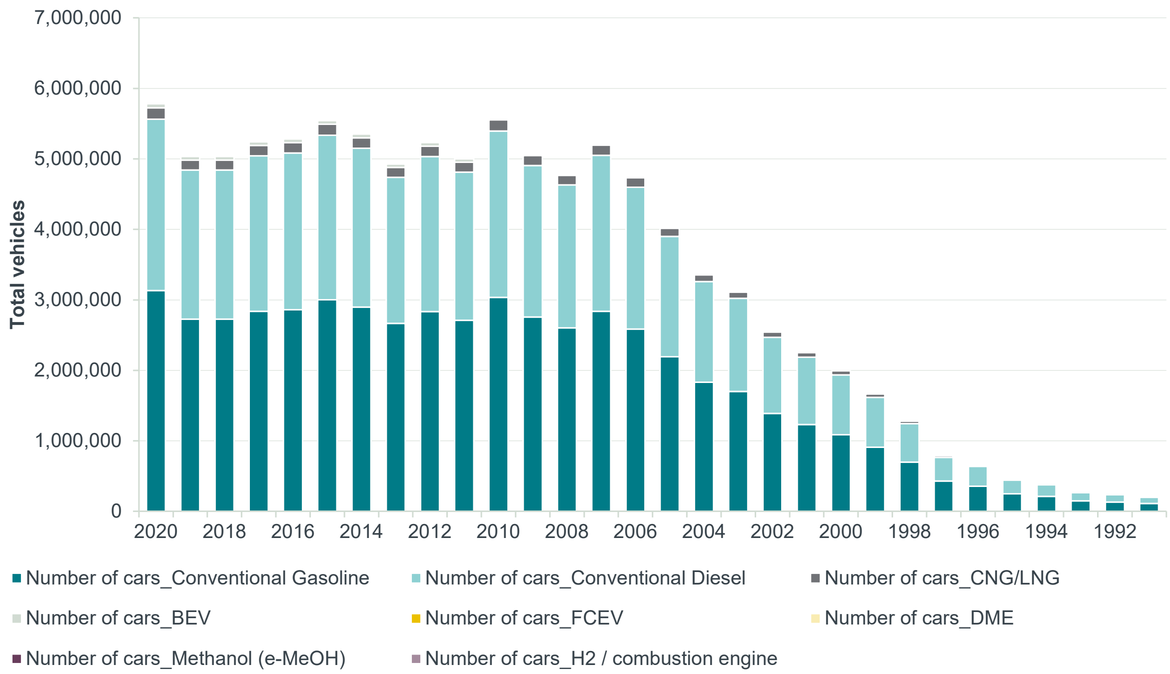


Figure 14: Registration years of the vehicle stock in 2020. Note: Depicted by way of example for the Small vehicle segment [Source: Frontier Economics].

From the age distribution, we derive that the average "age at death" of a passenger car and light duty vehicle (LDV < 3.5t) in the EU is about 17 years. This time span may include multiple owners and "second hand" sales of the vehicle within Europe. Using the average lifetime and the age distribution, we compute the number of vehicles leaving the fleet for each year from now on until 2050.[10]

In each year, the total newly registered cars will need to replace all vehicles leaving the fleet and cover the projected increase in mobility demand. Regarding the split between technologies, the new registrations are modelled so that the respective 100% technology pathway is continuously introduced. The share of the new technology on the total new registrations is continuously ramped up until 100% sales share of passenger cars and LDV is achieved in 2033, so that in 2050 full market penetration is reached, meaning all vehicles are fuelled by the respective GHG neutral technology. This implies that the last "conventional" / fossil passenger cars and LDV with ICE (fuelled with fossil fuels) can be introduced into the market in 2033 (17 years prior to 2050), so that the last passenger vehicle exits the fleet in 2050. By way of example, Figure 15 illustrates the gradual change of new registrations in the 100% FCEV scenario. The share of new registrations which are FCEV is modelled to linearly increase from 6% as of 2020 to 100 % by 2033. From 2033 on, all new registrations in the passenger segment are FCEV.

[10] In the current vehicle fleet, there are some vehicles which are older than our assumed maximum lifetime of 17 years (vintage cars, etc.). We assume that these cars are uniformly replaced over the next 9 years to avoid volatile developments in the new registrations.

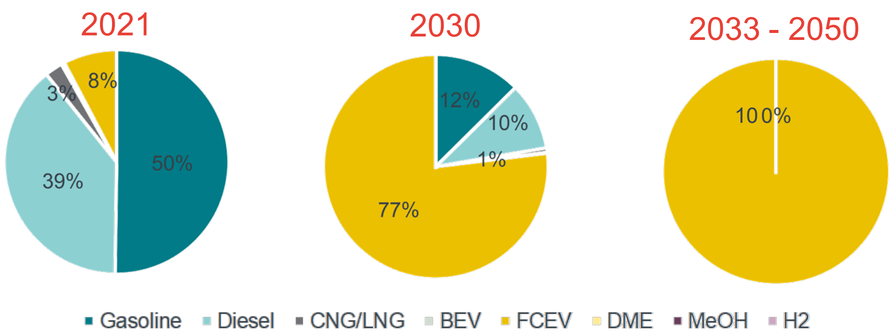


Figure 15: Split of new registrations between technologies in the base years. Note: Depicted by way of example for the Small vehicle segment in the fuel cell electric scenario. All other fuels are modelled analogously. [Source: Frontier Economics].

Following on from this, the vehicle stock in the successive year is determined by progressing the entire vehicle fleet by a year, adding the newly registered vehicles and removing the vehicles exiting from the fleet. Figure 16 provides a schematic summary of the fleet model.

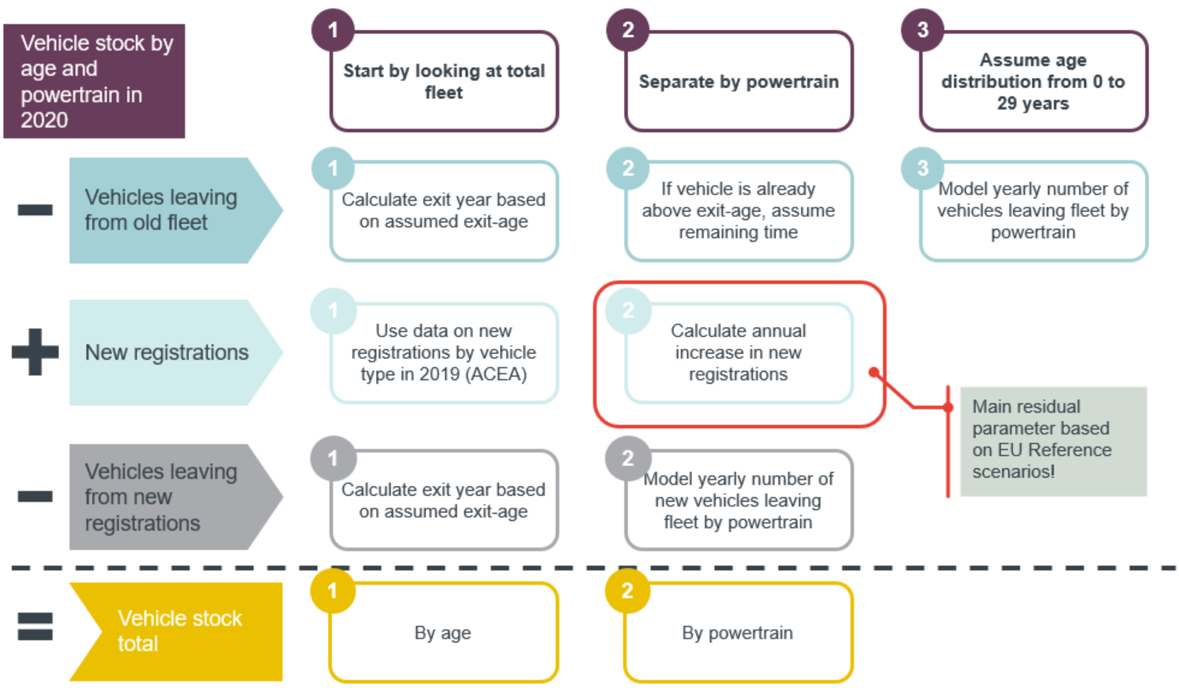


Figure 16: Schematic overview of the vehicle fleet modelling [Source: Frontier Economics].

We separately carry out the modelling for each of the vehicle segments, as vehicle costs and fuel consumption differ from segment to segment and are therefore required on a granular level.

For heavy duty (HD) vehicles, we utilise an analogous approach, implementing heavy duty specific age distributions (also based on TRACCs Data) and lifetimes which vary from 8 to 14 years depending on the segment (for details see Table 3).

Table 3 – Lifetimes of HD segment [Source: FVV Working group].

Segment	Unit	Lifetime
3.5 - 7.5t Rigid	years	10
7.5 - 16t "Regional Delivery"	years	12
16 - 40t "Long Haul"	years	8
>40t "Super Long Haul"	years	8
Urban	years	14
Coaches	years	12

The vehicle fleet modelling yields two core results which we then use as input for our further modelling:

- **Total number of new registrations per year**. Annual new registrations are essential to assess the annual (and also total) vehicle costs and the required raw materials and environmental impacts from production. Section 12.1 provides further detail on the vehicle cost modelling Figure 17 illustrates the number of newly registered vehicles per year exemplarily for the 100 % FCEV scenario.[11]

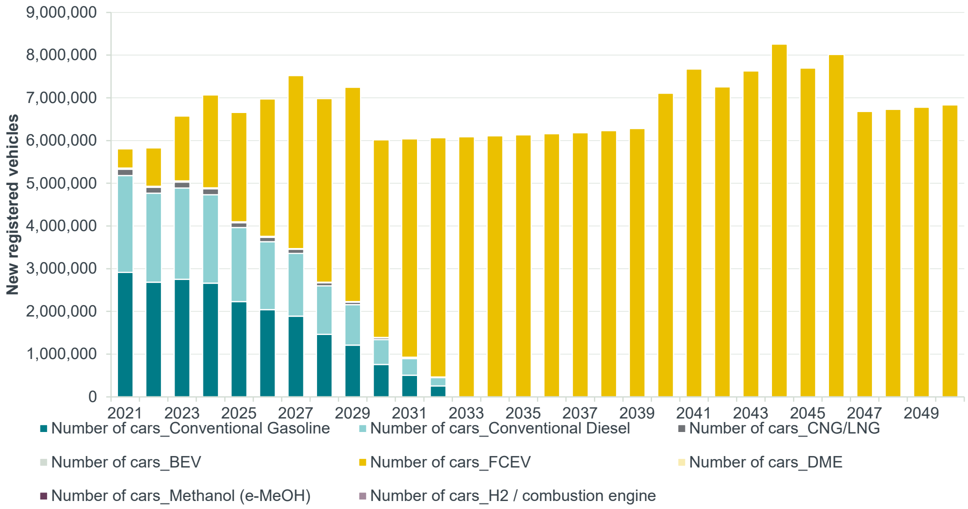


Figure 17 – Number of newly registered vehicles year, split by fuel for 100% FCEV scenario. Note: Depicted by way of example for the Small vehicle segment in the fuel cell electric scenario. All other fuels and segments are modelled analogously. [Source: Frontier Economics].

- **Composition of the fleet** by drivetrain technology per year for each segment. To assess the fuel demand for each fuel in each year, the total number of vehicles in operation per technology as illustrated in Figure 18 is required. In combination with details on the fuel efficiency and the annual mileage of each vehicle, we use the number of vehicles to calculate the total demand for the various fuels required by the actual fleet. Chapter 8 provides further details on our approach to assessing the total fuel demand.

[11] We assume constant annual mileage per vehicle, therefore any change in total mobility demand over time has also an effect on the number of vehicles in the fleet. Because we model replacement investment based on average lifetimes for each vehicle, new registrations in the future follow similar patterns over time as in the past.

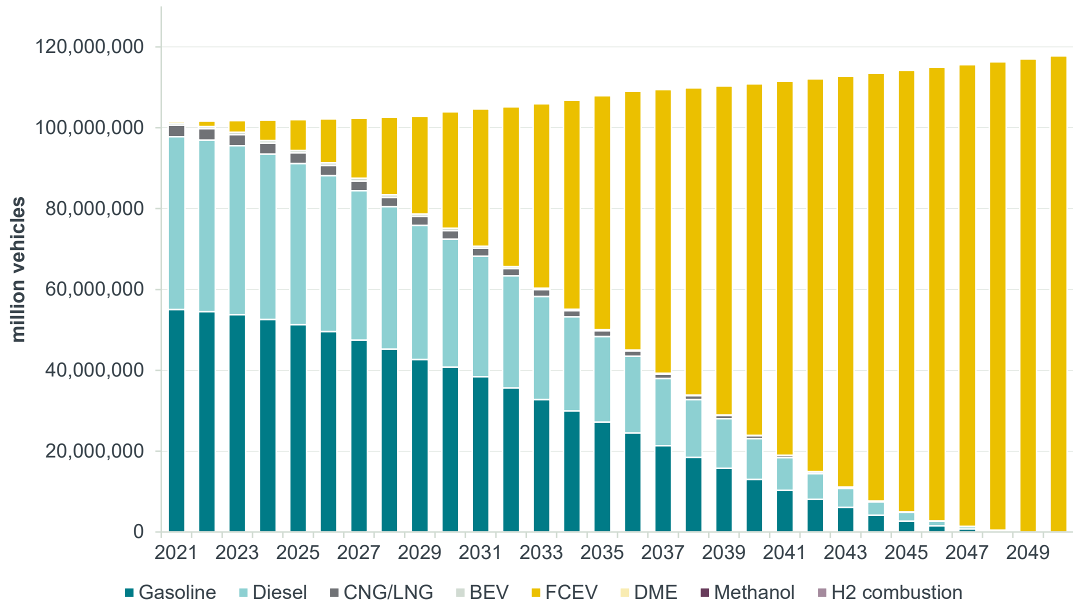


Figure 18: Composition of the vehicle fleet for the 100% FCEV scenario. Note: Depicted by way of example for the Small vehicle segment in the fuel cell electric scenario. All other fuels are modelled analogously. [Source: Frontier Economics].

7 Resulting Fuel demand

The fuel demand is a key parameter to assess future infrastructure requirements and its monetary and environmental implications. As previously addressed, the road sector is of specific importance for the total transport sector. Therefore, we differentiate two separate approaches to calculate the fuel demand: One detailed for the road sector and a more high-level approach for all other sectors.

7.1 Road Sector

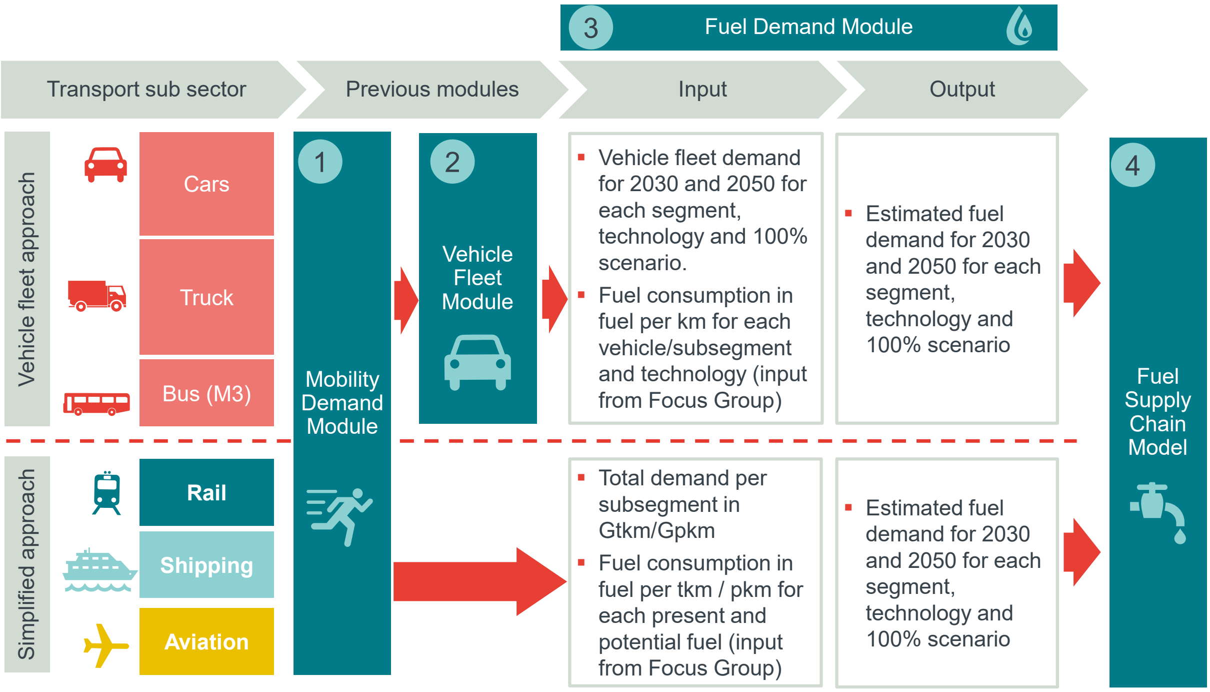


Figure 19: Overview of the Fuel Demand Module [Source: Frontier Economics].

As previously set out in section 7, we follow a detailed approach for the road segment due to its specific importance for the entire transport sector.

Using the vehicle fleet composition in each photo year, the annual mileages per each vehicle segment and the fuel efficiency for each segment, we calculate the fuel demand for each segment in each photo year, as follows:

$$Fuel\ Demand = Total\ No.of\ vehicles * Fuel\ efficiency * Annual\ Mileage$$

We determine the composition of the vehicle fleet, including leaving vehicles and new registrations, as set out in section 7. The granular breakdown of the total vehicle fleet by age is required as we assume that the fuel efficiency can vary over time. For all newly registered vehicles, the fuel demand will also depend on the pathway scenario, Status Quo, Balanced and All-In, which we address later in this section.

Generally, the fuel consumption is expressed in kWh/km. The way we assess the specific fuel demand then has to be differentiated between the existing fleet and newly registered vehicles.

For the existing vehicle fleet, we use the current fuel efficiency of diesel, gasoline, electrified and CNG cars as a base line and assume that a gradual improvement of fuel consumption of

0.006[12] kWh/km p.a. was achieved in the past. Figure 20 illustrates the implication of this assumption by way of example for diesel and gasoline in medium sized cars. Starting from the baseline assumption of a fuel efficiency of 0.167 kWh/km in 2020, we calculate the fuel efficiency in 2019 to be 0.173 kWh/km and so on.

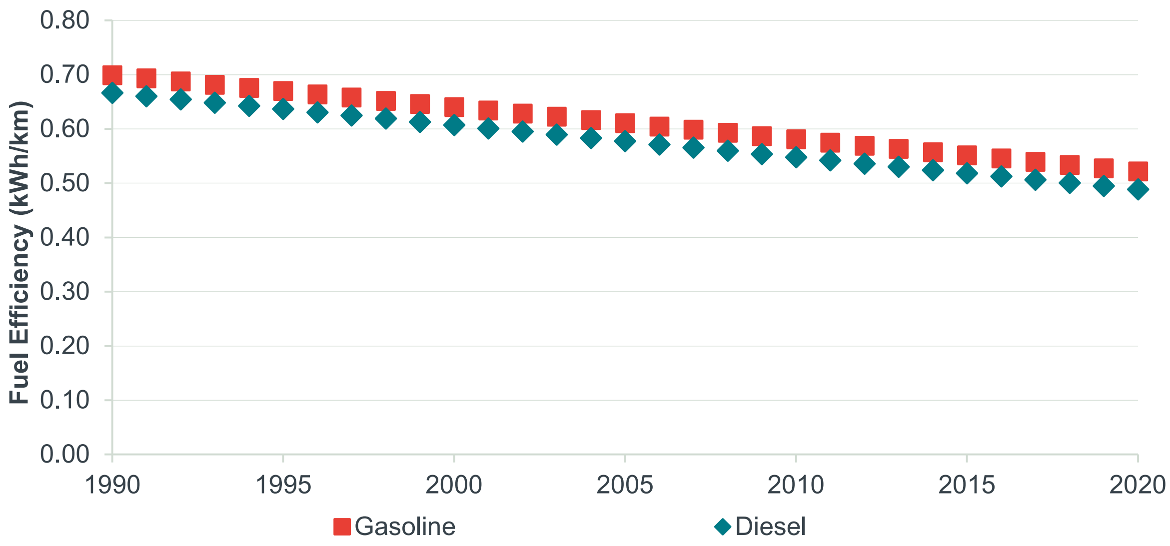


Figure 20: Development of fuel consumption in kWh/km exemplary for Medium diesel and gasoline vehicles [Source: Frontier Economics based on input from FVV experts].

For the newly registered cars, the fuel consumption will vary with the pathway scenarios – Status Quo, Balanced and All-In. By definition, the fuel demand for the All-In scenario is lowest across all fuels while the fuel demand for Status Quo is highest, as we assume no efficiency increases in the future in this scenario. In the Balanced and All-In scenarios, an improved efficiency is assumed from 2026 onwards. Figure 21 illustrates the development of the fuel efficiencies across different scenarios exemplarily for diesel-fuelled vehicles in the small, medium and large segments. The fuel consumption across all vehicles, segments and fuels is provided in Table 206 and Table 207.

[12] (Umweltbundesamt, 2021).

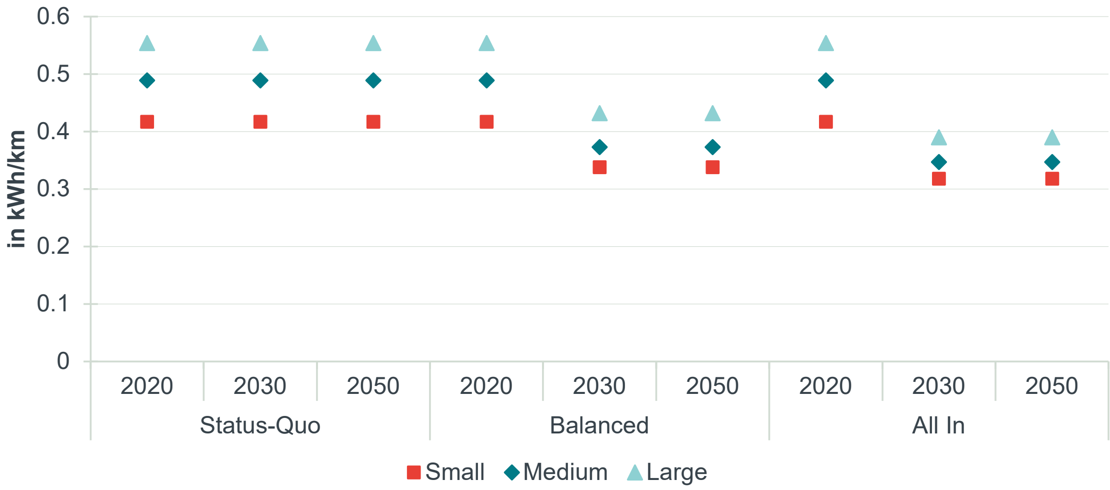


Figure 21: Fuel consumptions exemplary for Small, Medium and Large diesel vehicles [Source: Frontier Economics based on input from FVV experts].

Lastly, information on the annual mileage per segment is required to then calculate the total fuel demand. For each segment, we assume an annual mileage per vehicle and year to calculate how many kilometres each segment will cover within a year. We further assume that this annual mileage per vehicle will remain constant until 2050. Table 204 and Table 205 provide further detail on the annual mileages for all vehicles considered in this study. Multiplying the total number of vehicles of one segment with the annual mileage yields the total distance of all vehicles in that segment within the respective year.

We assume that all vehicles will leave the European market after their assumed lifetime (either because they are scrapped or sold to outside Europe). For the Long Haul and Super Long Haul trucks, the total vehicle lifetime is split into a first and second life within the European market. These vehicles are often used for (international) long haul in the first half of their lifetime and then shorter distances in the later phase of their lifetime. Therefore, we assume a lower annual mileage in the second half of their lifetime.

The total final fuel demand for the vehicle fleet in each of the photo years is calculated as the sum of the fuel demand for newly registered vehicles and the fuel demand for the existing fleet, minus the fuel demand for vehicles leaving the fleet. For newly registered vehicles, the annual mileage of all newly registered vehicles is also multiplied with the fuel consumption of the pathway scenario, yielding the fuel demand for all new vehicles. To identify the fuel demand for the existing fleet, the total number of vehicles registered in one year is multiplied with the annual mileage and then with the fuel consumption of vehicles of the respective cohort. This must be repeated for every cohort represented in the current fleet. To consider that old vehicles leave the market, we deduct the fuel consumption of the cohort leaving the fleet in each respective year.

To assess the infrastructure requirements for the respective 100% scenario, the fuel demand of that specific technology pathway in each year is relevant, which in turn is determined by the ramp-up of the new fuel.

For all fuels except for FT diesel or gasoline, specific alterations, such as switching to an electric drivetrain, including a fuel cell or changing the tank need to be made to the vehicle for the new technology. The demand for these “new” fuels therefore strictly mirrors the increasing penetration of new vehicles in the fleet.

For FT Fuel, no such alterations are required – hypothetically, the entire existing fleet could immediately be fuelled with renewable fuels. In order to provide comparability between all pathways, we assume the ramp-up of renewable FT fuel to follow a similar path as the demand for “new” fuels such as hydrogen or Methanol in other scenarios: As for all other technology pathways, we assume that by 2050, all vehicles will be fuelled with a renewable fuel. For 2030, we assume that the same share of vehicles as in the other 100% scenarios is fuelled renewably, which amounts to 27.6% of the final diesel/gasoline demand. Thereby we ensure that the quantitative results for specific years is comparable between the various fuel pathways. It is important to note though, that this is an assumption only to increase comparability between scenarios – because of the compatibility to the existing fleet FT fuels allow for a fuel ramp-up which could be completely independent from the introduction of new vehicles.

7.2 Rail, Aviation, Shipping

To assess the fuel demand for the Rail, Aviation and Shipping sectors, we follow a simplified approach without explicitly modelling the respective fleets.

Instead, we use the total demand for mobility for each of the sectors, as set out in section 5 and the fuel consumption per passenger or ton kilometre (pkm or tkm) for each of the fuels to calculate the fuel demand. Regarding the introduction of new fuels, we assume a linear ramp up from 2020 up to 100% until 2050.

Other than for the road sector, not all fuels are considered reasonable for each sector. Therefore, we only model a subset of technologies for these sectors, as illustrated in section 4.1.

As already set out in section 5, the total mobility demand for each sector is given in either tonnes or passenger kilometres from 2020 until 2050.

To then calculate the total fuel demand, we assume a specific fuel consumption for each of the existing and potential future fuels in this study (per pkm and tkm) for each of the pathway scenarios (Status quo, Balanced and All-In).

To determine the ramp-up of a 100% fuel without explicit vehicle fleet modelling, it is necessary to identify shares of today's fuel split for each segment. Table 4 sets out the distribution of the total fuel demand between different fuels today.

Table 4: Split today for Rail, Aviation and Shipping [Source: Frontier based on EU Pocketbook 2019 for rail and focus group for shipping and aviation].

Sector	**Electrified**	**diesel**	**kerosene**	**Gas Oil**	**Fuel Oil**
Rail	**54%**	**46%**	0%	0%	0%
Aviation	0%	0%	**100%**	0%	0%
Shipping	0%	**33%**	0%	**33%**	**33%**

We then assume a linear ramp-up towards the 100% fuel in 2050 which gives us the respective fuel demand for the photo year 2030. By way of example, in the hydrogen fuel cell scenario, we assume the above split for 2020 and a 100% FCEV split (all other fuels equal to zero) in 2050. For 2030, the values are linearly interpolated between 2020 and 2050 to assure a smooth ramp-up.

The rail sector requires additional assumptions, as it is already partially electrified. We assume that already electrified routes will remain electrified for each selected 100% fuel, as it does not seem reasonable to deconstruct existing infrastructure. That implies, that even in a 100% Hydrogen fuel cell scenario, 54% of the rail sector will remain electrified, while the other 46% will be fuelled by hydrogen by 2050.

As already set out, we assume a linear ramp-up for each fuel. We assume that in 2030 the total fuel demand of the 100% fuel scenarios will be fuelled with renewable fuel for all scenarios. Similar to road, we need to make an additional assumption for FT fuel as this is already predominantly used for aviation, shipping and rail today. To make all 100% fuel scenarios comparable with each other, we assume that the same share of fuel demand as for the other 100% fuel scenarios is renewable which amounts to 52% of the final diesel/gasoline/kerosene demand in 2030. In 2050, the total fuel is renewable for all 100% fuel scenarios.

7.3 Results

Just like the mobility demand, the total resulting European fuel demand is mostly driven by the road sector, compared to other mobility sectors. The fuel demand of the passenger vehicles dominates both the fuel demand of other sectors but also the fuel demand for Heavy Duty (see Figure 22).

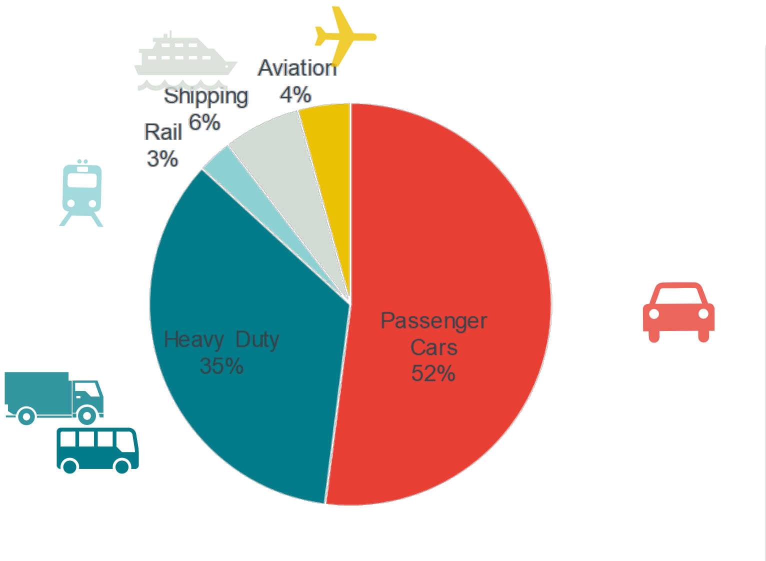


Figure 22: Current split of fuel demand across all sectors [Source: Frontier Economics based on EU Reference Scenarios and fuel consumptions agreed by the expert groups].

The ramp-up of renewable fuel is slightly different between the Road and other sectors but follows a similar approach. The renewable share in the non-road segments is higher, as the total amount of fuel is lower and therefore easier to achieve. Additionally, it relies on the assumption, that the already electrified share of the rail sector will be fuelled with renewable energy completely already in 2030 (across all scenarios). Figure 23 shows the share of renewable fuel for the photo years (and 2040) exemplary for the 100% BEV Balanced scenario for both the road and other sectors.

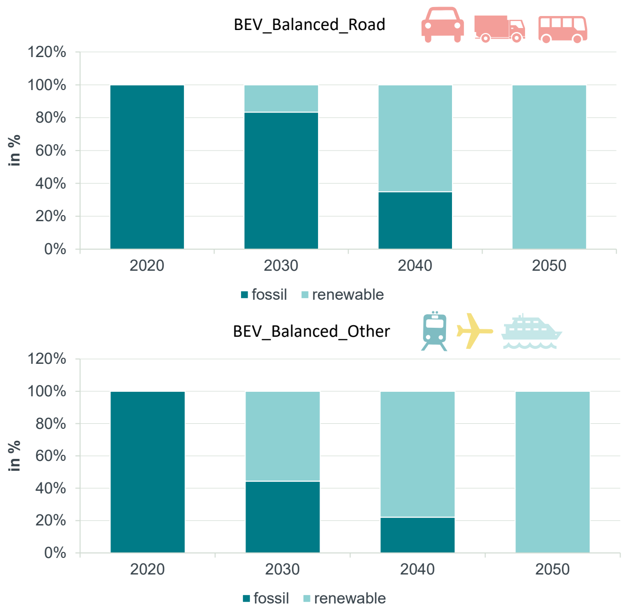


Figure 23: Share of renewable fuel from 2020 to 2050 exemplary for the 100% BEV Balanced scenario [Source: Frontier Economics].

The total ramp-up of the various fuels for all segments varies with the respective 100% pathway scenario. In the Status Quo scenarios, the total fuel demand decreases from 2020 until 2050 for BEV and FCEV while it increases for all other fuels (see Figure 24). The increase in the FT Fuel Status Quo scenario reflects the general increase in mobility, while for BEV and FCEV the higher efficiencies outweigh the increasing mobility effect over time. In the All-In scenarios the fuel demand decreases for all fuels due to the higher efficiency of the vehicles. Here, the additional fuel demand from the increase in mobility will be outweighed by the higher efficiency assumptions for the vehicles.

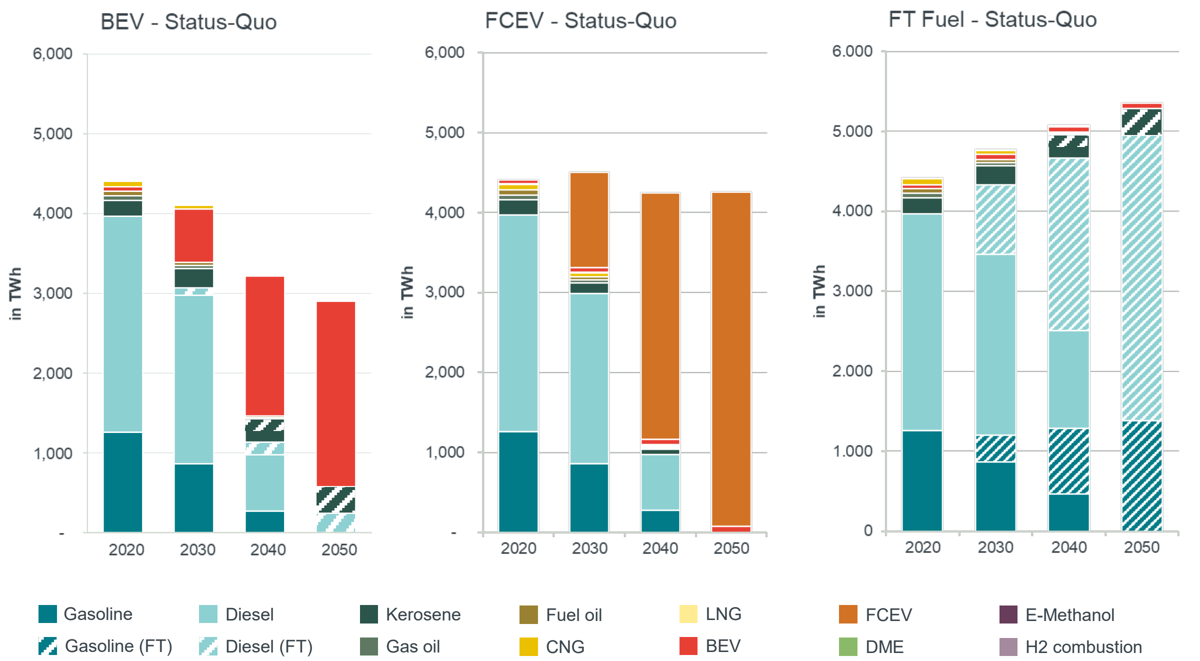


Figure 24: Fuel composition exemplary for the 100% BEV, FCEV and FT Fuel Status Quo scenario from 2020 to 2050 [Source: Frontier Economics]. Note: The fuel of the respective 100% scenario will be completely defossilised in 2030, 2040 and 2050 except for FT Fuel where partly fossil fuel will be used in 2030 and 2040. Note that electrified rail will stay electrified and will be defossilised irrespective which fuel is chosen.

Comparing across all 100% pathway scenarios and degrees of technological advancement, the 100% electrified scenarios (BEV) bear the lowest fuel demand (Tank-to-Wheel (TtW) energy demand) followed by the hydrogen fuel cell scenarios (FCEV). By definition, the Status Quo scenarios have the highest TtW Demand, followed by the Balanced and All-In scenarios. The H2 Combustion scenarios require the highest amount of TtW Demand, followed by Methane, MeOH, FT Fuel and then DME. Reason for the higher fuel consumption of H2 Combustion vs. other ICE pathways is the significantly higher vehicle weight caused by the 700 bar H2 pressure tanks.

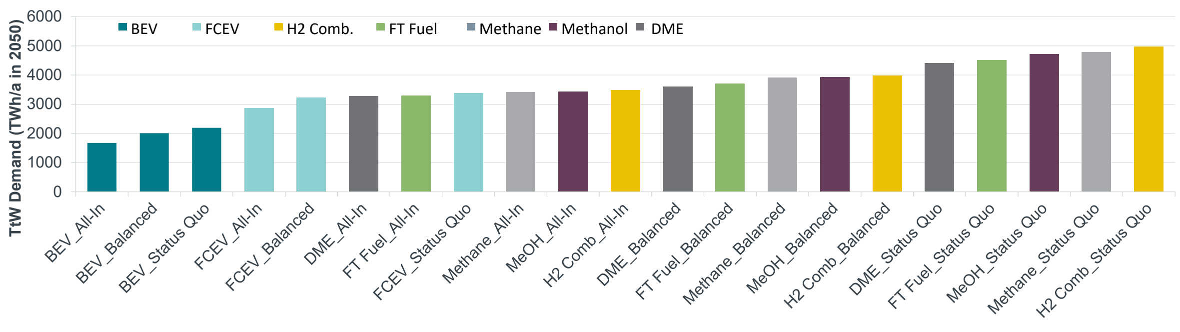


Figure 25: TtW Demand in 2050 for all pathways and fuel scenarios for road sector [Source: Frontier Economics].

8 Modelling of Energy Supply Chains

To assess costs and environmental impacts caused by the fuel demand, it is necessary to model all fuel supply chain (FSC) elements (including power generation and conversion assets as well as infrastructure such as networks or pipelines) which are required to provide the fuel – starting from energy production down to the distribution infrastructure (chargers, filling stations etc.).

8.1 Configuration / assumptions

The aim of this segment of the study is to model the total infrastructure required to supply the fuel for each 100% scenario. For some of the fuel supply chains, certain elements may already be in place (such as gas pipelines) or only need slight alterations (conversion of filling stations to be fit for MeOH). In these cases, the focus of the study is on **incremental** infrastructure relative to today.

For each pathway, our approach to modelling the fuel supply chains starts with the fuel demand and then follows the fuel supply chain from the "bottom to the top". Based on the TtW Fuel Demand, we derive the requirements for distribution, storage, transmission, depending on the scenario the fuel synthesis, direct air capturing (DAC) capacities, the electrolysis capacities and finally the Wind and Solar generation capacities. At each stage, we consider the respective conversion losses. Any additional energy requirements at each stage, for example for the synthesis, are indirectly reflected through efficiencies / conversion losses, so that there is no need to purchase or use fossil energy.

Similarly, if transportation or distribution via trucks are required, we assume that the additional fuel consumption is already indirectly included in the freight fuel demand - as the total fuel demand is input of the model and therefore an additional consideration would be double counting. However, due to the geographic scope of our analysis, this only holds for transportation of fuels within Europe. If we assume import from other countries and the fuel is imported via ship, than the additional fuel consumption is included at the import stage as an additional loss.

Again, this section follows a more detailed approach for the road sector, while for the other sectors we apply a more simplified approach. This affects solely the later stages of the fuel supply chain such as distribution or fuel stations which are primarily relevant for the road sector. For rail, aviation and shipping, we include all stages except for distribution and fuel stations in our modelling, as those stages are unlikely to have a major impact on either costs or environmentally given their centralized nature.

8.2 General Assumptions for all Fuel Supply Chains

Across the different fuel supply chains, several stages are identical, because they are required for many of the considered fuels and follow the same modelling methodology. As for example the main input for all drivetrain technologies is renewable energy, the necessary generation and related transmission infrastructure of offshore generated electricity needs to be modelled across all scenarios. The intermittent nature of the power sources (wind and solar) also makes central storage essential in any scenario. Similarly, hydrogen is required in all scenarios (albeit for different purposes), making the modelling of electrolysis capacities necessary. Lastly, all hydrocarbon fuels (Methane, MeOH, DME and FT Fuels) require a source of carbon and therefore direct air capturing, as well as additional synthesis step.

8.2.1 Electricity Generation and Offshore Transmission

As the aim of the study is to assess different pathways to fully defossilise the transport sector by 2050, all fuels need to be sourced from renewable energy sources, in particular from PV and wind (onshore and offshore). In order to avoid any acceptance issue, biofuels and also synthetic fuels produced with nuclear power were not considered within the scope of our analysis, since both have environmental disadvantages controversially discussed.

The split of total generation between the different energy sources is not an outcome of our modelling but rather set exogenously following projections on the future allocation of energy generation in the relevant locations.

Table 5: Split of renewable energy generation by source and location [Source: Frontier Economics based on (International Energy Agency, 2019)].

	European (Domestic)			**Middle East, Northern Africa (MENA)**			**Rest of World (RoW)**		
	2020	**2030**	**2050**	**2020**	**2030**	**2050**	**2020**	**2030**	**2050**
Offshore	30%	33%	40%	25%	25%	25%	10%	10%	10%
Onshore	30%	22%	17%	25%	25%	25%	90%	90%	90%
PV Standalone	27%	32%	30%	50%	50%	50%	n/a	n/a	n/a
PV Slanted Roof	12%	14%	13%	n/a	n/a	n/a	n/a	n/a	n/a

We consider slanted rooftop PV as an energy source in the 100% electrified scenario only. This approach assumes that energy generated via rooftop PV is most efficiently decentral used where it is generated. While in the electric scenario, this is possible as the produced electricity can often be directly used for at-home. For the other fuels, this precondition is not fulfilled and rooftop PV therefore not considered. Instead, the total share of PV remains unchanged, but assigned to standalone facilities.

To assess the generation capacities which are required to fulfil the energy demand, assumptions on the full load hours (FLH) for Offshore, Onshore, PV are required. These need to be specific to the different locations (Europe, nearby good locations such as the MENA region and far off top locations such as Patagonia). Table 6 illustrates the assumptions the experts have agreed on regarding the utilization of capacities. Particularly for Onshore and Offshore Wind, technological advancements are expected to lead to improved utilization rates. More details on assumed capacities can be found in section 16.5.

Table 6: Utilisation of renewable energy sources split by location [Source: Input FVV Working Group].

		European (Domestic)			**Middle East, Northern Africa (MENA)**			**Rest of World (RoW)**		
		2020	**2030**	**2050**	**2020**	**2030**	**2050**	**2020**	**2030**	**2050**
Offshore	h/ year	3700	3867	4200	3700	4133	5000	3700	4133	5000
Onshore	h/ year	2282	2522	3000	3700	3967	4500	3700	3967	4500
PV Standalone	h/ year	1300	1300	1300	2400	2400	2400	N/A	N/A	N/A

We assume that electricity produced by offshore wind farms needs to be transported to the coast where it is fed into the onshore AC transmission network. This is modelled using a simplified approach for offshore converter stations and HVDC electricity sea cables for all fuel chains. The number of cables is assumed to be proportional to the overall primary energy demand of the fuel supply chain, as an increase in energy demand triggers an increase in generation capacity and thus offshore connections. Table 7 summarizes the assumptions regarding offshore connections (for more details see section 16.5).

Table 7: Technical assumptions for offshore transmission for 2050 [Source: FVV Working Group based on (Entsoe, 2021) and exemplary existing projects].

Type	**Capacity per cable**	**Average distance from coast**
HVDC 525 kV Subsea cable	2 GW	200 km

8.2.2 Hydrogen Production via Electrolysis

Green hydrogen (produced from electricity via electrolysis) is required across all 100% scenarios. It is either used

- for central storage purposes in the 100% electric scenario (long-term storage via power-to-gas-to-power),
- as the fuel itself, either for a fuel cell electric vehicle or for a hydrogen combustion engine,
- or as an input for the synthesis of a final hydrocarbon fuel.

Therefore, electrolyser capacities need to be established in all 100% pathways scenarios.

We assume that the hydrogen is produced via alkaline electrolysis, which is suitable for discontinuous operation. This is particularly important as the underlying energy is supplied from renewable sources and therefore volatile across different times in the day as well as seasons over the year. Additionally, alkaline electrolysis is at a sufficient technological maturity to be ready for industry level scale up in the near future. Nevertheless, efficiencies of the electrolysis process are assumed to further increase in the future with further research and developments effort and resulting learning curves, as illustrated in Table 8. For more details see section 16.5.

Table 8: System efficiency of electrolysis based on calorific value [Source: Frontier Economics based on input from FVV Working Group].

	Unit	**2020**	**2030**	**2050**
Efficiency Electrolysis	kWh(H2)/kWh(el)	64%	69%	71%

In order to assess the required capacities in each of the scenarios, assumptions on the utilization of the electrolysis need to be made. Given that the electrolysis is fuelled by renewable energy, we assume that it is directly following power generation, i.e. it is active whenever power can be supplied, so that the utilization of the electrolysis is equal to that of the renewable energy sources. Due to increasing utilization of the generation facilities, the utilization of the electrolysis will gradually increase over time as well.

Regarding the geographic location of the electrolyser, we model it to be located next to generation or close to the coast in case of offshore generation to minimize the need for high voltage transmission lines.

8.2.3 Central Storage

In each 100% pathway, the final fuel is stored within the central energy system (analogue to strategic reserves today) if feasible. However, the exact type of storage depends on the respective pathway.

For the electrified scenario, the central storage consists partly of batteries for short periods but also storage for longer dark doldrums.

8.2.4 Hydrogen Storage

As already set out, all scenarios require hydrogen irrespectively of the final fuel. For the electrified and the hydrogen scenarios, hydrogen is considered as part of a centralised storage technology. For all other fuels, hydrogen buffer storage is included to ensure that the synthesis can operate continuously, while hydrogen is only produced when renewable energy is generated. The decision to include a hydrogen buffer storage is driven by two factors: (i) technical reasons, as the synthesis processes typically have long ramp-up times and (ii) cost reasons as continuous operation leads to lower synthesis capacities.

We consider two technologies for storing Hydrogen: using refurbished caverns or alternatively using hydrogen pressure storage. Caverns are generally preferable due to lower costs, smaller storage losses and larger sizes compared to hydrogen pressure storages. To store hydrogen in pressure storage, constant compression and therefore energy supply is required. We have included hydrogen pressure storage only to a small degree in the international scenarios. In some regions of the world, caverns may not exist, making hydrogen pressure storage necessary. As caverns are not always located close to the generation, we assume that hydrogen is transported via pipelines to the cavern storage, which are therefore included in the study in terms of costs and environmental impact. For more details see section 16.5.

8.2.5 Direct Air Capturing and Synthesis

All hydrocarbon fuels (Methane, MeOH, DME and FT diesel/gasoline/kerosene) require a source of carbon and (at least) one additional synthesis step after the electrolysis to produce the final fuel.

There are multiple ways coming into consideration to source the carbon required for the fuel production. As fuels are required to be carbon neutral, technologies based on fossil carbon sources, such as obtaining the CO2 from Methane are not suitable. Given the expected overall defossilisation of all sectors, industry capture of fossil based CO2 (e.g. from cement production) is not expected to suffice for the demand from the transport sector. Therefore, we assume that the demand for CO2 will be covered by direct air capturing (DAC). The DAC requires both thermal energy and electricity, both of which are considered in our analysis. However, if waste heat is available from a synthesis process, it will be used for the DAC. Therefore, we assumed that DAC is located close to the synthesis plant in an integrated facility. Table 9 lays out the underlying efficiencies of the CO2 capturing process. See section 16.5 for more details.

Table 9: Technical assumptions direct air capturing. Note: We assume low temperature solid absorbent DAC; as currently already used by different firms. [Source: Fahisi, Efimova and Breyer (2019), Viebahn (2018), FVV (2016)].

	unit	**2020**	**2030**	**2050**
Electricity demand	kWh(el)/kg CO2	0.5	0.4	0.28
Thermal energy demand	kWh(therm)/kg CO2	2.2	1.5	1.39

For all hydrocarbon fuels, we model an additional storage of CO2. Similar to hydrogen buffer storage, CO2 storage is required because the DAC only captures CO2 as long as renewable energy is generated while the synthesis plant is operated continuously. The size of the CO2 storage is based on the size of the hydrogen storage, following the ratio of carbon to hydrogen of the different syntheses processes. For details see section 16.5.

8.2.6 Fuel Transmission and Distribution

Generally, only fuel which is not consumed right where it is produced needs to be transported via grid/pipeline/truck. The share of fuel which is directly consumed – referring to “close consumption” and does not need transportation depends on the type of renewable generation. For example, in the 100% electric pathway, we assume that electricity generated via rooftop PV is to a large degree consumed locally without a need for transportation.

In the international scenarios, close consumption means that the energy or fuel will be consumed close to the “landing point” without significant transport requirements – i.e. the end of the import pipeline or the final destination of the ship. We assume that the split between distant and close consumption is similar to the split for domestic offshore generation.

Table 10: Split between distant and close consumption for the domestic and international scenarios [Source: Frontier Economics].

Type	European		International	
	Distant consumption	**Close consumption**	**Distant consumption**	**Close consumption**
Offshore	90%	10%	90%	10%
Onshore	70%	30%	90%	10%
PV Standalone	50%	50%	90%	10%
PV Slanted Roof	10%	90%	n/a	n/a

The modelling approach for fuel station distribution is similar across all physical fuels, as the distribution requirements are driven by the geographic environment, rather than the fuel. The number of fuel stations needs to provide a sufficient, comprehensive coverage of Europe. We have scaled up the assumptions from the predecessor study (Forschungsvereinigung Verbrennungskraftmaschinen, 2018) on the optimal number of fuel stations in Germany by the size of Europe to determine that across Europe, 89,742 fuel stations will be required in 2050 for passenger vehicles with 8 pumps per fuel station on average. For heavy duty vehicles, it is assumed that 26,922 fuel stations will be required in 2050 with 4 pumps per fuel station on average. For all liquid fuels losses of 0.34% are taken into account analogue to the predecessor FVV study (Forschungsvereinigung Verbrennungskraftmaschinen, 2018).

As the charging process for electric vehicles differs substantially from the refuelling of other fuels, we have chosen a different approach to determine the required number of chargers. section 8.3.1 provides further details on this question.

8.3 Specifics of Each Modelled Fuel Supply Chain

In addition to the stages set out above, each fuel supply chain requires stages specific to the fuel. These stages vary from fuel to fuel and also depend on whether existing infrastructure can be used. Those will be addressed in turn for each considered fuel.

8.3.1 Electrification (”BEV“)

Overview – Figure 26 and Figure 27 show the stages of the underlying fuel supply chain for the 100% electrified scenario. The energy flow is depicted from left to right, starting with the renewable energy generation, followed by transmission and ending on charging points on the right. As already set out in the previous section, renewable energy will be generated via wind (on- and offshore) or PV (both slanted roof and standalone). Following this, it can travel down two pathways, a path which directly links supply and demand and an indirect path where energy is stored in-between and therefore supply and demand do not have to occur simultaneously.

- Along the direct path, the generated energy will be transported across Europe via the transmission grid and then distributed to the chargers and/or households. As already set out above, we assume catenary electrification for long haul heavy duty vehicles with high daily mileage, which implies that an overhead grid for trucks and coaches is required. This overhead grid is also connected to the grid and supplied with energy. Energy generated by rooftop PV is assumed to be consumed close to generating– either directly feeding into a Wallbox or after being stored in a battery to allow for more flexibility regarding the timing of the charging process.
- The indirect (storage) path is required to ensure that vehicles can be charged at all times even if no renewable energy is generated in that specific moment. In this path, energy which exceeds demand at the time of production is used to produce hydrogen via electrolysis. The hydrogen will then be either (i) stored in pressure storage located close to the electrolyser or (ii) transported to the closest hydrogen

cavern via pipeline and stored there. In times where the demand for energy exceeds supply (energy shortage on the supply side), the hydrogen will then be reconverted to power and fed into the transmission grid. From there, the energy will follow the same path as described above in the direct path.

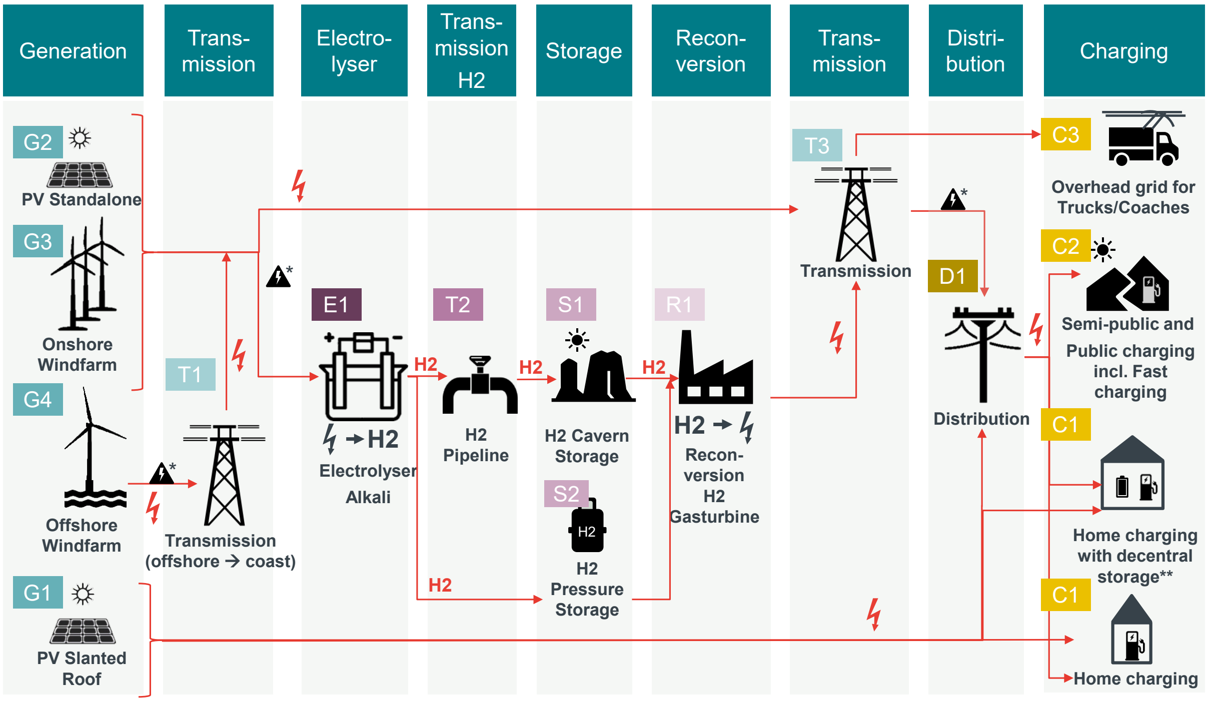


Figure 26: Schematic Overview domestic BEV fuel supply chain [Source: Frontier Economics].

Key (technological) assumptions –For the electrified scenario, various specific infrastructure elements need to be built to ensure that the renewable generated energy will reach the charging points and the final customer:

- Transmission Grid – As the generated energy will be consumed across Europe wherever there is demand for mobility and not only in the locations where it is generated, a transmission grid is required. For this reason, an (expanded) transmission grid is required to transport energy. To identify the total amount of energy that requires transportation (as opposed to energy that can be consumed directly in the region), a split between close and distant consumption is assumed for each type of generation, as set out in section 8.2.6. While there is an existing transmission grid, the increase in electricity demand from the electrification of the transport sector is significant enough to exceed its capacity. The FVV working group thus assume that 20% of the required transmission grid demand can be met by spare capacity from the existing transmission grid, while 80% of the required transport capacity needs to be newly built. For details see section 16.5.
- Distribution Grid – Following the transmission grid, the distribution grid is then required to distribute energy to charging points in urban but also in remote locations. Again, even though there is an existing distribution grid, it needs to be expanded and adjusted for the additional demand. We differentiate the distribution grid along three different voltage levels: (i) High voltage (110kV), (ii) medium voltage (25-60kV) and (iii) low voltage (400V). For details see section 16.5.
- Charging Infrastructure – Charging infrastructure is the key element to ensure a comprehensive supply of electricity for vehicles. In a first step, we identify the different types of chargers that will be required, to then determine the total demand for each kind. We differentiate between private chargers and publicly accessible ones. Private chargers include Wallboxes for passenger vehicles and depot

chargers for heavy duty vehicles (e.g. in logistic centres). The latter are required for non-catenary trucks (trucks ≤16 tonnes) as well as to charge the batteries in catenary trucks to which enable them to cover the final distances without overhead grid. For public chargers, we also differentiate between two chargers: Semi-public chargers (44kW) and fast-chargers (150kW). Semi-public chargers can be found in public parking areas in city centres but also at car parks of supermarkets or big furniture stores. Fast-chargers are expected to be located at highways or other long distance roads allowing for intermediate charging. We assess the total number of charging points for the 100% electrified scenario based on the number of vehicles of the relevant segment (passenger car vs. heavy duty) and chargers per vehicle ratios, combined with the charging split/behaviour (see Table 11 and Table 12). For more details see section 16.5.

Table 11: Charger Types.

Category	Type	Performance	Charger per vehicle	Charging-Losses
Private Charger	Wallbox	11 kW	1.125	0%*
	Depot Charger	150 kW	0.055	8%
Public Charger	Semi-Public	44 kW	0.061	0%
	Fast Charger	150 kW	0.006	8%

Note: Main losses are already taken into account in the fuel consumption of the vehicles and are therefore excluded here to avoid double counting [Source: FVV working group based on various studies (ADAC & Ludwig-Bölkow-Stiftung , 2019), (ABB, kein Datum), and (Transport & Environment, 2020b) and (Channegowda, et al., 2015)].

Table 12: Shares of Charging.

	Passenger Vehicles			Heavy Duty Vehicles		
	2020	**2030**	**2050**	**2020**	**2030**	**2050**
Share of private charging	85%	60%	60%	80%	80%	80%
Share of semi-public charging	10%	35%	35%	10%	10%	10%
Share of fast-charging	5%	5%	5%	10%	10%	10%

[Source: Frontier Economics based on FVV working group and (Transport & Environment, 2020)].

- Overhead grid – An overhead grid for catenary trucks and coaches needs to be built, as we assume that large trucks (i.e. > 16t) will not be equipped with large batteries to allow for the same ranges as today, but instead use an overhead grid for large parts of their trip. To ensure that all roads relevant for the heavy duty segment today are equipped with an overhead grid, we determined the total distance for each of the EU27+UK countries by using the maximum length of either Motorways, E-Road (as reported on EUROSTAT) or “TEN-T comprehensive”. Following this approach, this leads to a total distance of 118,248 km in 2050 (see section 16.5 for details).

- Re-Conversion of H2 Storage – As previously set out , we consider hydrogen for central (seasonal) storage in the electrified scenario. However, as the vehicles are ultimately powered by electricity, the hydrogen needs to be re-converted back to electricity using a hydrogen powered turbine. The required hydrogen to fuel the turbine is considered in the total energy demand. The additional energy demand that is required to supply the gas turbine is considered in the total energy demand.

Table 13: Re-conversion from hydrogen to energy - gas turbine.

	2020	2030	2050
Capacity in MW per unit	500	500	500
Efficiency in %	45.0%	47.5%	50.0%

[Source: Frontier based on methane gas turbines see section 16.5.].

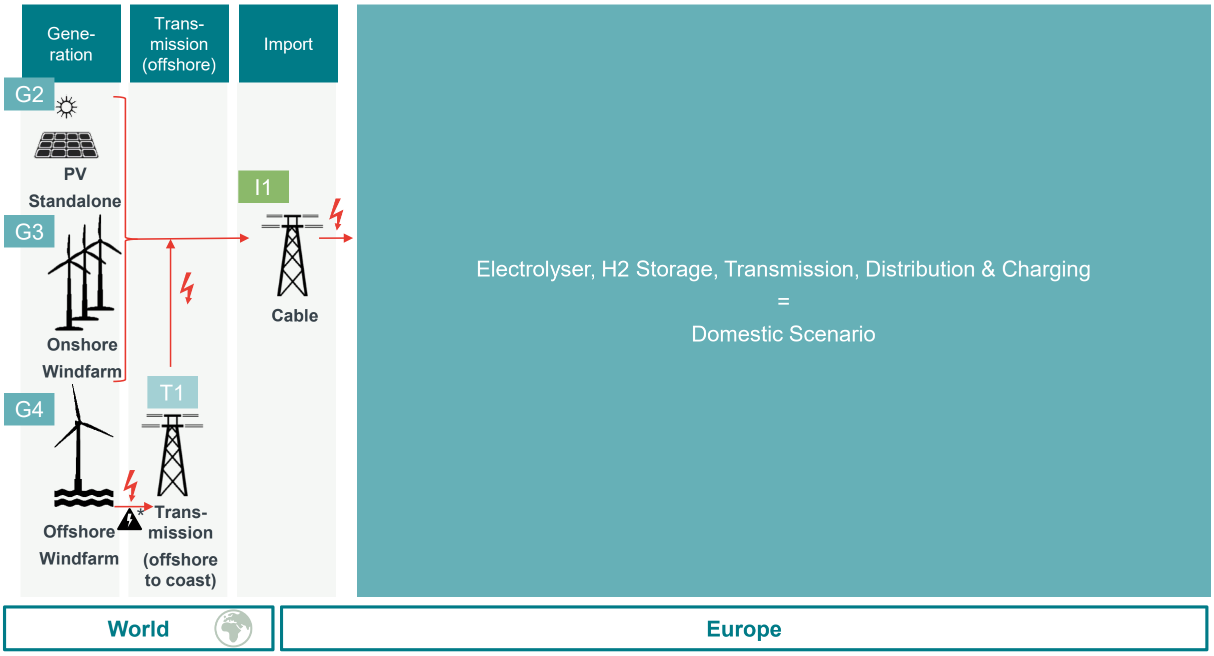


Figure 27: Schematic Overview international BEV fuel supply chain [Source: Frontier Economics].

- Import cable – The international scenario requires import as additional element of the fuel supply chain. As set out in section Origin of Energy 4.3, renewable energy will be produced in both Europe (30%) and MENA (70%). The energy will be imported from MENA via power cable with a capacity of 2 GW, as we assume that the final fuel will be imported directly. For more details, see section 15.1.

Key Results – The final fuel demand (TtW) has previously been calculated[13] by using the mobility demand and the vehicle efficiencies. Based on the TtW demand, we then calculate the total primary renewable energy (Well-To-Wheel (WtW) demand) that needs to be generated. The total generated energy depends not only on the final fuel demand but also on the losses and additional energy demand required at each stage of the fuel supply chain.

In the domestic electrified scenario, the main losses relate to hydrogen storage to bridge dark periods. This includes not only the energy demand required for storing hydrogen (i.e. to power compressors) but also the losses and energy demand occurring due to the (re-) conversion of electricity to and from hydrogen. Note that only 8.9% of the final fuel demand passes through storage in the domestic sourcing scenario. Losses caused by the distribution are the second largest position in the fuel supply chain, followed by losses occurring during the charging process. Minor losses also occur when transporting renewable energy either from offshore loca-tions to the coast or over long distances within the EU. In general, 26% of the total generated energy (WtW Demand) in the domestic are lost along the fuel supply chain scenario, as can be seen in Figure 28.

[13] C.f. section 8.

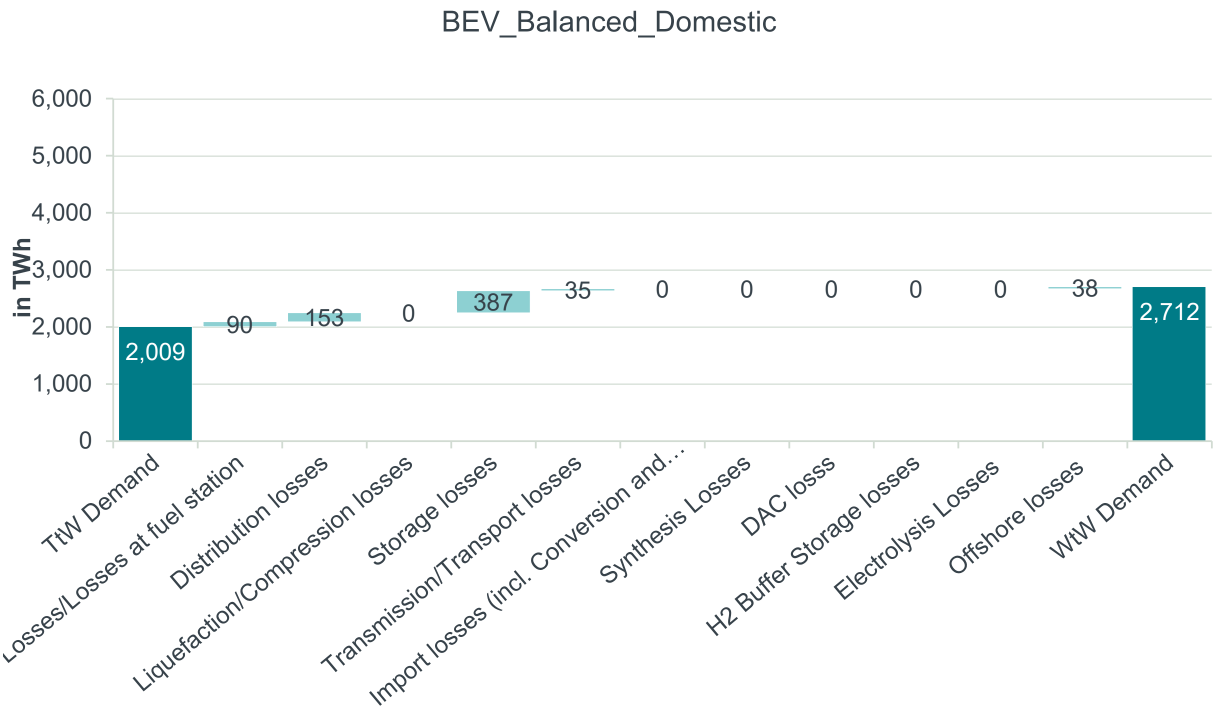


Figure 28: Energy demand along the domestic BEV fuel supply chain [Source: Frontier Economics].

In the international electrified scenario, the main losses occur due to storage and when distributing energy to the charging points. Compared to the domestic scenario, the losses due to storage are much lower as less energy passes through storage (only 3% of final fuel demand). The need for storage compared to the domestic scenario decreases because of a more diver-sified generation portfolio. Generation is broader distributed not only within but also outside Europe which makes it more likely that energy is generated at the same time it is demanded. Naturally, there are also (small) losses from the import of the fuel which occur only in the international scenario. Apart from this the losses along the fuel supply chain are quite similar to the domestic scenario. Overall, in the balanced international scenario, the losses are 19% of the WtW Demand and therefore lower as in the domestic scenario (26%). Even though energy will partly be imported in this scenario (leading to import-losses), the total WtW energy demand is lower than in the domestic scenario, as the storage losses which can be avoided outweigh the additional import losses.

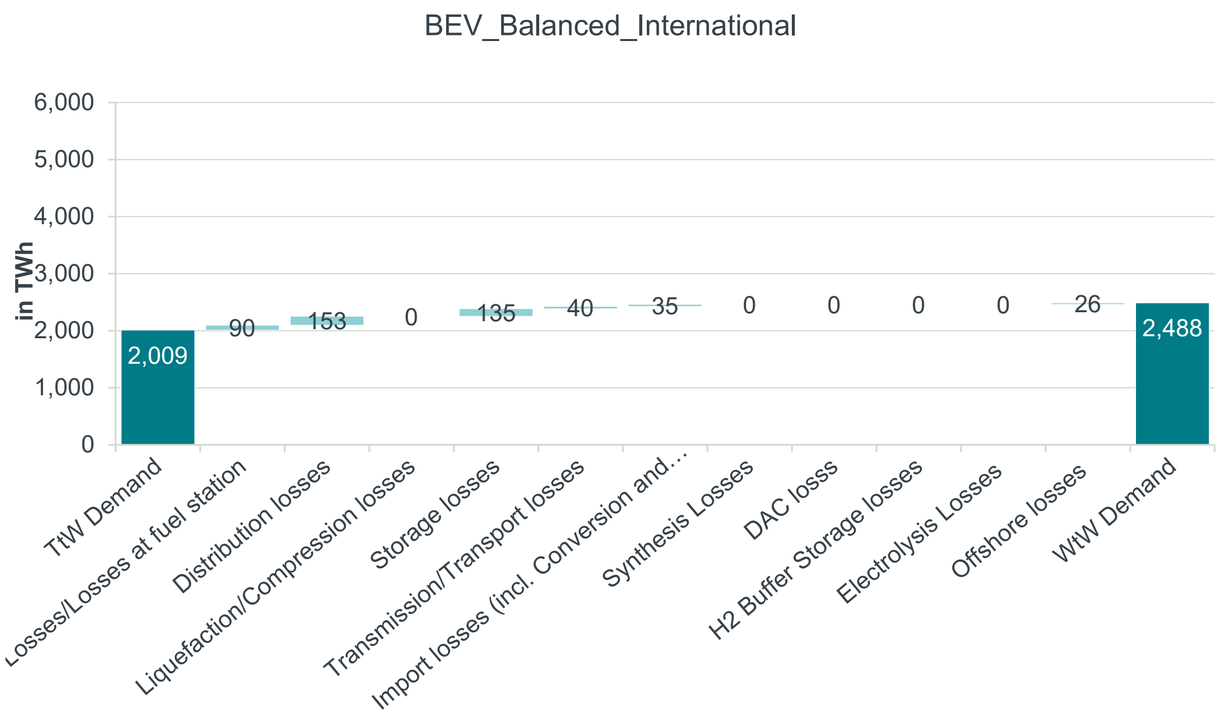


Figure 29: Energy demand along the international BEV fuel supply chain [Source: Frontier Economics].

8.3.2 Hydrogen ("H2")

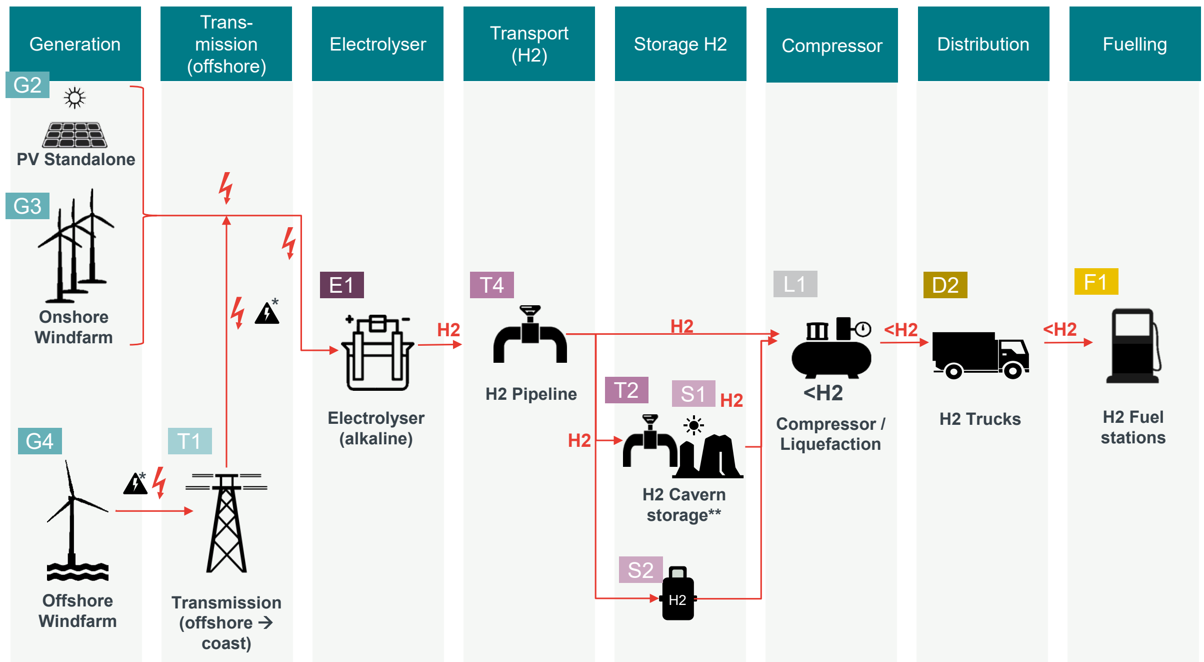


Figure 30: Schematic overview of the domestic hydrogen fuel supply chain [Source: Frontier Economics].

Overview – Figure 30 and Figure 31 show the steps of the underlying fuel supply chain for the two 100% hydrogen scenarios – fuel cell electric (FCEV) and hydrogen combustion (H2 Comb). The energy flow is depicted from left to right, starting with renewable energy generation, followed by the production of green hydrogen via electrolysis and the distribution, up to the hydrogen fuel stations. Again, there are two pathways: the main direct path and the indirect (storage) path.

- Along the direct path, the produced hydrogen will be transported across Europe via hydrogen pipelines to various distribution nodes. From there, it will be compressed to be distributed to fuel stations via trucks (container trailer) in gaseous form. If renewable energy is also generated in MENA (in the international scenario), the hydrogen is assumed to be imported via hydrogen pipelines which is considered as the most cost and energy efficient option.
- The indirect (storage) path is similar to the direct path but includes the additional detour of storing hydrogen. After producing hydrogen via electrolysis, the hydrogen is transported to central storage facilities via pipelines. As for the other scenarios, storage is required to bridge periods when no renewable energy is available to produce hydrogen. The hydrogen will be stored in caverns, as set out in section 8.2.4. No storage facilities are required outside of Europe, as the hydrogen will immediately be imported.

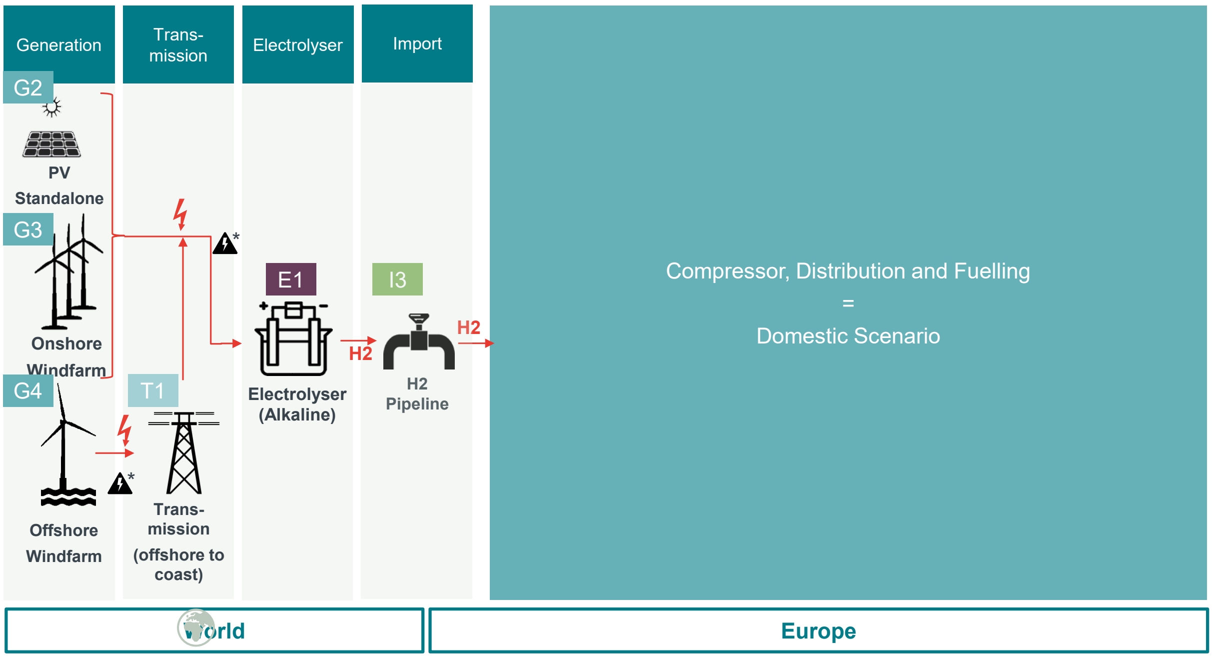


Figure 31: Schematic overview of the international hydrogen fuel supply chain [Source: Frontier Economics].

Critical (technological) assumptions – While some stages overlap for all fuel supply chains (as described in section 8.2), several stages are specific to the hydrogen scenarios. Various specific infrastructure elements need to be built to ensure that hydrogen can be produced, transported and distributed to the fuel stations.

- Transmission Pipelines – As all vehicles across Europe require hydrogen in the 100% hydrogen scenario, the hydrogen demand rises. To ensure that hydrogen is available wherever there is demand for it, it has to be transported from the electrolysis facility to the consumer. We assume that transport will solely take place via hydrogen pipelines. To establish a hydrogen grid, pipelines can either be newly built or existing methane pipelines can be retrofitted to be suitable for hydrogen. We assume that in a 100% hydrogen scenario, it is possible to cover 80% of the required H2 grid through retrofitting existing methane pipelines. Irrespective of whether a pipeline will be retrofitted or newly built, new compressors are required to transport hydrogen via pipelines due to the specific properties of hydrogen. Table 14 summarises the underlying technical assumptions for the transmission of hydrogen.

Table 14: Technical assumptions for pipelines for international transport of hydrogen.

	Average Capacity of line	**Compressor capacity**	**Losses due to compression**
Hydrogen Pipelines	13 GW	260 MW(el)/1000 km	2 **%**/1000km

[Source: Frontier Economics based on (Wang, et al., 2020)].

- Distribution (incl. Compression) – The last step of distributing hydrogen from the distribution node to the fuelling station is carried out using container trailers. Container trailers are able to carry around 1,000 kg hydrogen. To load the trucks, it is necessary to compress the hydrogen to about 500 bar. The additional energy demand required for the compression and operation of the fuel stations is taken into account for the total WtW demand. For details see section 16.5.
- Fuel stations – Fuel stations for hydrogen need to be built in large scale to meet demand and provide comprehensive coverage across Europe. Although a few hydrogen fuel stations exist already, those have not been taken into account, as their current size is negligibly small. The total number of fuel stations required has been calculated using the approach set out in the section 8.2.6. The FVV working group agreed that the tanks in all vehicles (both LDV and HDV) will operate at a pressure of 700 bar. All hydrogen fuel stations need to be newly built as they are quite different from diesel and/or gasoline fuel and retrofit is thus not an option. Losses occurring at fuel stations or additional energy demand that is required to compress the hydrogen is considered here (2.3 kWh(H2)/kg(H2) see (ADAC & Ludwig-Bölkow-Stiftung , 2019).
- Import – In the international scenario, hydrogen will be imported from the MENA region via hydrogen pipelines. For details see section 16.5.

Results – The final fuel demand (TtW) has previously been calculated[14] using the mobility demand and the fuel efficiencies. Based on the TtW demand, we then calculate the total renewable energy (Well-To-Wheel (WtW) Demand) that needs to be generated. The total generated energy depends not only on the final fuel demand but also on the losses and additional energy demand that is required at each stage of the fuel supply chain. These losses add up to 39% (40%) of the WtW Demand in the domestic (international) scenario in 2050.

The highest losses along the supply chain occur by far through producing hydrogen via electrolysis. The efficiency of the electrolysis is set to 71% (kWh_{H2}/kWh_{el}), in turn leading to losses of 29%. Compression at the distribution and fuel station levels causes the second largest position of losses or additional energy demand. At the distribution level, the hydrogen is compressed to a pressure of 500 bar to make it transportable using a gaseous trailer. At the fuel station, the hydrogen needs to be compressed up to 700 bar and requires pre-cooling to be filled into the vehicle tank. Some smaller losses also occur when transporting hydrogen via pipeline (both within and outside Europe), through the transmission of offshore electricity or related to storage. In the international scenario, the losses are slightly higher because there are some small additional losses from importing hydrogen via pipeline.

When comparing the WtW demand for the two 100% hydrogen scenarios, the WtW demand is lower for the 100% fuel cell scenario than for the 100% H2 combustion scenario. This is

[14] C.f. section 8.

driven by the lower TtW demand, as the final fuel demand in the fuel cell scenario is lower due to the higher efficiency of the FCEV.

Figure 32: Energy demand along the domestic FCEV fuel supply chain [Source: Frontier Economics].

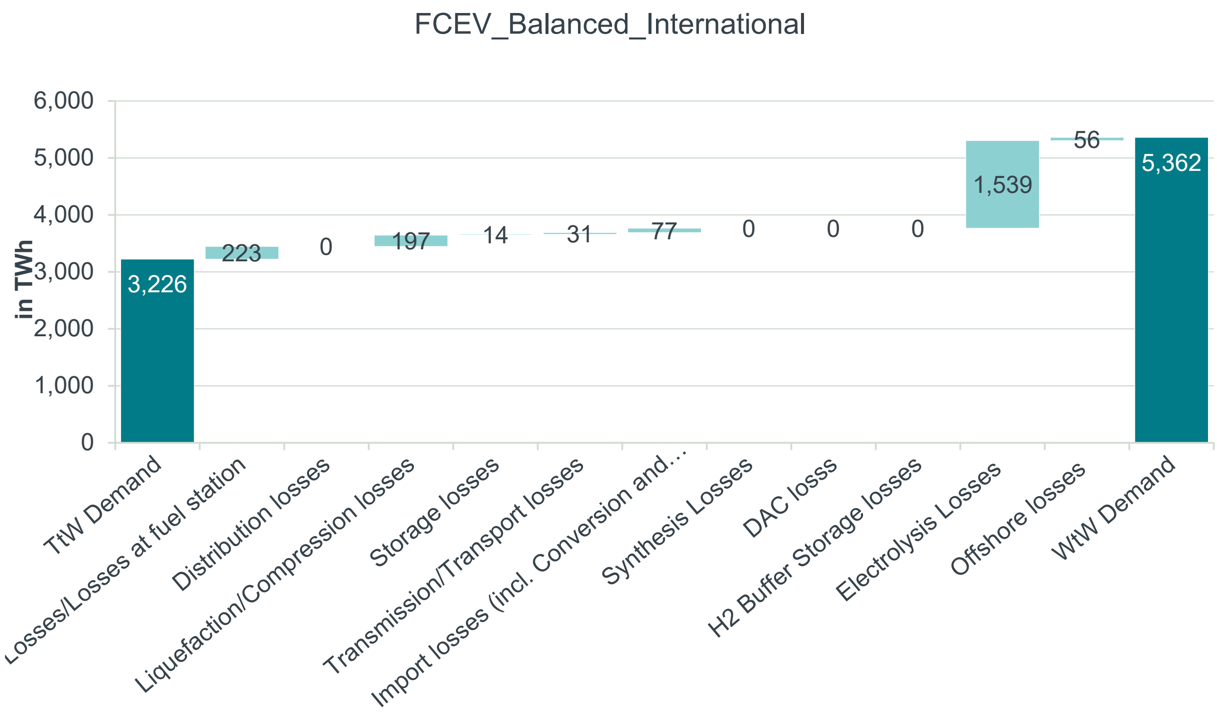


Figure 33: Energy demand along the international FCEV fuel supply chain [Source: Frontier Economics].

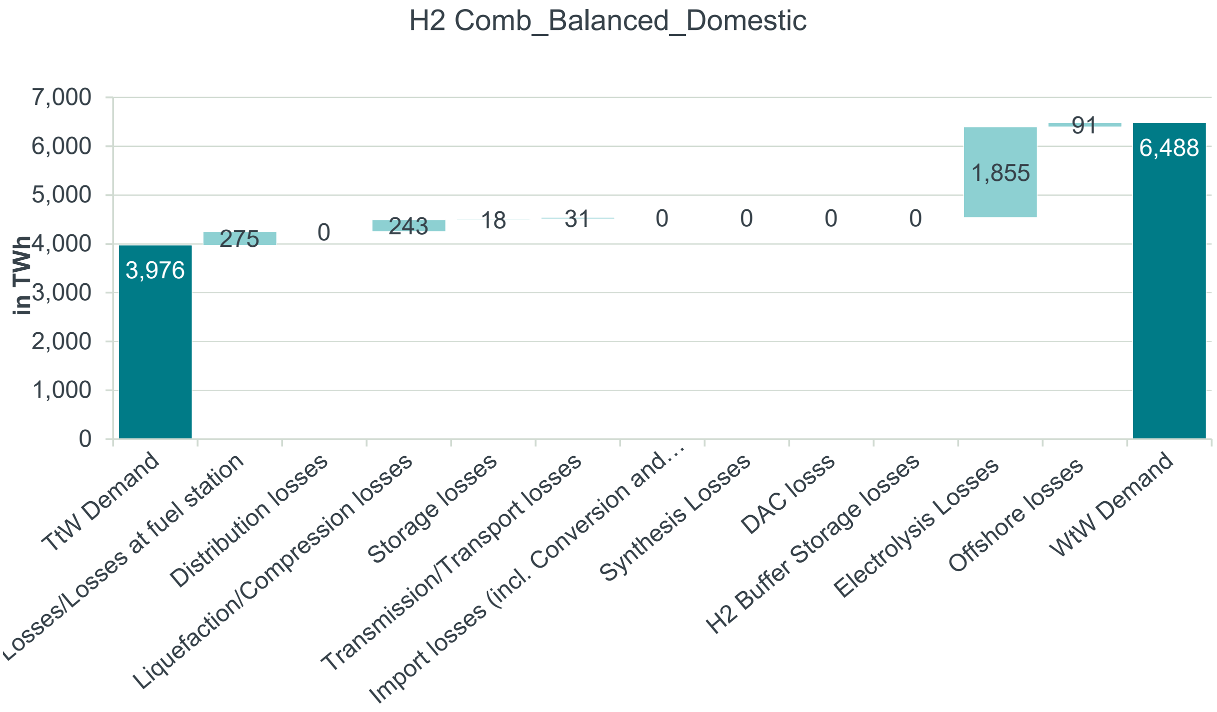


Figure 34: Energy demand along the domestic H2 Comb fuel supply chain [Source: Frontier Economics].

Figure 35: Energy demand along the international H2 Comb fuel supply chain [Source: Frontier Economics].

8.3.3 Fischer-Tropsch based Synthetic Fuels ("FT Fuel")

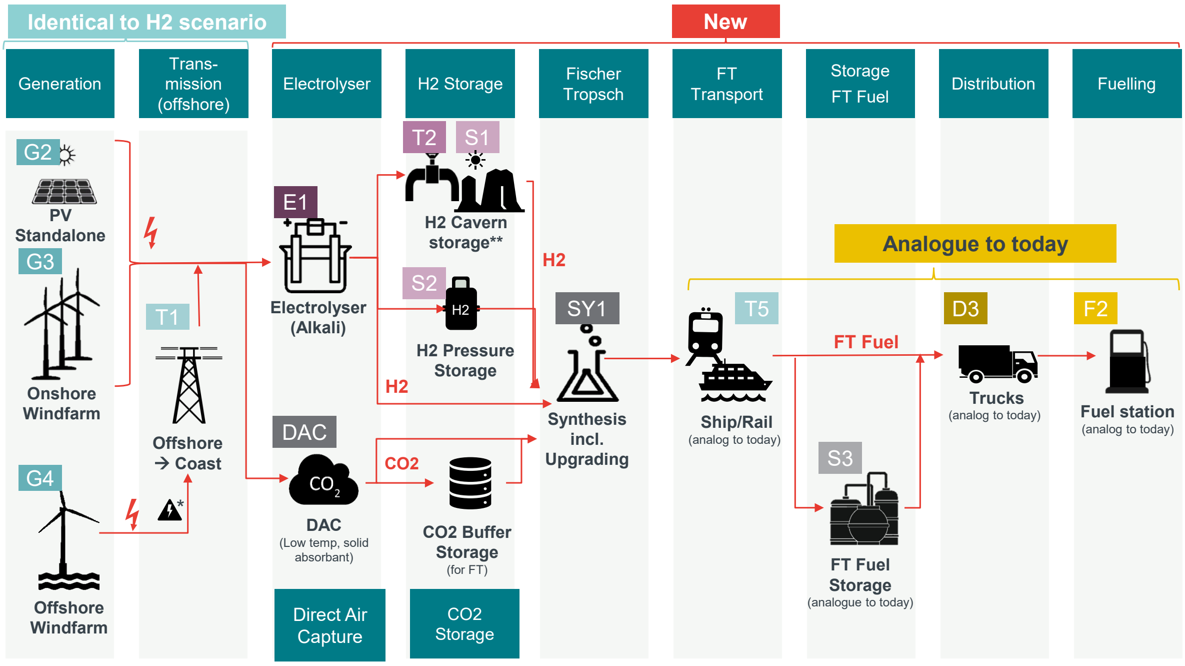


Figure 36: Schematic overview of the domestic FT Fuel supply chain [Source: Frontier Economics].

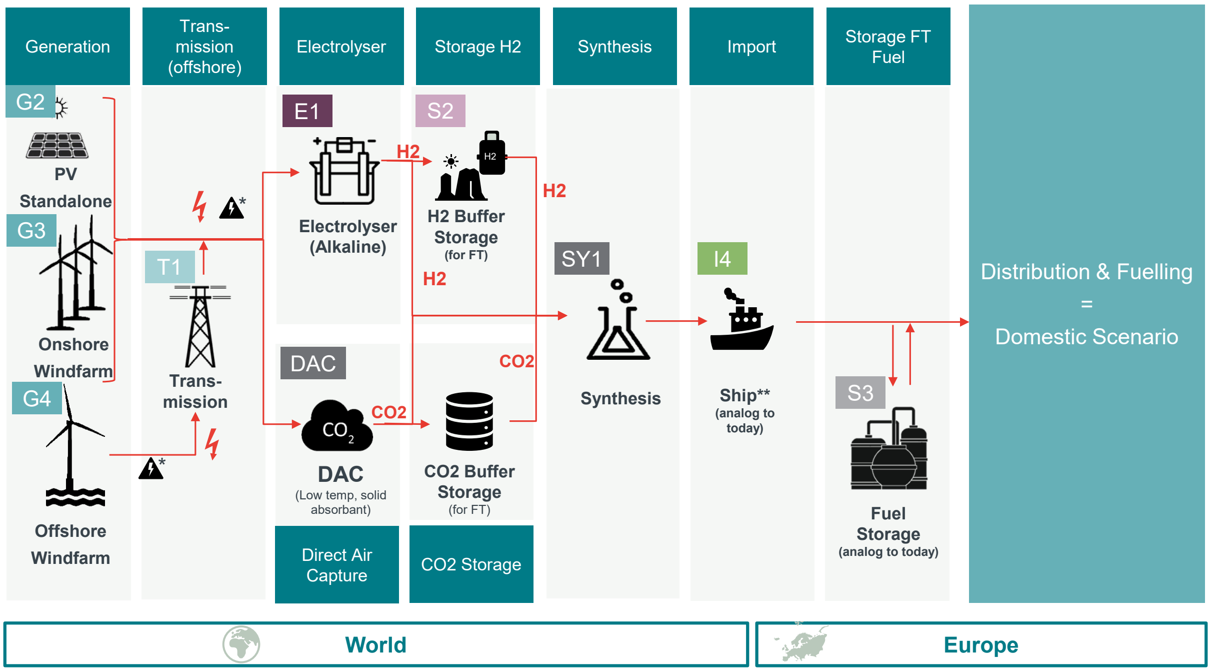


Figure 37: Schematic overview of the international FT Fuel supply chain [Source: Frontier Economics].

Overview – Figure 36 and Figure 37 show the underlying fuel supply chain for the Fischer Tropsch (FT) scenario. As FT fuel aims to replicate fossil diesel and gasoline, some elements of the existing infrastructure can be used, however, others need to be newly built.

Newly built – In Figure 36, the energy flow is depicted from left to right, starting with renewable energy generation via wind or PV. The energy will then be used to produce hydrogen via electrolysis. In parallel, renewable energy is used to capture CO_2 from the air. Both –hydrogen and CO_2 – are then used for FT synthesis to produce FT crude, which is finally upgraded to synthetic FT fuel (diesel, gasoline, kerosene, etc.). Both, electrolysis and direct air capturing, are only able to operate when energy is supplied. To avoid cost-intensive storage of electricity, we assume that both electrolysis and DAC are only in operation when renewable energy is supplied (discontinuous operation). The FT synthesis itself is ideally operated continuously due to their long start-up time, high energy expenses for the start-up and to achieve optimal utilization of the present capacities. Therefore, hydrogen and CO_2 buffer storage are included.

Existing infrastructure – Once the final fuel has been produced (following the upgrading process), the infrastructure is similar to today's one for fossil fuels. As the majority of vehicles today are fuelled by either diesel or gasoline, we assume that the entire infrastructure, from the fuel-transportation to the fuel station can be used for FT fuel, with minimal adjustments for fuel stations. The FT diesel and gasoline are transported across Europe by ship, pipelines, rail or trucks and stored in various locations, as today. To deliver the final fuel to the fuel station, the FT fuel will be transported by trucks. In the international scenario, the fuel supply chain is identical to the domestic one, aside from an additional import stage. Similarly to fossil crude today, fuel is assumed to be imported to Europe using large tanker ships. However, as for all other scenarios, we assume that only the final fuel will be imported, so that both the synthesis and the upgrading take place outside of Europe.

Key (technological) assumptions – As laid out before, some elements of the FT Fuel supply chain comply with the current infrastructure and can therefore be re-used. However, some elements, particularly related to the synthesis need to be either newly built or retrofitted.

- Electrolysis – As set out in section 8.2.2, hydrogen is required as a "raw material", making the build-up of electrolysis facilities necessary.
- Synthesis – FT Synthesis plants need to be built in large scale both in Europe and outside Europe (in the international scenario). We rely on the assumptions set out in the following Table 15. More detailed information on the production of FT Fuel is provided in section 10.2.1.3. and section 16.5.

Table 15: Technical Assumptions FT-Fuel Synthesis.

Parameter	**Value**
Efficiency (LHV: FT fuel/H2-Input)	68 % (excl. waste heat)
Utilization	8,000 FLH
Waste heat available	0.52 $kWh_{therm}/kWh_{FT\ fuel}$

[Source: Frontier Economics based on FVV Working group].

- DAC – The process is modelled as laid out in section 9.2.5 and 10.2.1.3. However, the specific CO_2 demand per kWh is different for each fuel and determined by the molecular structure. For FT Fuel, we assume that 3.14 kg CO_2 are required for 1 kg of FT Fuel (Liebich, et al., 2019).
- Transport – Utilizing the pre-existing infrastructure, we assume the final fuel will be transported via ship, rail or truck. These means of transportation do not cause any additional losses at this stage due to the liquid property of the fuel. The fuel demand from the road-tankers is already implicitly included in the total fuel demand.
- Central Fuel Storage – Similar to transportation, existing infrastructure can be used for the storage of the fuel and no additional losses occur at this stage.
- Distribution – Again, we assume that the fuel will be distributed to the fuel station like today's diesel/gasoline by trucks. Therefore, the existing infrastructure can be used entirely and no additional losses occur at this stage. The relevant fuel demand for the trucks is already implicitly included in the total fuel demand.

- Fuel stations – The study relies on the assumption that today's fuel stations can be adjusted to be suitable for FT fuel. As this is easily feasible, we assume that all of today's existing fuel stations will be adjusted for the use of FT fuel. It is assumed that the existing density of fuel stations will suffice also considering the increasing mobility demand.
- Import – Just as most of today's crude oil, we assume that the final fuel will be imported by ship. Existing vessels can be used entirely. The fuel demand required for this stage is explicitly considered, as the international transportation is not included in the Intra-European fuel demand (other than the transport and distribution stages). The different transport distance from MENA and "far off" locations is taken into account. For assumed distances see section 16.5.

Table 16: Fuel consumption for sea ships.

	2020	**2030**	**2050**
Consumption in kWh/tkm	0.016	0.014	0.012

[Source: ifeu calculations based on (EcoTranIT World, 2021), (DNV-GL, 2018) and (ICCT, 2020)].

Key Results – The final fuel demand (TtW) has previously been calculated[15] using the mobility demand and the fuel consumption. Based on the TtW demand, we then assess the total renewable energy (Well-To-Wheel (WtW) demand) that needs to be generated. The total generated energy depends not only on the final fuel demand, but also on the losses and additional energy demand that is required at each stage of the fuel supply chain. These losses add up to 55% (55%) of the WtW demand in the domestic (international) scenario in 2050.

The highest losses occur at the electrolysis stage, followed by the synthesis. These two processes are the main driver for the high losses along the FT fuel supply chain. Additional energy demand for direct air capturing accounts for the third largest position, but is significantly smaller than losses from electrolysis and synthesis. Losses at most other stages such as at fuel stations and hydrogen storage losses are negligibly small. Similarly, import losses in the international scenario only play a minor role.

[15] Cf. Section 8.

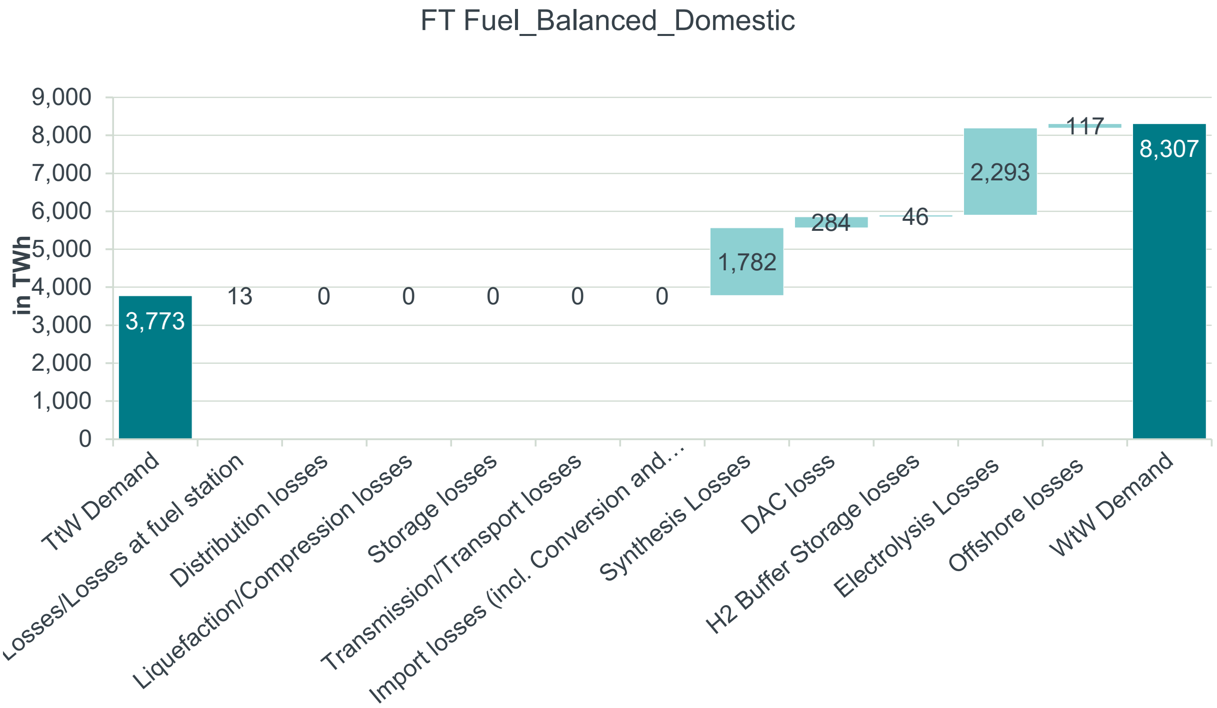


Figure 38: Energy demand along the domestic FT Fuel supply chain [Source: Frontier Economics].

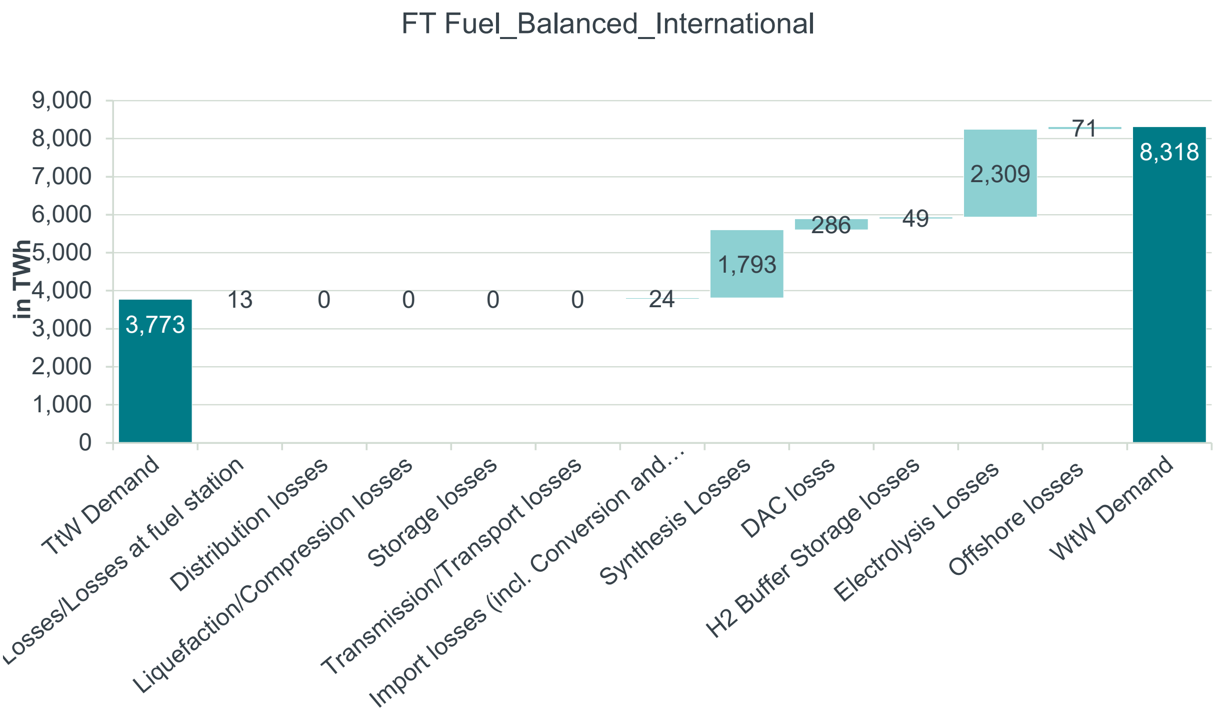


Figure 39: Energy demand along the international FT Fuel supply chain [Source: Frontier Economics].

8.3.4 Methane

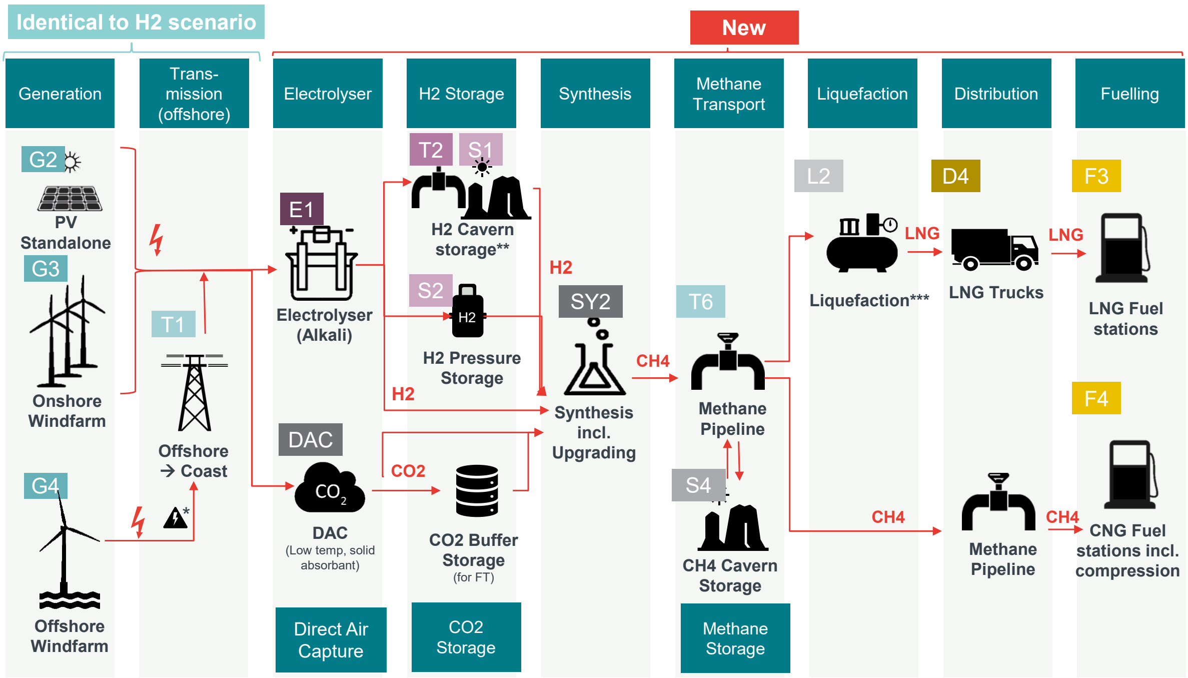
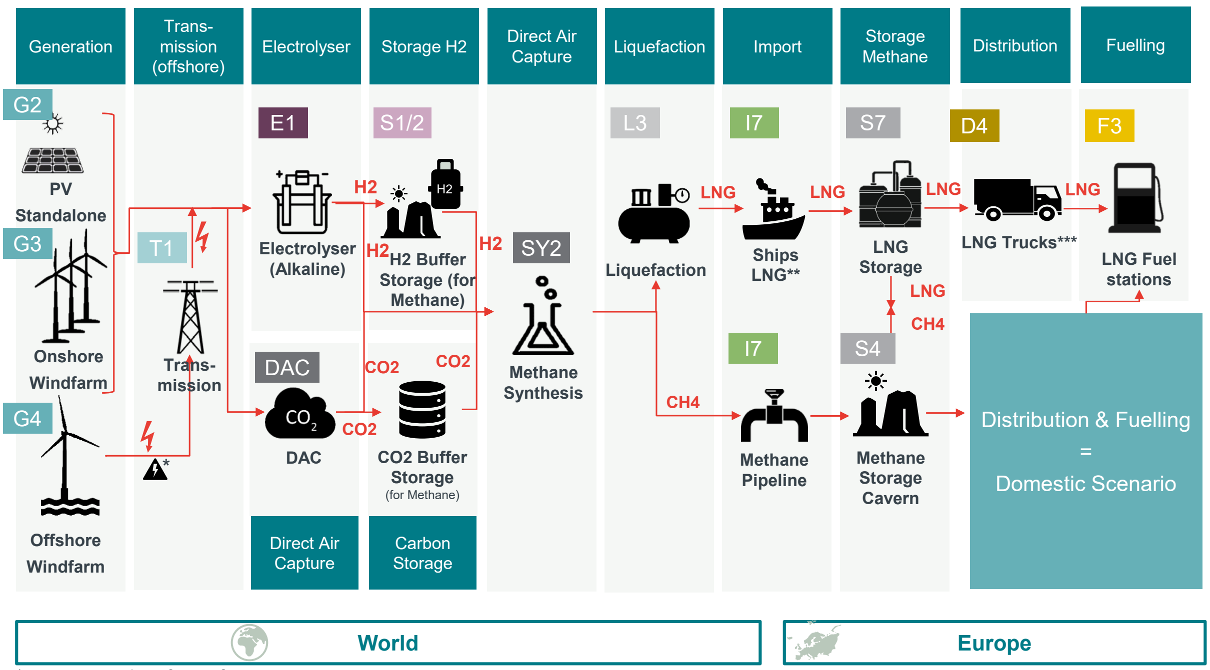


Figure 40: Schematic Overview of the domestic Methane fuel supply chain [Source: Frontier Economics].



* converter stations & transformers **including export storage ***longer distances compared to domestic scenario

Figure 41: Schematic Overview of the international Methane fuel supply chain [Source: Frontier Economics].

Overview – Figure 40 and Figure 41 show the underlying fuel supply chain for the Methane scenario. The energy flow is depicted from left to right, starting with renewable energy generation via wind or PV on the left side. Energy will then be converted to hydrogen by electrolysis. In parallel, renewable energy is used to capture CO_2 from the air. Both –hydrogen and CO_2 – are then used to produce synthetic Methane. As set out in section 8.3.3, electrolysis and direct air capturing are operated discontinuously to avoid cost intensive electricity storage, while the methane synthesis is laid out for continuous operation. As light duty vehicles are assumed to be fuelled with compressed natural gas (CNG) and heavy duty vehicles with Liquified Natural Gas (LNG), there are two different paths to be considered: the (i) CNG path and the (ii) LNG path.

Note that in the international scenario, 30% of the energy demand is still generated in Europe, while 35% will be imported from MENA and 35% will be imported from a "far off" location outside Europe. Pipelines will import the produced methane from MENA, while ships will import the methane from a far off location as LNG.

- CNG – Following the synthesis stage, Methane will be transported across Europe via pipelines . To allow for a continuous supply, gaseous Methane will be stored in caverns for both short and long term storage. Transmission pipelines are connected to the distribution pipelines, which are required to deliver the methane to the fuel stations. At the fuel station, the methane will then be compressed to be suitable for the vehicle tank. Apart from an additional stage for the fuel import, the fuel-paths are identical in the domestic and international scenario.
- LNG – In the domestic scenario, the LNG path is identical to CNG, up to the distribution stage. However, along the LNG path, the methane needs to be liquified, which is done in centralised distribution nodes across Europe.[16] The energy required for the liquefaction will be produced via a gas turbine allowing the liquefaction plant to operate continuously. Following liquefaction, the LNG will be distributed to the fuel stations via trucks. The international scenario deviates slightly. The share of Methane which is produced in "far off" locations where import via pipeline is not feasible (such as Patagonia), is imported by ship as LNG. Once the LNG ship arrives in Europe, the LNG will be transported and distributed to the fuel stations via trucks. Where necessary, we model storage in tanks in liquefied form. Already liquefied methane will not be re-converted back to gaseous Methane, as it can directly be used for the heavy duty segment and conversion to gaseous methane for the purpose of transmission and storage with subsequent liquefaction leads to significant inefficiencies As the demand for LNG is at least as high as the imported LNG, no regasification plants (for the transport sector) are required.

Key (technological) assumptions – As Methane (in the form of natural gas) is relevant and utilized in large scale for other sectors today, some elements of the infrastructure are already established. This relates particularly to transportation, distribution and storage. However, only a share of the existing infrastructure can be used for the mobility sector. Other than in the FT Fuel scenario, the existing infrastructure today is not mainly dedicated to the mobility sector but rather required by other sectors, such as the heating sector or different industries. As the methane utilized today has a fossil origin, new stages along the fuel supply chains need to be built to produce carbon neutral methane from green hydrogen.

- Electrolysis – As set out in section 9.2.2, hydrogen is required as a "raw material", making the build-up of electrolysis facilities necessary.
- Synthesis – Methanation plants need to be built in large scale, both in Europe (domestic scenario) and outside Europe (international scenario). We rely on the assumptions set out in the following Table 17. More detailed information on the production of Methane is provided in section 10.2.1.3 and section 16.5.

[16] The alternative would be to model decentralised liquefaction at fuel stations, which may simplify the transportation stage but leads to significant efficiency losses (due to lost economies of scale) and is therefore not considered.

Table 17: Technical Assumptions Methanation.

Parameter	**Value**
Efficiency (LHV: CH4/H2)	83 %
Utilization	8000 FLH
Waste heat available	0.19 kWh_{therm}/kWh_{CH4}

[Source: Frontier Economics based on FVV Working group].

- DAC –The process is modelled as laid out in section 9.2.5 and 10.2.1.3. However, the specific CO_2 demand per kWh is different for each fuel and determined by the molecular structure. For Methane 2.67 kg CO_2 are required for 1 kg of Methane (Liebich, et al., 2019).
- Transport – Transmission pipelines will transport Methane from the production locations across Europe. As previously set out, there is an extensive existing methane grid today. However, since the future of fossil methane is quite unclear, we assume that the mobility sector can only use a share of the existing pipelines and compressor stations. We assume that 20% of the required methane pipelines in the 100% methane scenario need to be newly built, while for the remaining 80% existing pipelines and compressors can be used. In the international scenario when LNG is imported via ship, trucks will transport the LNG within Europe rather than of pipelines.

Table 18: Methane transmission pipelines.

Average Capacity of line	**Compressor capacity**	**Transmission losses***
18 GW	89 MW(el)/1000 km]	0.004%

*Note: *Losses do not refer to compression losses but to methane slip [Source: Frontier Economics based on FVV Working Group, Frontier Calculations based on* (FNB Gas, 2019) *and* (European Commission, 2020)*].*

- Liquefaction – As the study considers LNG as the fuel for vehicles in the heavy duty segment, liquefaction is required for the LNG path. We take into account the additional energy required for the liquefaction process. Liquefaction takes place in numerous centralized locations ahead of the distribution to the fuel stations. For more details see section 16.5.
- Central Fuel Storage Domestic – In the domestic scenario, gaseous Methane will be stored in caverns. In the international scenario, additional LNG storage for the imported LNG is required to avoid regasification of imported LNG. For more details see section 16.5.
- Distribution – For the distribution stage, differentiation between (i) the gaseous path and (ii) the liquefied path of methane is necessary. Along the gaseous path, the methane will be distributed to the fuel stations by a distribution pipeline. Along the LNG path, LNG trucks will cover the “last mile” from liquefaction to the fuel station. To assess the size of the distribution network, we assumed that 50% of the fuel stations can make use of existing methane distribution pipelines while the remaining 50% of the fuel stations require an additional expansion of the distribution grid with an average distance of 5 km.
- Fuel stations – Some fuel stations today already include pumps for CNG and/or LNG. The existing CNG/LNG pumps are considered in this study – in particular 3,926 CNG (passenger) pumps and 360 LNG (truck) pumps (Frontier calculations based on (Forschungsvereinigung Verbrennungskraftmaschinen, 2018)).

However, to ensure a comprehensive distribution of fuel stations, new pumps and fuel stations need to be built across the EU. The total number of fuel stations and pumps for a 100% scenario is determined as set out in section 8.2.6. It is assumed that 0.5% kWh/kWh(CH4) energy is required to compress the Methane at the fuel stations (Forschungsvereinigung Verbrennungskraftmaschinen, 2018).

- Import – Methane will be imported either by pipeline from nearby locations or by ship (as LNG) from a far off location. We do not consider the use of existing infrastructure for import purposes. The fuel demand required for this stage is explicitly considered here, as international transportation is not included in the Intra-European fuel demand. The technical requirements for each are set out in Table 19. In the far off location, we assume a LNG storage facility at the export terminal to allow for short term storage. For assumed shipping distances see section 16.5.1.

Table 19: Technical assumptions Methane import.

	Capacity	**Compressor capacity**	**Average distance per line or ship**
Import pipeline	34 GW	150 MW/1000km	1,500 km
LNG Ship	170,000 m^3	n/a	15,000 km

[Source: Frontier Economics based on existing projects, (International Gas Union, 2020) and see details in section 16.5.1].

Table 20: Fuel consumption for LNG sea ships.

	2020	**2030**	**2050**
Consumption in kWh/tkm	0.029	0.025	0.017

[Source: ifeu calculations based on (EcoTranIT World, 2021), (DNV-GL, 2018) and (ICCT, 2020)].

Key Results – The final fuel demand (TtW) has previously been calculated by using the mobility demand and the fuel efficiencies. Based on the TtW demand, we then assess the total renewable energy (Well-To-Wheel (WtW) Demand) that needs to be generated. The total generated energy depends not only on the final fuel demand but also on the losses and additional energy demand that is required at each stage of the fuel supply chain. These losses add up to 47% (49%) of the WtW Demand in the domestic (international) scenario in 2050.

As for FT fuel, the highest losses occur at the electrolysis stage, followed by the synthesis. The two processes are the main driver for the high losses along the Methane fuel supply chain. Direct air capturing forms the third largest position but compared to electrolysis and synthesis, the losses are of subordinate importance. Other losses, such as those caused by offshore-transmission and liquefaction also have a small impact. General transmission, distribution and storage only add negligibly small losses. In the international scenario, import losses only play a minor role, however they cause the domestic scenario to be slightly more efficient overall.

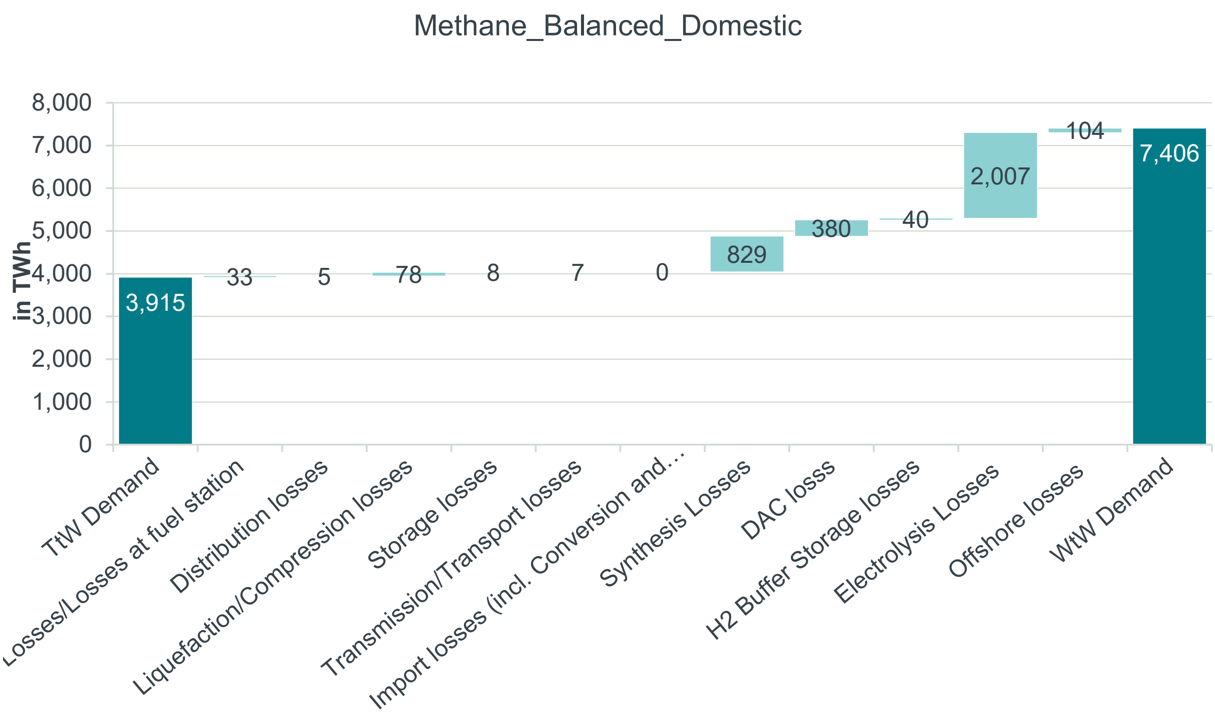


Figure 42: Energy demand along the domestic Methane fuel supply chain [Source: Frontier Economics].

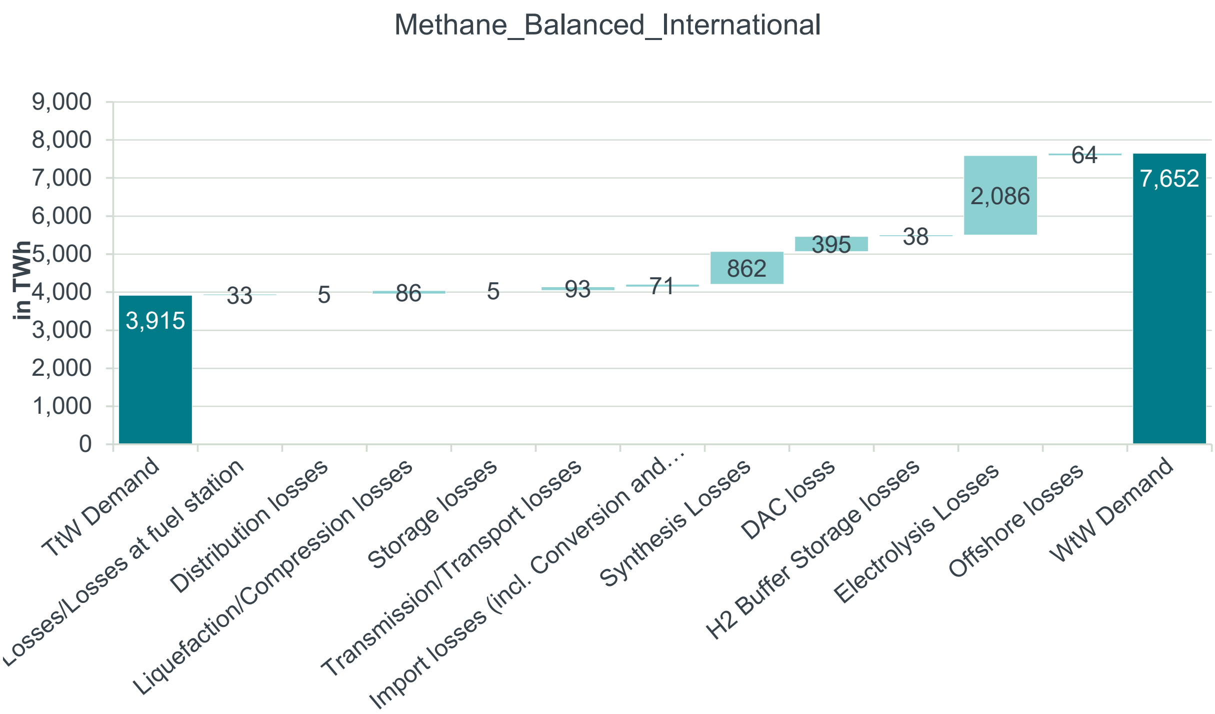


Figure 43: Energy demand along the international Methane fuel supply chain [Source: Frontier Economics].

8.3.5 Methanol ("MeOH")

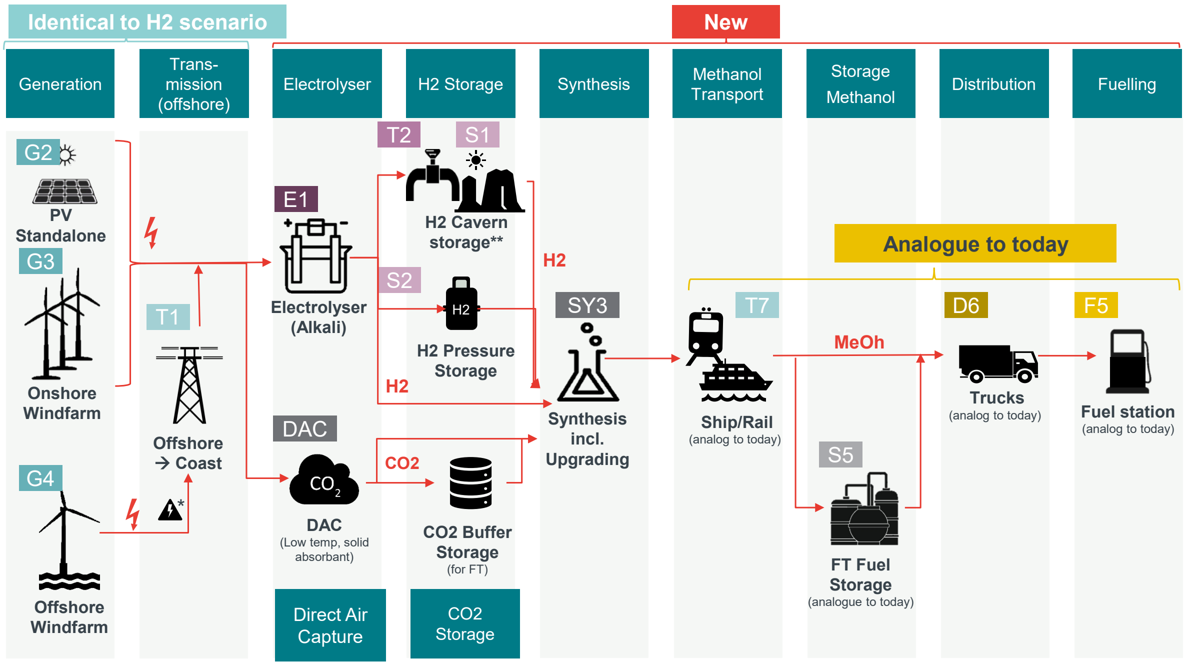


Figure 44: Schematic Overview domestic MeOH fuel supply chain [Source: Frontier Economics].

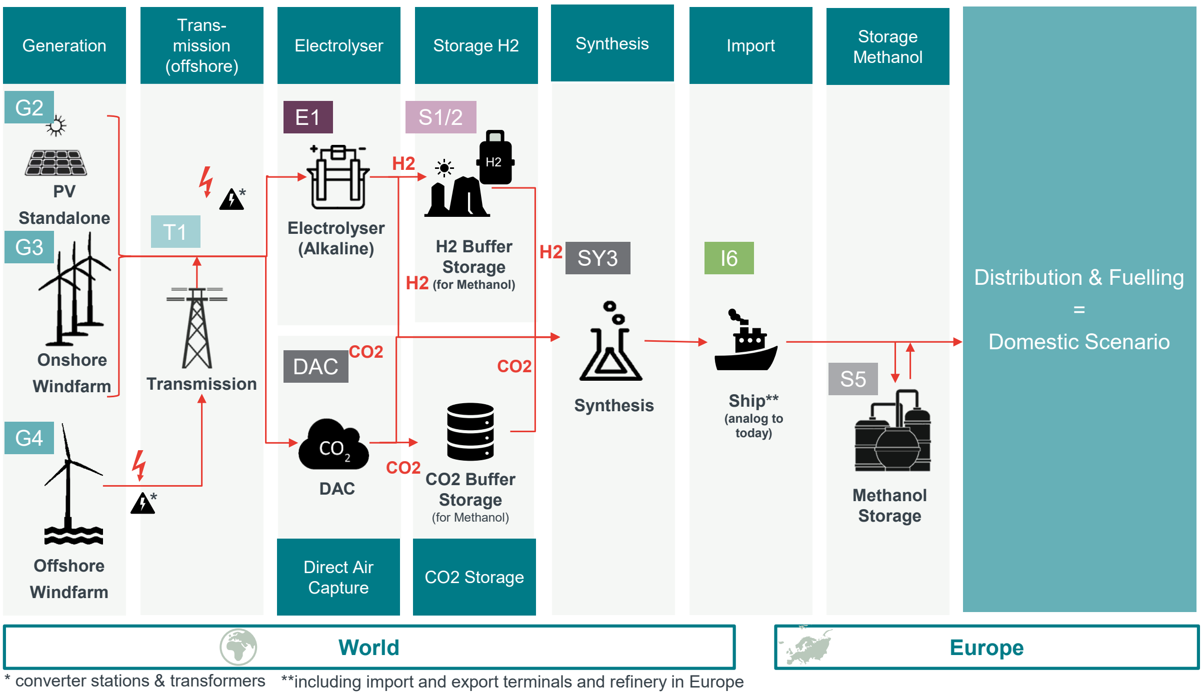


Figure 45: Schematic Overview international MeOH fuel supply chain [Source: Frontier Economics].

Overview - Figure 44 and Figure 45 show the underlying fuel supply chain for the MeOH scenario. As MeOH is a liquid fuel and somehow similar in handling to today's diesel or gasoline, some of the existing infrastructure can be used while most of it needs to be newly built.

Newly built – In Figure 44, the energy flow is depicted from left to right, starting with renewable energy generation via wind or PV. The energy is then used to produce hydrogen via electrolysis. In parallel, renewable energy is used to capture CO_2 from the air. Both – hydrogen and CO_2 – are then used for MeOH synthesis, including distillation and upgrading. Electrolysis and direct air capturing are only able to operate when energy is supplied (discontinuous operation). The MeOH Synthesis itself is ideally operated continuously, which is why hydrogen and CO_2 buffer storages are included.

Existing infrastructure – Once the final fuel has been produced, the required infrastructure is similar to what is currently in use for today's liquid fuels. As the majority of vehicles today are fuelled by either diesel or gasoline, it is assumed that the complete infrastructure from transport to fuel station can easily be adjusted for MeOH with only minor adaptations. The MeOH is transported across Europe by ship, rail or trucks and stored in various locations, similarly to gasoline/diesel today. To deliver the final fuel to the fuel station, the MeOH will be transported by trucks. In the international scenario, the fuel supply chain is identical to the domestic one, aside from an additional import stage. MeOH is imported to Europe using large tanker ships. However, as for all other scenarios, we assume that only the final fuel will be imported, so that both the synthesis and the upgrading take place outside of Europe.

Key (technological) assumptions – As for the FT and Methane scenario, some elements of the existing infrastructure can either directly be used or retrofitted to be used in the MeOH scenario. Nevertheless, certain stages need to be newly built.

- Electrolysis – As set out in section 9.2.2, hydrogen is required as a "raw material", making the build-up of electrolysis facilities necessary.
- Synthesis – MeOH Synthesis plants need to be built in large scale in Europe (and outside Europe in the international scenario). We rely on the assumptions set out in the following Table 21. More detailed information on the production of Methanol is provided in section 10.2.1.3 and section 16.5.

Table 21: Technological characteristics of MeOH synthesis.

Parameter	**Value**
Efficiency (LHV: MeOH/H2-Input)	86 %
Utilization	8000 FLH
Waste heat available	0.18 kWh_{therm}/kWh_{MeOH}

[Source: FVV Working Group].

- DAC – The process is modelled as laid out in section 9.2.5 and 10.2.1.3. However, the specific CO_2 demand per kWh is different for each fuel and determined by the molecular structure. For MeOH, 1.37 kg CO_2 are required for 1kg of MeOH (FVV working group).
- Transport, Central Fuel Storage and Distribution – Due to the comparable properties of MeOH and FT Fuel (particularly both being liquid fuels), transport, fuel storage and distribution of MeOH are modelled analogue to FT Fuel, as set out in section 8.3.3.
- Fuel stations – We assume that existing diesel and gasoline pumps can be retrofitted to be suitable for MeOH. The total number of fuel stations (and pumps) which need to be retrofitted to ensure a comprehensive distribution of fuel stations is set out in the section 8.2.6 and similar to the other fuels considered in this study.

- Import – Again, due to the similar properties, the import of MeOH is modelled analogue to FT Fuel. The specific fuel consumption of the import ships is adjusted to MeOH as fuel and modelled as set out in Table 22. For assumed distances see section 16.5.

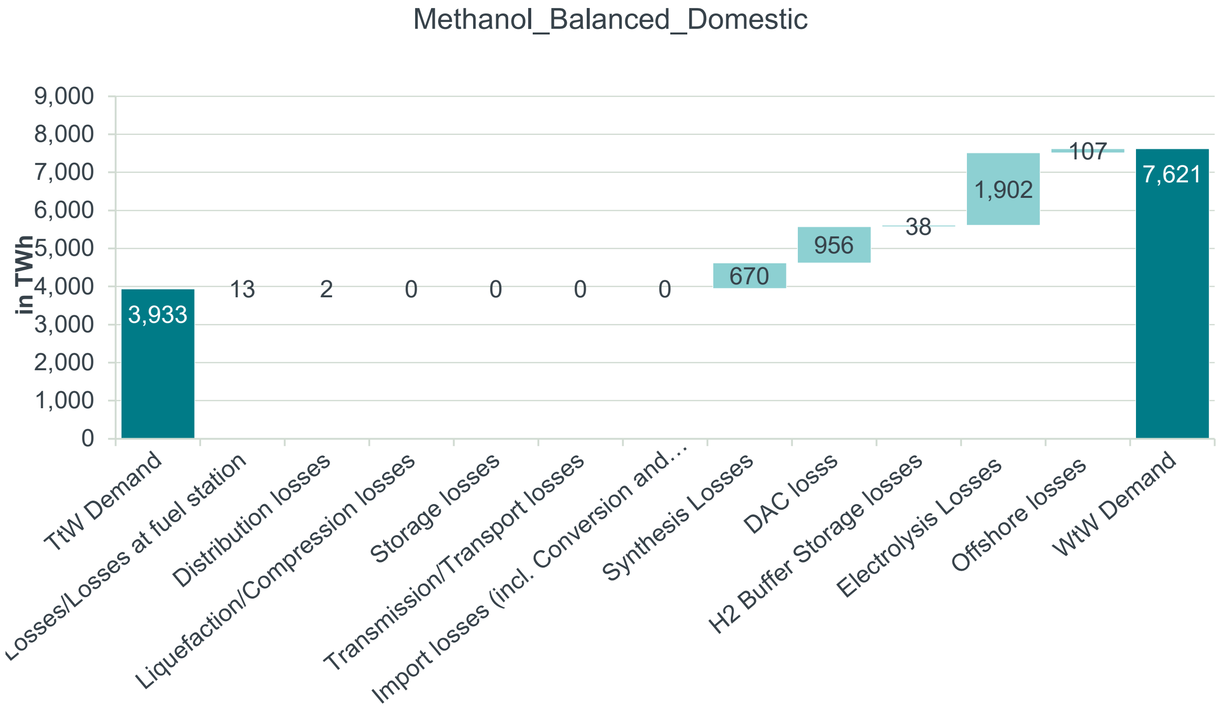
Table 22: Fuel consumption for sea ships.

	2020	2030	2050
Consumption in kWh/tkm	0.016	0.014	0.012

[Source: ifeu calculations based on (EcoTranIT World, 2021), (DNV-GL, 2018) and (ICCT, 2020)].

Key Results – The final fuel demand (TtW) has previously been calculated using the mobility demand and the fuel efficiencies. Based on the TtW demand, we then assess the total renewable energy (Well-To-Wheel (WtW) Demand) that needs to be generated. The total generated energy depends not only on the final fuel demand, but also on the losses and additional energy demand that is required at each stage of the fuel supply chain. These losses add up to 48% (49%) of the WtW demand in the domestic (international) scenario in 2050.

The highest losses occur at the electrolysis stage, followed by the energy demand for capturing CO_2 from the air and MeOH synthesis. Losses at most other stages such as at fuel stations, hydrogen storage losses and offshore losses are negligible small. Import losses also only play a minor role.



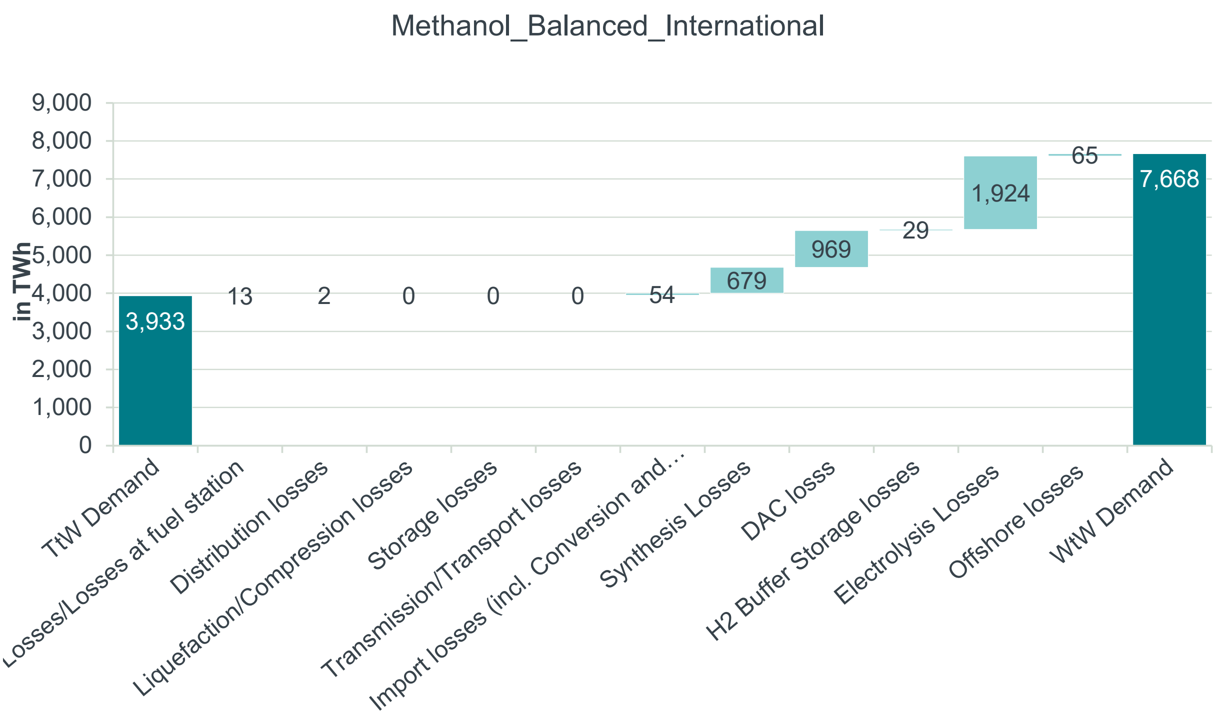


Figure 47: Energy demand along the international MeOH fuel supply chain [Source: Frontier Economics].

8.3.6 Dimethyl ether ("DME")

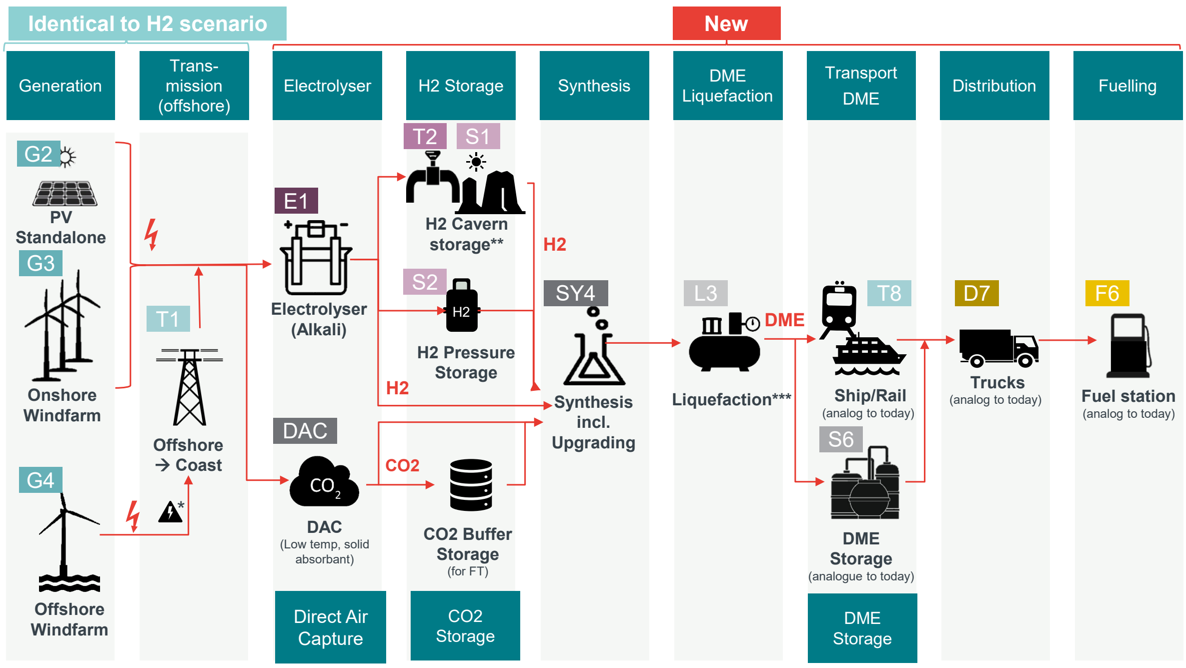


Figure 48: Schematic Overview domestic DME fuel supply chain [Source: Frontier Economics].

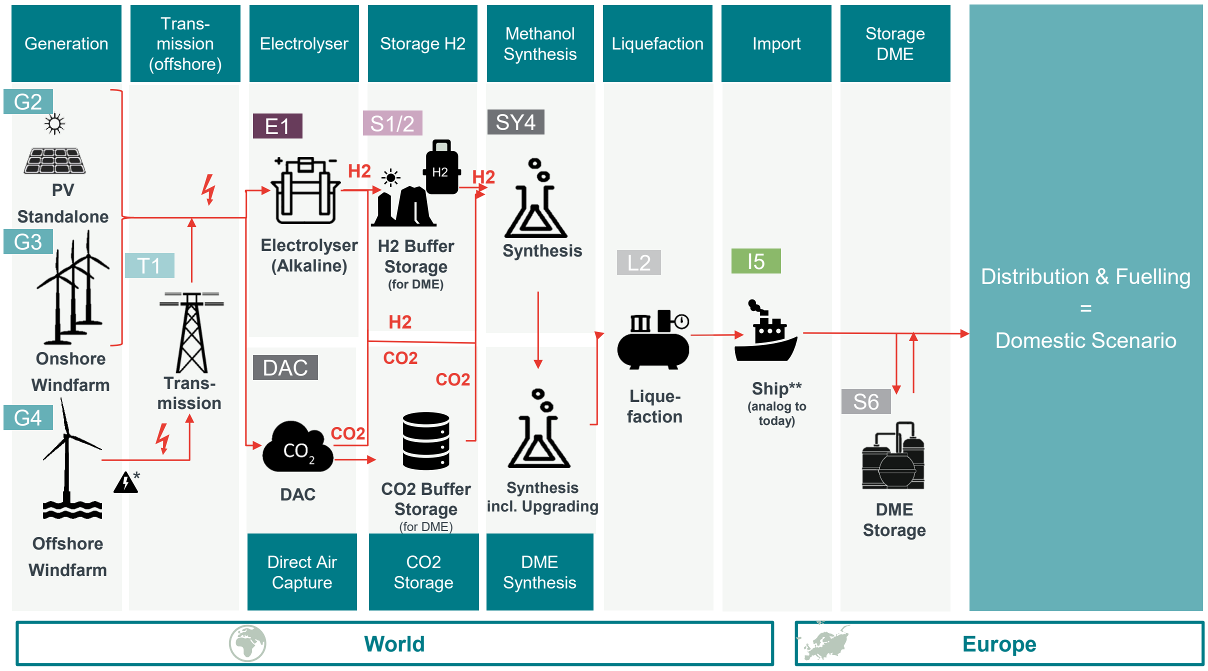


Figure 49: Schematic Overview international DME fuel supply chain [Source: Frontier Economics].

Overview –Figure 48 and Figure 49 show the underlying fuel supply chain for the DME scenario. While DME is gaseous under normal conditions, it can easily be liquefied. This allows for the further utilisation of some elements of existing infrastructure for liquid fuels. However, the majority needs to be newly built as DME is not commonly used in any sector yet.

<u>Newly built</u> – The energy flow is depicted from left to right, starting with renewable energy generation via wind or PV. The energy is then used to produce hydrogen via electrolysis. In parallel, renewable energy is used to capture CO_2 from the air. Both –hydrogen and CO_2 – are then used for DME synthesis including upgrading. As set out in section 8.3.3, electrolysis and direct air capturing are operated discontinuously to avoid cost intensive electricity storage, while the DME synthesis is laid out for continuous operation. After the synthesis and upgrading, DME needs to be liquified to be used in vehicle tanks.

<u>Existing infrastructure</u> – Following the liquefaction, the infrastructure requirements are similar to today, allowing for further use of existing infrastructure. We assume that the infrastructure elements from transport to fuel station can be retrofitted to be suitable for DME, with small adjustments. DME is transported across Europe by ship or rail and stored in various locations. To deliver the final fuel to the fuel station, the DME will be transported by trucks. In the international scenario, the fuel supply chain is identical to the domestic one, aside from an additional import stage. Ships will import the final fuel from outside Europe similar to today.

Key (technological) assumptions – As for the FT, Methane and MeOH scenario, some elements of the existing infrastructure can either directly be used or retrofitted to be used for the DME scenario. Nevertheless, certain stages need to be newly build.

- <u>Electrolysis</u> – As set out in section 9.2.2, hydrogen is required as a “raw material”, making the build-up of electrolysis facilities necessary.

- <u>Synthesis</u> – DME synthesis plants need to be built in large scale in Europe (and outside Europe in the international scenario). We have assumed a two-step synthesis of DME via Methanol. We rely on the assumptions set out in the following Table 23. More detailed information on the production of DME are described in section 10.2.1.3 and section 16.5 .

Table 23: Technological characteristics of DME synthesis.

Parameter	**Value**
Efficiency (LHV: DME/H2-Input)	77 %
Utilization	7884 FLH
Waste heat available	0.048 kWh_{therm}/kWh_{DME}

[Source: Frontier Economics based on FVV Working Group].

- DAC – The process is modelled as laid out in section 8.2.5 and 10.2.1.3. However, the specific CO_2 demand is different for each fuel and determined by the molecular structure. For DME, 1.911 kg CO_2 are required for 1kg of DME (FVV Working Group).
- Liquefaction – We take into account the additional energy required for the liquefaction process by modelling gas turbines located near the liquefaction plants to produce the required electricity. DME will be liquified immediately after the upgrading process. For more details see section 16.5.
- Transport – We assume that once liquefied, the fuel will be transported via ship, rail or truck, allowing for utilization of existing infrastructure. These means of transportation do not cause any additional losses at this stage due to the liquid property of the fuel. The relevant fuel demand for the trucks is already implicitly included in the total fuel demand.
- Central Fuel Storage – Similarly to transportation, existing infrastructure can be used for the storage of the fuel and no additional losses occur at this stage.
- Distribution – Again, we assume that the fuel will be distributed to the fuel station as today's diesel/gasoline by trucks. Therefore, the existing infrastructure can be used entirely and no additional losses occur at this stage. The relevant fuel demand for the trucks is implicitly already included in the total fuel demand.
- Fuel stations – We assume that new fuel stations including pumps need to be built dieselgasolineto be suitable for DME. The total number of fuel stations (and pumps) which need to be built to ensure a comprehensive distribution of fuel stations is set out in section 8.2.6 and similar to most other fuels considered in this study.
- Import Ship – Due to the comparable properties, we assume that similar to LPG today, DME is imported by ship. The fuel demand required for this stage is explicitly considered here as the international transportation is not included in the intra-European fuel demand (which is different from transport and distribution stage). The different transport distance from MENA and far off locations is taken into account. Each ship is modelled with a capacity of 200,000 t. For assumed distances see section 16.5.1.

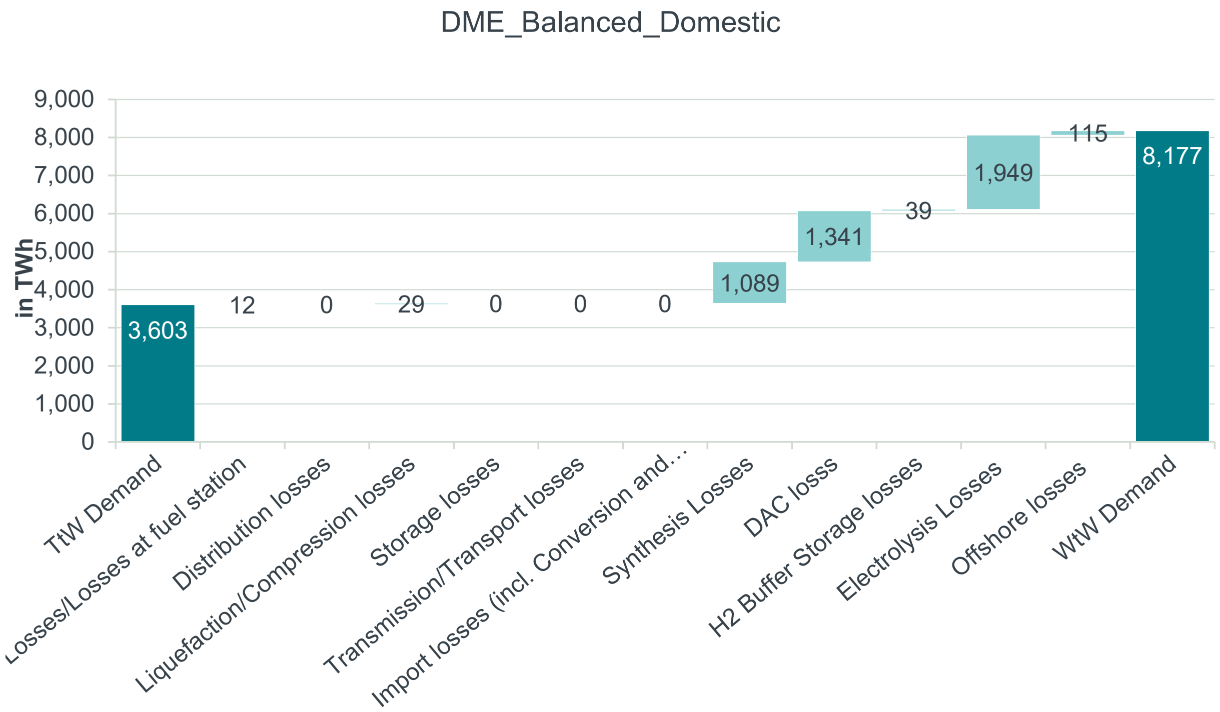
Table 24: Fuel consumption for sea ships.

	2020	**2030**	**2050**
Consumption in kWh/tkm	0.016	0.014	0.012

[Source: ifeu calculations based on (EcoTranIT World, 2021), (DNV-GL, 2018) and (ICCT, 2020)].

Key Results – The final fuel demand (TtW) has previously been calculated using the mobility demand and the fuel efficiencies.[17] Based on the TtW demand, we then assess the total renewable energy (Well-To-Wheel (WtW) demand) that needs to be generated. The total generated energy depends not only on the final fuel demand but also on the losses and additional energy demand that is required at each stage of the fuel supply chain. These losses add up to 56% (56%) of the WtW Demand in the domestic (international) scenario in 2050.

The highest losses occur at the electrolysis stage, followed by the energy demand for capturing CO_2 from the air and the DME synthesis. Losses at most other stages such as at fuel stations, hydrogen storage losses and offshore losses are negligible small. Import losses only play a minor role.



[17] Cf. Section 8.

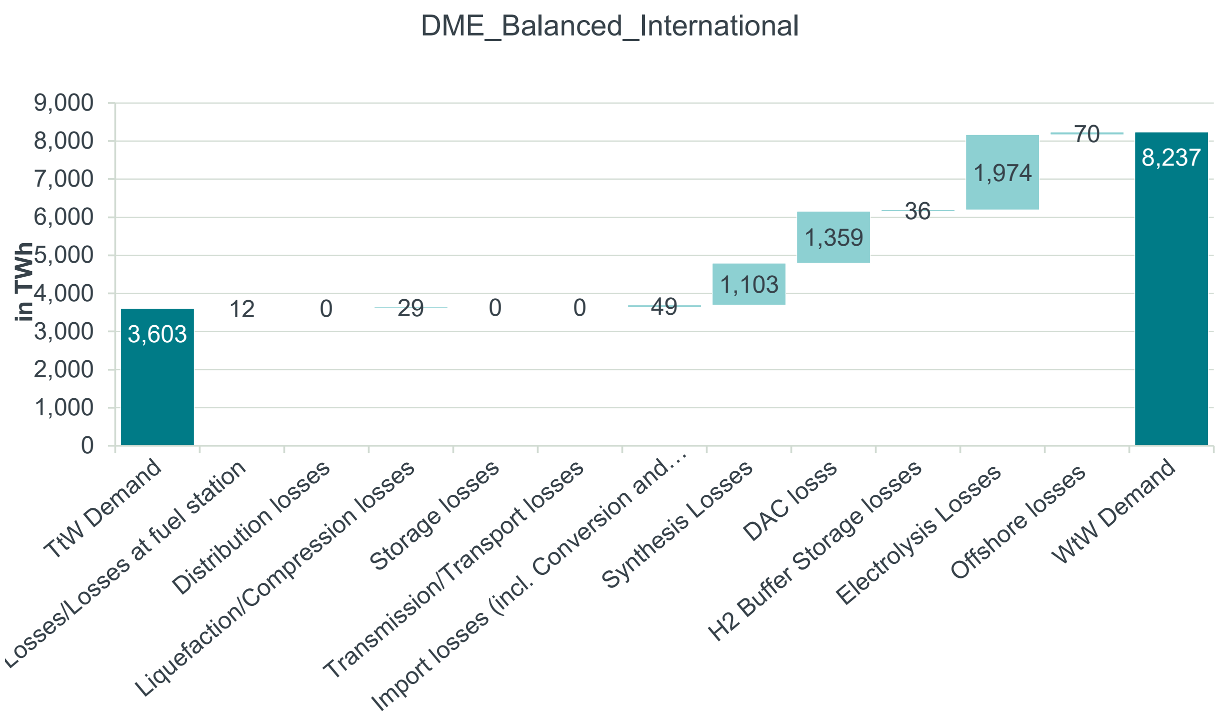


Figure 51: Energy demand along the international DME fuel supply chain [Source: Frontier Economics].

9 Comparison of Energy Supply Chains for Road Segment

In this section, we summarize the key quantitative results of our analysis and compare the 42 different drivetrain / fuel supply chain combinations with regard to

- The WtW energy demand in 2050 (see section 9.1) and
- The corresponding required capacity requirements in 2050 (see section 9.2).

Based on the results from this section, we then proceed to assess the environmental impacts (see section 10) and the required raw materials (see section 11) and finally the total costs of each option (see section 12).

As previously set out in section 7, the total fuel demand for non-road sectors is rather small and not all fuels are applicable to rail, aviation and shipping. The results of the WtW energy demand as well as for capacities are thus presented in detail for the road sector, however a brief overview for the other sectors (aviation, rail, shipping) is presented at the end of each section.

9.1 WtW Energy Demand in 2050

Based on the final energy requirements of the fleet as modelled in section 7 ("Tank to wheel" - TtW) and the conversion losses along the fuel supply chain as laid out in section 8 we can compare the total primary energy requirements ("Well to wheel" - WtW) for the different drivetrain options. Figure 52 shows WtW and TtW energy requirements for all 42 fuel supply chain side by side.

We thereby focus on the road segment as it has by far the highest fuel demand and is therefore investigated in more depth. Most results of the other segments (aviation, rail, shipping) are in line with those of the road sector. Note that the findings for the other segments are primarily of indicative character, as certain sector specific stages are not fully covered in the more high-level approach applied for these other sectors. Nevertheless, we briefly show the results for rail, aviation and shipping at the end of each section.

Road

It is striking that, although the TtW demand accounts for a significant share of the WtW demand for each fuel, it is not the main driver for all fuels. Losses and additional energy demand along the fuel supply chain can have a significant impact on the WtW demand, which affects the required infrastructure. The 100% scenario with the lowest or highest fuel demand does not necessarily end up with the lowest or highest WtW energy demand. For example, the TtW demand for FT Fuel is lower than the one for H2 combustion but has a much higher WtW demand. Figure 53 therefore shows the key differences between TtW and WtW demand for each fuel exemplary for the balanced scenario in 2050, reflecting all losses along the fuel supply chain.

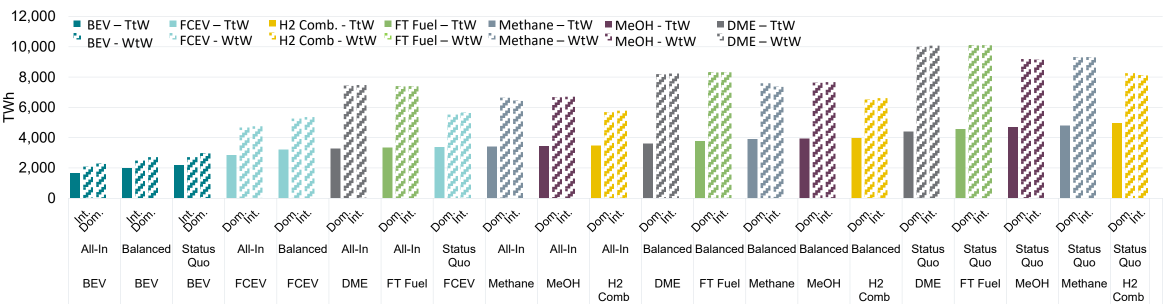


Figure 52: WtW and TtW Demand for all fuels for the domestic and international balanced scenarios [Source: Frontier Economics]. Note: Ranked by TtW demand.

Aside from the TtW energy demand, electrolysis and the associated conversion losses are a main driver of the WtW demand for all fuels.[18] Although electrolysis reaches an efficiency of 71% by 2050, the losses at this stage remain significant. Losses occurring for synthesis and DAC also have a meaningful impact for all considered synthetic fuels – FT Fuel, Methane, MeOH and DME. The shares of the losses for synthesis and DAC vary between the different synthetic fuels. This result is driven by three factors. First, the efficiencies of the different synthesis processes vary from fuel to fuel. While MeOH synthesis is the most efficient at 86%, FT synthesis is the least efficient at 68%. Second, all synthetic fuels have a different CO2 demand. FT fuel has the highest CO2 demand with 3.14 $kg_{CO2}/kg_{FT\ Fuel}$, while MeOH has the lowest with 1.37 kg_{CO2}/kg_{MeOH}. Third, each synthesis produces a different amount of waste heat that can be used for capturing CO2. DAC requires thermal energy for capturing CO2. If the waste heat of the synthesis does not suffice, additional thermal energy needs to be generated, increasing the WtW demand. For the hydrogen scenarios, compression losses at fuel stations and for distribution account for additional but relatively small losses. All other stages of the fuel supply chains generate only minor or no losses. Comparing the international and the domestic scenarios, the WtW demand looks similar for both across all technology scenarios. Import losses are of minor importance across all fuels.

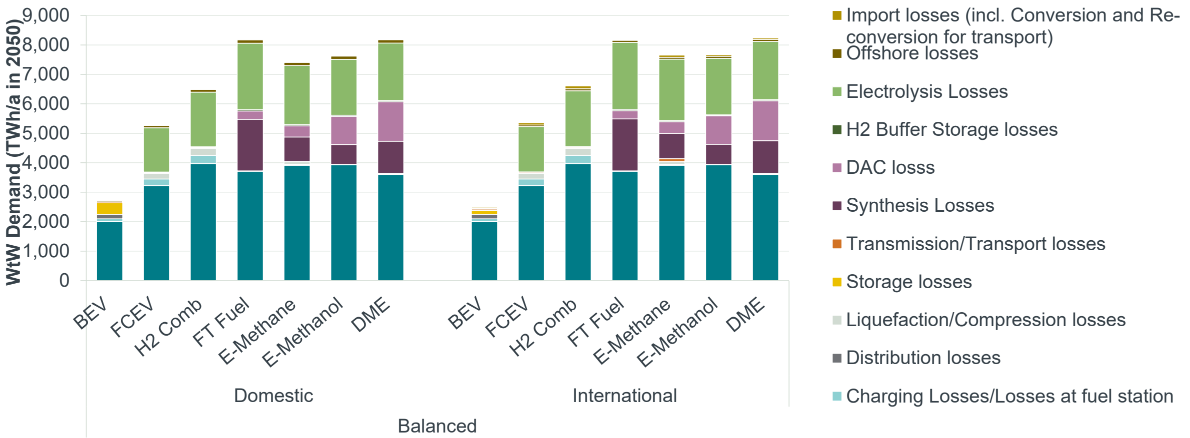


Figure 53: WtW Demand for all fuels for the domestic and international balanced scenarios.

Comparing across all possible 42 scenarios (see Figure 54), the WtW demand is lowest for all BEV scenarios. This is primarily driven by high fuel efficiencies and low losses along the fuel supply chain: Not only is the TtW demand lowest in the BEV scenario, but also the hydrogen demand as it is only used for storage. Therefore fewer losses due to electrolysis occur compared to all other fuels.

All hydrogen scenarios have a higher WtW demand, but still lower than the other remaining fuels. Synthetic fuels are located on the higher end of the spectrum, with the FT Status Quo scenarios requiring the highest amount of WtW energy. This is driven by the fact that all synthetic fuels require synthesis and DAC, inducing particularly high losses along the fuel supply chain for these fuels.

[18] In the BEV scenario, the losses due to electrolysis are assigned to storage losses.

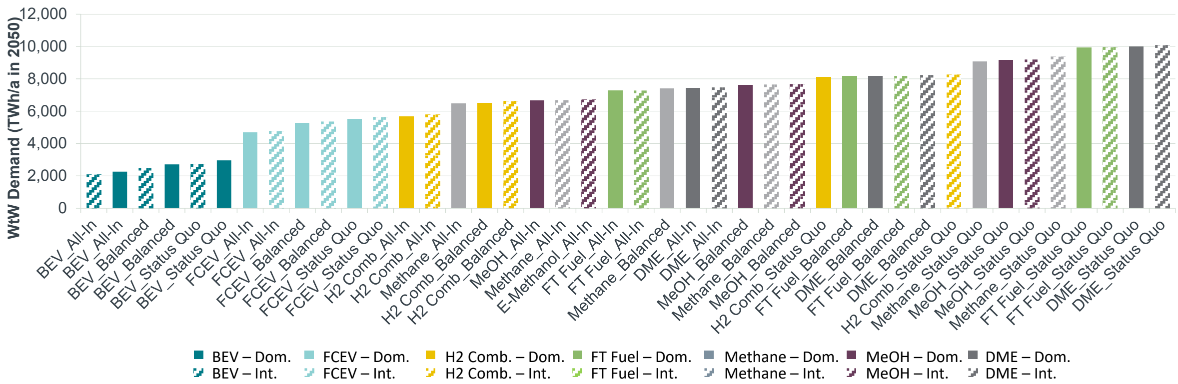


Figure 54: WtW Demand in TWh/a in 2050 for 42 scenarios [Source: Frontier Economics].

For all fuels except BEV, the international scenarios have a slightly higher WtW demand compared to the domestic scenarios due to the (small) import losses (nevertheless these losses are often outweighed by better conditions for renewable energy generation abroad which lower the overall capacity requirements as will be shown in section 9.2). For BEV on the contrary, the international scenario has a lower WtW demand compared to the domestic scenario which is driven by two effects: First, import losses in the BEV scenarios are existent but negligibly small. Second, at the same time, the demand for hydrogen storage in the international scenario is lower compared to the domestic scenario due to a more diversified energy generation portfolio when importing from outside Europe.

Across all fuels, the Status Quo scenarios have the highest WtW demand, while All-In scenarios have the lowest WtW demand. This is driven by the improving fuel efficiencies, leading to a lower TtW and in turn WtW demand.

Other sectors (aviation, rail, shipping)

As already set out in section 7 the total fuel demand for other sectors is significantly smaller than for the road sector. Additionally, not all fuels can be considered for each segment due to technical limitations (e.g. electrified aviation). Therefore, we followed a simplified approach for the other segments, excluding the modelling of the “fleet” as well as any sector specific elements of the fuel supply chain (such as for example the fuel distribution to airports, train depots or harbours) and the associated additional energy demand/losses. However, these stages are unlikely to have a significant impact

The fuel demand in 2050 for aviation ranges from 200 to 400 TWh depending on the 100% scenario which is only 5 to 10% of the road FT fuel demand in 2050. The core driver for the WtW-demand is the TtW-demand and losses due to electrolysis, synthesis and DAC – as for the road sector. The 100% FCEV scenario requires the highest WtW-demand. The high WtW-demand is driven by the low efficiency in fuel consumption, caused by the additional weight of the fuel cell and fuel tank. On the contrary, the H2 combustion scenario has the lowest WtW-demand due to low losses along the fuel supply chain, mainly driven by the production of green hydrogen via electrolysis.

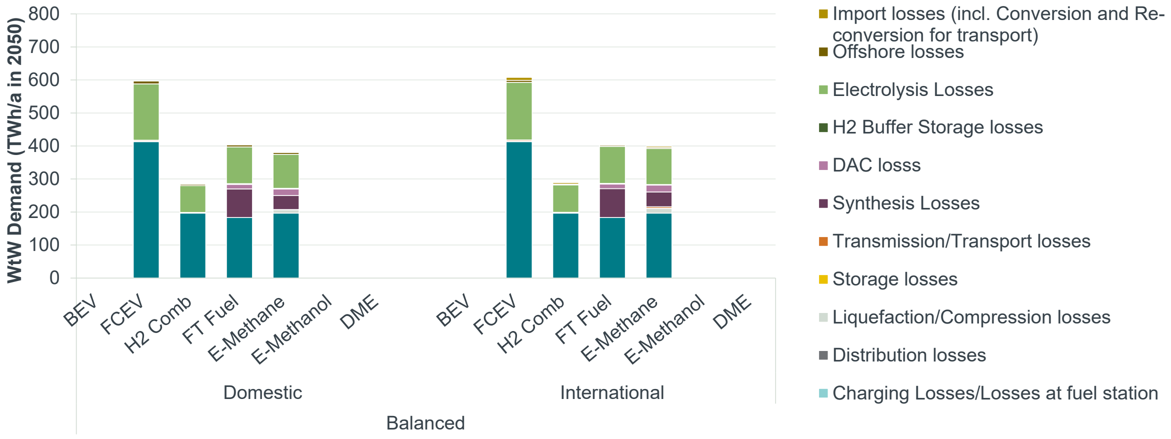


Figure 55: Aviation WtW Demand exemplary for the balanced scenario [Source: Frontier Economics].

The fuel demand in 2050 for Shipping ranges from 240 to 270 TWh, depending on the selected fuel scenario, which accounts only for 6 to 7% of the road FT fuel demand in 2050. As for the aviation sector, the lowest WtW-demand occurs in the H2 combustion scenario. The highest WtW-demand is required in the FT Fuel scenario, followed by other synthetic fuels (Methanol and Methane). For all synthetic fuels, the high WtW-demand is driven by high losses due to electrolysis, synthesis and DAC analogue to road sector.

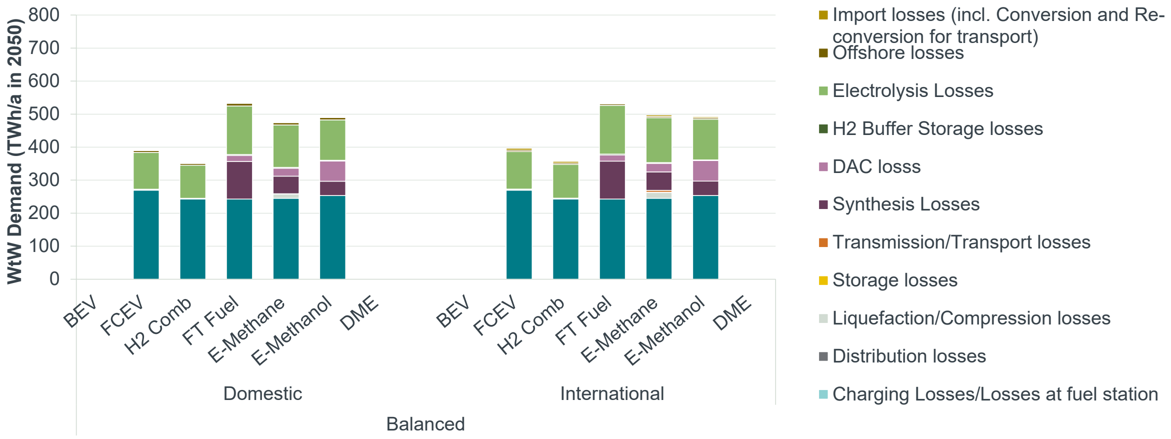


Figure 56: Shipping WtW Demand exemplary for the balanced scenario [Source: Frontier Economics].

The fuel demand in 2050 for Rail ranges from 130 to 210 TWh, depending on the selected fuel scenario, which accounts only for 4 to 5% of the road FT fuel demand. Note that already electrified rails will stay electrified irrespective of the selected 100% scenario.

Other than for the aviation and rail sectors, the lowest WtW-demand occurs in the electrified scenario. The highest WtW-demand is required in the DME Scenario, followed by other synthetic fuels (FT Fuel, Methane and Methanol). Again, for all synthetic fuels, the high WtW-demand is driven by high losses due to electrolysis, electrolysis and DAC analogue to road sector. These findings are similar to the road sector.

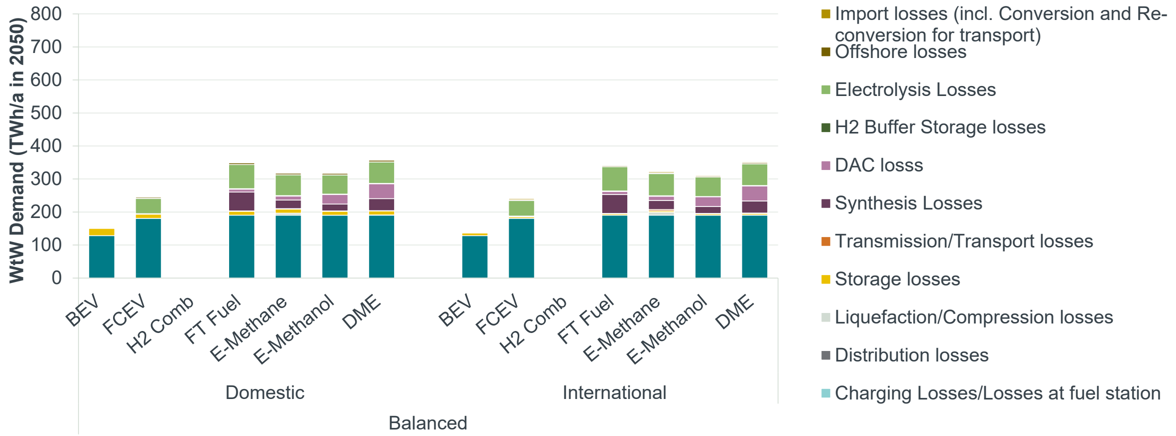


Figure 57: Rail WtW Demand exemplary for the balanced scenario [Source: Frontier Economics].

9.2 Capacity Requirements in 2050

In the following sections we describe the capacity requirements for the road segment for:

- Generation assets for PV and Wind power (see section 9.2.1) and
- Electrolysis (see section 9.2.2).

Details to capacities for other stages of the fuel supply chain or for other sectors (such as rail, aviation and shipping) can be found in the 15.

9.2.1 Generation

It is important to note that the energy units required in the various scenarios, as presented in the preceding section, are becoming less relevant in an energy system which is fully renewable. In such a system typically not the amount or energy matters, but rather the capacity installations required to fulfil the supply task.

The WtW demand though is a key parameter (though not the only one) to determine the generation capacity. It may therefore seem trivial that the total generation capacities are ranked in a similar order as the WtW demand. However, this is only the case for domestic scenarios. When including the international scenarios, it is striking that the international scenarios require less generation capacities compared to the domestic scenarios for each of the considered fuels, changing the ranking, as illustrated in Figure 58. Regions outside of Europe such as MENA or Patagonia have better conditions for generating renewable energy (e.g. hours of sunshine and/or wind). These conditions lead to higher full load hours of a wind turbine or PV plant. Therefore, a solar park of the same size located in e.g. MENA generates more energy in the same period of time than the same solar park located in e.g. Germany. To generate 1 TWh electrical energy less generation capacity needs to be installed in MENA than within Europe. The BEV scenarios require by far the lowest generation capacity, driven by the low WtW demand. Highest installed generation capacities are required for synthetic fuels such as DME, FT Fuel and MeOH.

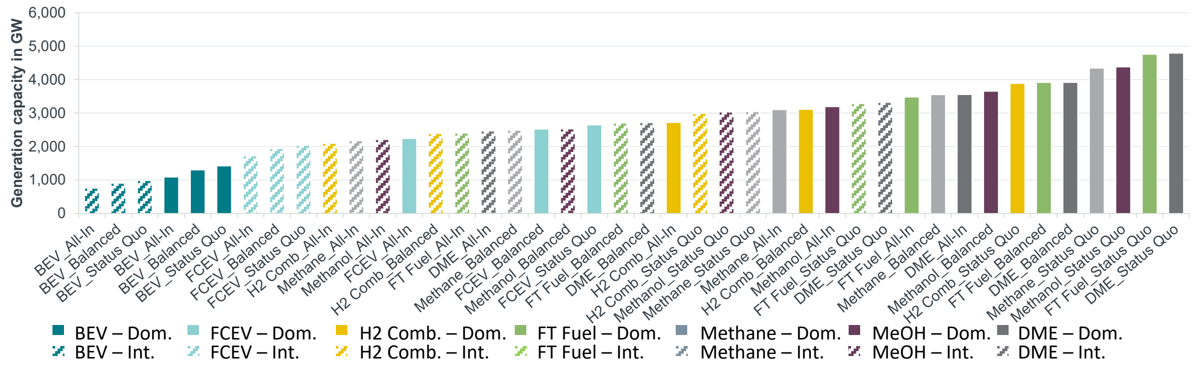


Figure 58: Generation capacity in GW in 2050 for all 42 scenarios [Source: Frontier Economics].

9.2.2 Electrolysis

While certain stages of the fuel supply chain are specific to some fuels, installed capacities for generation and electrolysers are relevant for all fuels and therefore can be compared across all fuel chains. Hydrogen is the basis for all synthetic fuels considered in this study. In the hydrogen scenarios, it was used directly as a fuel and even in the BEV scenario it is required for central storage. The highest electrolysis capacities are required for the FT Fuel Status Quo scenario and for the other hydrocarbon fuels. The findings are similar to the generation capacities.

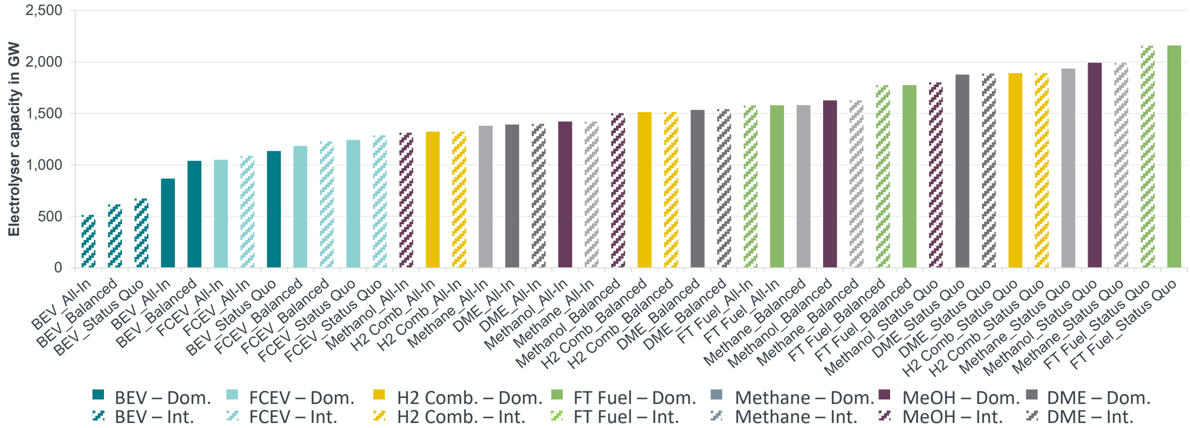


Figure 59: Electrolysis capacities in GW in 2050 for all 42 scenarios [Source: Frontier Economics].

The lowest electrolysis capacities are required in the BEV scenarios see Figure 59. Hydrogen is solely required for storage and therefore the total demand for hydrogen is low in general. Although only 8.9% (3%) of the final fuel demand passes through the hydrogen storage in the domestic (international) scenario, the required electrolyser capacity remains significant. This is caused by the high efficiency losses along the storage path (power-to-H2-to-power) in the BEV scenario. Both conversion stages – electrolysis and also re-conversion – generate signif-icant additional losses.

10 Environmental Impacts Analysis

10.1 General Methodology

10.1.1 Scope of the Analysis of Environmental Impacts

In the scenarios presented here, we use a backcasting approach to model future developments of the transport sector in Europe (EU27+UK) in order to reach a 100% fossil-free mobility with a dedicated powertrain or fuel pathway in the year 2050 (see explanations in section 4). One main condition in the scenarios is that all new vehicles with alternative powertrain technologies (e.g. methanol, H_2, electric) entering the fleet are operated exclusively with additional renewable energy. Accordingly, additional renewable electricity or fuel supply (via PtX) needs to be established in parallel to the fleet ramp-up of vehicles with alternative powertrains.

Our analysis of environmental impacts of the defossilisation of Europe's transport sector covers the total time frame from 2020 to 2050 and includes a cradle-to-grave (C2G) approach.

We cover:

- direct impacts during vehicle use (Tank-to-Wheel) for all transport modes (road, rail, intra-European navigation and aviation) in EU27+UK countries,
- upstream emissions from supply with fossil fuels (Well-to-Tank),
- building-up of fuel supply chain (FSC) infrastructure for defossilised electricity and fuels,
- vehicle production and disposal for the road vehicle fleet in EU27+UK countries[19].

Similar to national emission inventories, all environmental impacts are accounted for in the year when they physically occur. Accordingly, we do not distribute emissions resulting from vehicle production and FSC infrastructure over their operational life (years, km, fuel output), but account them fully in the year a plant is built and starts operation.

The main focus is the development of **GHG emissions** from the transport sector. In this study, we model not only annual GHG emissions, but also cumulative GHG emissions in CO_2 equivalents over the entire period. Afterwards we compare these cumulative emissions to the remaining CO_2 budget for an emission development that is compatible with the Paris agreement. Global warming impact is characterized in a time-horizon of 100 years (GWP_{100}), following the IPCC recommendations (IPCC, 2013) for emissions of greenhouse gases to air.

Furthermore, the following environmental impact categories are included in the assessment:

- **Acidification potential** (AP, in kg SO_2 equivalents): Emissions of acidificating substances in soil and water due to the release of gases such as nitrogen oxides and sulphur oxides are treated according to (Hauschild / Wenzel, 1998) and (CML, 2015).
- **Eutrophication potential** (EP, in kg PO_4 equivalents): Enrichment of the aquatic and terrestrial ecosystem with nutritional elements, due to the emission of nitrogen or phosphor containing compounds are treated according to (Hauschild / Wenzel, 1998) and (Heijungs et al., 1992).
- **Particulate matter formation potential** ($PM_{2.5}$, in g $PM_{2.5}$ equivalents) from emissions to air that cause damage to human health is treated according to (De Leeuw, 2002) and (SAEFL, 2003).

[19] Manufacturing of non-road vehicles is not included in this study due to the long operating life of trains, ships and airplanes and, thus, very low contribution to total impacts from the transport sector.

10.1.2 Model Approach and Databases

Figure 60 illustrates the environmental analyses including inputs from interim steps and databases. Main steps in the environmental analyses are:

- Analysis of specific environmental impacts caused by building-up the fuel supply chain infrastructure, vehicle production and disposal as well as vehicle operation;
- Modelling of total annual environmental impacts of the EU27+UK transport sector in all 42 scenarios on a Cradle to Grave basis. We linked the specific environmental impacts with the scenario-specific developments of vehicle fleets and operation and the ramp-up of energy/fuel supply chain infrastructure.

The configurations of all components in the fuel supply chain infrastructure, the different vehicle concepts as well as scenario-specific information on vehicle fleets, operation and ramp-up of fuel supply chain infrastructure are supplied by other working steps in this project (see section 8). Methodological explanations in this chapter summarize the modelling approach and input data for the derivation of specific environmental impacts for today as well as with different defossilisation levels of material supply and production processes in 2050.

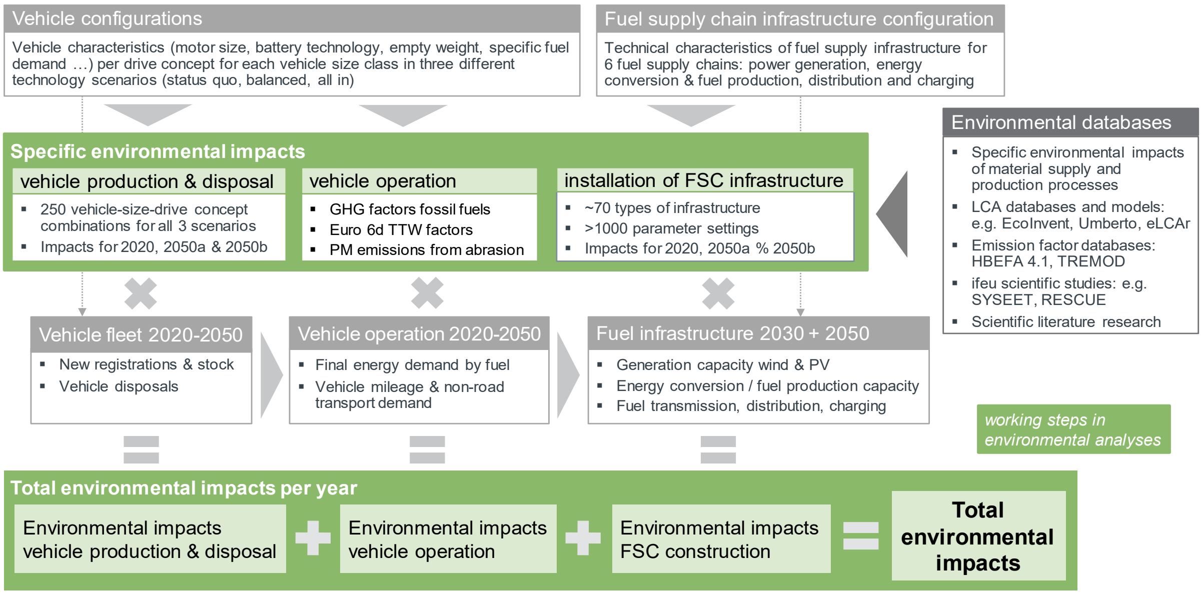


Figure 60: Working process scheme of environmental impact analyses.

10.1.2.1 Model background for today's material supply and production processes

We modelled material and energy flows for all components of the fuel supply chain (FSC) infrastructure using the LCA software tool Umberto (Wernet et al., 2016). This includes, for example, primary and secondary material inputs like steel and concrete, construction work for building up plant infrastructure, electricity and heat demand during construction, as well as water demand and areas occupied and transformed by industrial sites. According to European and global markets, we modelled material and energy supply chains in respect to their actual and projected composition. For vehicle production and disposal, we used our own eLCAr life cycle assessment model, which is developed and continuously updated at ifeu (Agora Verkehrswende, 2019a; Helms et al., 2021; Helms / Jöhrens / et al., 2016; Julius Jöhrens et al., 2020). The model for the fuel supply chain (FSC) is based on ifeu's "PtX model", a life cycle assessment model developed in the UBA SYSEET project (Liebich et al., 2021). For model background data we use common LCA databases, primarily ecoinvent database version 3.6. The results of the UBA project "Update and evaluation of life cycle assessments of wind energy and photovoltaic plants considering current technological developments" (Hengstler et al., 2021) were used for modelling the construction and operation of wind power and PV plants. Furthermore, we considered expert contributions from the focus group process during this project as well as recent literature sources for specific process parameters in single processes and conversions steps (see explanations to individual FSC components in section 10.2).

An important aspect in the fuel supply chain is a coordinated configuration of the various components in the fuel production process. All configurations were discussed and agreed in the project-specific focus groups and are described in detail in sections 5, 6, 7 and 8. Special attention was paid to comparable conditions when defining the technology parameters.

Fuel efficiency of all vehicle types and size classes was derived during this project in different focus groups (road light-duty, road heavy-duty, non-road), see section 6. All other environmentally relevant vehicle operation parameters come from recognized German and European emission factor databases. We use Handbook Emission Factors for Road Transport HBEFA 4.1 for air pollutant emissions from road vehicles and the German inventory model TREMOD for emission factors of rail, inland navigation and aviation. Both models cover the recent state of European emission legislation for the transport sector. Specific GHG emission factors for fossil fuels are in accordance with European Standard EN 16258 (Methodology for calculation and declaration of energy consumption and GHG emissions of transport services (freight and passengers) (EN 16258, 2012).

10.1.2.2 Future defossilisation of material supply and production processes

Defossilisation of the EU27+UK transport sector in this project does not only cover the supply with renewable defossilised fuels, but also an increasing defossilisation of the whole background system of material supply and production processes for vehicle production and construction of fuel supply chain infrastructure. Based on today's production conditions, we have derived two different degrees of defossilisation of the background system in the year 2050.

- 2050a “Defossilised Europe”: All processes in EU27+UK are fully defossilised in 2050. The rest of the world has a time lag of 10 years reaching 75% defossilisation in 2050.
- 2050b “Defossilised World”: All production processes worldwide are fully defossilised in 2050 (including all raw material extraction and processing).

Defossilisation level **2050a “Defossilised Europe”** is based on ifeu’s study for the German Environment Agency "Resource-Efficient Pathways to Greenhouse-Gas-Neutrality – RESCUE" published in (Dittrich / Gerhardt / Schoer / Dünnebeil / Sara Becker / et al., 2020; UBA, 2019). Environmental impacts of material extraction and processing as well as production processes are expected to change considerably during the transformation to a largely carbon-neutral economic system. This transformation is supposed to be almost completely established in Germany by 2050. Electricity generation will gradually switch to renewable sources. Recycling rates in the production of iron, steel and other metals will increase. Fossil raw materials and fuels for industrial and transportation purposes will be replaced by materials with a lower carbon footprint. Energy efficiency will increase in all sectors of the economy.

Based on today’s production conditions and potential future developments modelled in the RESCUE study, we adapted numerous processes in our modelling with the LCA and material flow software Umberto in order to estimate the impact of a changing background system on the environmental impacts associated with plant construction and vehicle manufacturing in the scenario year 2050. In particular, the following processes in the present study are based on the "GreenEe1" scenario of the RESCUE study:

- Electricity generation (with share of renewable energies; including PtG with conversion into electricity)
- Steel production (increasing recycling rates, conversion to hydrogen as a reducing agent in the DRI (direct reduced iron) process),
- Cement production (firing with methane from PtG production, reduction of the clinker factor, novel binders),
- Aluminium and copper production (increasing recycling rates, conversion to inert anodes),

- Plastics production (covering the raw material and process heat requirements with regeneratively produced methane).

We assume the same transformation path as in Germany for the energy systems and production processes within the European Union, a similar development with a ten-year time lag is assumed for the rest of the world (by 2050: 75% defossilisation). Further explanation on the implemented methodology is given in (Dittrich / Gerhardt / Schoer / Dünnebeil / Sara Becker / et al., 2020; UBA, 2019) and (Liebich et al., 2021).

Defossilisation level **2050b "Defossilised World"** assumes an extremely ambitious complete worldwide defossilisation. This describes a completely defossilised global industry where all material and energy pre-chains worldwide are fossil free. In this 2050b world, we assume – in a simplified approach – all CO_2 emissions from fossil energy usage to be replaced by renewable electricity or PtX fuels (Figure 61). Only unavoidable GHG emissions remain in the production processes; these cannot be reduced by avoiding fossil resources or using renewable energy. They are, for example, CO_2 originating from cement/quicklime in the calcination process and non-CO_2 emissions like methane and nitrous oxide (N_2O) originating from agriculture and other processes.

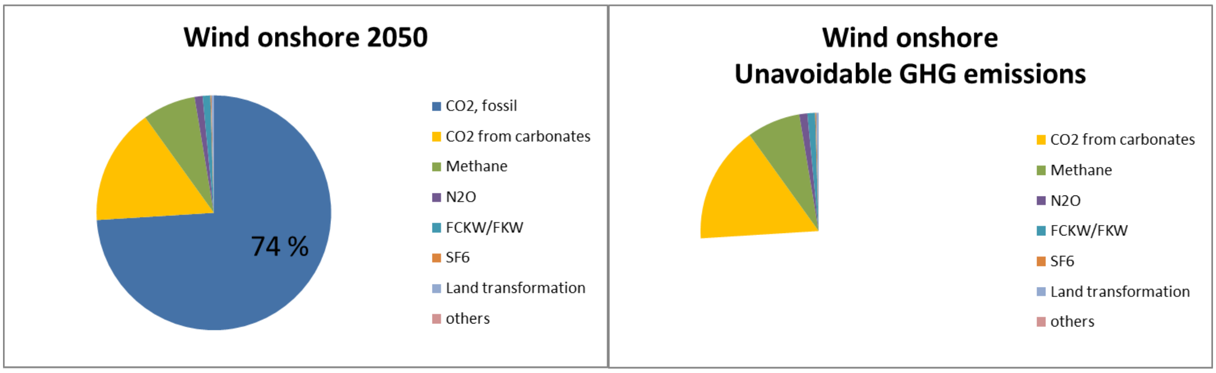


Figure 61: Simplified schematic presentation of GHG emissions for the construction of a wind onshore plant in the 2050a scenario (left) and 2050b scenario (right).

10.2 Specific Environmental Impacts

10.2.1 Build-up of Fuel Supply Chain Infrastructure

Assumptions for all fuel supply chain (FSC) processes were derived in the project-specific FVV focus group. In general, these assumptions correspond to a technical optimum with the aim of establishing GHG-free production (see explanations in section 8). This does not necessarily correspond to an economic optimum. Important assumptions are, for example:

- Energy management: A thermal heat integration is considered to maximize efficiency. E.g. excess thermal energy from exothermic reactions of e-fuel synthesis processes with a temperature level above 100 °C is send to DAC and utilized for the desorption of CO_2. Internal energy demand and excess heat amounts are calculated in ASPEN+ (Aspentech, n.d.) using thermodynamic models and pinch-point analysis.
- Full load hours (FLH): For hydrogen (AEL) and CO_2 (DAC) production, operating units are linked to the respective renewable energy sources operating hours. This ensures simultaneous production and usage of renewable energies without building exceeding electricity storage capacity. FLH of fuel production units are set at 8000 h/year in general, e.g. taking into account maintenance time.
- FSC Upscaling: For FSC infrastructure, particularly for fuel production plants, we used generic datasets with a capacity of 50,000 t/a. We determine the output power of a fuel production plant through the lower heating value of the respective fuel. Upscaling to the respective output power used in this study was accomplished using the capacity method. With growing capacity, in general, specific production expenditures are lower which can

be described with a degression exponent (Lühe, 2013). Degression of investment costs and environmental impacts (e.g. GHG emissions) are applied up to a production power of 1000 MW, using a degression exponent of 0.66. For plants with a production power >1000 MW we apply linear scaling of additional impacts proportional to power increases.

In this section, we give an overview of environmentally relevant influencing factors and additional data sources for the individual components of the fuel supply chain infrastructure. Furthermore, we present selected GHG results for important components of the FSC infrastructure. Tables with all specific results (GHG emissions and other environmental impact categories) can be found in annex section 16.3.

The modelling of the environmental impacts from building-up fuel supply chain infrastructure includes a total of about 70 different plant types. For each of these, we have modelled the specific environmental impacts of production under current production conditions (2020) as well as with two different levels of defossilisation of the background system (2050a, 2050b). To provide a better overview, we structure FSC infrastructure into

- Renewable power generation: Wind and PV power systems and electricity transmission lines (including sea cables offshore to coast and for EU import from MENA)
- Hydrogen supply: electrolysers, H_2 caverns
- Production of hydrocarbon fuels: CO_2 production (DAC), fuel synthesis, LNG storage
- Distribution, charging and fuelling infrastructure: H_2 and methane pipelines and fuel stations, electricity distribution network, overhead catenary network, charging stations.

In general, the infrastructure for renewable power generation dominates environmental impacts of the FSC. Significant contributions often come from the provision of steel, aluminium, copper and concrete. With increasing defossilisation, the importance of energy provision is reduced, but process-specific emissions remain. Construction work and energy used in manufacturing the FSC infrastructure components are less important for the overall environmental impacts.

10.2.1.1 Renewable power generation and transmission

For the construction of photovoltaic and wind power plants in the year 2020 we use data from the ecoinvent 3.6 database (Wernet et al., 2016) and literature research, mainly results of the project "Update and evaluation of life cycle assessments of wind energy and photovoltaic plants considering current technological developments" (Hengstler et al., 2021). Additionally, we use progression coefficients to scale up onshore and offshore wind turbines according to (Engel, 2014). As the specific material demand per MW power output increases with higher wind plant sizes, progression of material demand and thus specific environmental impacts is applied instead of degression. Due to fixed operational cost and higher revenues from electricity generation these material progressions may still pay off economically for a specific location. Future defossilisation of plant construction follows the approach explained in section 10.1.2.

<u>Photovoltaic plants slanted-roof</u>: Capacity for electricity generation from PV on slanted roofs is 0.005 MW_{peak} per unit for all years. Considered construction parts are inverters, electric cables, mounting frameworks and silicon wafers for PV-cell modules (57% multi-/ 43% mono-crystalline Si technology). Main influencing factors on specific GHG emissions and other environmental impacts from PV plant manufacturing are primarily aluminium and reinforcing steel as well as solar glass for construction, electronics for inverters and the electricity used for silicon wafer production. Inverters mainly consist of low-alloyed steel, copper, aluminium and glass fibre reinforced plastics (polyamides). Emissions from these construction materials are greatly reduced in 2050a. Due to the complete defossilisation in 2050b, emissions are further reduced with the defossilisation of less important materials, e.g. plastics and other metals.

<u>Photovoltaic plants standalone</u>: Capacity for electricity generation from PV standalone units is 5 MW per unit for all years. In general, there is no difference in the construction materials used in respect to slanted-roof PV units. However, for mounting on open ground a higher amount of

aluminium, reinforced steel and concrete is needed, leading to higher specific environmental impacts per installed capacity.

Wind onshore: Capacity for electricity generation from new onshore wind turbines is 2.9 MW in 2020 and doubles to 6 MW in 2050. Construction parts of wind onshore plants are the foundation (mainly concrete), the tower, nacelle including main shaft, gearbox, generator, control systems and rotors. Main influencing factors for GHG emissions in these components are the required materials steel, glass fibre reinforced plastics, aluminium and concrete. Additional components contributing to the emissions are copper, iron, chromium steel and permanent magnets (from neodymium oxide) as well as the transportation emissions. Emission reduction in 2050a is mainly due to less emission intensive concrete, aluminium and steel production. Due to the complete defossilisation in 2050b, emissions are further reduced with the defossilisation of less important materials, e.g. plastics and other metals.

Wind offshore: Capacity for electricity generation from new offshore wind turbines is 4.15 MW in 2020 and increases to 15 MW in 2050. Accordingly, the size of offshore plants will increase significantly more than for onshore plants. A new wind offshore plant in 2020 is about 1.4 times as large as an onshore plant, whereas in 2050 it is 2.5 times as large. The average installed capacity per offshore converter platform is 900 MW in 2020 and 2000 MW in 2030/2050. In general, construction materials do not differ for offshore wind turbines in respect to onshore turbines. Less concrete is used for the foundation, whereas more steel is needed for the monopile anchor or mooring system. Additionally, nacelles are reinforced with epoxy resins. (Hengstler et al., 2021). The higher share of onshore wind plants in concrete per MW is also the reason that full defossilisation 2050b results in a lower GHG reduction effect than for offshore plants.

Electricity transmission: Production of transmission lines includes electricity transmission from offshore converter platforms to the coast and submarine cables for the electricity import from MENA to Europe with a transmission voltage of 325-520 kV and 700-2000 MW capacity. Furthermore, in 100% electric mobility scenarios, the expansion of electricity transmission networks on land is considered with 1.4-2.0 GW average capacity as AC overhead lines (80%) and HVDC cables (20%).

Specific results: Today, the installation of PV plants generates significantly higher specific GHG emissions per MW of installed capacity than the construction of wind power plants:

- 1,700 t CO_2 equivalents are generated per MW for PV standalone, and 1,300 t CO_2 equivalents per MW for PV slanted-roof. The higher specific GHG emissions from PV standalone plants result from the additional mounting structure.
- Installation of wind power plants generates only 750-850 t CO_2 equivalents per MW, thus, about half as much GHG emissions as PV plants. Differences between onshore and offshore plants result from different size classes as well as from different impacts of foundations of onshore plants and the anchoring of offshore wind turbines.

With increasing defossilisation of material supply and production processes, the specific GHG emissions of PV and wind power plant installation will decrease significantly. With defossilisation level 2050a, specific GHG emissions decrease by 70-75% (PV) and 50-60% (wind). In case of a complete worldwide defossilisation (only unavoidable non-fossil GHG emissions occur), specific GHG emissions are about 94% lower for the installation of PV plants and 86% lower for wind power plants than in 2020. In this case, unavoidable GHG emissions per MW of installed capacity are similar for PV and wind power plants. Reasons for the weaker specific GHG reduction for wind power plants are the lower process energy demand, the higher concrete proportion and that the assumed increasing size class of new wind turbines is accompanied by a higher specific material demand per MW.[20]

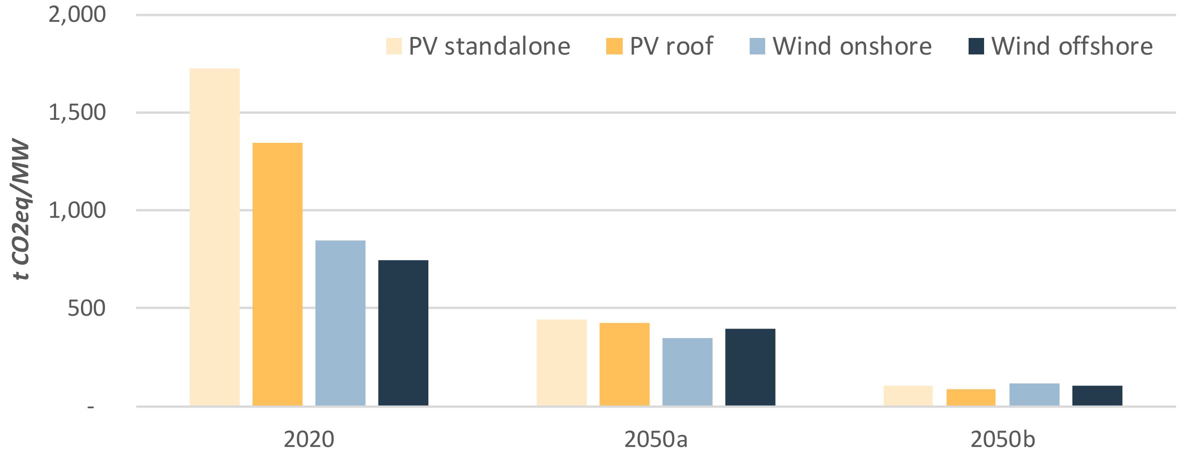


Figure 62: Specific GHG emissions from installation of PV and wind power plants in 2020 and with different defossilsation levels of production in 2050.

10.2.1.2 Hydrogen supply

In this study, we model hydrogen production via alkaline electrolysis. Further hydrogen related infrastructure includes storage of hydrogen, pipelines for import and transmission.

Hydrogen alkaline electrolysers: Data for alkaline electrolysis construction are taken from the study "System comparison of storable energy carriers from renewable energies" (SYSEET) by (Liebich et al., 2021). Alkaline electrolysis (AE) of water is achieved in solutions of 20–30wt% NaOH or KOH with nickel electrodes, separated by a diaphragm. Hydrogen is produced at the cathode, while oxygen is produced at the anode. Main materials for hydrogen electrolyser stacks are steel and nickel, in lower extent copper, aluminium and zirconium oxide. Additionally, various chemicals are needed for construction, e.g. polysulfones, polyphenylene and other organic chemicals. Important electronic components are inverter units (see PV slanted-roof). Electrolyser capacity per unit is 10 MW in 2020, growing to 250 MW in 2030 and 1000 MW in 2050. For plants up to 100 MW a degression coefficient of 0.9 is assumed for environmental impacts, above this capacity modular growth is expected.

H_2 Pipelines are required for the hydrogen transport from electrolysers to storage, import from MENA and transmission across Europe. Environmental impacts for building H_2 pipelines with technical parameters as explained in section 8.3.2 come from existing methane pipeline infrastructure, including pipes as well as pumping stations and compression units as documented in the ecoinvent database.

H_2 storage: Storage of hydrogen can be realized in caverns or in a pressure storage unit. In this project, we assume hydrogen storage in caverns, considering an analogue drilling process as for natural gas. An average drilling depth of 1000 m is considered, using 210 kg steel and 1 m³ concrete or 200 kg cement per meter. Total capacity of a single cavern is 460 million m³. Environmental data for building cavern infrastructure come from the ecoinvent database, considering analogue methane infrastructure.

[20] Please note: Comparison of specific emissions per installed capacity is not the same as per amount of energy generated, as these also depend on the annual site-dependent full load hours and the lifetime of the plant. This will be discussed later in the scenario results in section 10.3.5.

Gas turbines: If hydrogen is used for electricity generation (seasonal energy buffering in scenarios with 100% electric mobility), we also consider construction of gas turbines for H_2 reconversion in the scenarios.

Specific results: Together with renewable power generation, electrolysers are one key component of the FSC infrastructure for all fuel and powertrain pathways. Assumed capacity per electrolyser increases from 10 MW to 1000 MW between 2020 and 2050. This has only little influence on the specific emissions per MW of capacity due to the good scalability of electrolysis plants. However, the increasing defossilisation of material supply and manufacturing processes has a significant impact: With defossilisation level 2050a, specific GHG emissions decrease by about 50%. In case of a complete worldwide defossilisation, specific GHG emissions are about 90% lower compared with today.

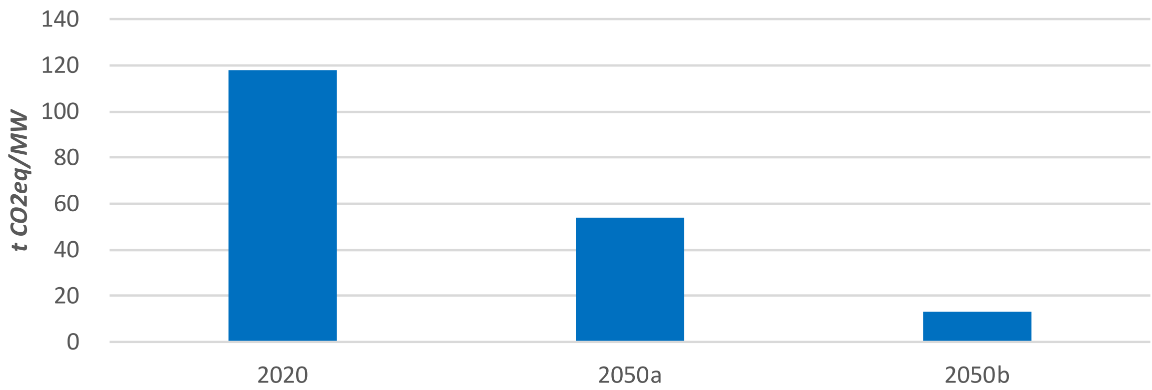


Figure 63: Specific GHG emissions from installation of alkaline electrolysers in 2020 and with different defossilisation levels of production in 2050.

10.2.1.3 Production of hydrocarbon fuels

Fuel supply chains for hydrocarbon fuels using renewable H_2 include CO_2 capture from air (DAC) and synthesis units for the respective synthetic fuels: Fischer-Tropsch (FT) fuel, synthetic methane, methanol (MeOH) and dimethyl ether (DME). Fuel supply chain data are primarily taken from the study “System comparison of storable energy carriers from renewable energies” (SYSEET) by (Liebich et al., 2021), process parameters areadopted based on the dissertation of (König, 2016). We deriveadditional information for methanol and DME synthesis from the dissertation of (Schemme, 2020). Hydrocarbon fuels in international scenarios are imported by ships. As existing tanker ships can continue to be used, no additional ship production has to be considered in the fuel supply chain.

Direct Air Capture (DAC): In the DAC unit, air is filtered through an amine functionalized adsorbent capturing CO_2. After reaching full capacity, the unit is evacuated and heated to release purified CO_2. DAC units are used to supply CO_2 to hydrocarbon fuels described below, namely FT, MeOH, methane and DME. Capacity for carbon capture is set at 0.135 t/day/module in all base years. For CO_2 storage a storage unit with a capacity of 12,310 t CO_2 per DAC unit is considered, assuming no CO_2 losses. Relevant infrastructure materials for DAC units are aluminium, low-alloyed steel and chromium steel, concrete, sand and crushed gravel. For the amine functionalized adsorbent we assume an anionic resin compound as model proxy. Less relevant materials for construction and DAC operation are polyethylene, stone wool, ethylene glycol and reinforcing steel.

Fischer-Tropsch: FT-Synthesis is achieved in a two-step process, first converting hydrogen and CO_2 to syngas in a reverse water-gas-shift reaction (RWGS) with subsequent FT-synthesis to liquid hydrocarbons. Products are purified and refined, unreacted gases are recycled. Flue gases are treated in an oxy-fuel burner giving a CO_2 rich gas, which is fed back into the RWGS. Heat from combustion in the oxy-fuel burner is used in the RWGS, while high temperature heat from the FT reaction is utilized for DAC at a temperature level of 100 °C. CO_2 demand for FT fuels is 3.14 kg CO_2/kg FT fuel. As the reaction is highly exothermic, 0.52 kWh heat/kWh fuel can be utilized in DAC. Capacity of the FT synthesis unit is set at 90 MW (fuel output power) in 2020 growing linear to 1300 MW in 2050. For FT plant construction we apply the econinvent dataset for “chemical factory, organics”. Relevant input parameters are electricity and heat demand, “electronics for control units” and steel. Breaking down “electronics for control units” into material inputs, important materials in the fabrication process are gold and silicon for circuits as well as the electricity requirement for their production. Degression of specific environmental impacts with increasing plant size is applied as described in the methodology section. From 1000 MW upward we considered no further efficiency improvement in plant upscaling.

Synthetic natural gas: Methane synthesis is a catalytically assisted reaction that converts carbon dioxide and hydrogen into methane and water at 200–500 °C and 3–80 bar. This Sabatier reaction is known in the opposite direction as steam reforming of natural gas and is the most common process for producing SNG. The reaction is strongly exothermic, thus 0.19 kWh heat/kWh SNG can be utilized for DAC. CO_2 demand for SNG-synthesis is 2.67 kg CO_2/kg SNG. In our study, methanation capacity per synthesis plant is set at 20 MW (SNG output power) in 2020 with linear ramp-up to 500 MW in 2050 (see section 16.5). For SNG plant construction we apply the ecoinvent dataset for “synthetic gas factory” (Wernet et al., 2016). Relevant inputs for construction are reinforcing steel, concrete, low-alloyed steel and copper as well as diesel burned in building machines. Degression of environmental impacts with increasing plant size is applied as described in the methodology. From 100 MW onward no further scaling effect is taken into consideration assuming modular growth. For further downstreaming, SNG is liquefied and stored in LNG tanks.

Methanol: MeOH synthesis is achieved in a one-step reaction directly feeding hydrogen and CO_2 into the reactor at 250 °C and 80 bar. Crude methanol is purified in a distillation column and unreacted gases fed back into the reactor. The reaction is strongly exothermic, thus 0.18 kWh heat/kWh MeOH can be utilized for DAC. CO_2 demand for MeOH-synthesis is 1.37 kg CO_2/kg MeOH which implies stoichiometric conversion of CO_2 and no formation of by-products through novel catalyst systems (e.g. indium oxide). Production capacity is set at 90 MW (MeOH output power) in 2020 with linear ramp-up to 1000 MW in 2050. For MeOH plant construction we apply the econinvent dataset for “chemical factory, organics” (Wernet et al., 2016). MeOH production units are expected to operate in combination with DME synthesis. Thus, we applied an allocation factor of 2/3 for MeOH production units, representing infrastructure necessary for MeOH production at a specific site.

Dimethyl ether: DME-Synthesis is a two-step process, with MeOH-synthesis in the first step as described above and subsequent conversion of MeOH to DME in the second step. The condensation reaction is exothermic, although distillation of DME to separate water requires much energy. Still, a low heat excess of 0.048 kWh heat/kWh DME can be utilized for DAC. CO_2 demand for the two-step process is 1.91 kg CO_2/kg DME in total. DME capacity is set at 90 MW (DME output power) in 2020 with linear increase to 1000 MW in 2050. For DME plant construction we apply the econinvent dataset for “chemical factory, organics” (Wernet et al., 2016). DME production units are expected to operate in combination with MeOH synthesis. Thus, we apply an allocation factor of 1/3 for DME production units, representing infrastructure necessary for DME production. Since DME will be produced in combination with MeOH, both, MeOH and DME infrastructure must be considered for DME production.

Specific results: For all hydrocarbon fuels, CO_2 is extracted from air (direct air capture). The assumed plant size is 0.135 t CO_2 production capacity per day and DAC module. For a typical DAC unit GHG emissions of 607 kg CO_2 equivalents are generated from construction, raw material and energy demand in 2020. With defossilisation level 2050a, specific GHG emissions decrease by about 40%. In case of a complete worldwide defossilisation, specific GHG emissions are 85% lower compared with today.

Specific GHG emissions for the installation of fuel synthesis plants for FT fuel, methanol and DME are shown in Figure 64. Installation of synthesis plants in 2020 causes similar specific GHG emissions for FT plants (3,500 t/MW) and methanol plants (3,900 t/MW). MeOH plant construction is associated with slightly higher specific GHG emissions per MW than FT plant construction, owing to the lower LHV of MeOH, which needs a larger upscaling to reach a respective output power. The higher duties for upscaling are then largely compensated by the allocation factor applied for MeOH and DME, leading to nearly equivalent impacts of MeOH and FT sites. In contrast, specific GHG emissions for DME synthesis plants are 40% higher than for methanol plants as methanol is a pre-product of DME and therefore both, MeOH and DME synthesis plants must be included in the specific factors.

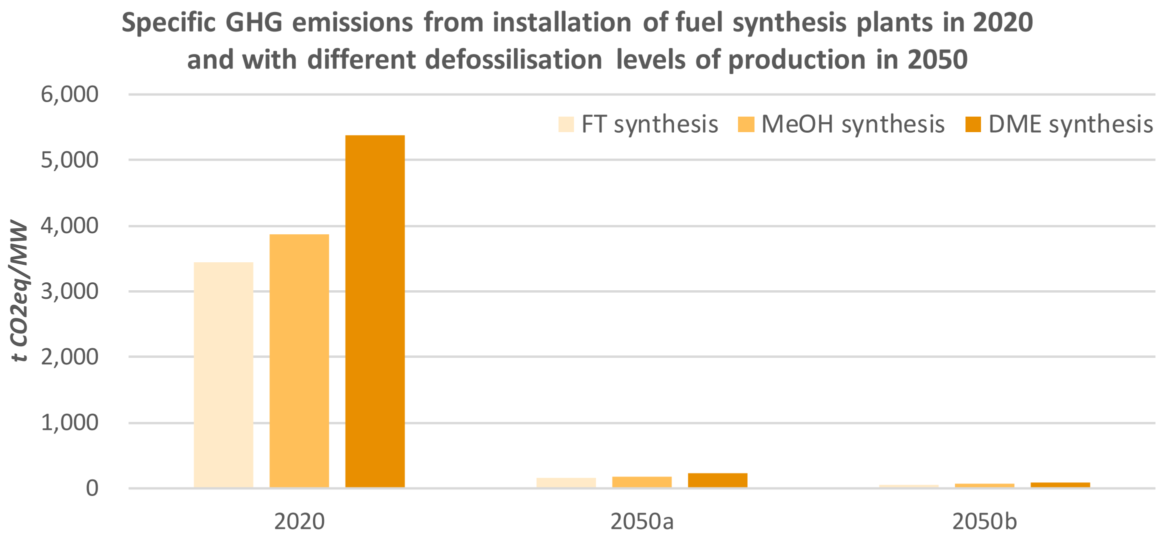


Figure 64: Specific GHG emissions from installation of fuel synthesis plants in 2020 and with different defossilisation levels of production in 2050.

With increasing plant sizes and defossilised manufacturing processes, specific GHG emissions decrease from 2020 to 2050 by 96% (2050a) to 98% (2050b). Compared to other components of the fuel supply chain, the specific GHG emissions already decrease very strongly with the degree of defossilisation 2050a: Firstly, due to the strong upscaling of plant sizes, secondly, due to the higher share of energy input in plant construction, thirdly, due to the predominant use of materials with a high degree of defossilisation already in 2050a (aluminium, copper, steel) and fourthly, due to the assumption that the production of the synthesis plants takes place predominantly in Europe (with complete defossilisation 2050a). Additional GHG reduction through complete defossilisation in 2050b accounts for materials with minor impacts in the overall supply chain, thus, only leads to minor improvements in GHG decrease.

Analyses of specific GHG impacts from installation of fuel synthesis plants show huge discrepancies between methane synthesis plants and other fuel production plants. Specific data for all fuel production plants come from the ecoinvent database. For methane, the dataset “synthetic gas factory, construction” and for FT, methanol and DME the dataset “chemical factory construction, organics” is used. These differences are likely to be unrealistic. However, building-up fuel synthesis plants accounts for a maximum of 6–14% in FSC infrastructure construction and 1–3% of the total cumulative GHG emissions from the transport sector in all scenarios. Therefore, we did not further analyse potential reasons for these discrepancies in this study.

10.2.1.4 Distribution, charging and fuelling infrastructure

All liquid fuels and H_2 are distributed via trucks analogous to today’s fuel distribution. Therefore, we consider no additional vehicle production beyond general truck fleet exchange in our scenarios. Only the 100% methane scenarios include distribution to the fuel stations via existing and newly built pipelines. Furthermore, expansion of electricity distribution networks is part of the 100% electric mobility scenarios.

Liquid hydrocarbon fuels can continue to use the existing fuel stations network. For methane, the existing fuel stations network has to be extended. For H_2, a Europe-wide network of fuel stations has to be built-up. Electric mobility requires a Europe-wide network of charging points for battery-electric vehicles and a network of overhead lines for catenary trucks.

Methane distribution pipelines: Environmental impacts for building additional methane distribution pipelines with technical parameters as explained in section 8.3.4 come from existing methane pipeline infrastructure as documented in the ecoinvent database (Wernet et al., 2016).

H_2 fuelling stations are modelled for passenger cars with 8 fuelling points and 1500 kg capacity per day, truck stations have 4 fuelling points and 5000 kg capacity per day. Construction and materials of these fuel stations are based on (Bekel, Kai / Pauliuk, Stefan, 2019).

Charging points for electric vehicles: In this study, we have analysed three types of charging stations: wall boxes with 11 kW, charging points with 44kW AC and high-speed chargers with 150 kW DC. Material demand and environmental impacts from production of the wall boxes and the 44 kW chargers are based on (Bekel, Kai / Pauliuk, Stefan, 2019). We found no data source for the material demand of high-speed chargers. Since high-speed chargers constitute only 0.5 percent of all charging stations, we used the same data as for the 44 kW charger as a proxy.

Overhead lines for catenary trucks: We based the construction of the overhead catenary infrastructure for trucks on (Julius Jöhrens et al., 2020).

10.2.1.5 Specific land use for renewable power generation and CO_2 supply

Land use is defined as the temporary or permanent occupation of land by human activities. As local conditions are very heterogeneous, environmental impacts of human activities are usually evaluated with respect to the specific conditions of the particular piece of land. Thus, evaluating land use without particular information on the specific local conditions is limited, but different concepts are available (Kauertz et al., 2020):

- (Temporary) occupation of land and land use changes: this quantifies the amount of area in square meter (or ha, km², etc.) for one use (e.g. for the production of a product or service), which cannot be used for anything else. This concept includes fundaments, buildings, access roads and furthermore clouded areas with limited use (e.g. land below photovoltaic panels) as well as in-between areas with limited use (e.g. land between photovoltaic panels).
- Occupation according to the degree of hemeroby: hemeroby is defined as closeness to nature. Seven types are differentiated: I) virgin nature, II) near-natural, III) limited near-natural, IV) semi-natural, V) limited semi-natural, VI) far from nature, VII) not natural/ artifical.
- Impact on landscape image, including the degree of visibility, proportionality compared to natural high differences etc.

In this study, we use the first approach. We evaluate land use of wind power plants, photovoltaic plants and direct air capture sites as they are the most land consuming installations. The factors applied are listed in the following table.

Table 25: Factors applied for the evaluation of land use.

	Factor	Unit	Remark	Source
WEA-onshore	2992.63	m²/unit WEA	*also used for WEA-offshore as no specific factor is available*	Fehrenbach (forthcoming)
PV stand alone	1.47	ha/MWp	*weighted by efficiency improvements*	Fehrenbach (forthcoming)
DAC	0.13	m²*a/t CO_2		(Liebich et al., 2020)

10.2.2 Vehicle Production and Disposal

10.2.2.1 Methodology and data

We have based our modelling of vehicle production and disposal on the eLCAr life cycle assessment model developed and continuously updated at ifeu. The model covers the environmental impacts of generic heavy and light duty vehicles with conventional and alternative drivetrains over their entire life cycle. Different components such as body, drivetrain, battery and other drivetrain-specific additional components are distinguished and further differentiated. Due to the great importance of the European Union as an automotive manufacturing location, vehicle production is based in the EU. However, materials for vehicle manufacturing (e.g. steel or aluminium) as well as certain vehicle parts (e.g. batteries) are sourced in different countries worldwide. Background data for raw materials and energy provision comes from the ecoinvent v 3.6 database (Wernet et al., 2016) using a cut-off approach for all end-of-life processes. Thus, we included the full environmental burdens for all primary materials, but provided secondary materials for “free”. Instead, the burdens from waste treatment are balanced and no credit for recovered secondary materials is given. Further information on the eLCAr model for cars can be found in (Agora Verkehrswende, 2019b), (Agora Verkehrswende, 2019c). Modelling of the heavy-duty vehicles is described in (Zimmer et al., 2016).

The ifeu model for light and heavy-duty vehicles follows a modular approach and allows scaling all relevant vehicle parts according to their technical characteristics. Sizing is done according to the vehicles empty weight, engine power, fuel cell power and storage size (tank or battery). We have also included a lightweight glider version using aluminium.

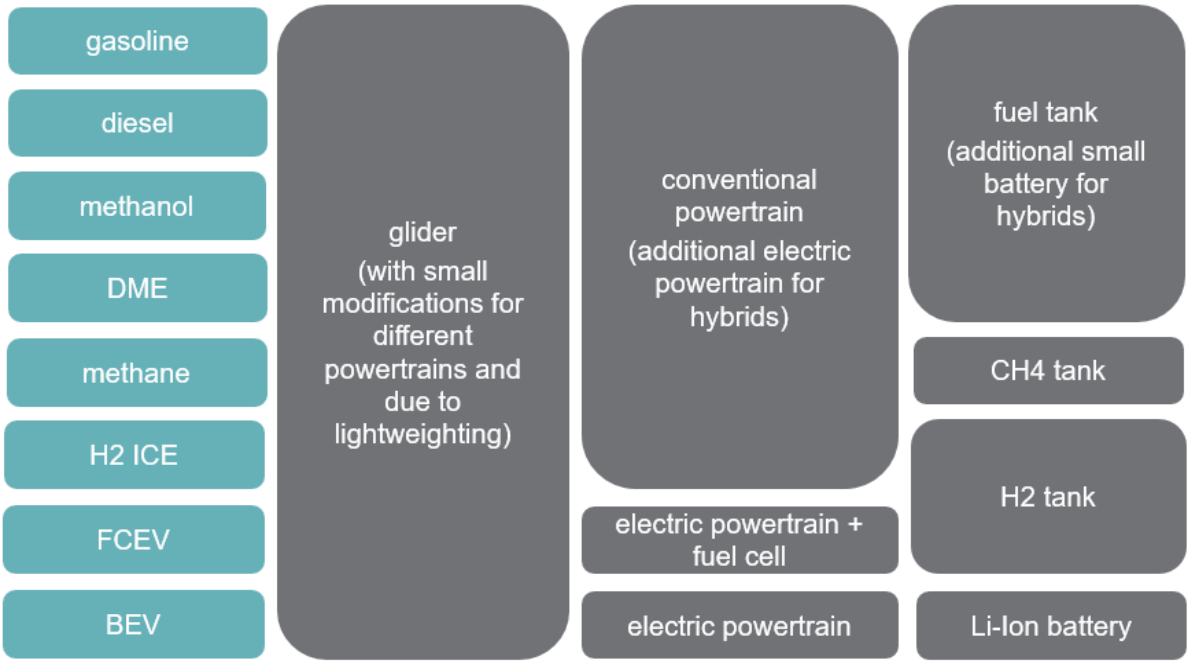


Figure 65: Schematic overview of the modular approach to vehicle manufacturing for passenger cars.

All technical vehicle characteristics are provided by the project-specific FVV focus groups, for light-duty and heavy-duty vehicles consisting of representatives from different OEMs as well as other stakeholders from industry and research/development. Annex 16.3 shows the main vehicle characteristics.

10.2.2.2 Battery production

The vehicle battery is a central component of all vehicles with alternative drivetrains. The FVV focus group agreed on its main characteristics. Table 26 shows energy density values together with the cell chemistry. Currently, Nickel-Manganese-Cobalt (NMC) lithium-ion batteries

dominate the European vehicle market. During the last years, Li-Ion battery technology developed very rapidly, leading to higher energy densities, lower manufacturing energy demand, changes in battery chemistry (e.g. lower amounts of cobalt in the cell). Batteries are getting cheaper and more lightweight. For the All-In scenario, the FVV focus group decided to include solid-state NMC batteries due to their expected higher market readiness compared to other new battery types. However, there is also an ongoing trend for OEMs to equip their vehicles with bigger batteries and thus achieve a higher electric range. The focus group decided an operating range of 300 km (WLTP all-season) for all small cars and 500 km for all larger size classes, including SUVs and light commercial vehicles (see technical specifications of all vehicle classes in annex section 16.3).
Usually, the usable (net) capacity of a battery in a vehicle is a bit lower than the overall gross battery capacity to ensure a higher battery lifetime. Based on average market data the FVV focus group agreed that gross battery capacities are higher by 10 percent than the net battery capacities for all battery-electric vehicles. For hybrids, the gross battery capacity is 46% higher compared to the net capacity.

Table 26: Energy density and cell chemistry of vehicle batteries.

	Status Quo	**Balanced**	**All-In**
Battery type	NMC 622	NMC 811	Solid-state NMC 811
Energy density (system level)	150 Wh/ kg	200 Wh/kg	300 Wh/ kg

Each vehicle battery consists of several main parts, battery cell, cooling, battery management system and packaging. The ifeu model bases the battery modelling mainly on (Ellingsen et al., 2014). For the present study we have updated the battery cell manufacturing and included data from the GREET database: We based the provision of nickel-manganese-cobalt active material on (Q. Dai, J. C. Kelly, J. Dunn, P.T. Benavides, 2018) and took the provision of $CoSO_4$ (cobalt sulphate) from (Q. Dai, J. C. Kelly, A. Elgowainy, 2018). For the energy demand from cell manufacturing, we split the energy between heat and electricity and used the values from (Dai et al., 2017).

The battery cell is one main driver of the environmental impacts from battery manufacturing as it needs high amounts of energy (electricity as well as heat). China, Korea, Japan and the US are currently the biggest cell producing countries; however, there is an ongoing effort to shift cell production to Europe until 2030. Therefore, we use a European energy mix for cell manufacturing after 2030.

Solid-state NMC batteries use the same active material as “classical” NMC batteries, but do not need a liquid electrolyte. They achieve higher energy densities and are easier to manufacture. The anode of a solid-state battery consists of lithium (with a carbon dopant) and a copper anode current conductor. The solid electrolyte is a ceramic called LIPON (lithium phosphorus oxynitrite). The cathode uses a nickel conductor. Data for an industry-scale life cycle inventory for solid-state battery cells have not been available. Therefore, we base our assessment on (Lastoskie / Dai, 2014). All other battery components remain unchanged.

The FVV focus group agreed on battery characteristics mid of 2020 as basis for our modelling of battery manufacturing. Accordingly, our environmental analyses cannot include recent developments in the very dynamic battery market that might lead to substantial market shares of other battery technologies than considered in this study. Several new (or improved) battery technologies currently compete for inclusion into the future vehicle fleet. Asian manufacturers or manufacturers of budget cars (including the Tesla model 3) and of heavy-duty vehicles may use lithium-iron-phosphate (LFP) batteries with reduced cobalt and lithium demand, but also with lower energy density than the battery technologies assumed in this study. End of year 2020, Tesla introduced new cars with LFP batteries also to the European market, other manufacturers have announced the future use of LFP technology in budget cars (JESMB, 2021). Several large companies develop Sodium Ion batteries (SIB) as completely lithium and cobalt free alternatives. In June 2021, two large manufacturers have announced production start of commercial SIB cells for this year (Wunderlich-Pfeiffer, 2021).

10.2.2.3 Specific environmental impacts

In this subsection, we discuss selected main results from the vehicle manufacturing of cars in detail. This section helps to understand the overall trends for the different technology levels and defossilisation scenarios as well as the contributions from different vehicle parts.

In general, we find that the chosen drivetrain technology as well as the specific technical configuration influences the environmental impacts from vehicle manufacturing. An FVV focus group supplied the data for the different technology scenarios (for details see annex 16.3).

Balanced vehicle technology introduces a hybridisation for all non-electric drivetrain configurations (vehicles with internal combustion engine (ICE)). Thus, we add an electric drivetrain as well as a small battery. This leads to higher emissions from car manufacturing.

For the All-In scenario, the FVV group chose to include light weighting by changing from a steel glider to an aluminium one. Even though the mass of aluminium needed is smaller than the previous mass of steel, this drives up the emissions from car manufacturing due to the more favourable environmental performance of steel compared to aluminium.

We also introduc improvements in the fuel cell design and the vehicle battery in the Balanced and All-In scenario, which lead to lower environmental impacts compared to the Status Quo technology.

10.2.2.4 GHG emissions from vehicle production

The first figure shows the GHG emissions from vehicle manufacturing in the year 2020 for selected drivetrain concepts and technology levels of a C-segment car. In general, fuel cell as well as electric cars have higher GHG emissions from vehicle manufacturing than the gasoline cars, which we use here as an example for conventional drivetrain concepts.

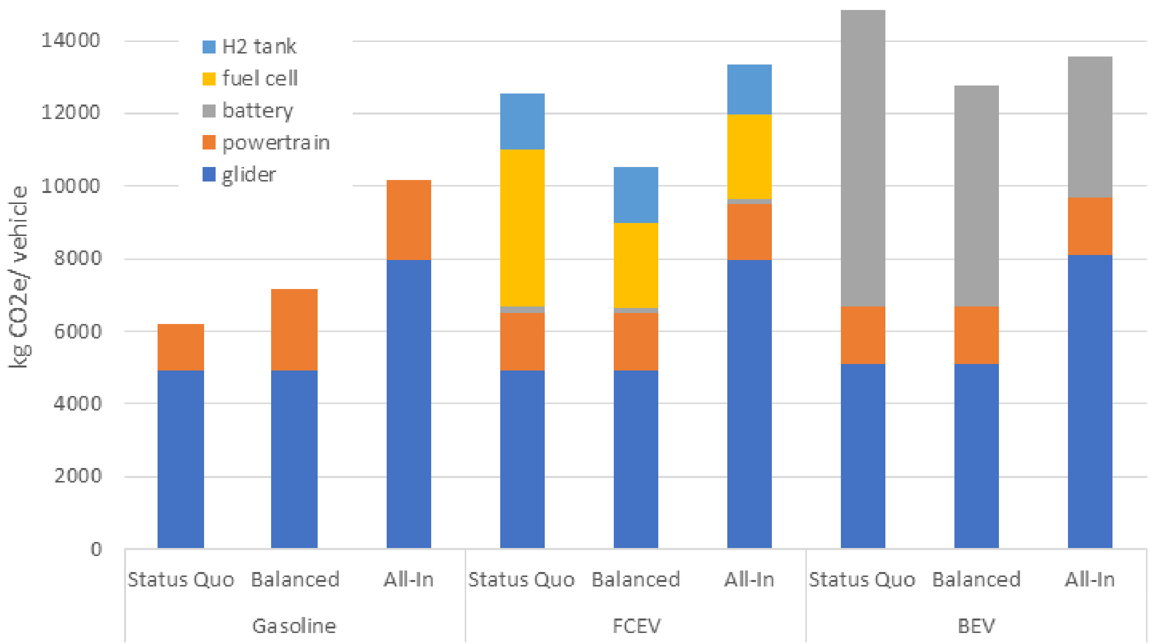


Figure 66: Detailed results GHG emissions from manufacturing of selected C-segment cars (2020).

The glider is similar for all drivetrain concepts. Variations occur in the additional components needed for the alternative drivetrain technologies. Exchanging the conventional powertrain with an electric powertrains changes the GHG emissions only slightly. However, the addition of the fuel cell and the type IV carbon-fibre reinforced hydrogen tank for the fuel cell car drive up the GHG emissions considerably. The electric car achieves a driving range of 500 kilometres according to the FVV focus group assumptions. C-segment cars have thus an 95 kWh Li-Ion battery (gross installed battery capacity, Status Quo). This raises the GHG emissions of the electric car compared to the gasoline car considerably.

- For the gasoline car, higher technology levels lead to an increase in GHG emissions from vehicle manufacturing. This GHG increase is at 17% for the Balanced scenario (compared to the Status Quo) and at 65% for the All-In scenario (also compared to the Status Quo).
- For the fuel cell car, GHG emissions in the Balanced scenario are 17% lower than for the Status Quo and only 5% higher for the All-In scenario (also compared to the Status Quo). The reason for this trend is lower platinum loading of the fuel cell in the Balanced and All-In scenarios compared to the Status Quo as well as the smaller hydrogen tank in the All-In fuel cell car, which partly balances out the additional emissions from the lightweight vehicle glider.
- The battery-electric car shows an opposite trend and has lower GHG emissions for the Balanced (-15%) as well as the All-In (-8%%) scenario compared to the Status Quo, resulting from increased energy density of the batteries and in the All-In scenario also from reduced battery capacity demand as a result of improved energy efficiency.

When looking at the results from vehicle manufacturing of conventional cars in more detail, we found that the increase in manufacturing emissions is mainly due to the additional vehicle components required for hybridisation (Balanced + All-In) and changes in the glider materialization due to light weighting (shift from steel to aluminium for All-In). However, the reader should keep in mind that while the higher technology levels lead to an increase in manufacturing emissions, they decrease the specific fuel demand and thus the GHG emissions from the vehicles use phase with fossil fuels and the demand for defossilised fuels supply.

For the battery-electric car, battery technology and capacity have a strong influence on the emissions from manufacturing, overlaying the effects of aluminium light weighting. All three technology levels achieve the same driving range (small passenger cars: 300km, all other passenger cars and light commercial vehicles: 500km).

- The improved battery technology for the Balanced scenario leads to a slight decrease in gross battery capacity (from 95 kWh to 92 kWh) while the rest of the car is unchanged.
- For the All-In scenario, the battery-electric vehicle uses a lightweight glider. Here, the gross battery capacity is decreased even further to 76 kWh, but GHG benefits are partly compensated by the change in glider materialisation to aluminium.

For the vehicle battery in Figure 67, cell manufacturing plays a key part in the GHG emissions (Agora Verkehrswende 2019a). Therefore, improvements in energy density (leading to less material being needed per kWh battery) and a diminished energy demand in cell manufacturing lead to considerably lower emissions for the Balanced (25%) and the All-In (40%) battery type compared to the Status Quo even under 2020s manufacturing conditions.

Defossilisation of the background system reduces the GHG emissions for all battery concepts in a similar fashion. Here, we shifted cell manufacturing to Europe and used renewable energy sources. Further improvements in the worldwide material sourcing also lower the GHG emissions of the battery. This is especially true for the 2050b scenario of background system defossilisation, where no fossil GHG emissions from any part of the worldwide process chain remain.

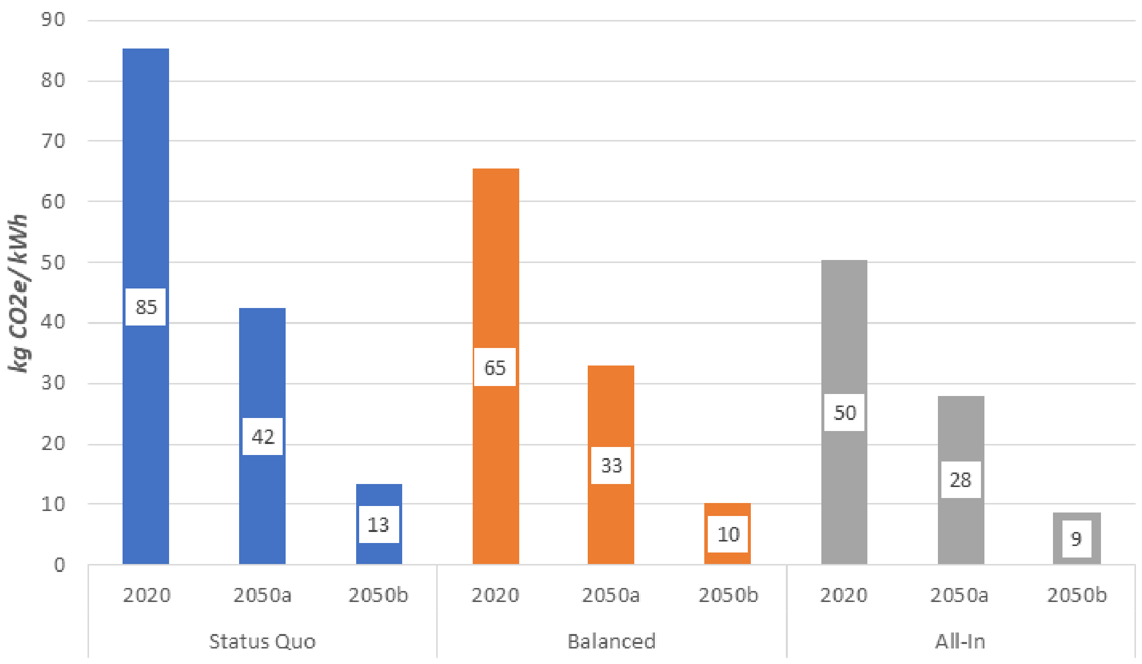


Figure 67: GHG emissions for manufacturing of 1kWh battery.

Figure 68 shows the GHG emissions from vehicle manufacturing in the year 2020 for all drivetrain concepts and technology levels of a C-segment car. In general, all conventional cars show a similar trend like the gasoline car with slightly higher GHG emissions for the diesel, Methane, DME and H_2 combustion. GHG emissions from car manufacturing rise with the technology level. Only BEV and FCEV show improvements in GHG emissions for the Balanced and All-In (only BEV) scenarios.

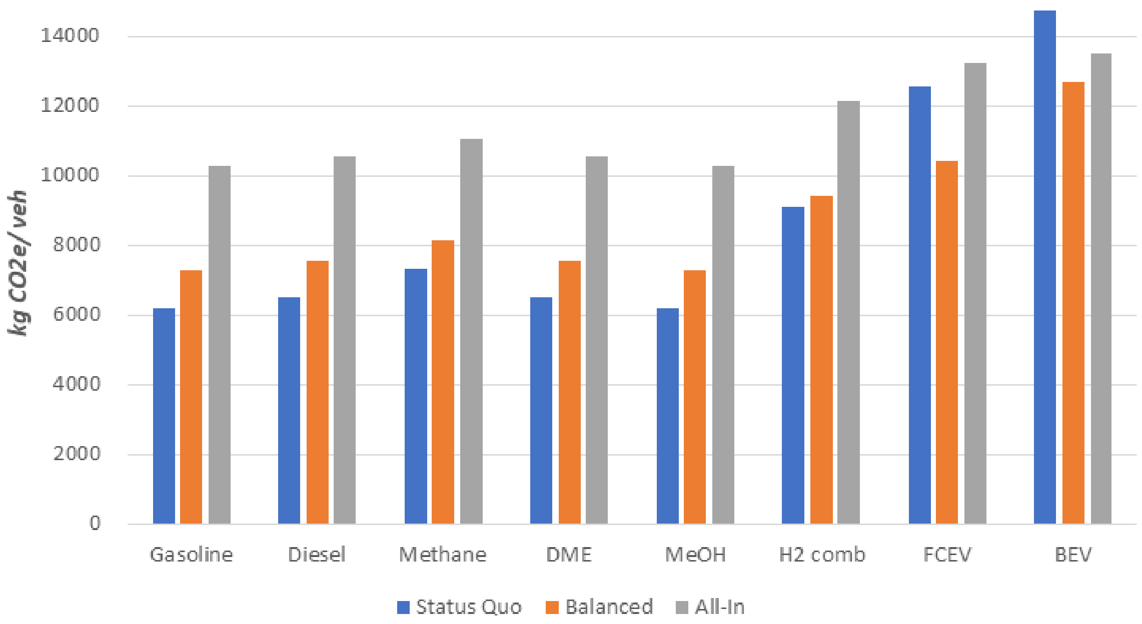


Figure 68: GHG emissions from manufacturing of a C-segment car (2020) with different technology levels.

In Figure 69 the GHG emissions of a C-segment car with a Balanced technology level with future defossilisation of material supply and production processes are given. A decrease of the GHG emissions in the background system (improvements in materials and energy emission factors as explained in 10.1.2) leads to a strong future decrease for the manufacturing emissions of all drivetrain concepts. Overall trends (e.g. higher emissions for the alternative drivetrain concepts) remain unchanged.

The scenario 2050a decreases GHG emissions between 47% and 60% for the different drivetrain concepts. This is mainly due to a defossilisation of car manufacturing in Europe as well as improvements in the pre-chains of the most important car materials like steel, aluminium and copper. Since the rest of the world lags behind the European defossilisation by 10 years, not all materials are entirely decarbonised yet (see also section 10.1.2 for more details).

In the 2050b scenario the entire world is assumed to be fossil free by 2050. Thus, only the unavoidable GHG emissions remain. Here, GHG emissions are decreased by more than 80% for all vehicle configurations.

Looking at other size classes and heavy-duty vehicles, we have observed similar trends like for the C-segment cars. A complete overview of all GHG emission results from vehicle manufacturing can be found in annex 15.2.2.

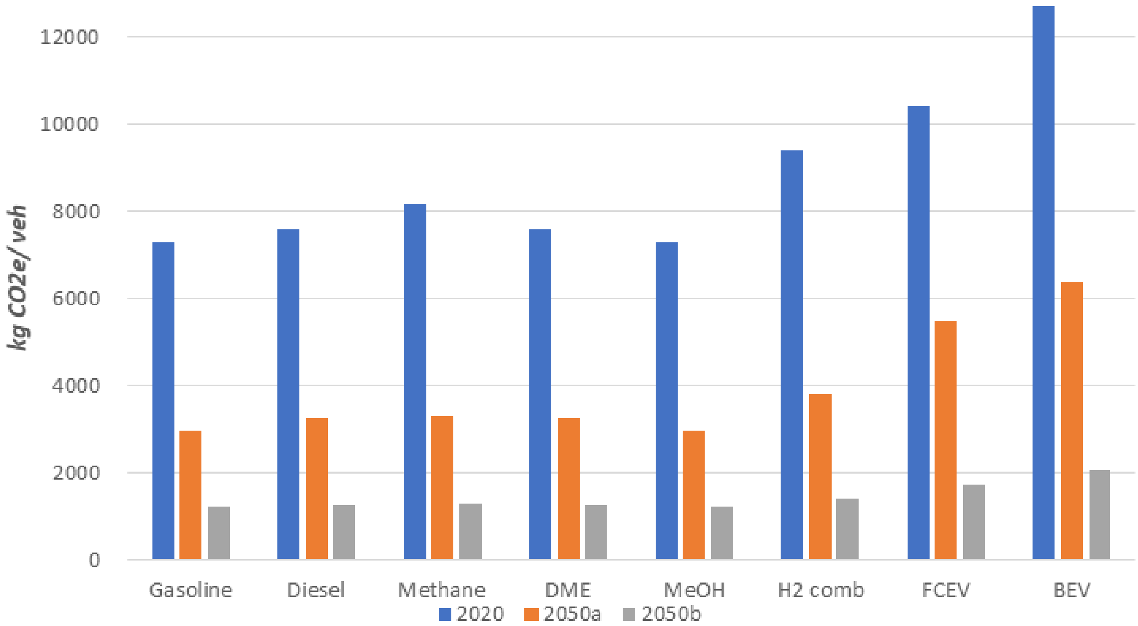


Figure 69: GHG emissions from manufacturing of a C-segment car (Balanced) with future defossilisation.

10.2.2.5 Other environmental impacts from vehicle production

Generally, we observed similar trends for acidification, eutrophication and PM formation like for the GHG emissions. As shown in Figure 70, cars with alternative drivetrains have higher impacts than the conventional cars. For conventional cars, the emissions rise with the technology level, while for the BEV they decrease for Balanced and All-In compared to the Status Quo. A strong decrease was also found for FCEV from Status Quo to Balanced due to the reduced platinum content of the fuel cell.

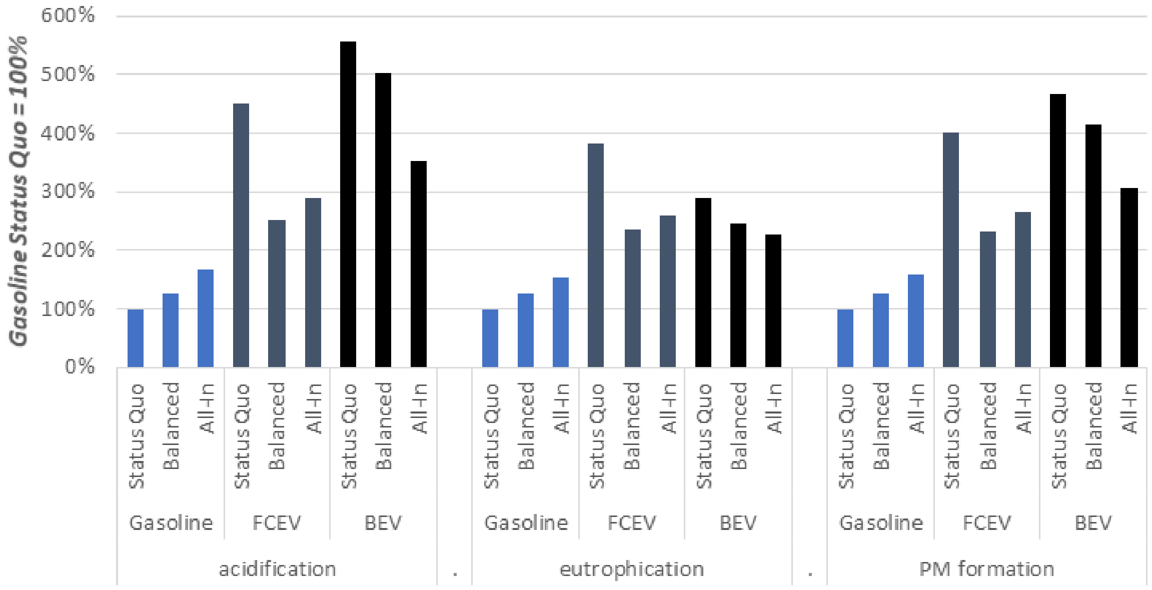


Figure 70: Acidification, eutrophication and PM formation for manufacturing a C-segment car (2020).

Lowering the greenhouse gas emissions also lowers all other impact categories. All other trends (e.g. alternative drivetrains have higher manufacturing emissions than conventional drivetrain concepts) remain unchanged.

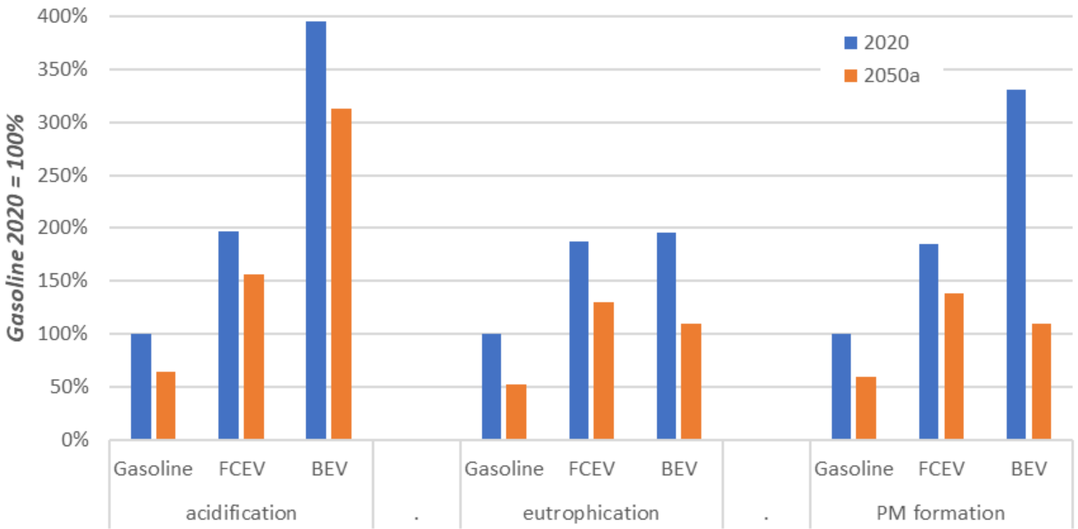


Figure 71: Acidification, Eutrophication and PM formation for manufacturing a C-segment car (Balanced) 2020 and with defossilisation 2050a.

10.2.2.6 Specific environmental impacts from vehicle disposal

In this study, we we also include the end-of-life phase of the vehicles. Disposal usually takes place in several steps: First, the vehicle is manually dismantled into various parts and the tires, starter batteries, remaining mineral oil and glass are separated and disposed of. Subsequently, the remaining vehicle is dismantled in a shredder. Various materials can be separated from this shredder fraction for recycling. This mainly concerns steel and iron, aluminium and copper. In addition, the plastic fraction is separated and disposed of. What remains are the shredder residues, which are mostly incinerated. We used data sets from ecoinvent (Wernet et al., 2016) for the disposal of the various waste fractions. The waste quantities of the fractions resulted from the specific material composition of the vehicles.

Overall, we found that the impact of the vehicle disposal is low. Figure 72 shows the specific GHG emissions from manufacturing and disposal of a C-segment car (Balanced, 2020). The disposal only accounts for approximately 5 percent of the GHG emissions.

We observed a similar trend for the other impact categories.

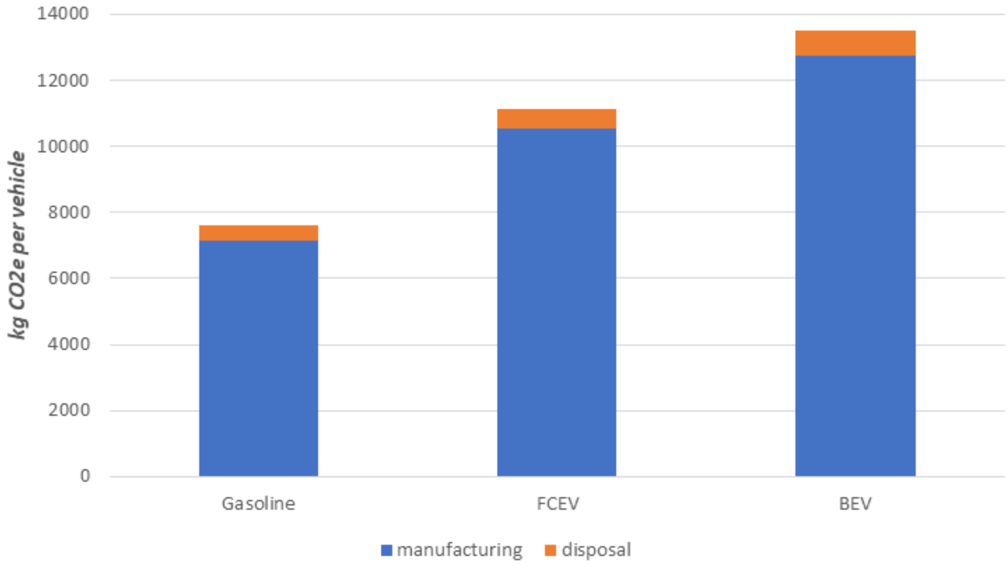


Figure 72: GHG emissions from manufacturing and disposal of a C-segment car (2020, Balanced).

10.2.2.7 Specific material demand

In this study, we analysed material demand in vehicle production for selected critical raw materials. Platinum is a key material for fuel-cell vehicles, furthermore platinum group metals are required in the exhaust treatment of conventional cars. Lithium and cobalt are key materials for battery-electric mobility with current battery technologies. Further materials, such as copper are required in vehicles with all drivetrain technologies as well as in several components of the fuel supply chain. We modelled the vehicle-specific demand for all materials considered in this study based on our model eLCAr and including recent literature and feedback from the focus groups within the project.

Cars with internal combustion engine need platinum group materials (PGM) for the exhaust treatment, and platinum, rhodium and palladium can be interchanged. Experts of the FVV focus group supplied current platinum group metal demand data for the different powertrain options for the internal combustion engines as well as the fuel cell. In general, diesel engines need a more sophisticated exhaust gas treatment than gasoline engines, resulting in a higher PGM demand. H_2 combustion and methanol engines realise similar PGM demand like the gasoline variant. However, current Methane (CNG) cars need even more PGM for the exhaust gas treatment than diesel cars due to their higher light-off temperatures. The PGM demand for the conventional vehicles remains constant for the different technology scenarios.

Fuel cells on the other hand require platinum. Specific platinum amounts for fuel cells today are 0.43 g per kW. Future developments (used for the Balanced and All-In scenario) will lower this platinum demand to 0.165 g per kW of fuel cell (Sternberg et al., 2019).

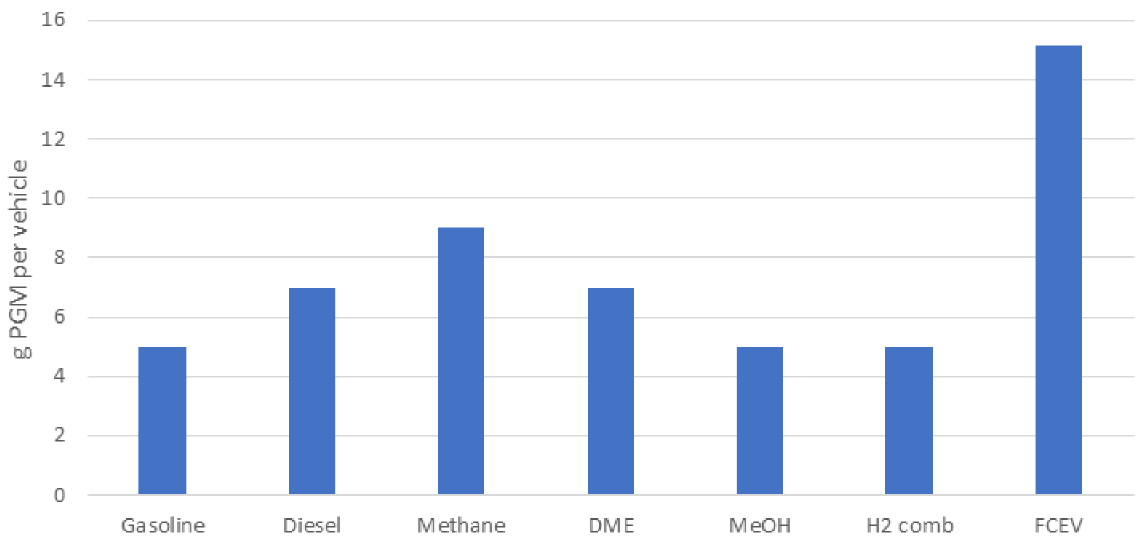


Figure 73: PGM in a C-segment car (Balanced).

Lithium and cobalt are key materials for electric mobility with current battery Li-Ion NMC technologies. In this study, we consider Li-Ion NMC as the only battery technology (see explanations in section 10.2.2.1). In the individual technology levels, we have different energy densities and cathode material compositions affecting the specific lithium and cobalt demand.

- In Figure 74 we show that the cobalt demand per kilowatt-hour of battery significantly decreases with the shift from Status Quo (NMC622, 150 Wh/kg) to Balanced (NMC811, 200 Wh/kg). Better energy densities lead to a further decrease of the amount of cobalt in the battery for the All-In scenario (solid-state NMC811).
- The lithium demand for Balanced is slightly lower than for Status Quo because of the increase in energy density. However, switching to an All-In solid-state NMC811 battery substantially increases the lithium demand. This is due to the additional lithium demand from the lithium anode of the solid-state battery.

Bigger batteries directly lead to a higher material demand. In consequence, both materials are primarily an issue for battery-electric vehicles, but less for hybridized conventional powertrains and for fuel cell vehicles.

Alternative battery technologies with lower demands of lithium and cobalt, but also lower energy densities, are already in the market (lithium iron phosphate batteries LFP) or close to market entry (e.g. sodium-ion batteries SIB), but have not been selected and analysed in detail in this study (see section 10.2.2.1). A mix of different battery technologies as expected in most forecasts and scenarios would substantially reduce global material demands. Therefore, we roughly estimated potential reductions of total lithium and cobalt demand in our scenarios with alternative battery technologies in an additional sensitivity analysis (see section 11.3.1).

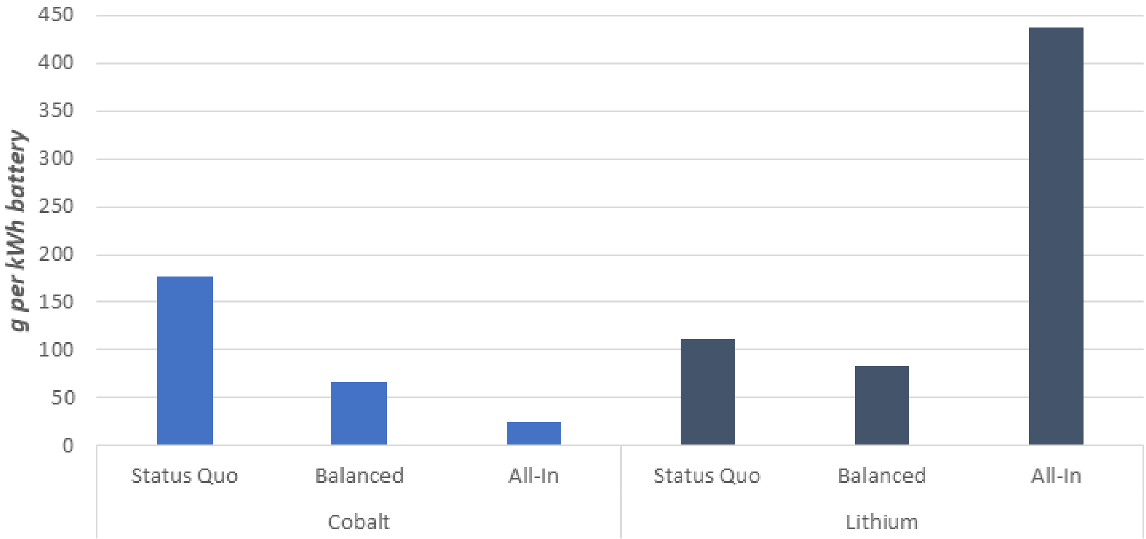


Figure 74: Cobalt and lithium in the Lithium-Ion batteries.

The copper demand is fairly similar for all drivetrain concepts except for the battery- electric vehicles. It increases slightly for the Balanced and All-In scenario gasoline car due to the hybridisation. We observed the highest copper demand for the electric vehicles. Here, the vehicle battery drives up the overall copper demand of the car significantly.

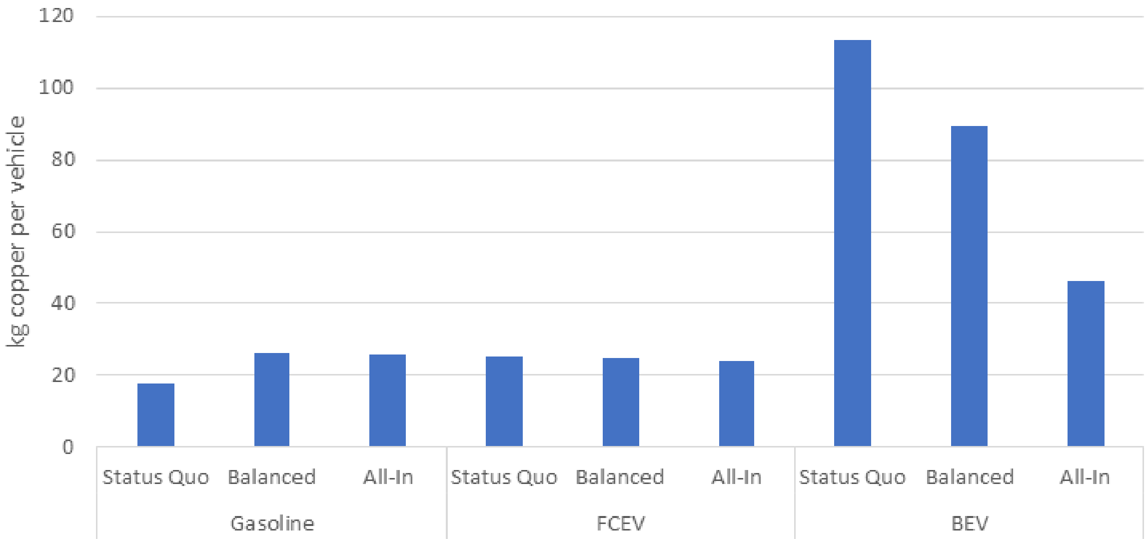


Figure 75: Copper in a C-Segment car.

10.2.3 Vehicle Operation

Environmental impacts from vehicle operation are of high relevance for the scenario results. As long as transport is not fully defossilised, the consumption of fossil fuels will lead to high, tailpipe (tank-to-wheel) as well as upstream (well-to-tank) greenhouse gas emissions. Furthermore, also defossilised transport activities lead to environmental impacts from vehicle operation, particle abrasion from tires, brakes and road surface as well as minor air pollutant tailpipe emissions, which also occur with renewable fuels. Defossilised fuel supply has no significant direct emissions from running fuel production, except for methane slip during production and transport of defossilised methane. In the following, we explain the methodology and databases of relevant environmental impacts from vehicle operation.

10.2.3.1 Specific emissions from fossil fuels

In this study, we apply the same tank-to-wheel specific CO_2 emission factors for fossil fuels as in the European standard EN ISO 16258 “Methodology for calculation and declaration of energy consumption and GHG emissions of transport services (freight and passengers)”. Tank-to-wheel emissions of other greenhouse gases (CH_4, N_2O) are of very low relevance (except for gas vehicles) and depend on the vehicle technologies. They are calculated with the same methodology as tank-to-wheel air pollutant emissions (see following explanations). For well-to-tank GHG emissions as well as other environmental impacts, we apply up-to-date factors from our model TREMOD (ifeu, 2020) and from the SYSEET project (Liebich et al., 2021).

Table 27: Specific emission factors and environmental impact potentials for fossil fuels.

	CO_2 ttw	**GHG wtt**	**Acidification potential**	**Eutrophication potential**	**PM formation potential**
	g/kWh	*g CO2 eq / kWh*	*g SO_2 eq / kWh*	*g PO_4 eq / kWh*	*g $PM_{2.5}$ eq / kWh*
gasoline	264.2	56.7	0.283	0.0746	0.230
diesel	263.9	54.7	0.248	0.0755	0.208
CNG	202.3	35.3	0.126	0.0313	0.097
LNG	202.3	44.5	0.074	0.0138	0.092
kerosene	257.4	54.7	0.248	0.0755	0.208

Additionally, we assume an average biofuels blending ratio of 7% (except for kerosene) with a specific well-to-wheel GHG reduction of 60% compared to fossil fuels in all years.

10.2.3.2 Specific tailpipe emissions

Today’s acidification, eutrophication and PM formation potentials from road transport result primarily from tank-to-wheel emissions of air pollutants (NO_x, NMVOC, NH_3, SO_2, exhaust and non-exhaust particles) during vehicle operation. Specific air pollutant emissions depend strongly on the fuel type and on the emission standard of the vehicles. Furthermore, low quantities of the greenhouse gases CH_4 and N_2O are emitted during vehicle operation regardless of whether fossil or renewable fuels are burned. We used up-to-date emission factors for all road vehicles, which are available in the Handbook Emission Factors for Road Transport HBEFA version 4.1 (Notter et al., 2019).

No detailed information on current road fleet composition in all EU27+UK countries could be derived as part of this project, detailed information was only available for the German road vehicle fleet. However, as the European vehicle fleet is on average significantly older than the fleet in Germany (Papadimitriou et al., 2013), fleet compositions from Germany cannot be applied directly for EU27+UK calculations. In this study, we therefore make the simplified assumption that, on average, vehicles in Europe are around 3-5 years older than in Germany. Resulting inaccuracies in the pollutant emissions of the EU27+UK fleet in the year 2020 are low, since specific emissions especially of passenger cars hardly improved in the past years before the introduction of the Euro 6d temp emissions standard.

For all new vehicles coming into the fleet after 2020, we assume the latest European emission standard Euro 6d. Accordingly, the whole vehicle fleet in 2050 meets Euro 6d.

In this study, we analyse several alternative powertrains and fuels that are not yet on the market and consequently not covered in the HBEFA emission factors database. However, drivetrain technologies are mainly comparable to existing gasoline and diesel drivetrains. We therefore take the following the following assumptions:

- DME vehicles have the same specific emissions as diesel vehicles.
- Methanol vehicles have the same specific emissions as gasoline vehicles.
- H_2 combustion vehicles have the same specific NO_x emissions as gasoline vehicles, but no further tailpipe emissions

All drivetrains, including fuel cell and battery-electric vehicles have the same specific non-exhaust particle emissions from abrasion (brake, tires, road surface).[21]

SO_2 emissions do not depend on the vehicle technology, but on the sulphur content in fuels. Accordingly, we calculate SO_2 emissions only for vehicle operation with fossil fuels, but not for operation with defossilised fuels, which are expected to be 100% sulphur free.

Specific tailpipe emissions in the non-road sector (rail, navigation, aviation) have very low importance for the total European transport. We apply specific emission factors from our model TREMOD, which covers the latest European emission standards for these transport modes.

10.2.3.3 Energy efficiency and specific emissions from fuel import with tank ships

In the international scenario, environmental impacts also come from fuels import with ocean-going tank ships. We adopted specific energy consumption and emission factors for today's ships from the emission calculation model for international freight transport EcoTransIT World (EcoTransIT, 2021) and future fuel efficiency improvements of 27% up to 2050 based on (DNV-GL, 2018). In our scenarios, all tank ships are powered by the same defossilised fuel they import. Nevertheless, pollutant emissions are generated that contribute to other environmental impacts. The following ship classes covered in the EcoTransIT database are assumed based on input from the focus groups and reviews with additional literature research on ships in service today:

- FT fuel, methanol and DME: VLCC (Very Large Crude Carrier)[22]
- Methane (as LNG): SuezMax-like[23]

10.2.3.4 Methane slip during fuel production and distribution of defossilised methane

GHG emissions for the production of defossilised fuels occur largely during the building-up of the infrastructure. Direct emissions during running fuel production are very low and come primarily from fuel transport, which is included in the vehicle mileage in the scenarios. However, in the methane pathway, GHG contributions from fuel production could be relevant for the total GHG emissions due to unavoidable methane slip in several process steps. Therefore, we additionally estimated potential methane slip from methane production including ship import.

During fuel production, methane slip occurs at several process steps, mainly refuelling and storage, liquefaction -and transport via pipelines and ships. Methane slip during ship transport depends highly on the ship propulsion. LNG spark ignition engines have 1.5-2.5% methane slip, however LNG diesel engines (dual-fuel) can reduce methane slip to 0.1% per kWh fuel burned (ICCT, 2020; IMO, 2020; Thinkstep, 2019). In this study, we assume that not only road vehicles in Europe, but also LNG tanker ships for methane import use advanced propulsion technologies and can, therefore, minimize methane slip.

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[21] In principle, it can be assumed that electric vehicles have different abrasion emissions due to their higher weight (higher tire and road surface abrasion), but also due to the recuperation of braking energy (lower abrasion from brakes). However, there are not yet reliable data available that allow a differentiated modelling. (OECD, 2020) states "Assuming lightweight EVs (i.e. with battery packs enabling a driving range of about 100 miles), the report finds that EVs emit an estimated 11-13% less non-exhaust PM2.5 and 18-19% less PM10 than ICEVs. Assuming that EV models are heavier (with battery packs enabling a driving range of 300 miles or higher), however, the report finds that they reduce PM10 by only 4-7% and increase PM2.5 by 3-8% relative to conventional vehicles." Overall, the resulting inaccuracies for the total PM formation potential, which also includes exhaust particles and the formation of secondary particles, are likely to be small.

[22] E.g. Sirius Star, New Diamond.

[23] Q-Max class for liquefied natural gas, e.g. Mozah, is not covered in EcoTransIT, therefore the next class up has been selected.

Table 28 shows the derived GHG emission factors for methane slip in the fuel production. Methane slip in the international scenario is about 27% higher than in domestic scenarios. In general, GHG emissions from methane slip in the production of defossilised methane are very low (only 3-4% to well-to-tank GHG emissions for fossil methane) and therefore without major influence on the total GHG emissions in this fuel pathway.

Table 28: Specific GHG potential from methane slip in the methane fuel production.

	Domestic	**International**	Data source
	g CO_2eq/kWh	*g CO_2eq/kWh*	
Refuelling	0.500	0.500	(Hagos / Ahlgren, 2018)
Storage	0.161	0.161	(ConocoPhillips, 2015)
Transmission	0.163	0.163	(Wernet et al., 2016)
Pipeline	-	0.094	(Wernet et al., 2016)
LNG carrier	-	0.205	(Brynolf et al., 2014)
Liquefaction-	0.295	0.295	(SPHERA, 2019)
Total	**1.120**	**1.418**	

10.3 GHG Emissions in the 100% Scenarios

In this section, we present the scenario results of the environmental impacts analysis for the defossilisation of the transport sector in EU27+UK. The focus of the results is on greenhouse gas emissions. Other environmental impacts considered are the potential for acidification, eutrophication and particle formation, as well as land use associated with the infrastructure for renewable power generation required for defossilised final energy supply.

The basis for modelling the environmental impacts in the scenarios are the specific environmental impacts from the production of vehicles and infrastructure as well as vehicle operation (see Chapter 73) and the following scenario-specific developments:

- Annual new vehicle registrations by vehicle size, powertrain and technology level (Status Quo, Balanced, All-In) and annual vehicle disposals
- Annual build-up rates for fuel supply chain infrastructure (new construction, replacement of plants after end of its service life)
- Annual final energy demand of fossil and defossilised fuels
- Annual vehicle mileage and transport demand in road and non-road transport

Similar to national emission inventories, all environmental impacts are accounted for in the year when they physically occur. Accordingly, we do not distribute emissions resulting from vehicle production and fuel supply chain (FSC) infrastructure over their operational life (years, km, fuel output), but account them fully in the year a plant is built and starts operation.

In this study, we modelled annual GHG emissions for a total of 84 scenario configurations (7 fuel pathways, 3 technology levels, 2 energy sourcing profiles and 2 defossilisation levels of the background system for vehicle and infrastructure production in 2050). To keep the results clear and comprehensible, we will therefore focus on crucial results in selected scenarios, but not always present all scenario configurations.

10.3.1 Development of annual GHG Emissions

The objective of all 100% backcasting scenarios is a complete defossilisation of the transport sector in EU27+UK by 2050. This is reflected accordingly in the future development of GHG emissions. In the case of full defossilisation by 2050, including global material supply and production processes of vehicle production and infrastructure build-up (defossilisation level 2050b), only those GHG emissions remain in 2050 that are unavoidable even with an energy supply based exclusively on renewable electricity (process emissions, methane slip, etc.).

Accordingly, annual GHG emissions in the year 2050 are in all fuel pathways 95-97% lower than in the baseline year 2020. Furthermore, annual development trends are similar between the different fuel pathways in case of similar assumptions on vehicle technology levels and identical ramp-up speed of defossilisation in the vehicle fleet, as the comparison of Balanced scenarios in Figure 76 shows.

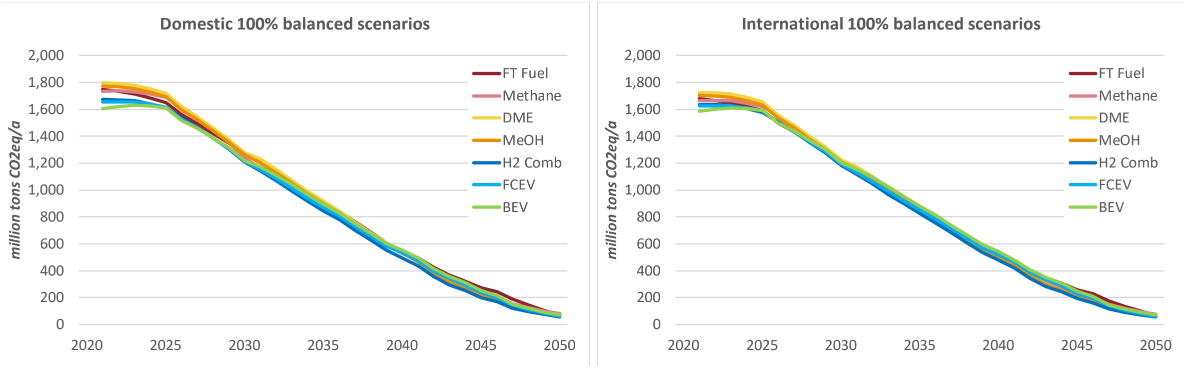

Figure 76: Annual GHG emissions 2021-2050 in all 100% balanced scenarios with defossilisation 2050b.

A closer look at the composition of annual emissions shows similarities and differences between the pathways, exemplarily shown for FT Fuel, FCEV and BEV scenarios in Figure 77. Vehicle operation of the out-phasing vehicle fleet with fossil fuels (already including 7% bio fuel blend) has a dominating role for the annual GHG emissions in all fuel pathways[24]. Though the share of defossilised fuels increases gradually and a 100% defossilisation is achieved in 2050 in all scenarios, GHG emissions from burning fossil fuels are the main source of annual GHG emissions even in 2040-2045. In the total period 2021-2050, vehicle operation with fossil fuels (already including 7% bio fuel blend) contributes 66-74% to GHG emissions.

Contributions from vehicle production and build-up of fuel supply chain infrastructure gain higher shares in the later years. They show clear differences between the fuel pathways.

- In the FT fuel pathway, build-up of FSC infrastructure has higher contributions than in FCEV and BEV scenarios due to the substantially higher demand of power generation capacities for synthetic fuel production compared to hydrogen production and direct use of electricity in the vehicles.
- Conversely, FCEV and BEV pathway have higher annual GHG emissions from vehicle production as the specific GHG emissions during the production of fuel cell and battery-electric vehicles are considerably higher than for vehicles with conventional powertrains.

Figure 77 furthermore shows the contributions of different vehicle groups to the annual GHG emissions. Light-duty vehicles (cars, SUV, LCV) make the largest contribution with about 60% of the GHG emissions in 2021 in our scenarios and 66-75% in 2050. Heavy-duty vehicles (trucks and buses) contribute 16-35%, only 5-10% come from non-road transport.

[24] GHG emissions from operation include also small amounts of unavoidable emissions (CH_4, N_2O) from defossilised fuels (see section 10.2.3). However, fossil fuels account for 99.5-99.8% (in methane scenarios still >99%) of emissions from vehicle operation.

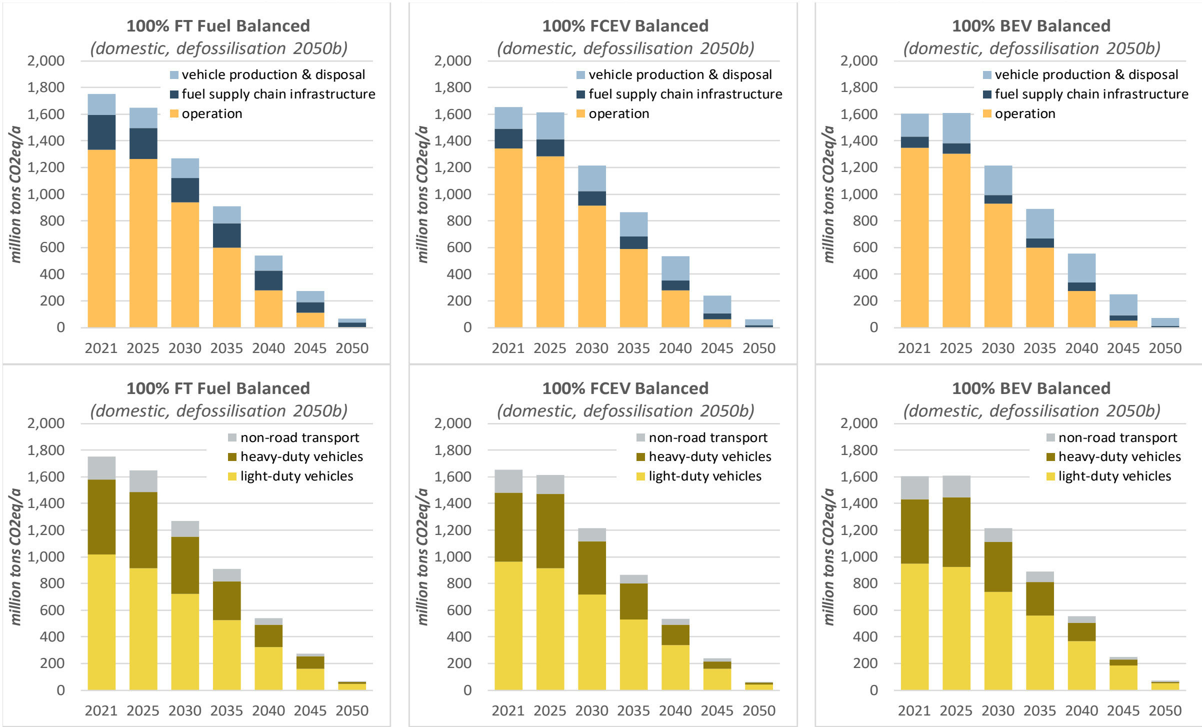

Figure 77: Annual GHG emissions 2021-2050 in selected 100% scenarios with linear ramp-up of defossilised vehicle fleets by sub segments (top) and vehicle categories (bottom).

10.3.2 Cumulative GHG Emissions in all 100% backcasting Sscenarios

Assessing the GHG mitigation effectiveness of the different defossilisation pathways requires not only the question to which level GHG emissions can be reduced by 2050. The decisive factor is rather how much GHG is emitted over the entire period, so which GHG backpack is associated with the ramp-up to 100% defossilisation of transport. For this purpose, we evaluate the cumulative emissions of all scenarios, i.e. we add up the annual emissions from 2021 to 2050 to the total emissions generated over this period.

Figure 78 shows the cumulative GHG emissions 2021-2050 for all 42 scenarios with assumed worldwide defossilisation up to 2050 (2050b). As expected from the similar annual developments, the cumulative GHG emissions in all pathways are of a comparable order of magnitude. However, the composition of cumulative GHG emissions differs between the pathways:

- Vehicle operation with fossil fuels has a dominating role for cumulative GHG emission in all defossilisation pathways with a total contribution of 66-74%.
- The ramp-up of infrastructure for defossilised final energy supply contributes to total cumulative GHG emissions in the scenarios only 5% to 20% with lowest contributions in 100% electric scenarios and highest contributions in scenarios with 100% FT fuel.
- Vehicle production and disposals contribute 11-24% to total cumulative GHG emissions in the 100% scenarios with lowest contributions in 100% FT fuel scenarios with Status Quo vehicle technology and highest contributions in 100% electric All-In scenarios.

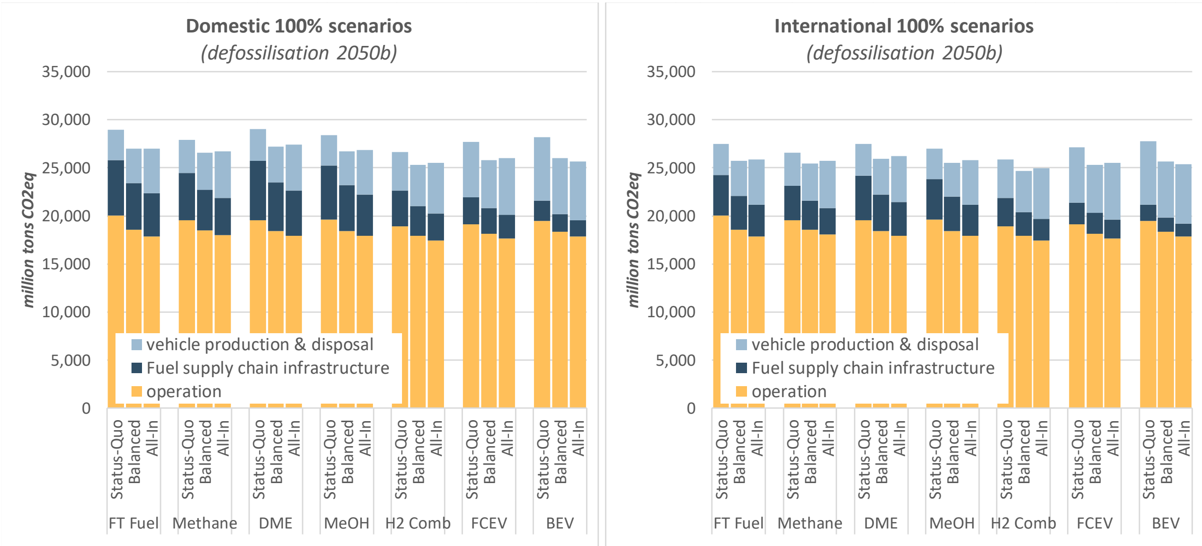

Figure 78: Cumulative GHG emissions 2021-2050 by sub segments in all Domestic and International 100% scenarios with linear ramp-up of defossilised vehicle fleets.

Improved vehicle fuel efficiencies from Status Quo to Balanced lead to 4-8% additional GHG reduction in all fuel pathways. Primarily, GHG emissions from vehicle operation with fossil fuels decrease, but also the demand of defossilised fuels and thus GHG emissions from FSC infrastructure build-up. In pathways with hydrocarbon fuels and, thus, retention of internal combustion engines, these emission reductions are partly compensated by additional GHG emissions from vehicle production due to the additional hybridisation. In contrast, vehicle production in FCEV and BEV pathways contributes additional emission savings due to improved fuel cell and battery technologies. However, further efficiency improvements through aluminium lightweighting in the All-In scenario do not lead to any significant additional changes in cumulative emissions. The further GHG savings in operation and FSC infrastructure are roughly offset by the additional emissions from vehicle production.

International energy sourcing slightly reduces cumulative GHG emissions in all scenarios. GHG contribution from FSC infrastructure decreases as a result of lower demands on building-up power generation capacities due to higher annual operation time (full-load hours) at good international locations. These emission savings are only partly offset by the additional demand for import infrastructure (pipelines, submarine cables, additional defossilised fuel demand for tank ships). For hydrocarbon fuels, the additional GHG savings are 4-5%, for hydrogen-based pathways 2-3%. In the BEV scenarios, GHG emissions are about 1% lower, thus showing no significant GHG difference between domestic and international energy sourcing.

Figure 79 shows the cumulative GHG emissions in the 100% backcasting scenarios differentiated by the time periods when the emissions occur. In all scenarios the GHG backpack is dominated by emissions up to 2030. From a total of 24.7 to 29.0 gigatons of cumulative GHG emissions, 14.8 to 16.7 gigatons occur in the next 10 years (55-60% of cumulative emissions in the scenarios). Less than 10% of the emissions occur after 2040. This picture is in line with expectations, as the consumption of fossil fuels, which dominate overall emissions, is still highest in the next 10 years and will only gradually decrease. It thus clearly underlines that emission levels in the target year 2050 are less crucial for minimising cumulative GHG emission, but fast action for a quick and substantial reduction in fossil fuel demand already in the next years is the decisive factor.

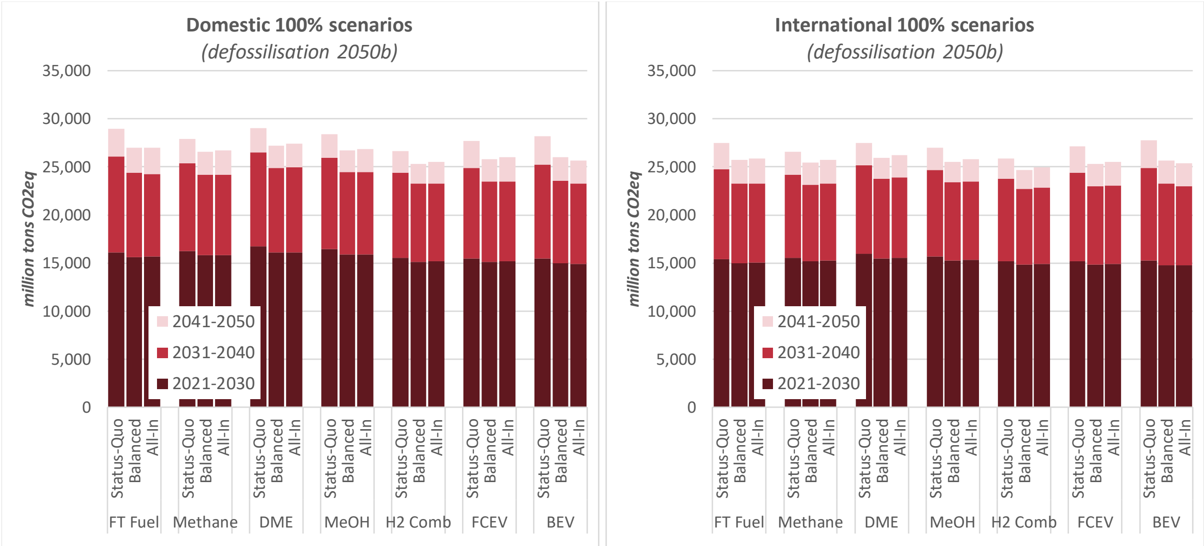

Figure 79: Contributions to cumulative GHG emissions 2021-2050 by emission periods in all Domestic and International 100% scenarios with linear ramp-up of defossilised vehicle fleets.

In Figure 80, the total cumulative GHG emissions from road transport of all 42 backcasting scenarios are shown. The overall range across all scenarios is 3.1 gigatons (14% of the total level). However, no ranking of the GHG mitigation effectiveness of different fuel pathways can be derived from this order. The results of the 12 scenarios with the lowest cumulative emissions are only 2% apart, including hydrocarbon fuels, H_2 as well as electric mobility. All three defossilisation options are also found in scenarios with higher cumulative GHG emissions. This is because the bandwidth of GHG emissions is not only determined by the chosen fuel pathway, but scenario assumptions on vehicle efficiency and energy sourcing (domestic, international) have a high relevance for the results. Even small changes in the scenario assumptions (e.g. battery and fuel cell sizes, lightweight construction shares) will lead to a different order of defossilisation scenarios in the cumulative GHG emissions. E.g. the FVV focus group decided for 100% penetration to assume full customer use case coverage and thus high operating ranges for all drivetrains (300 - 500km WLTP range + heating)and consequently large battery sizes in the BEV scenarios. Assuming smaller batteries would reduce GHG emissions from electric vehicle production and in consequence also cumulative GHG emissions.

Most importantly, in this study we have only modelled backcasting scenarios with identical ramp-up rates for all fuel pathways of vehicle new registrations with alternative drivetrains and accompanying build-up of energy/fuel supply chain infrastructure, which would be required to achieve a 100% defossilised transport sector by 2050. In 2030, a share of 28% of the respective alternative vehicle drivetrain technology and defossilised final energy supply is assumed in all scenarios. This means e.g. in the Balanced scenarios ~1,000 TWh FT fuel, 76 million fuel cell cars and 1.9 million trucks with green hydrogen or 78 million battery-electric cars in the vehicle stock with additionally generated renewable electricity.

In reality, however, considerable differences in the actually reachable ramp-up speed exist, especially in the short and medium term. They depend on the market readiness of different drivetrains (e.g. availability of fuel cell vs. battery-electric cars) and fuel supply chain technologies (e.g. large-scale industrial production of syngas by RWGS in FT fuel production), on the highly differing expansion needs for renewable electricity production (synthetic fuels vs. direct electricity use) and other preconditions (e.g. particular production capacities, skilled workers). In a sensitivity analysis in the following section we show that ramp-up speed is a crucial factor for the assessment of the GHG mitigation effectiveness of a defossilisation pathway and, thus, also on comparative assessments between different pathways.

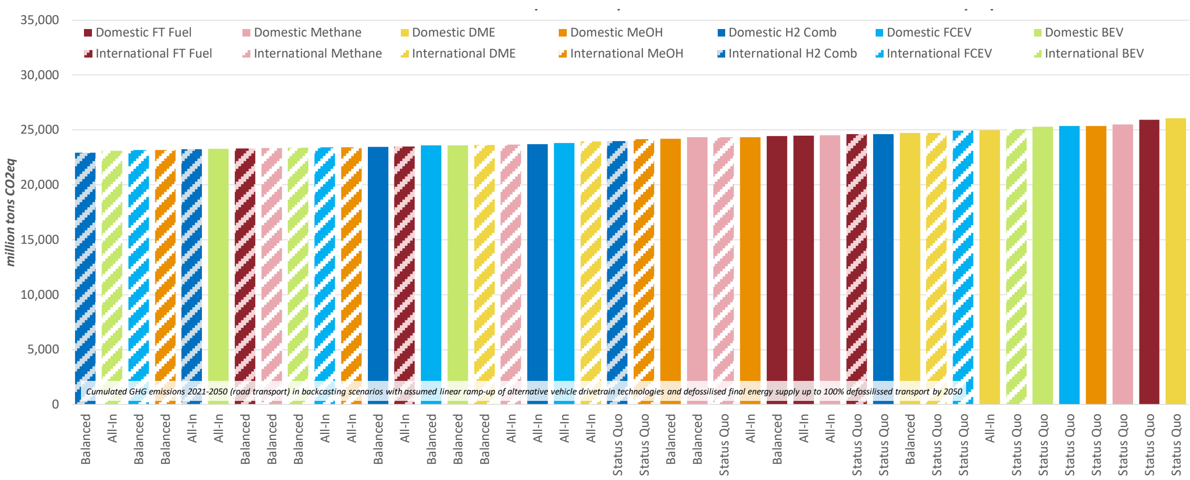

Figure 80: Cumulative GHG emissions 2021-2050 in all 100% backcasting scenarios for road transport with linear ramp-up of defossilised vehicle fleets and final energy supply in the order of cumulative emission level.

In the 100% backcasting scenarios, the respective defossilisation pathway is assumed equally for light-duty vehicles and heavy-duty vehicles. However, different fuel pathways and vehicle efficiency levels can be more GHG effective for cars than for trucks. The bandwidth between lowest and highest cumulative GHG emissions is 15 % (2.3 gigatons) for LDV, but 38 % (2.7 gigatons) for HDV, resulting from the fuel pathways as well as from different fuel efficiency improvements between vehicle technology levels in the light-duty respective heavy-duty sector.

10.3.3 Relevance of ramp-up speed for cumulative GHG emissions

In all 100% backcasting scenarios, we assume a linear ramp-up of new registrations of alternative drivetrain technologies and, thus, equal penetration rates of the vehicle fleets with defossilised final energy supply until 100% market penetration is achieved in 2050. In reality, however, actually reachable ramp-up speed differs considerably between the technology paths, especially in the short and medium term. This is driven by the market readiness of drivetrains (e.g. availability of fuel cell vs. battery-electric cars) and fuel supply chain technologies (e.g. large-scale industrial production of syngas by RWGS in FT fuel production), highly differing expansion needs for renewable electricity production (synthetic fuels vs. direct electricity use) and other preconditions (e.g. particular production capacities, skilled workers). On the one hand, a lack of market readiness or other barriers can lead to significantly delayed market ramp-ups. On the other hand, under optimal conditions, the market ramp-up of a defossilisation pathway could also take place more quickly and, in the best case, a complete defossilisation of transport in Europe could be achieved before 2050.

The cumulative GHG emissions until 2050 are mainly determined by the gradually decreasing use of fossil fuels (see previous sections). Therefore, ramp-up rates are not solely relevant for achieving 100% defossilised transport by 2050. Moreover, the development of the next 10-15 years is decisive for how fast the consumption of fossil fuels can be reduced by increasing the use of defossilised energy sources.

An in-depth analysis of realistically possible ramp-up speeds is beyond the scope of this study. In a sensitivity analysis, we estimate for legacy fleet compatible Fischer-Tropsch fuel (FT Fuel) as an exemplary pathway how different market ramp-up speeds affect the development of GHG emissions and in consequence the assessment of the GHG mitigation effectiveness of this pathway. In a follow-up study, we plan to analyse realistic and feasible ramp-up speeds for all defossilisation pathways considered here.

Figure 81 (left) shows assumed FT fuel ramp-up speeds in the sensitivity analysis. Based on the ramp-up in the backcasting scenario, reaching 28% FT fuel on total fuel supply in the year 2030 we modelled to alternative ramp-up speeds:

- Slower ramp-up: FT fuel contributes 8% to total fuel consumption in 2030. This corresponds to a FT fuel demand of ~320-370 TWh in 2030. 100% FT fuel is reached in 2050.
- Faster ramp-up: FT fuel contributes 48% to total fuel consumption in 2030 (1,900-2,200 TWh) and, thus 4 years earlier than in the main scenario. In this accelerated ramp-up, 100% FT fuel are reached already in the year 2046.

Neither the main pathway nor the sensitivities represent estimates of how fast a realistic FT ramp-up could be. They only serve to illustrate the significance of the ramp-up speed for GHG emission reduction.

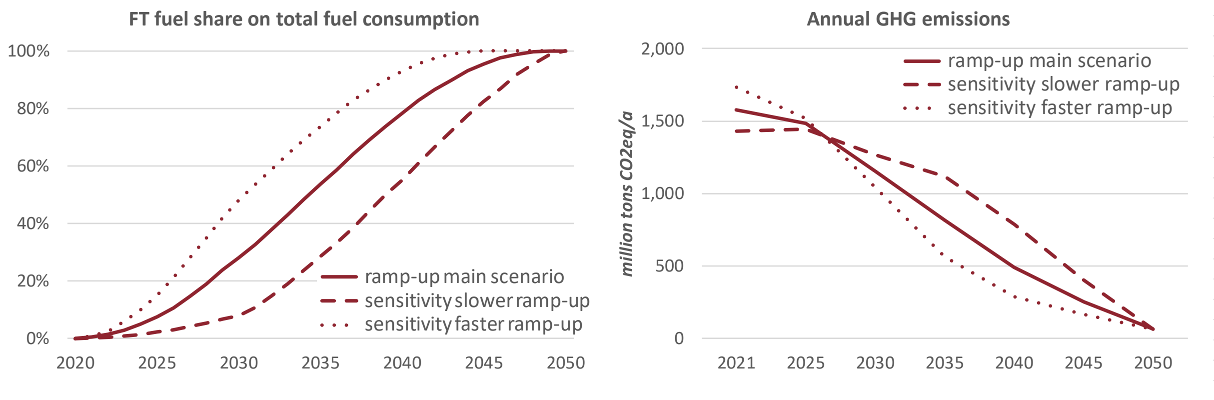

Figure 81: Shares of FT fuel on total fuel consumption (left) and annual GHG emissions (right) in road transport the 100% backcasting scenario FT Fuel Balanced Domestic and in the sensitivities for slower and faster ramp-up.

Figure 81 (right) shows the annual GHG emissions in road transport in the sensitivity analysis. In a slower ramp-up, annual GHG emissions are lower in the first years as fossil fuel consumption is only slightly different, but less emissions result from slower build-up of fuel supply chain infrastructure. However, as of 2025 smaller amounts of defossilised fuel are available and, thus, higher consumption of fossil fuels dominates total annual GHG emissions that are substantially higher than in the main scenario. In case of a very fast ramp-up the picture is reversed. Annual emissions are higher in the first years due to the additional emissions from fast build-up of fuel supply chain infrastructure. However, this leads to a substantial additional reduction of fossil fuel demand in the following years and in consequence faster reduction of total GHG emissions.

According to the different annual emission reduction rates, this has significant effects on cumulative GHG emissions in road transport. These are 15-18% higher with assumed slower ramp-up, but 12-13% lower with accelerated ramp-up compared to the main scenario. The total difference in cumulative emissions between slower and faster ramp-up is 6.6-8.2 gigatons - thus more than doubling the bandwidth of cumulative GHG emissions shown for all backcasting scenarios with linear-ramp-up. In Figure 82, we now sort the cumulative emissions of the FT fuel pathway different ramp-up speeds against the cumulative emissions of the other defossilisation pathways with linear ramp-up.

- FT Fuel pathway with ***linear ramp-up*** has cumulative GHG emissions in a similar range compared to other defossilisation pathways with same vehicle efficiency (Status quo, Balanced, All-In).
- With a ***slower ramp-up***, the FT Fuel pathway has even with additional vehicle efficiency improvements higher cumulative GHG emissions than all pathways with linear ramp-up.
- With a ***faster ramp-up***, all three FT fuel pathways (but particularly those with Balanced or All-In vehicle efficiency) would be more GHG effective than all other pathways if these only reach a linear ramp-up.

This sensitivity analysis shows that ramp-up speed of defossilised final energy supply is the crucial factor for a fast and effective reduction of GHG emissions. It has a high impact on the picture of the GHG mitigation effectiveness of each pathway and, thus, also on comparative assessments between different fuel pathways. Quickest possible applicability of substantial quantities of renewable energy to reduce dependencies on fossil fuels is essential for minimizing GHG emissions from transport. Measures applied in the next decade are most important for the reduction of the GHG backpack until 2050. Therefore, reliable assessments of actually achievable GHG reductions in all fuel pathways must include assessments of achievable ramp-up speeds for required vehicle technologies as well as fuel supply chain infrastructure.

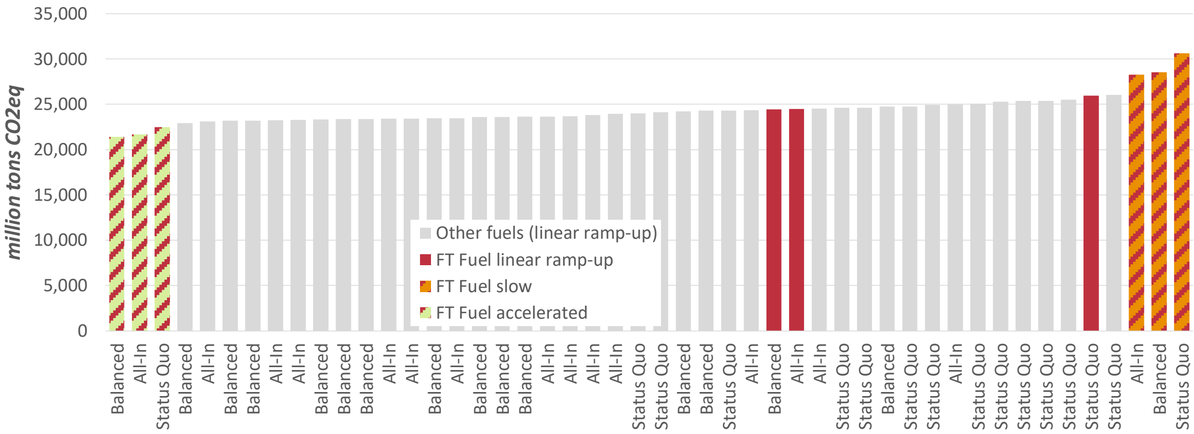

Figure 82: Sensitivity analysis for the impact of different market ramp-up speeds for FT fuels on cumulative GHG emissions 2021-2050 associated with the EU27+UK road transport.

10.3.4 Comparison of cumulative GHG emissions with the remaining CO_2 budget

According to Art. 2 of the Paris Agreement, the increase in the global average temperature is to be kept ***well below 2°C*** above pre-industrial levels and efforts are to be pursued to ***limit the temperature increase to 1.5°C*** (UN, 2015). In order to assess compatibility of the 100% scenarios with the Paris climate targets, cumulative GHG emissions have been compared with estimates of the remaining CO_2 budget for the European Union.

IPCC reports global CO_2 emissions budgets[25] in its Special Report on Global Warming of 1.5°C (IPCC, 2018). The remaining global budget for the 1.5°C target with 50-67% TCRE (= probability of meeting the target) is 420-580 gigatons as from 01.Jan.2018. A "well below 2°C" target is often interpreted as 1.75°C and correlates to a remaining global budget of 800-1040 gigatons.

National budgets for fair emission reductions can be calculated on different bases, e.g. by population size, by current emission share, by economic power, by historical responsibility (see (SRU, 2020)) and lead to significantly different results. Furthermore, admission of temporary overshooting of the target (global warming exceeds 1.5°C temporary, but returns below 1.5°C during the 21st century) leads to different estimates of acceptable CO_2 budgets in different time horizons (2050, 2070, 2100). In consequence, different publications come to a high bandwidth of remaining CO_2 budgets for the European Union. Main influencing factors for different CO_2 budgets are:

- Target level: 1.5°C or "well below 2°C" (e.g. 1.75°C)
- Probability of meeting the target: 50^{th} vs. 67^{th} TCRE

[25] IPCC indicates concrete budgets only for anthropogenic CO_2, but gives bandwidths of key uncertainties and variations for further impacts (including earth system feedbacks reduces 1.5°C budgets by about 100 Gt), other greenhouse gases (+/- 250 Gt for non-CO_2 emissions) and further uncertainties.

- Acceptance of limited temporary overshoot
- Allocation method of global budget to individual nations
- Considered time period: starting year (2018-2021) and end year (2050, 2070, 2100)

Figure 83 illustrates a bandwidth of CO_2 budget estimates for European Union in several publications with different methods in a range of 17 to 47 gigatons.

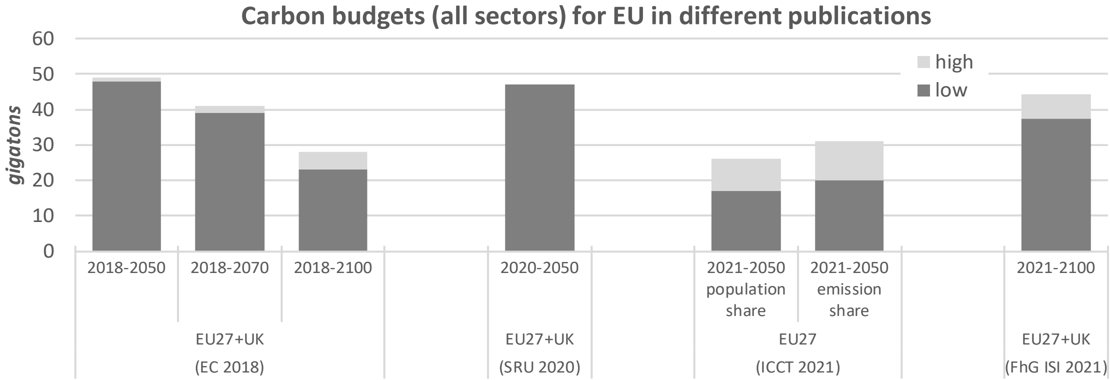

Figure 83: Carbon budgets (all sectors) for EU in different publications. [(European Commission, 2018a): Cumulative CO2 emissions in different 1.5° scenarios (TECH, LIFE). Decreasing cumulative emissions for longer time periods result from negative net CO2 emissions after 2050.(SRU, 2020): 67th probability for 1.75°C, based on EU28 share on global population 2018 (ICCT, 2021): 50th – 67th probability for 1.5°C, based on EU27 population share (left) and based on current emission share (right) (FhG-ISI, 2021): EU GHG budget (CO2eq) consistent with long-term warming of 1.5°C with no or limited temporary overshoot].

In this study, we derived own estimates for remaining CO2 budgets in the European Union + United Kingdom for a simpler understanding and better transparency based on the methodology described in (SRU 2020), considering:

- Global budget for 1.5°C and 1.75°C target with 50th and 67th probability
- EU27+UK budget by current population share: 6.6% (515 million of 7.8 billion)
- Used up CO_2 budget 2018-2020: 11.2 gigatons (2018-2019 total net emissions UNFCCC without international transport in (EEA, 2021), 2020 own estimate based on preliminary inventory data of single countries).

On this basis, the remaining CO2 budget for EU27+UK including all emission sectors is 16-27 gigatons for the 1.5°C target and 42-57 gigatons for the 1.75°C target. These budgets are, thus, in a similar range as in studies presented above.

Total cumulative GHG emissions of the transport sector in the 100% backcasting scenarios are in the range of 25-29 gigatons. This means:

- The lower 1.5°C budget (67th TCRE) is exceeded by GHG emissions from transportation alone (including Well-to-Wheel emissions, vehicle production and disposal and build-up of fuel supply chain infrastructure for defossilised transport) in all 100% scenarios already in 2031-2032.
- The higher 1.5°C budget (50th TCRE) is exceeded in 14 out of 42 100% scenarios as from 2043-2050.
- The 1.75°C budgets for all sectors are not exceeded by the transportation alone. However, GHG emissions associated with transportation will require 59-70% (67th TCRE) or 43-51% (50th TCRE) of the remaining budget for all emission sectors.

In conclusion, the scenario results of this study indicate that an exclusively technical defossilisation with one single pathway will unlikely meet the GHG reduction requirements on Europe's transport sector. Further GHG reduction potentials need to be tapped, as e.g. joint efforts for multiple defossilisation pathways. Furthermore, a significant fast reduction of transport-related energy demand as a whole can help to accelerate the ramp-down of fossil energy usage.

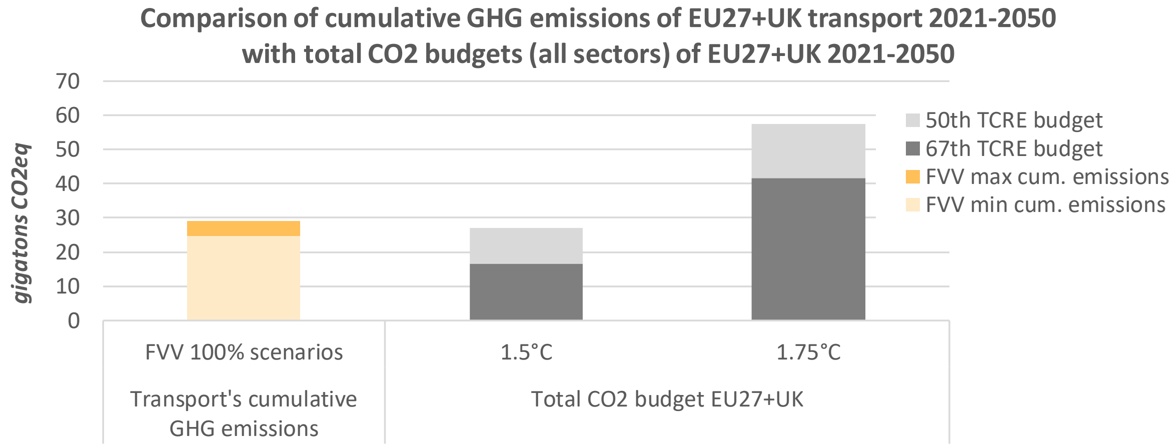

Figure 84: Comparison of cumulative GHG emissions of EU27+UK transport 2021-2050 with total CO_2 budgets (own estimates for all sectors) of EU27+UK 2021-2050.

10.3.5 Role of fuel supply chain infrastructure and vehicle production

10.3.5.1 Fuel supply chain infrastructure

The ramp-up of infrastructure for defossilised final energy supply contributes to total cumulative GHG emissions in the scenarios only 5% to 20% with lowest contributions in 100% electric scenarios and highest contributions in scenarios with 100% FT fuel (section 10.3.2).

Figure 85 illustrates that GHG emissions from fuel supply chain infrastructure in all scenarios are dominated by power generation with both domestic and international energy sourcing: 89-95% in H_2 pathways, 63-81% in hydrocarbon fuel pathways, 62-75% in electric pathways.

Other components have only smaller contributions to total GHG emissions from the ramp-up of fuel supply chain infrastructure.

- Additional GHG emissions in scenarios with hydrocarbon fuels come primarily from installation of DAC and fuel synthesis plants; in the methane scenarios also from the expansion of the distribution pipeline network[26].
- In the BEV scenarios, charging infrastructure has a significant share within FSC infrastructure, however less than 1% compared to total cumulative GHG emissions.
- Electrolysers are required in all pathways, but have very small contributions in the range of 2-6% in the FSC infrastructure and, thus, only 0.3-0.6% of total cumulative GHG emissions.

[26] Calculated GHG impacts from installation of fuel synthesis plants show huge discrepancies between methane synthesis plants and other fuel production plants. These differences result from the specific GHG emission factors for plant construction available in the ecoinvent database (see explanations in 10.1.2) and are likely to be unrealistic. Due to the very low relevance of building-up fuel synthesis plants (1–3% of total cumulative GHG emissions in all scenarios) we did not further analyse potential reasons for the discrepancies of available basic data in this study.

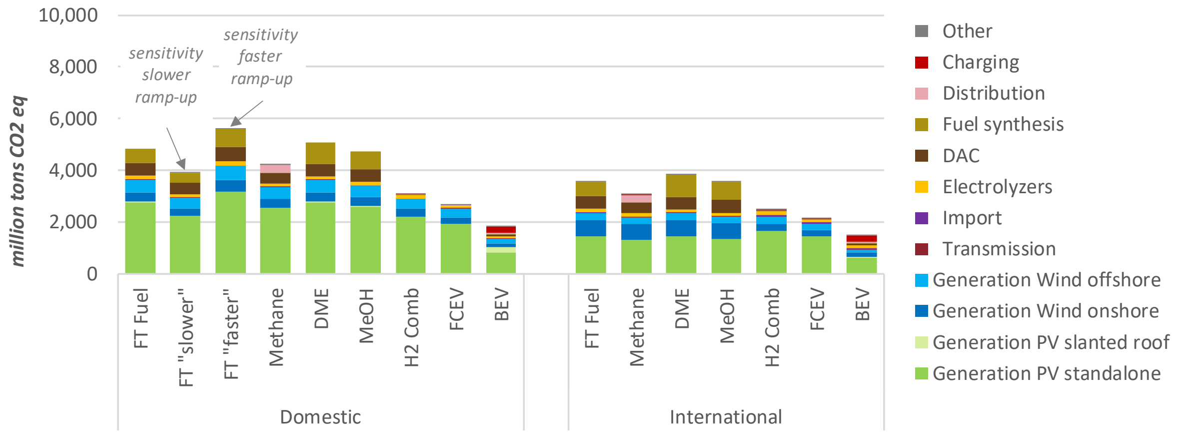

Figure 85: Cumulative GHG emissions from ramp-up of fuel supply chain infrastructure (100% scenarios with balanced vehicle technology) with full defossilisation of worldwide production processes by 2050 (2050b).

Figure 85 shows also the effect of different ramp-up speeds on cumulative GHG emissions from the fuel supply chain (sensitivity analysis in section 10.3.3). In case of a slower ramp-up of FT fuel supply, FSC infrastructure will be built up in later years with a higher degree of defossilisation in the background system and, in consequence, lower GHG emissions from the FSC ramp-up. In contrast, a very fast ramp-up would cause higher GHG emissions from FSC infrastructure as a major part of the infrastructure is produced with low defossilisation of the background system. Nevertheless, as analyses in section 10.3.3 show, GHG impacts from different ramp-up speeds of FSC infrastructure are substantially lower than GHG impacts from the additionally saved or required usage of fossil fuels in case of slower or faster ramp-ups of defossilised fuel supply.

GHG emissions from power generation infrastructure are dominated by installation of photovoltaic plants for several reasons. Figure 86 illustrates this exemplarily for the 100% FT Status Quo scenarios:

- Photovoltaic plants have the major contribution to power supply: 43% in the domestic scenario and 31% in the international scenario.
- PV plants have considerably lower full-load hours per year than wind power plants. In Europe, a PV plant has only about 1.300 FLH per year, whereas wind power plants have 3.000-4.200 FLH. Therefore, a share of 68% on installed capacity in 2050 is required to achieve the 43% contribution to power generation in the domestic scenario. In the international scenarios, FLH per year are higher for both PV as well as wind power plants, but wind power plants still have about twice the FLH compared to PV plants.
- Finally, the installation of PV plants has higher specific GHG emissions than wind power plants (see section 10.2.1).

In consequence, PV plants contribute considerably more to GHG emissions from building-up power generation capacities compared to their share on power generation in the scenarios.

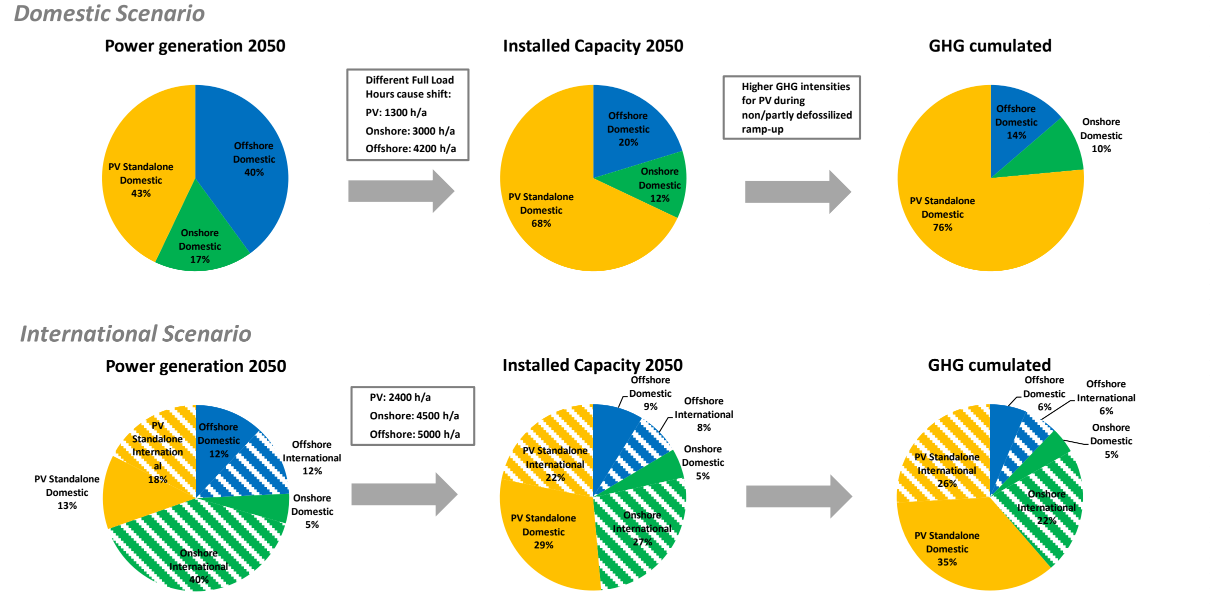

Figure 86: Shares of PV and wind power on power generation, installed capacities and cumulative GHG emissions in the 100% FT Status Quo scenarios.

10.3.5.2 Vehicle production and disposal

Vehicle production and disposals contribute 11-24% to total cumulative GHG emissions in the 100% scenarios with lowest contributions in 100% FT fuel scenarios with Status Quo vehicle technology and highest contributions in 100% electric All-In scenarios (section 10.3.2).

Main influencing factors on GHG emissions from vehicle production are the number of annual new registrations (section 6) and the specific GHG emissions per new vehicle, which depend on the vehicle technology and the defossilisation degree of production processes (section 10.2.2). The total number of new registrations and the breakdown by vehicle size classes is identical in all scenarios. As the fleet ramp-up of the scenario-specific powertrain technologies (methane, FCEV, BEV et.) reaches 100% new registration share in the years 2033 (passenger cars) to 2042 (long-haul trucks), new registrations in the earlier years include also vehicles with conventional gasoline and diesel powertrains.

Figure 87 shows exemplary results of annual GHG emissions from vehicle production in the scenario years 2030 and 2050. The highest annual GHG emissions from vehicle production in both 2030 and 2050 are in the BEV scenarios and in the FCEV Status Quo and All-In scenario. In the FT and H_2 Combustion scenarios, emissions are highest in Balanced and All-In scenarios, as hybridisation and aluminium lightweighting lead to higher specific GHG emissions (see section 10.2.2). However, in the BEV scenarios, further development of battery technologies has an emission-reducing effect. Therefore, the Balanced and All-In scenario have lower GHG emissions from vehicle production than the Status Quo scenario. In 2050, the annual GHG emissions from vehicle production are about a factor of 4 lower compared to 2030 despite slightly increasing total number of new registrations if a full worldwide defossilisation (2050b) of production processes is achieved.

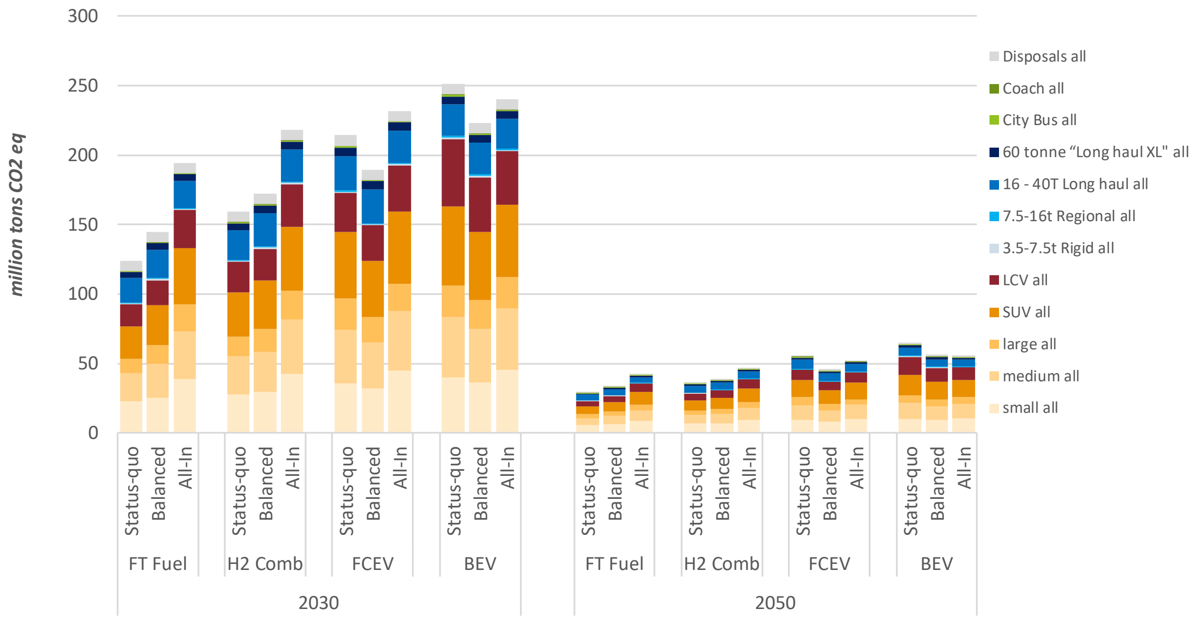

Figure 87 - Annual GHG emissions from vehicle production in 2030 and 2050 in selected pathways with full defossilisation of worldwide production processes by the year 2050 (2050b).

Figure 88 shows cumulative GHG emissions from vehicle production and disposals. Manufacturing of cars and light duty vehicles dominates the overall results with a cumulative emission share of 75- 84%. Primarily, SUVs and light commercial vehicles (LCV) together account for about 33% in fuel scenarios and 40% in BEV scenarios. Manufacturing of heavy-duty vehicles contributes about 12-18% to cumulative GHG emissions in this section. Disposals contribute only 4-7% to total cumulative emissions from vehicle production and disposal.

Scenarios with battery-electric and fuel cell vehicles have generally considerably higher GHG emissions from vehicle production than scenarios with conventional powertrains. Cumulative GHG emissions from vehicle production are in the BEV balanced scenario 61% higher and in the FCEV balanced scenario 36% higher than in the Fischer-Tropsch balanced scenario.

However, emission differences do not only depend on the drivetrain technology, but also on technical specifications of the vehicles.

- In the FT scenarios, additional hybridisation and aluminium lightweighting lead to 50% higher cumulative GHG emissions from vehicle production in the "All-In" scenario compared to the "Status Quo".
- In the FCEV scenarios, high platinum loads (Status Quo) and additional aluminium lightweighting (All-In) affect emissions. The cumulative GHG emissions from vehicle production in the Balanced scenario are 14-15% lower than in the other technology levels.
- In the BEV scenarios, aluminium lightweighting and further development of battery technology affect emissions. The lowest cumulative GHG emissions from vehicle production in the "Balanced" scenario are 5-11% lower than in the other technology scenarios.

In consequence, technical specifications also affect the comparison between different powertrains. Cumulative GHG emissions of vehicle production in the FCEV "Balanced" scenario are only 5% higher compared to FT "All-In" scenario. The BEV "Balanced" scenario has still about 24% higher cumulative GHG emissions compared to the FT "All-In" scenario. As GHG emissions of BEV production are mainly driven by battery production and we assume sufficiently large battery sizes for a majority of customer use cases in our scenarios (300-500km WLTP range + heating), this difference would further shrink in case of smaller batteries, applicable to some use cases with less range demand. This would not only help to further reduce cumulative GHG emissions (10.3.2), but also to avoid potential raw material bottlenecks (11.3.1.6).

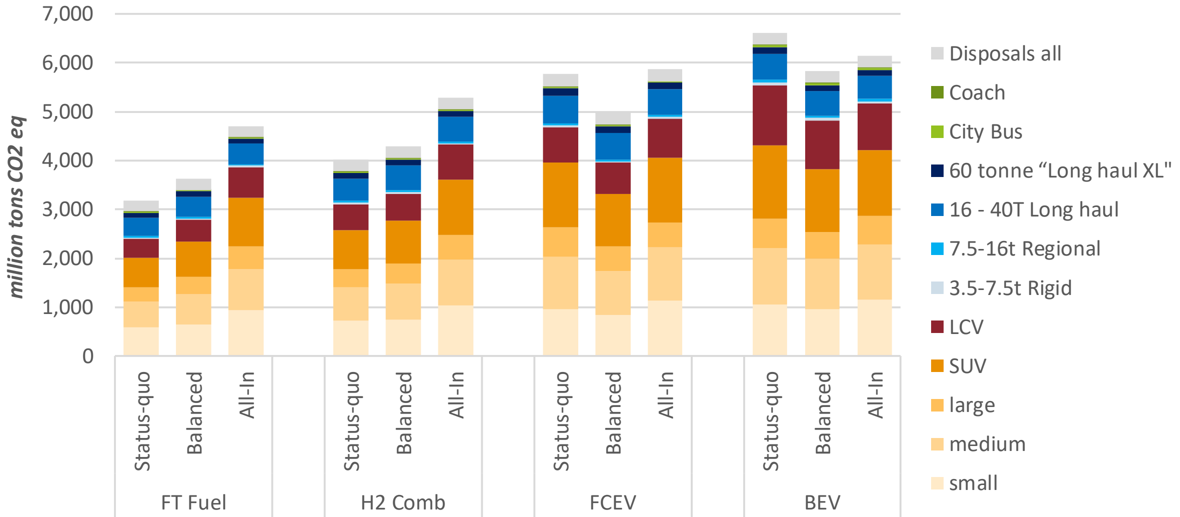

Figure 88: Cumulative GHG emissions 2021-2050 from vehicle production and disposal in selected pathways with full defossilisation of worldwide production processes by the year 2050 (2050b).

10.3.6 Relevance of a full defossilisation for annual and cumulative GHG emissions

One specific target of the study is analysing the relevance of a complete defossilisation of the transport sector, including fully defossilised (worldwide) production processes for vehicles and fuel supply chain infrastructure. Therefore, all scenarios are carried out with two different degrees of defossilisation in 2050 as explained in section 10.1. All scenario results shown in the previous sections are based on the assumption of a full worldwide defossilisation of the background system (“Defossilised world”; 2050b). They illustrate emission developments with extremely ambitious assumptions for a complete worldwide defossilisation of all raw material supply and production processes of vehicle manufacturing and building up new plants until the year 2050.

We model all scenarios in parallel under the still very ambitious assumption that in 2050 all processes in EU27+UK are fully defossilised, but the rest of the world has a time lag of 10 years reaching 75% defossilisation in 2050 (“Defossilised Europe”; 2050a). A comparison of emission trends with both defossilisation levels enables an evaluation of the importance of defossilising all background processes for the total GHG emissions associated with transport in Europe.

Annual GHG emissions associated with the transport sector in 2050 are almost exclusively caused by vehicle production and by the completion (respectively in some cases the renewal) of infrastructure for defossilised final energy supply. Only very small shares are originated by fuel production and vehicle operation (mainly methane emissions in the methane pathway). With a „defossilised Europe“(2050a), GHG emission reduction from 2020 to 2050 reaches 82-88%. In contrast, in a fully “Defossilised world” (2050b), GHG emissions in 2050 are 95-97% lower than in 2020. Therefore, a complete worldwide defossilisation should be pursued not only of fuels themselves, but also of vehicle manufacturing and infrastructure construction.

In contrast, the cumulative GHG emissions in the period 2021-2050 are only about 3-4% lower if full worldwide defossilisation is achieved by 2050 (2050b) than if only the production systems in Europe are fully defossilised by 2050 (2050a). This is because the majority of the cumulative emissions will occur over the next 10-20 years. It results mainly from the continued operation of vehicles with fossil fuels (see section 10.3.2) as the fleet will only gradually be converted to defossilised fuels, but not from vehicle production and build-up of energy/fuel supply chain infrastructure. In consequence, it is not a decisive factor for the cumulative GHG emissions of defossilising EU‘s transport sector, if complete defossilisation of this background system is achieved already in 2050 (2050b) or in a later year (2050a).

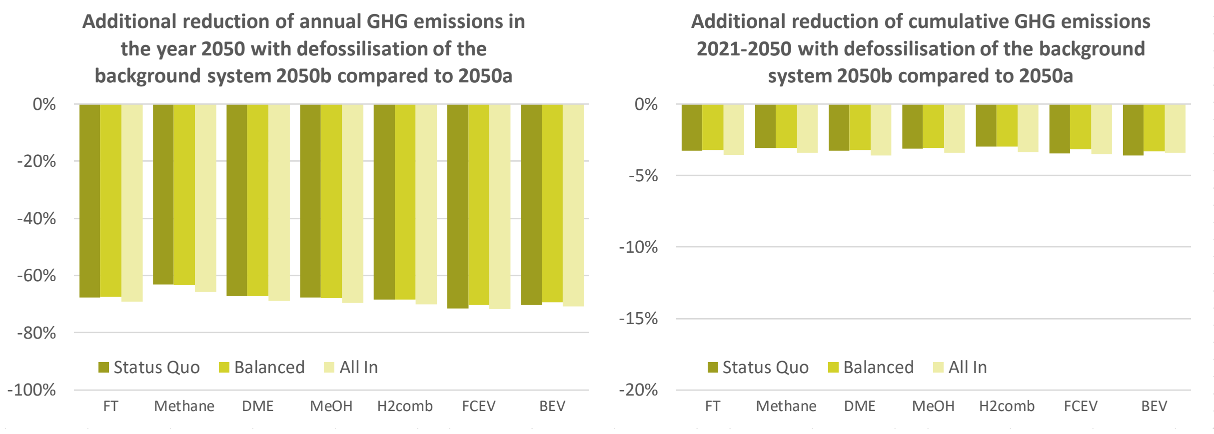

Figure 89: Comparison of annual GHG emissions in 2050 and cumulative GHG emissions 2021-2050 in domestic scenarios with different defossilisation levels of vehicle manufacturing and infrastructure construction.

10.4 Further environmental impacts in the 100% scenarios

Defossilisation of the transport sector with alternative powertrains and fuels also affects other environmental impacts. In this study, we analyse acidification, eutrophication and PM formation potentials resulting from vehicle operation, vehicle manufacturing and installation of fuel supply chain infrastructure in the year 2050 with our approach of a “Defossilised Europe” (2050a)[27]. Furthermore, we analyse land use requirements for renewable power generation and for CO_2 air capturing.

In summary, it can be stated that in total analysed environmental impacts will not increase, but decrease significantly by 2050 for all alternative powertrain or fuel pathways. In conclusion, there are no general ecological risks in the analysed environmental impact categories for any of the defossilisation pathways. It should be noted that the environmental categories under consideration cannot be assessed only in a location-independent manner analogous to GHG, since the local distribution of pollutant inputs is also decisive for the resulting environmental impacts. Although environmental burden will decrease significantly on average, local increases are possible and must be avoided accordingly.

Furthermore, land use is no ecological bottleneck for a defossilised transport sector[28]. However, installation of renewable power generation capacities in Europe as well as in other international locations should avoid environmentally sensitive areas in order to minimize land use related environmental impacts. In the following section, we present the scenario results for the individual environmental impact categories.

10.4.1 Acidification

Annual acidification potential decreases from 2020 to 2050 by 10-50 % in all hydrogen and fuel scenarios and in the BEV All-In scenario. Only the BEV scenarios with Status Quo and balanced vehicle technology show a slight increase due to the additional impacts from battery manufacturing. However, contribution of land-based transport to total acidification from all polluting sectors is very low. Therefore, even a slight increase of acidification potential associated with EU27+UK transport sector would not cause an ecological bottleneck.

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[27] The simplified methodological approach for a full worldwide defossilisation (2050b) in this study, eliminating all CO_2 emissions from fossil fuel usage is not suitable for other environmental impacts where detailed modelling of all relevant material supply and production processes is required.
[28] We did not analyse social and political constrains that can complicate the ramp-up of renewable power generation to a considerable extent.

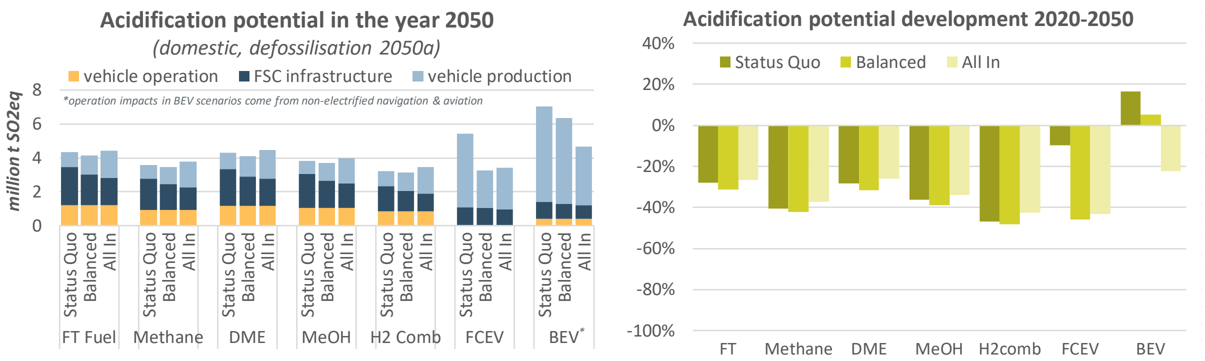

Figure 90: Acidification potential associated with the EU27+UK transport sector in the year 2050.

10.4.2 Eutrophication and PM formation

Eutrophication and PM formation show a strong reduction from 2020 to 2050 in all fuel pathways. Main reason are strongly reduced (Euro 6d) and completely omitted (BEV) direct emissions from vehicle operation in road transport. Remaining PM formation comes mainly from secondary particles (NO_x and NH_3 emissions in road and non-road transport) and to a smaller amount from abrasion of tyres, brakes, road surface.

These strongly decreased impacts from vehicle operation are not offset by additional eutrophication and PM formation potentials from vehicle production and installation of energy/fuel supply chain infrastructure. In consequence, there are no ecological bottlenecks but considerable environmental improvements associated with EU27+UK transport sector in all scenarios.

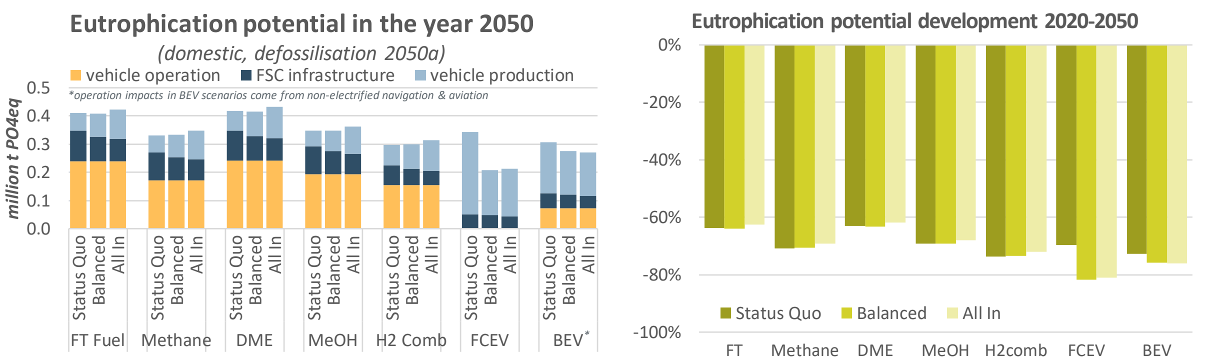

Figure 91: Eutrophication potential associated with the EU27+UK transport sector in the year 2050.

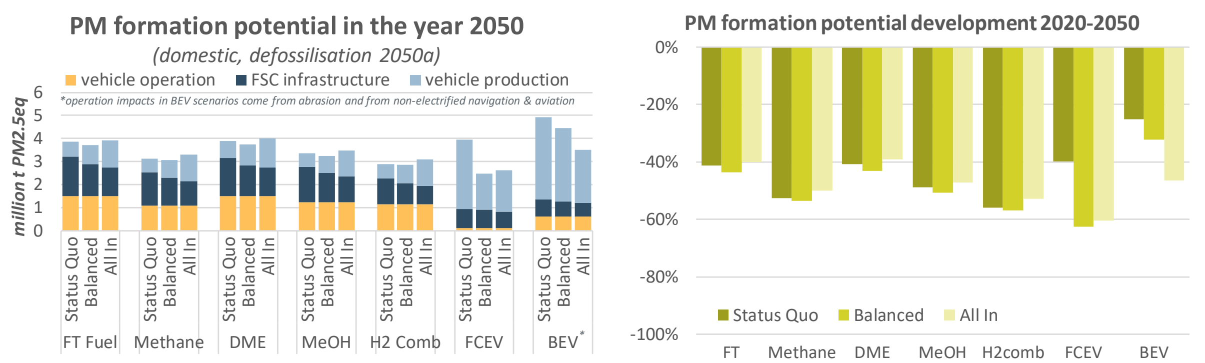

Figure 92: PM formation potential associated with the EU27+UK transport sector in the year 2050.

10.4.3 Land use

The ecological relevance of land use change depends on the amount of area covered by the facilities, which cannot be used for other applications, but also on the degree of hemeroby (“closeness to nature”) of the affected area. In the following, we analyse the first approach.

Renewable power generation for direct use of electricity in the transport sector and for the production of defossilised fuels leads to **substantial additional land use for renewable power generation**. Standalone photovoltaic plants occupy most area (and implicate most hemeroby changes) as they have a more than factor 10 higher specific land use per MWh power generation than wind plants. Land use of all other facilities in the defossilised fuel supply chain (DAC, synthesis plants etc.) is negligible.

Total land use in the 100% scenarios goes hand in hand with the amount of electricity production and installed generation capacities:

- The domestic scenarios require more land than the international scenarios as electricity production is less efficient: International energy sourcing causes about one third less land use compared to energy sourcing only in Europe due to higher annual operation time (full-load hours) of power plants at good international locations and thus less installed capacities for the same annual power generation.
- In the domestic scenario with highest electricity demand (FT Status Quo), additional power generation requires 1.3 % of EU27+UK land area[29]. Land use in the most energy efficient BEV scenario (BEV All-In international) is only one sixth compared to the FT scenario.
- In all domestic and international scenarios, the technology level “All-In” occupies less land than “Balanced” as the higher vehicle efficiencies lead to reduced final energy consumption and thus renewable power generation demand. Highest land use is required in “Status Quo” scenarios.

Generally, **land use is no ecological bottleneck for a defossilised transport sector**. However, installation of renewable power generation capacities in Europe as well as in other international locations should avoid environmentally sensitive areas in order to minimize land use related environmental impacts. Other potential land use bottlenecks, mainly social and political constrains that can complicate the ramp-up of renewable power generation to a considerable extent, are not part of this study.

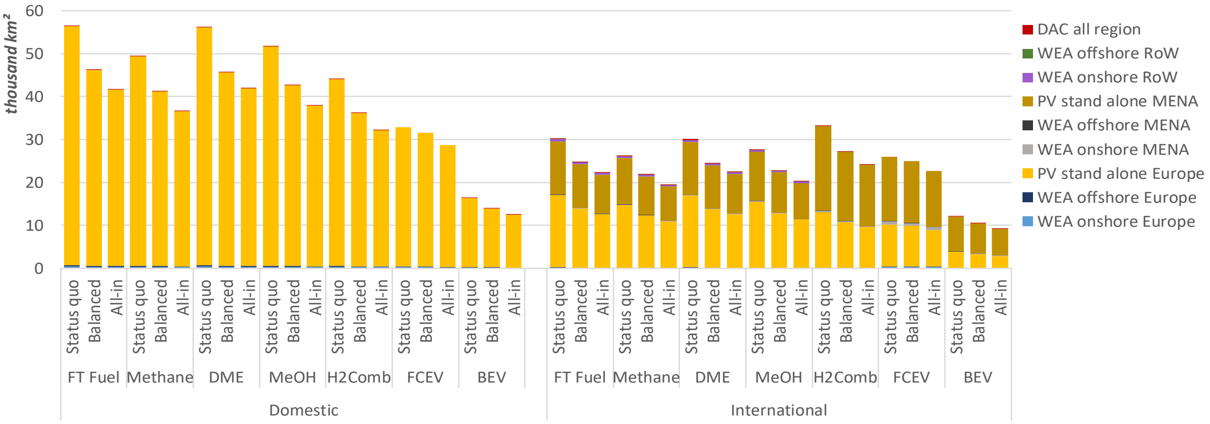

Figure 93: Land occupation for defossilised power generation for EU27+UK transport sector in 2050.

[29] For comparison: Transport area has a share of 5% on total land area in Germany.

11 Analysis of critical raw materials

11.1 Scope of analysis and selection of materials

An important issue for the defossilisation of the transport sector in Europe is the availability of critical raw materials, which are needed for the conversion of vehicle fleet in EU27+UK to alternative drivetrain technologies as well as for the renewable fuel supply chain infrastructure. In this study, we investigate future developments of material demand associated with the transport sector in EU27+UK in each of the 7 drivetrain and fuel pathways for selected raw materials. We compare the cumulative material demand with the currently known global resources and reserves of primary raw materials to assess potential shortages of raw materials in the selected pathways.

Defossilisation of transport is not only a European, but a worldwide challenge. Accordingly, European demand for raw materials must not restrict other countries in their development opportunities, but EU countries must only claim a fair share of the available raw materials for themselves. Therefore, we evaluate in simplified analyses how global material requirements could develop if the rest of the world strives for a complete conversion of transport to the respective fuel pathway analogous to EU27+UK and, in addition, all countries catch up economically with the European Union by 2050. By comparison with the globally available quantities, a rough assessment of temporary and absolute raw material bottlenecks is thus also possible in a global context.

For 4 selected raw materials, we carry out more in depth analyses. We roughly estimate the future global demand from non-transport sectors. Furthermore, we also determine annual material demands and compare these with available forecasts or scenarios of future production quantities (including also secondary materials) to assess possible temporary bottlenecks for the market ramp-up to the 100% scenarios.

The selection of the materials is based on scientific analysis of critical raw materials (among other: European Commission (2017) and European Commission (2020b), (DERA, 2016)) and relevant materials in the mobility sector (among other: (DERA, 2016), Huisman et al. (2020); Wittstock et al. (2019). Further selection criteria is availability of sufficient background information particularly provided by JRC in the Raw Material Information System (JRC, n.d.) and by USGS in the Mineral Information System (USGS, n.d.).

The selection comprises lithium, cobalt, copper, platinum group metals (PGM) with special focus on platinum, nickel, rare earth minerals as group and with particular focus on neodymium, silver and silicon metal. The four materials lithium, cobalt, copper, platinum group metals were chosen to be analysed in more detail as they are indispensable in the mobility sector in some or all analysed fuel pathways.

11.2 Methodology and data

11.2.1 Global material supply

Mineral deposits can be classified as:

- **Resources**: concentration or occurrence of material in or on the earth's crust in such form, quality and quantity that there are *reasonable prospects for eventual economic extraction*. Exploration and quantification of resources depend on demand and demand prospects; raw materials with a long history of demand (e.g. platinum) are rather well explored and thus amounts of resources do not change significantly; in contrast, raw materials which are demanded just recently (e.g. lithium), show very dynamic resource amounts due to active exploration activities (see Figure 94).
- **Reserves**: are the part of the resources known to be *economically feasible for extraction*. With increasing prices (due to higher global demand) and further development of mining technologies reserves increase in most cases.

Global resources and reserves for many minerals are analysed periodically depending on demand e.g. by United States Geological Survey (USGS).

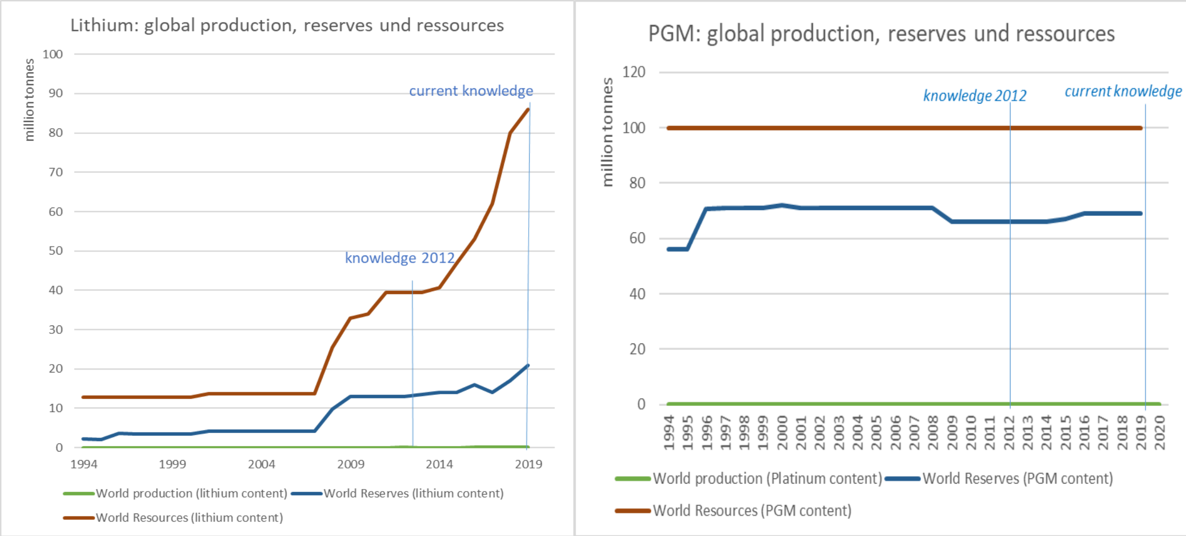

Figure 94: Developments of global production, reserves and resources of lithium and platinum group metals.

For each of the selected materials we researched the production dynamics, currently known reserves and resources, predominantly based on USGS. Table 29 gives an overview of currently known resources and reserves and on global production of the raw materials covered in this study.

Table 29: Resources, reserves and global production of selected raw materials.

		Li	**Co**	**PGM**	**Cu**	**Ni**	**AG**	**REE**	**Silicon metal**
Resources	*Million tonnes*	86 (230,000*)	25 (120*)	0.1	2,100	130	0.797	478	n.a.
Reserves	*Million tonnes*	21	7.1	0.069	870	94	0.65	120	n.a.
Global production 2019	*Thousand tonnes*	86	144	0.447 (Pt: 0.186; Pd: 0.227)	20,400	2,610	26.5	220 (Nd: 30.7)	3**
Dynamic of production	*Change 2019 versus 1994*	+1310%	+778%	Pt: +45 % Pd: +230%	+119 %	+288%	+191%	+341%	+400%

*[Data source: (Boubault, 2019; USGS, 2021a; b; c; d; e; f; g) *resources in the oceans Li: Yang et al. (2018); Co: USGS (2021), ** (Boubault 2019)].*

For the selected four materials, we furthermore researched supply forecasts based on scientific literature as well as current and prospects on secondary supply in Europe and in the rest of the world. Global supply covers the amount of material available on the global market per year. *Primary material supply* depends on the global mining activities etc. (and is only a fraction of existing reserves). In case of long-time industrial used materials (e.g. copper, platinum), also *secondary material supply* from recycling activities is relevant. Generally, all forecasts consider demand and supply depending on (available/future) technology as well as demand and price dynamics. However, assumptions of demand and technology dynamics may differ significantly between the forecasts, some assumptions and forecasts are rather conservative while others are optimistic.

In order to get an evaluation on the appropriateness of available supply forecasts and overall demand dynamics, we also estimated future material demand in other sectors than mobility with respect to the selected four raw materials. The underlying general assumptions on international economic development are very optimistic in this project. For this, we analysed the historical and current demand of other sectors for primary and secondary materials. Future demand was estimated at a yearly level using SSP 1 public database (version 2.0.) on economic development and population (IIASA, 2020) and specific information on technology development. Supply with secondary materials was substracted considering life span, collection and recycling rates of the specific use of the raw materials. Also dissipative losses were considered (e.g. for pigments, tyre adhesives as well as paint dryers). Furthermore, we quantified the future supply with secondary materials from the mobility sector applying the life span of the vehicles, a collection rate of 90 % and material specific recycling rates.

With respect to lithium, Greim et al. (2020) estimated future global supply of 18 scenarios, combining 8 demand and four supply scenarios.

- Global demand: The estimation of demand from *mobility sector* is lower than in the BEV scenarios in this study (see section 11.3.1), though substantially higher compared with today due to different study-specific assumptions on future increase of electric mobility and global demand structure. Greim's estimation of demand in *non-mobility sectors* is a trend scenario based on medium ambitious assumptions on development outside Europe resulting in 65 thousand tonnes in 2050. However, we estimate a considerably higher future demand reaching nearly 100 thousand tonnes in 2050, based on more ambitious assumptions on development in the rest of the world.
- Global supply: Greim's supply scenarios are based on different reserve values. The potential annual supply in 2030 is 800 to 900 thousand tons per year while it is in 2050
    - 400 thousand tons per year assuming today's technologies and costs
    - 1,400 thousand tons per year assuming significantly increasing reserves, but still some constrains in future enhancement of extraction technologies
    - 2,550 thousand tons assuming no constrains.

We use these supply scenarios in section 11.3.1. Although assumptions differ, Greim et al. (2020) as well as our analysis show that recycling markets are not yet well developed as several current uses of lithium are disperse and economically feasible recycling technologies are still limited. Thus, secondary supply may grow around 2035 significantly when batteries from mobility sector enter recycling markets in valuable amounts.

With respect to Cobalt, currently, there are no analyses that study Cobalt supply in the timeframe of the next 30 years. Therefore in the following, supply forecasts until 2030 were considered. Alves Dias et al. (2018) estimated the future global Cobalt mine supply until 2030. To reflect the considerable uncertainty about long-term mine production the authors use four scenarios covering different market conditions (e.g. growth of demand and rising prices) that mainly drives decision making of exploration projects. The supply projections of Alves Dias et al. (2018) does only consider exploration projects with a defined resource estimate; inactive projects are excluded as well from the analysis. In 2030, cobalt supply from mining activities varies between 193 and 237 thousand tonnes. Potential additional cobalt supply from EV battery recycling is estimated at 38 thousand tonnes in 2030, assuming a collection and recovery efficiency of 90 % and 80 % respectively.

Fu et al. (2020), estimate cobalt supply until 2030 against the background of low and high cobalt demand growth for electric vehicles and non-battery demand. Global demand for EV batteries in 2030 reaches 100 thousand tonnes in low growth scenario and 250 thousand tonnes in high growth scenario, respectively. Thus, the estimation of demand from *mobility sector* is substantially lower than in the BEV technology pathways Status Quo and Balanced, but lays within the demand in the BEV All-in technology pathway (see section 3.2.1). Cobalt demand of non-battery applications reaches almost 60 thousand tonnes in 2030, considering substitution effects in superalloys demand. We estimate a slightly higher primary demand for non-battery applications of 85 thousand tonnes in 2030. Total estimated cobalt demand of Fu et al. (2020) ranges from 235 to 430 thousand tonnes in 2030. The upper bound of demand thus exceeds global refinery capacity in 2016 by 280 %.

Global supply in 2030 according to Fu et al. (2020) comprises supply from scheduled as well as unscheduled mine production and secondary production. Supply from secondary production ranges from 47 to 93 thousand tonnes assuming a 100 % recovery and different product lifetimes. For future cobalt supply from mining the authors assume, that cobalt will be mined more as a by-product of nickel in 2030 compared to copper production because unscheduled mining potential for Nickel is larger. The total cobalt supply ranges from 323 to 458 thousand tonnes in 2030. Given the overestimation of secondary supply and optimistic projections from unscheduled demand we use the lower end of the estimate (323 thousand tonnes) for the following analysis.

In addition, we use the more conservative supply projection from Alves Dias et al. (2018), even though assumptions on cobalt demand differ. Both studies as well as our analysis show, that recycling markets only gain importance beyond 2025 and must then be sustained. Alves Dias et al (2018) also notices that substitution of cobalt in Li-ion batteries are already possible, but have not taken place in Europe.

With respect to PGM, Sverdrup and Ragnarsdottir (2016) estimate global PGM supply and production using a system dynamics model. The model takes into account and combines global mining activities, ore grade changes, trade markets, price mechanisms, supply, demand, estimates of stock-in-use, waste, dissipative losses and recycling and was tested against several historic data during 1900 - 2014. The authors, however, do not run their model against the background of an extreme transport sector. PGM supply to market is calculated, which is comprised of PGM from mining activities as well as recycling activities. It is estimated that PGM supply (from both primary and secondary PGM) in 2030 accounts for 1,189 tonnes and 1,115 tonnes in 2050. In 2030, approximately 56 % (660 thousand tonnes) of PGM supply comes from secondary PGM, in 2050 the share remains on the same level (625 thousand tonnes).

11.2.2 Future material demand and identification of potential bottlenecks

11.2.2.1 Material demand associated with the transport sector in Europe

We modelled annual demand of each material associated with the transport sector in EU27+UK by multiplying the annual vehicle new registrations (section 6) and annual installation rate of fuel supply chain infrastructure with the specific material demands per FSC component and vehicle with respective powertrain and technology level (section 10.2.2.7). This gives us the total material demand per year.

Furthermore, we estimated the future supply with secondary material for the four selected materials. This includes general availability from secondary materials for longtime industrial used materials, but we also modelled secondary materials coming from disposed vehicles applying the life span of the vehicles, a collection rate of 90 % and material specific recycling rates (see Table 30 and profiles of raw materials in the annex). For example, a car newly registered in 2021 will be disposed after 17 years. Recycled materials from this car will therefore be available as secondary material for new vehicles in 2038. In this way, we derive the demand of primary material per year and, based on this, the total cumulative primary material demand until the year 2050, which can be compared to available reserves and resources.

Table 30: Applied recycling rates for selected materials.

	Recycling rate mobile sector	Source
Lithium	85 %	European Commission (2020b)
Cobalt	80 %	Dominish et al. (2021)
PGM	55 %	European Commission (2020b); Hao et al. (2019)
Copper	90 %	Schipper et al. (2018)

11.2.2.2 Extrapolation of global material demand

Global demand of critical materials for the transport sector depends first on the worldwide market ramp-up of defossilised vehicle technologies. Here, we assume the same annual new registrations shares as in the scenarios for EU27+UK.

The second key influencing factor is how motorization as a whole develops outside the EU. In 2019, the EU accounted for around 20 % of a total of almost 90 million new cars (IEA, 2020). By 2030, forecasts assume an increase in annual global vehicle sales of more than 30 % to around 120 million vehicles per year, with new registrations in the EU barely increasing (Harrison 2020). By 2050, a further significant increase in the annual number of vehicles is expected, although the level of future developments is uncertain. European demand for raw materials must not restrict other countries in their development opportunities, but EU countries must only claim a fair share of the available raw materials for themselves. Therefore, we assume in our estimate of global vehicle sales in 2050 that all countries catch up economically with the European Union by 2050 and in consequence will reach the same per capita new vehicle sales as in EU. This would mean more than 300 million new vehicles per year worldwide in 2050. In consequence, the resulting factors for material demands of the mobility sector outside EU27+UK countries in our estimate are about factor 5 of EU27+UK demand in 2030 and about factor 14 in the year 2050.

However, a full economic catch-up is not necessarily to be expected by 2050 and, in addition, further developments such as mobility as a service with autonomous vehicles as well as transport avoidance and modal shift measures might slow down the increase of future worldwide motorization. Therefore, our estimate is to be regarded as an upper limit of worldwide vehicle sales and, thus, worst case of material demand for a worldwide defossilisation of the transport sector with 100% of one particular powertrain and fuel pathway.

11.2.2.3 Identification of potential temporary and absolute bottlenecks

We carried out the assessment of potential bottlenecks of critical raw materials for all 100 % scenarios, both for the transport sector in EU27+UK and for the simplified extrapolation of global defossilisation.

We identified *absolute bottlenecks* by comparing the cumulative demand for primary raw materials in each 100% scenario (fuel pathway and technology level) with currently known reserves and resources. With respect to the four selected materials, we included the demand of other sectors to consider the overall global demand. In addition, we considered information on dynamics of mining technologies in the interpretation of results. For selected materials and pathways where we identified potential bottlenecks with the study-specific assumptions, we carried out simplified sensitivity analyses on how these bottlenecks could be avoided.

With respect to the four selected materials, we identified *temporary bottlenecks* by comparing the yearly demand for raw materials with current production and forecasts of future production capacities, including dynamics in the mining sector, geological and environmental constrains of sources, mining technology developments in the interplay of demand and supply.

11.3 Demand of critical raw materials in the 100% scenarios

11.3.1 Lithium and cobalt

Lithium and cobalt are both critical key materials for electric mobility. Therefore, material demands and potential bottlenecks need to be assessed not only for each raw material individually, but also in combination.

11.3.1.1 Annual lithium demand

Demand for lithium associated with the transport sector is driven by vehicle production, particularly battery production, while demand from fuel supply chain is negligible. Accordingly, 100 % electric scenarios show substantially higher annual lithium demand in the transport sector for Europe and for the rest of the world compared to other fuel pathways (with batteries in hybridised and fuel cell vehicles).

The BEV Balanced scenario shows a lower annual lithium demand than the BEV Status Quo scenario due to the improved battery technologies with higher energy densities. The All-In scenario shows the by far highest demand, as the here assumed solid-state batteries have pure lithium anodes. In consequence, demand only from European mobility sector exceeds current global production in all BEV scenarios, particularly in All-In with 977 % of current lithium production. Including a global ramp-up of electric mobility and economic catch-up of rest of the world by 2050 (see explanations in 11.2.2.2) means even for the 100 % electric scenario with lowest lithium demand (BEV Balanced) a more than 36-fold increase of annual global lithium supply (primary and secondary) to meet the lithium demand 2050 from worldwide mobility.

Lithium demand from other sectors in 2050 is not that relevant for the total global lithium demand. It is estimated between 65 thousand tonnes (Greim et al. 2020, based on medium ambitious assumptions on development outside Europe) and 100 thousand tonnes (own estimate, based on ambitious assumptions on development in the rest of the world) and contributes 0.9 to 3.5 % to total annual lithium demand in 2050 in the BEV scenarios.

In the coming years, increasing lithium demand will have to be met mainly through an increase in primary lithium production. Relevance of secondary lithium increases after 2035 as old passenger cars enter more and more into recycling markets. A more detailed analysis of annual primary lithium demand and a comparison with forecasts of potential future primary lithium production to assess potential temporary supply bottlenecks is given in the following excursus.

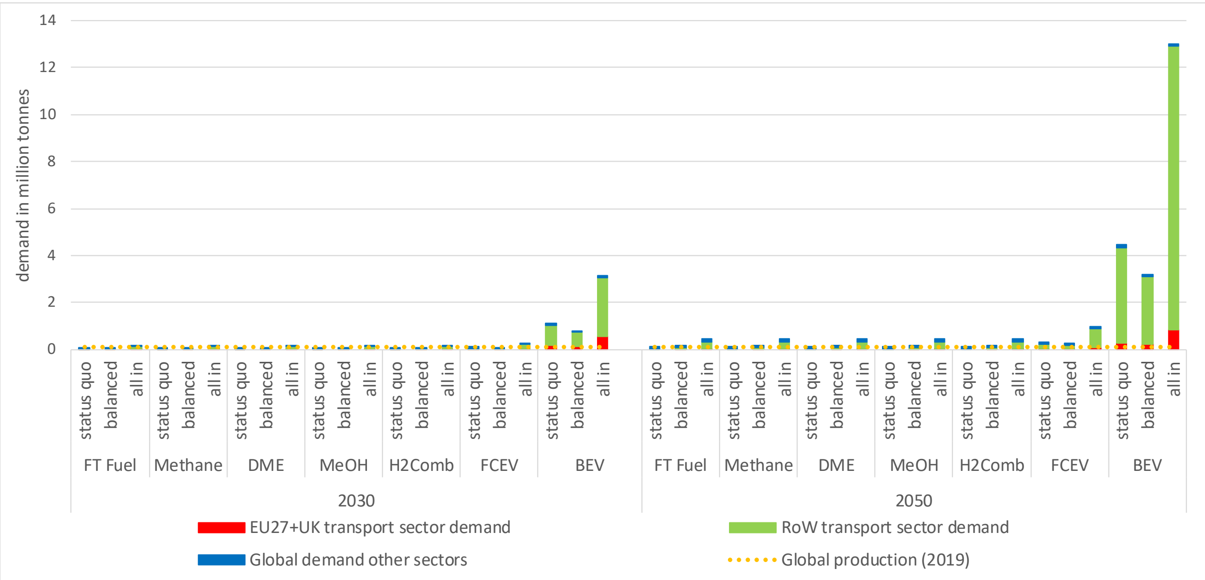

Figure 95: Total annual lithium in the 100% scenarios in 2030 (left) and 2050 (right).

Development of primary lithium demand 2021-2050 in 100 % electric scenarios

Lithium production volumes and knowledge on reserves and resources have been changing very fast in recent years. Against the background of global supply scenarios as calculated by Greim et al. (2020), the annual demand for lithium in all other pathways besides BEV is not a bottleneck. In Figure 96 these global supply scenarios are compared to the annual development of primary lithium demand for Europe and worldwide in the 100 % BEV scenarios. Primary lithium demand considers the total annual lithium demand reduced by the share, which can be satisfied with secondary lithium from scrapped vehicles in the according year. We consider a collection rate of 90 % and a recycling rate of 85 % for lithium from scrapped cars.

Looking at the EU27+UK transport sector only, primary lithium demand increases in the coming years, but will decrease after 2030 when the market ramp-up of electric mobility is largely complete and higher amounts of secondary lithium are available. In contrast, global primary lithium demand will continue to increase considerably in the following decades, driven by the assumed strong increase of worldwide motorisation rates.

Primary lithium demand from European transport sector in the BEV Status Quo and Balanced scenarios is lower than prospected annual global supply in all years. However, in the BEV All-In scenario (solid state batteries with pure lithium anodes), lithium could become a temporary bottleneck as of 2025, even if only Europe is going to introduce these battery types.

On a global scale, lithium demand is no bottleneck in the “BEV balanced” scenario until ~2035 when rest of the world is following Europe timewise. In later years up to 2050 annual primary lithium supply can become a bottleneck if motorization rates in the rest of the world catch up with Europe and no additional lithium reserves beyond those mines and extraction sources, which are already planned, are made accessible. In contrast, lithium will become a severe bottleneck already in 2025 in the “BEV All-In” scenario.

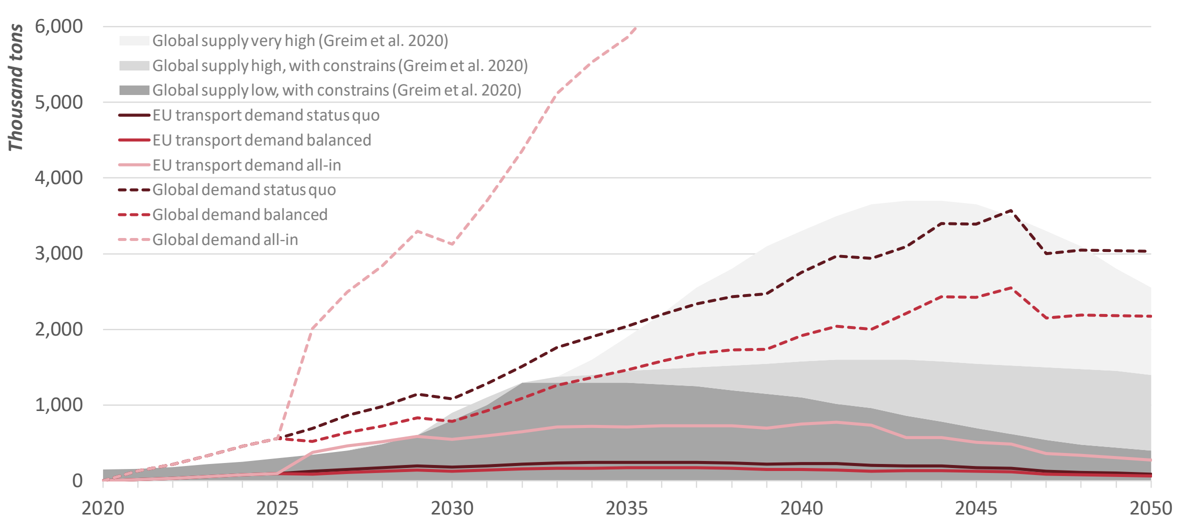

Figure 96: Annual primary lithium demand in BEV scenarios and potential global supply 2021-2050 [Source: own compilation and Greim et al. (2020)].

11.3.1.2 Cumulative primary lithium demand 2021-2050

The estimation of the cumulative primary lithium demand up to the year 2050 is needed to assess potential absolute resource bottlenecks. In addition to the total lithium demand, this also takes into account the proportion of lithium that can be recovered from the scrapping of vehicles during this period and thus reduces the demand for primary lithium.

Cumulative primary lithium demand is only an issue in BEV scenarios. In the BEV Status Quo and Balanced scenario, cumulative demand in Europe and the rest of the world exceeds currently known reserves, but is below global resources. In the BEV All-In scenario, European mobility sector only needs more than half of currently known global reserves. Including primary demand of the rest of the world and other sectors, the cumulative demand exceeds currently known reserves by factor 8 and requires nearly twice the currently known resources.

In other pathways, cumulative demand for primary lithium between 2021 and 2050 is clearly below currently known reserves.

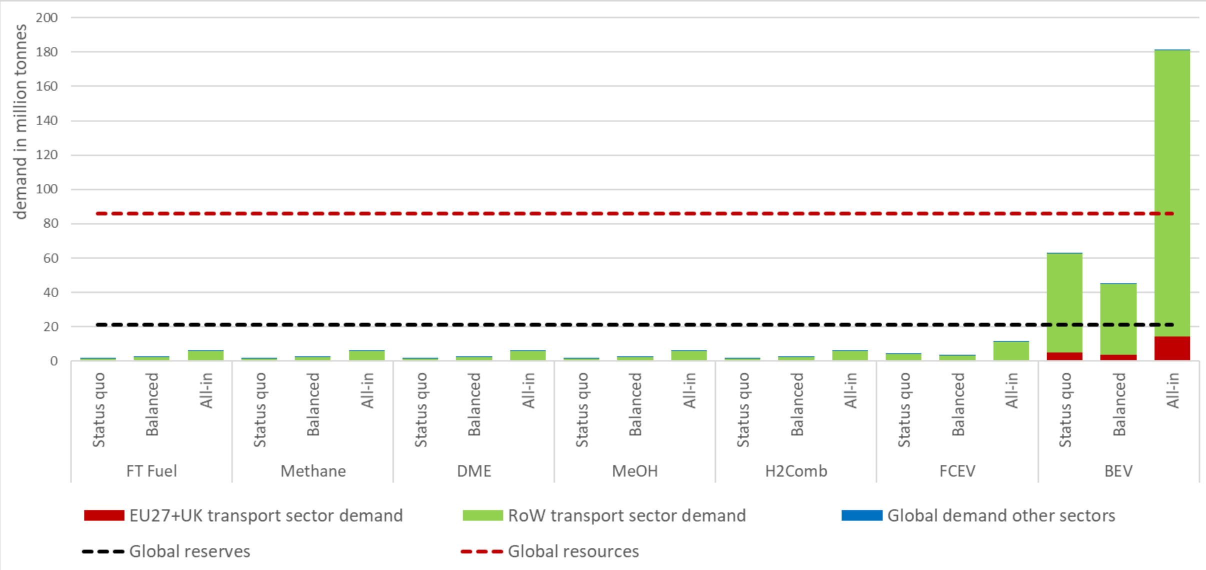

Figure 97: Cumulative primary lithium demand 2021-2050 in the 100% scenarios [Source: own compilation and (USGS, 2021a)].

11.3.1.3 Annual cobalt demand

Demand for cobalt associated with the transport sector is driven by vehicle production, particularly production of cobalt-containing Li-ion batteries[30]. Only a minor amount of cobalt is used in fuel supply chain infrastructure (European Commission 2020c). Therefore, results of scenarios with domestic and international fuel supply chains show only minor differences in cobalt demand. In the following, we present only results of the domestic scenarios.

Figure 98 shows the annual cobalt demand in the years 2030 and 2050 for the transport sector in EU27+UK and for the rest of the world, supplemented by the global demand of other sectors. 100 % electric scenarios show substantially higher annual cobalt demand in the transport sector for Europe and for the rest of the world compared to other fuel pathways (with small batteries in hybridised and fuel cell vehicles). In 2030, a new registration share of electric vehicles in passenger cars of 77% is achieved in the BEV scenarios. As a result, the annual cobalt demand in

[30] In our study, we assume Li-ion batteries with NMC cathodes in all scenarios. Also other battery types (NCA, LCO) contain cobalt. However, there are also battery types without cobalt (LFP, SIB). We analysed options for reducing cobalt demand through cobalt-free battery types in a sensitivity analysis in section 11.3.1.6.

2030 only for new vehicles in Europe exceeds in the BEV Status Quo scenario the current annual global production (294 thousand tons) by factor 2. BEV Balanced and All-In scenario assume lower specific cobalt contents (NMC811 instead of NMC622) and higher energy densities. Furthermore, battery capacities are lower due to higher vehicle efficiencies. Nevertheless, only transport in Europe requires 72 % of today’s world production in the balanced scenario and still 20 % of world production in the All-In scenario.

From 2030 to 2050, annual cobalt demand increases in all scenarios. Cobalt demand for new electric vehicles in Europe is rising by about 50 %, as in addition to 100 % new registrations share of electric vehicles the total number of new car registrations slightly increases. Accordingly, the EU27+UK transport sector needs from 49 to 449 thousand tonnes of cobalt in the BEV scenarios. However, the increase of cobalt demand is much stronger in the rest of the world if catching-up development will lead to a strong increase in overall annual vehicle sales. Total annual cobalt demand for worldwide transport is in 2050 more than factor 4 higher than in 2030 reaching 0.7-6.9 million tonnes of cobalt demand for 100 % electric mobility in 2050. In all other fuel pathways, cobalt demand in the mobility sector is very low. In these scenarios, only about 0.001-0.13 million tonnes of cobalt are needed for global transport in 2050, less than today's annual global production. The only exception is the FCEV Status Quo technology pathway; annual demand in 2050 (0.35 million tonnes) exceeds current global production.

Cobalt demand of non-transport applications is rather low compared to electric mobility, but should not be neglected. Cobalt is used in several applications such as batteries, superalloys, catalysts, carbides and magnets. In 2030, we estimate a cobalt demand of other sectors of 213,000 tonnes (primary: 136,000 tonnes); in 2050, the demand is expected to reach 404,000 tonnes (primary: 240,000 tonnes). In the BEV scenarios, the remaining sectors thus contribute 6 % (Status Quo) to 35 % (All-In) of the total global demand in 2050. In all other fuel pathways, non-transport sectors dominate total annual cobalt demand. As the analyses show, even in this case global cobalt production must double up to 2050, but this is not due to the defossilisation of the transport sector.

In the coming years, increasing cobalt demand will have to be met mainly through an increase in primary cobalt production. Relevance of secondary cobalt increases after 2035 as old passenger cars enter more and more into recycling markets. A more detailed analysis of annual primary cobalt demand and a comparison with forecasts of potential future primary production to assess potential temporary supply bottlenecks is given in the following excursus.

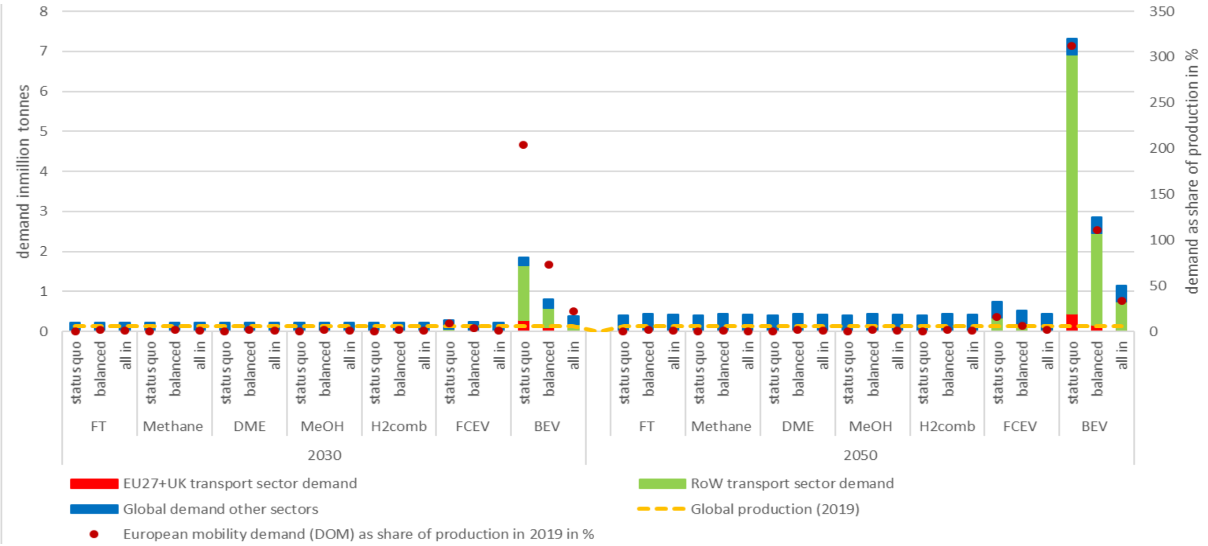

Figure 98: Total annual cobalt demand in the 100% scenarios in 2030 (top) and 2050 (bottom) [Source: own compilation and (USGS, 2021d)*].*

Development of primary cobalt demand 2021-2030 in 100 % electric scenarios

In a more specific analysis for the BEV scenarios in Figure 99, we compare the development of primary annual cobalt demand for Europe and worldwide against the background of future supply. Primary cobalt demand considers the total annual cobalt demand and the share that can be satisfied with secondary material from recycling in the stationary sector and from scrapped vehicles in the according year. We consider a collection rate of 90 % and a recycling rate of 80 % based on information from Dominish et al. (2021).

There are no analyses that study global cobalt supply in the timeframe of the next 30 years. Therefore, only supply forecasts until 2030 could be considered. Alves Dias et al. (2018) provide cobalt supply forecasts until 2030 varying with regard to market conditions that drive decision making of future mining projects (only unscheduled mine cobalt production from cobalt mines and additional supply of cobalt as a by-product from unscheduled nickel production). Based on these forecasts, an increase of global cobalt production by 50-90 % is expected. It has to be noticed that the supply forecasts do not take the technology change of mobility to 100% extreme scenarios into consideration.

Cobalt demand in the years 2021-2025 is equal in all BEV scenarios as we assume a shift to higher technology levels (Balanced, All-In) in the new registrations not before 2026. The cobalt demand for new vehicle registrations in Europe can be satisfied with the current cobalt production. If a comparably fast ramp-up of electric mobility (reaching 40 % new registrations share in 2025) is targeted worldwide with the same battery configurations as the Status-Quo technology level in this study (NMC622, 150 Wh/kg, 500km range of most passenger cars), annual worldwide production in 2025 would have to be about 4-5 times higher than in the available forecasts. Actually, numerous aspects are likely to lead to a weaker increase in reality in the next years, in particular smaller batteries, a mix of different, partly completely cobalt-free battery technologies and an overall slower increase in the share of electric vehicles in new registrations in many countries.

Looking at the year 2030, European demand of cobalt in the BEV Balanced and All-In scenarios can be met already by the conservative supply forecast (Alves Dias et al. (2018), low). In order to meet European demand of Status Quo, an ambitious exploitation of cobalt reserves as in the forecast of Fu et al. (2020) would be necessary.

Global cobalt demand will exceed global production by far in all years, if the rest of the world is ramping up battery electric vehicles with the same ramp-up speed and same battery technologies as assumed for Europe in this study. The temporary bottleneck is even more pronounced, if annual cobalt demand of other sectors is included.

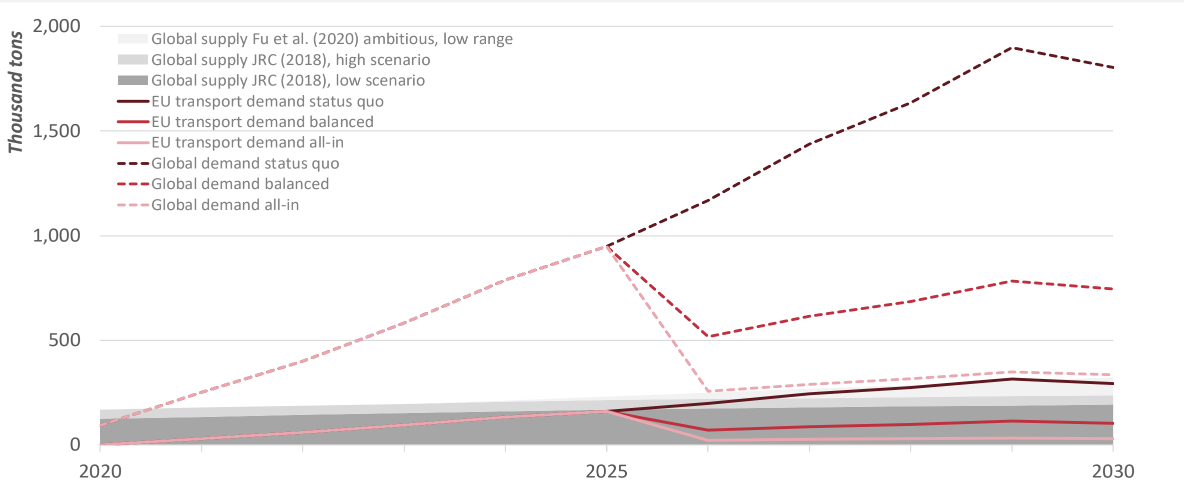

Figure 99: Annual primary cobalt demand in BEV scenarios 2021-2030 and forecasts of global supply [Source: own compilation and (Alves Dias et al., 2018; Fu et al., 2020; USGS, 2021d)].

11.3.1.4 Cumulative primary cobalt demand 2021-2050

Figure 100 shows the cumulative primary cobalt demand including EU27+UK transport sector, extrapolation to worldwide transport and demand of non-transport sectors. Primary demand considers total cumulative demand, but subtracts secondary cobalt supply. Cumulative primary cobalt demand is only an issue in the BEV scenarios. Demand in all other fuel pathways remains shortly below currently known reserves and is dominated by non-transport applications (4.9 million tonnes), which can be considered a rather conservative estimation compared to other forecasts, e.g. by Junne et al. (2020) projecting 12.5 million tonnes (2015-2050).

In the 100 % BEV pathway with Status Quo vehicle technology, European demand for the transport sector alone exceeds currently known global reserves (115 %). Balanced and All-In scenario require 42 % and 14 % of global reserves. The extrapolated global primary cobalt demand exceeds currently known reserves in all BEV scenarios by far. Furthermore, Status Quo and Balanced scenario even exceed the currently known resources, caused by the high cobalt demand of the worldwide mobility sector.

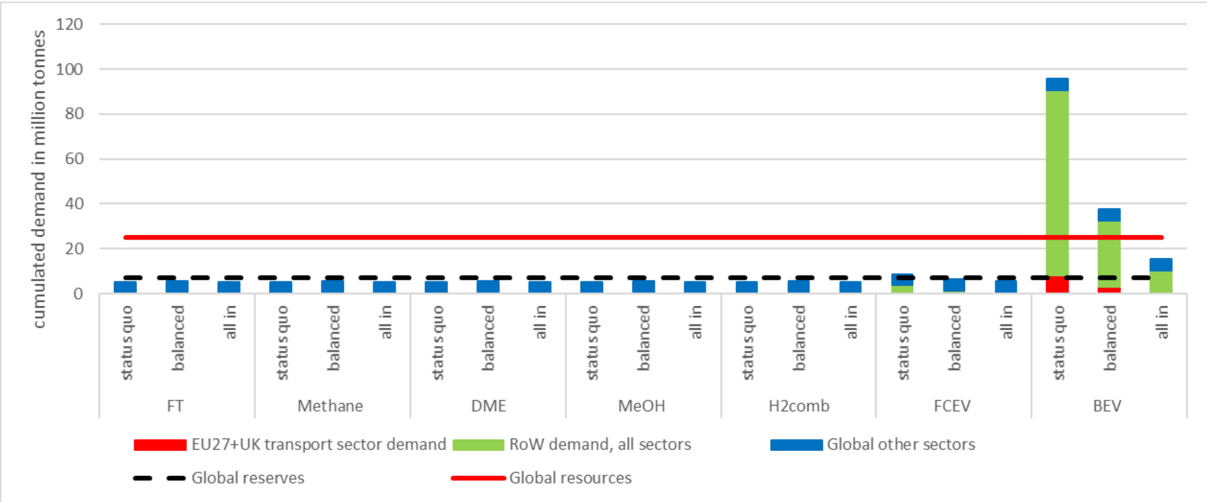

Figure 100: Cumulative primary cobalt demand 2021-2050 in the 100% scenarios [Source: own compilation and (USGS, 2021d)].

11.3.1.5 Lithium and cobalt bottlenecks in the 100% scenarios

Scenario results show that H_2 and hydrocarbon fuel pathways for a defossilisation of the transport sector do not face lithium or cobalt bottlenecks with the assumptions in this study. In contrast, a worldwide ramp-up of electric mobility can be affected by absolute and temporary material bottlenecks. With the specific battery configurations assumed in our scenarios and extrapolated worldwide material demand, 100 % worldwide electric mobility are not possible. Cobalt is a bottleneck in the Status Quo and Balanced scenario as the cobalt demand exceeds currently known terrestric resources. In the All-In scenario, the cobalt demand is below the known resources, but here the lithium demand exceeds the currently known resources.

Actually, this does not mean that 100 % electric mobility is generally not possible worldwide, but this finding is limited to the scenario configurations in our study. Other battery technologies and lower increases of worldwide motorisation can significantly reduce material demand. We analysed this in an additional sensitivity analysis in section 11.3.1.6 showing that 100 % worldwide electric mobility is possible with a mix of battery technologies including lithium and cobalt free alternatives with today known resources. Furthermore, global lithium and cobalt resources and reserves have developed very dynamically in the last few years as we explained in section 11.2.1. Therefore, a considerable future increase of primary material supply can be expected (even if ocean mining is not yet accessible in the medium term).

The results in this study confirm other studies on critical materials. Although particular assumptions on mobility demand, battery types and technology mixtures are different, several studies such as (Barazi, 2018; BGR, 2021a; Dittrich / Gerhardt / Schoer / Dünnebeil / Sara Becker / et al., 2020; European Commission, 2020b; b; Fu et al., 2020; IEA, 2021; Junne et al., 2020; Marscheider-Weidemann et al., 2021; UBA, 2019; UN IRP, 2017; World Bank, 2017; Xu et al., 2020) have shown that future lithium and cobalt demand are critical in a transformation pathway. Thus, this study along with other results concludes that 100 % electric mobility require:

- Further development and use of different battery types with less lithium and cobalt content. Existing substitutes for Cobalt in the non-transport sector should be used as well.
- Limit the increase of global car battery demand (slow down increase of worldwide motorisation, adopted vehicle-specific battery sizes for different mobility profiles),
- Increase global production volumes of lithium and cobalt and further development of sustainable mining technologies and exploration activities,
- Further development and installing collection- and closed-loops recycling systems.

11.3.1.6 Sensitivity: Reduction potentials for lithium and cobalt bottlenecks

Analyses in this study show that with here defined battery configurations, future EU transport increase and the additional assumption that worldwide economic prosperity will fully catch-up to European Union within next 30 years, 100 % battery electric mobility on a worldwide scale would not be possible. This raises the question if it is not possible in any case or if 100 % battery electric mobility can be achieved under different conditions than assumed in this study. The following sensitivity analysis based on the BEV balanced scenario shows that identified global bottlenecks are primarily result of the scenario configurations. However, there are alternative development pathways enabling 100 % electric mobility worldwide.

We analysed two main influencing factors not covered in our scenarios. Both factors can reduce global lithium and cobalt demand by far and, thus, enable 100% worldwide electric mobility:

- In our scenarios, we defined one **selected battery technology** per scenario and in all applications (Status Quo: NMC622 150 Wh/kg, Balanced: NMC811 200 Wh/kg, All-In: Li-solid state 300 Wh/kg). However, alternative battery technologies are already in the market or close to market entry. A mix of different battery technologies as expected in most forecasts and scenarios can substantially reduce global material demands. In particular:
  - Lithium iron phosphate batteries (LFP) contain no cobalt and specific lithium demand per kWh is slightly lower than for Li-NMC batteries (Xu et al., 2020). LFP batteries are widely used in stationary applications and heavy-duty vehicles on the Asian car market. They are also installed in cars sold e.g. in Germany. There are expectation, that LFP batteries may become a standard technology in all future budget cars (JESMB, 2021).
  - Sodium-ion batteries (SIB) contain neither cobalt nor lithium. Two large battery companies (Faradion/UK, CATL/China) have started pre-series production this year and could be available for mass production within 2 years. According to (Wunderlich-Pfeiffer, 2021) they are also suitable for mobility applications with relevant vehicle range and “closer to market entry than solid state batteries”, which we assume in our All-In scenario.
- One main reason for high global lithium and cobalt demands in our scenarios are our **assumptions for increase of global vehicle sales**: Global transport forecasts expect about 200 million vehicle sales worldwide in 2050 - more than doubling today’s global vehicle production. In our scenarios, we assume an even stronger increase as we defined a worldwide economic catch-up to EU prosperity level within next 30 years (fair share for EU27+UK not only for defossilised vehicle technologies, but also for the overall economic development). This would mean about 330 million vehicle sales worldwide in 2050 – more than tripling today’s global production and about 50 % higher than expected in global forecasts.

If we assume 100 % LFP batteries in light commercial vehicles and heavy-duty vehicles and 50 % LFP in stationary applications, global cobalt demand would be reduced by 35 %. If we additionally assume 100 % LFP also for small cars, global cobalt demand would even be cut by half. With these assumptions, lithium as well as cobalt demand in our balanced scenario would meet today known global resources. If we would add SIB to a global “NMC+LFP” battery mix, this would additionally reduce global lithium demand considerably.

If we adopt worldwide motorisation developments from existing forecasts, global lithium and cobalt demand in our Balanced scenario will be within the today known global resources – even only assuming Li-NMC battery technology. Combining alternative battery technologies and a lower motorisation increase would cut global lithium demand by half and global cobalt demand by more than 60 %.

A further factor for global raw material bottlenecks in the FVV IV scenarios are the assumed battery sizes in the 100% scenarios (300 – 500 km range). If a part of the vehicles (which do not necessarily require high operating ranges) were equipped with smaller batteries as is assumed in other studies, the raw material demand would be considerably reduced.

In conclusion, scenario definitions together with assumed worldwide economic catch-up to EU prosperity level within next 30 years have to be seen the upper limit of global lithium and cobalt demand for 100 % worldwide electric mobility. A mix of different probable battery technologies (already in the market) as well as general development trends (worldwide motorization, battery sizes per vehicle) will most probably lead to substantially lower raw material demand that is lower than today known global resources.

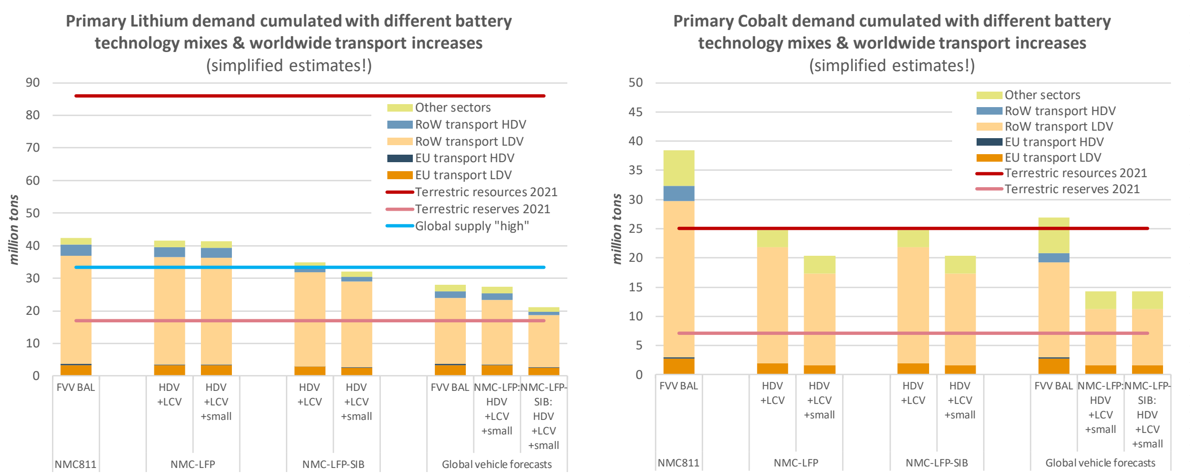

Figure 101: Sensitivity: Reduction potentials for lithium and cobalt bottlenecks in the balanced scenario.

Main assumptions in simplified estimates of primary Li and Co reduction potential

- *FVV BAL: FVV balanced scenario: 100% NMC811 batteries worldwide in all vehicle categories. Increase of world-wide vehicle sales to 330 million vehicles per year in 2050*
- *Sensitivity “NMC-LFP”*
  - *HDV+LCV: All HDV and LCV are equipped with LFP batteries. All cars with NMC811. Stationary sector with 50% LFP.*
  - *HDV+LCV+small: All HDV, LCV and small passenger cars are equipped with LFP. All other cars with NMC811. Stationary sector with 50% LFP.*
- *Sensitivity “NMC-LFP-SIB”: Same attribution of alternative battery technologies per vehicle category as in NMC-LFP, but instead of only LFP, a 50:50 mix of LFP and SIB batteries is assumed.*
- *Sensitivities “Global vehicle forecasts”: Worldwide vehicle sales increase to 210 million vehicles per year in 2050 according to existing global vehicle forecasts. Battery technology is as in the FVV balanced scenario resp. in the sensitivity checks for alternative battery technology mixes.*

11.3.2 Platinum group metals (PGM)

11.3.2.1 Annual total material demand in the years 2030 and 2050

PGM demand is mostly driven by the material demand for car fleet production; particularly fuel cell production. Only a very small amount of platinum is used in fuel supply chain infrastructure. Platinum is one of the most effective electrocatalysts for both the cathode and anode in fuel cells. Palladium, as catalyst, can partly replace platinum, e.g. as Pt-Pd alloy (European Commission, 2020b). Figure 102 shows the scenario results for annual PGM demand in the years 2030 and 2050 for the transport sector in EU27+UK and for the rest of the world, supplemented by the global demand of other sectors.

The FCEV scenarios show substantially higher annual PGM demand in the transport sector for Europe and for the rest of the world compared to other fuel pathways.

- In 2030, in the FCEV Status Quo scenario the PGM demand of EU27+UK alone exceeds the current annual global production by factor 1.2. FCEV Balanced and All-In scenario require less PGM but still require more than 50 % of today's world production.
- From 2030 to 2050 the material demand for PGM increases further in all scenarios; FCEV Status Quo then exceeds production levels by factor 1.8, FCEV Balanced and All-in require 70 % of current production levels.
- The total bandwidth of annual PGM demand in the other fuel pathways associated with the EU27+UK transport sector in 2050 is from 117 tonnes (H_2 Comb All-In) up to 203 tonnes (Methane Status Quo). This corresponds to a share of 24 % to 42 % of today's global PGM production.

Global PGM demand in 2050 exceeds in all scenarios production levels of 2019, except for the BEV scenarios. The transport sector of Europe and the rest of the world imply that production levels must be increased strongly to meet global PGM demand; 32fold in FCEV and 8fold in remaining scenarios. Non-transport sectors require 461 tonnes of Palladium and Platinum, e.g. for jewellery, chemical, medical and biochemical applications or electronics.

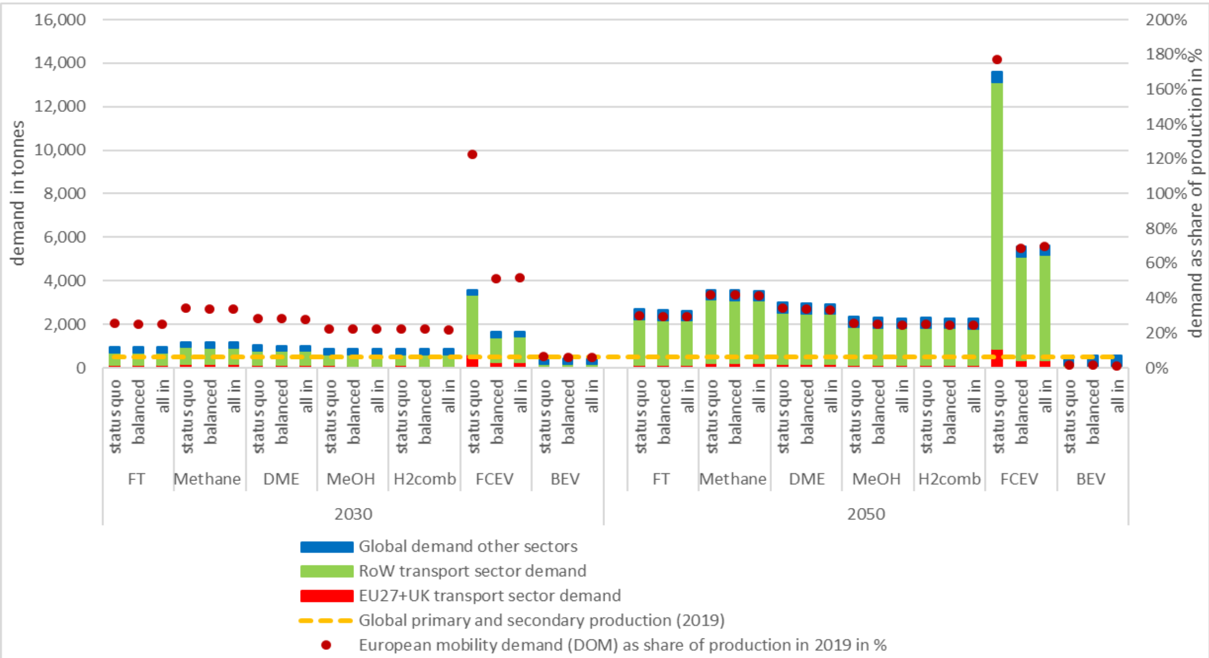

Figure 102: Total annual PGM demand in the 100% scenarios in 2030 (left) and 2050 (right) [Source: own compilation and (USGS, 2021c)].

11.3.2.2 Cumulative primary material demand 2021-2050

Figure 103 shows the total cumulative EU27+UK and global primary PGM demand of the mobility sectors as well as the demand of global non-transport sectors for all domestic scenarios from 2021 until 2050 in absolute values. In addition, current reserves (69,000 tonnes in 2019) and resources are depicted in the figure to illustrate relations more clearly.

Currently known reserves are sufficient to fulfil European cumulative demand for primary PGM for the mobility sector until 2050 in all scenarios. The highest PGM demand clearly arises in the FCEV technology pathway. In FCEV Status Quo 26 % of global reserves are needed to fulfil European demand. In FCEV Balanced and All-In 11 % of reserves are needed, respectively.

This picture barely changes for the international scenario as demand is triggered by car fleet production. On a global scale, except for the FCEV pathway (all technology levels), the cumulative primary PGM demand (of all sectors) until 2050 of all technology pathways does not exceed global reserves, which are estimated at more than 100,000 tonnes according to USGS (2021e).

For FCEV technology pathways, a bottleneck arises at global scale according to the underlying methodological assumptions. In Status quo, Balanced and All-In currently known reserves are exceeded; for Status Quo even resources are exceeded. If cumulative global secondary PGM supply until 2050 is included and added to reserves (approximately + 17,000 tonnes), FCEV Status quo technology pathway remains a clear bottleneck for PGM.

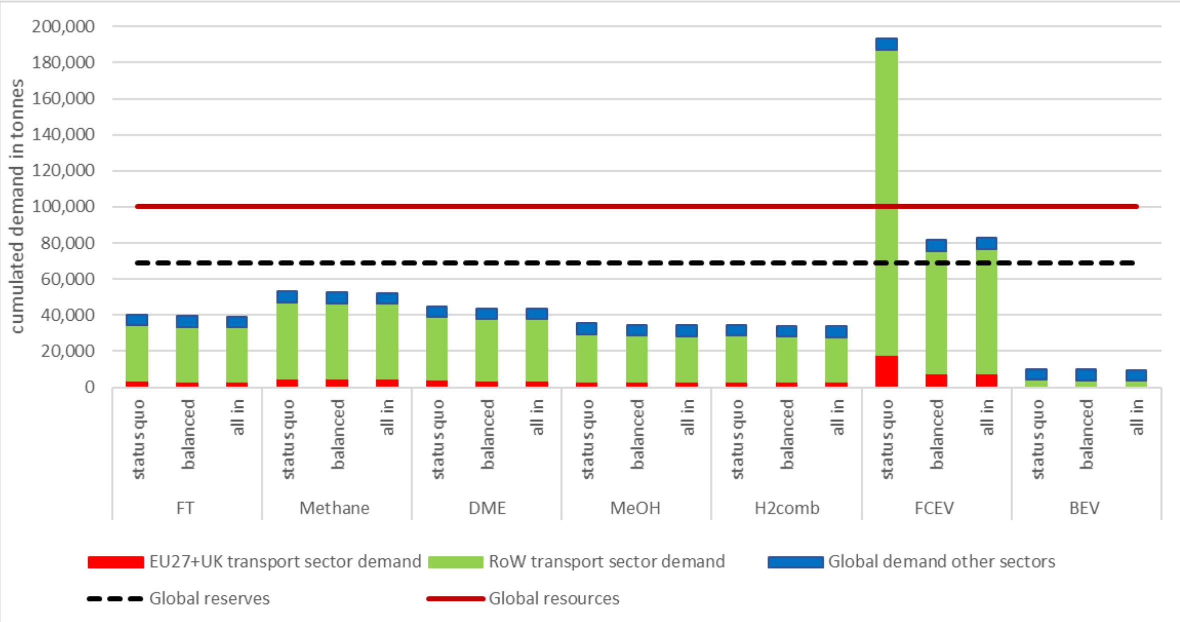

Figure 103: Cumulative primary PGM demand 2021-2050 in the 100% scenarios [Source: own compilation and (USGS, 2021c)].

11.3.2.3 Platinum bottlenecks in the 100 % scenarios

Platinum supply, reserves and resources are not separately available, but only together with other Platinum group metals (PGM). Therefore, actual Platinum availability will be lower than indicated here. Primary platinum production in 2017 comprised approximately 45 % of total PGM production (European Commission, 2020a; USGS, 2021c). As Platinum is long-used metal in industry, future demand is not only compared with primary lithium supply, but also with secondary platinum (recycling).

- Cumulative platinum demand for EU27+UK transport sector is in all scenario configurations lower than today’s global reserves and resources.
- Cumulative global platinum demand with FVV configurations and assumptions for increase of worldwide motorization would widely use up (Balanced, All-In) or clearly exceed (Status-quo) global platinum resources. This picture would not change significantly if total secondary platinum is considered, yet, for balanced and all in technology pathway, cumulative demand would stay just below platinum reserves.

The results in this study confirm results of other studies on critical materials for the transformation pathways. Although particular assumptions on mobility demand, fuel cell types and technology mixtures are different, several studies such as European Commission (2020c; b); Hao et al. (2019), Marscheider-Weidemann et al. (2021) have shown that future PGM demand is critical in a fuel cell related transformation pathway. Thus, this study along with other results conclude that FCEV pathways require:

- Increasing production volumes of PGM
- Further development of sustainable mining technologies and exploration activities
- Further development and installing collection- and closed-loops recycling systems
- Further development and use of substitution options wherever possible

With FCEV configurations as in FVV IV fuels study, future EU transport increase and assumption that worldwide economic prosperity will fully catch-up to European Union within next 30 years, 100 % FCEV mobility on a worldwide scale would not be possible. However, additional analyses show that identified global bottlenecks are primarily result of FVV scenario configurations. There are alternative development pathways, which can enable 100 % FCEV mobility worldwide. Following main factors can reduce global Pt demand or increase global Pt supply and, thus, enable 100% worldwide FCEV mobility.

- Simplified assumptions for increase of vehicle sales in RoW: As explained for lithium and cobalt, our simplified estimate for a worldwide economic catch-up to EU prosperity level within next 30 years overestimates global number of vehicle sales by about 50% compared to existing transport forecasts.

- Further exploration of resources: Further explorations of vast PGM resources can avoid bottlenecks. Sverdrup and Ragnarsdottir (2016) state that according to recent technological advances in deep mining PGM resources are much higher than earlier estimates (e.g. USGS). According to the authors, about 216 thousand ton of platinum group metals resources down to a mining depth of maximum 5 km can be estimated. For platinum alone, related reserves are estimated at 11.7 thousand tonnes and resources at 54.2 thousand tonnes according to the authors.

- Higher supply as projected: it has to be noted that supply forecast by Sverdrup and Ragnarsdottir (2016) does not take into account 100 % scenarios, thus, economic incentives e.g. for recycling and exploration of further reserves might change strongly, thus, resulting in more ambitious supply.

- Increase substitution possibilities in several applications: For platinum, the potential substitutes are other PGM or base metals, although these may have associated price or performance penalties. (European Commission, 2020a; USGS, 2021c)

11.3.3 Copper

11.3.3.1 Annual total material demand

Copper demand for a defossilisation of the EU27+UK transport sector is driven by both, vehicle production and fuel supply chain including infrastructure. In vehicle production, copper is required in all pathways and technology levels (see explanations in section 10.2.2.7) and is particularly high for battery-electric vehicles. Copper demand for the fuel supply chain infrastructure in BEV and H_2 based pathways is dominated by power generation, in hydrocarbon fuel pathways by power generation and fuel synthesis. Further copper demand in the BEV scenarios results from additional electricity distribution lines and charging infrastructure.

Figure 104 shows the annual copper demand associated with the EU27+UK transport sector in all 100 % scenarios for the year 2050. Status Quo and Balanced scenarios with battery-electric mobility (with both, domestic and international energy sourcing) and with hydrocarbon fuels (with domestic energy sourcing only) have the highest total copper demand in 2050 and are in the same range of about 3-4 million tons, though with different contributions of vehicle production and fuel supply chain infrastructure[31]. Scenarios with H_2 pathways need considerably less copper, only about 1.5 million tons with international energy sourcing. BEV scenarios with domestic and international energy sourcing have very similar copper demand (slightly higher in international scenarios due to submarine cables for electricity import). In all other pathways, international scenarios show a reduced copper demand due to lower installed power generation capacity.

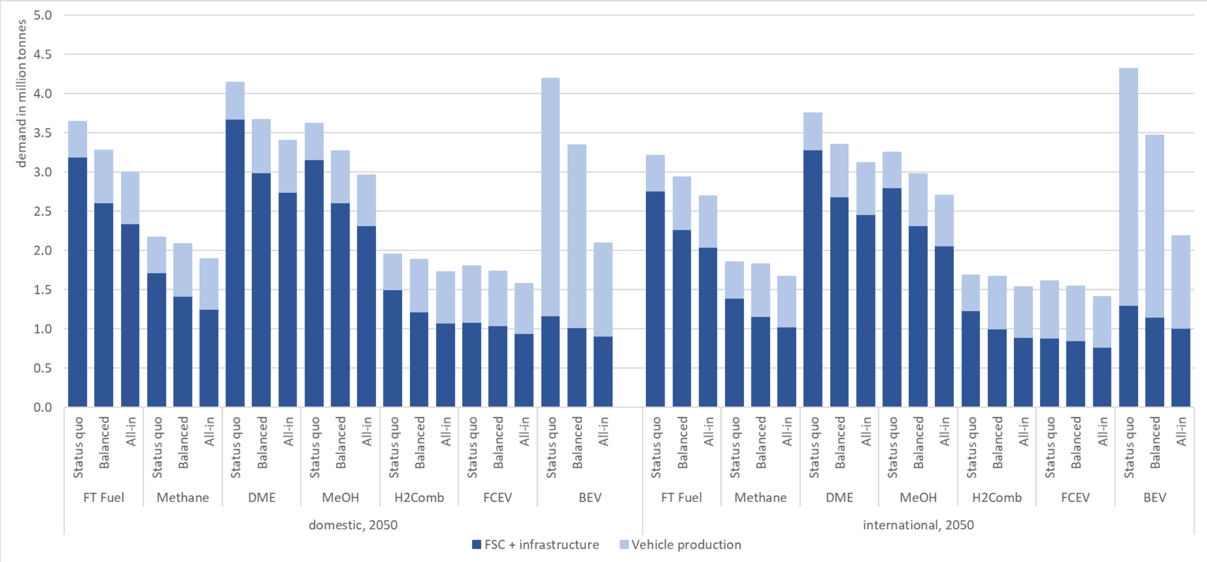

Figure 104: Copper demand for the EU27+UK transport sector in 2050 in domestic (left) and international (right) scenarios by source.

Copper demand for the mobility sector in Europe, the global mobility sector and other sectors increases significantly up to 2050 in all pathways compared to today's demand.

Figure 105 shows the annual copper demand for EU27+UK transport sector and extrapolated copper demand for a defossilisation of worldwide transport for the years 2030 and 2050. While copper demand in Europe will increase moderately from 2030 to 2050, the increase in global demand is much stronger as it is driven not only by the defossilisation efforts, but at the same time by a strong increase in overall annual vehicle sales. In the year 2050, copper demand associated with a defossilised worldwide transport is depending on the fuel pathway in a range of 2 to 66 million tons (88 - 272 % of global primary and secondary copper production in 2018). As already explained for European transport, the copper requirements are highest for hydrocarbon fuels and for BEV scenarios (Status Quo and Balanced), and lowest in the scenarios with hydrogen. If electricity can be supplied mainly at global locations with good conditions (international scenarios with high full-load hours of wind and PV power plants), the copper demand is lower than for regional generation close to fuel demand.

Actually, future global copper demand and potential bottlenecks will not only be driven by the defossilisation of transport, but at the same time by demand for other sectors. Demand for other sectors highly depends on the assumed economic development dynamics. For example, Schipper et al. (2018) calculated global copper demand for all sectors in 2050 with a minimum of 45 million tonnes and a maximum of 130 million tonnes. Our own estimation on global copper

[31] Calculated copper demand in the methane scenarios is also very low due to very low calculated demand for the synthesis infrastructure. This is likely to be unrealistic resulting from available specific data from the ecoinvent database, which show huge discrepancies for methane production compared to other fuel production plants (see explanations in section 10.2.1.3).

demand for non-transport sectors amount up to 34 million tons copper demand in 2030 and 63 million tonnes in 2050.

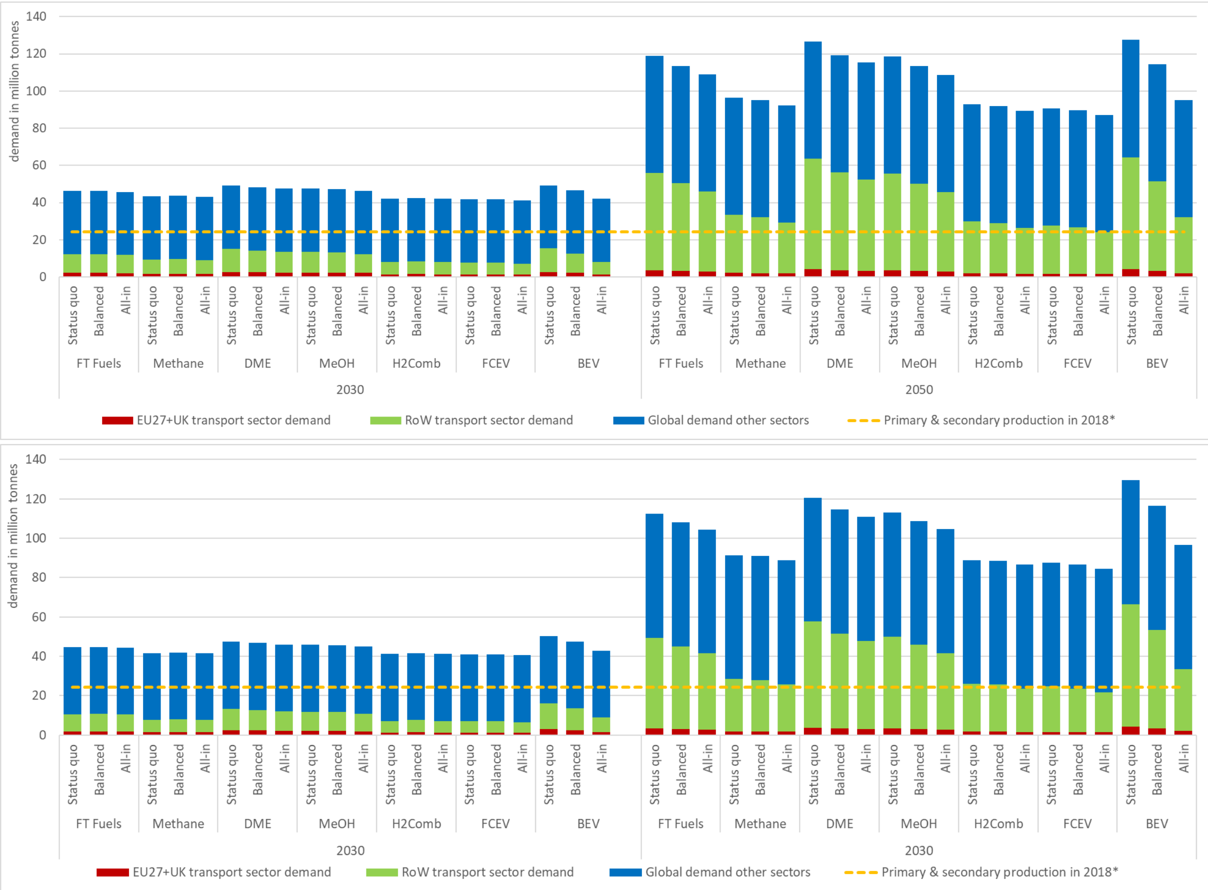

Figure 105: Total annual copper demand in the 100% scenarios with domestic (top) and international (bottom) energy sourcing [Source: own compilation and (ICSG - International Copper Study Group, 2020)].

11.3.3.2 Cumulative primary material demand 2021-2050

Cumulative primary copper demand is shown in Figure 106. Within the transport sector, cumulative primary copper demand is an issue particularly in BEV and hydrocarbon fuel scenarios with Status Quo vehicle technology, due to due to vehicle production in BEV and due to fuel supply chain demand in hydrocarbon fuel pathways. This holds true for both, domestic and international scenarios. Primary copper demand for global transport will require about 80% up to slightly more than 100% of currently known reserves. Scenarios with high vehicle technology levels (All-In) have a substantially lower cumulative primary copper demand in all fuel pathways. Lowest global cumulative demand for the mobility sector can be found in FCEV *All-In* with only 35 % of currently known reserves in international scenarios.

The cumulative primary copper demand of non-transport sectors is around 500 million tons (applying high recycling rates of 90 %). Total cumulative demand from mobility sector and from other sectors exceeds currently known reserves in all scenarios except for FCEV All-In and balanced international, which consume only 97 % and 100 % of global reserves.

Across all sectors, the cumulative primary copper demand is lower than the currently known resources in all pathways. Cumulative primary copper demand in BEV Status Quo international and DME Status Quo Domestic (the scenarios with the highest demand) sum up to 71 % of global resources. FCEV All-In international (the scenario with the lowest demand) requires 40 % of resources.

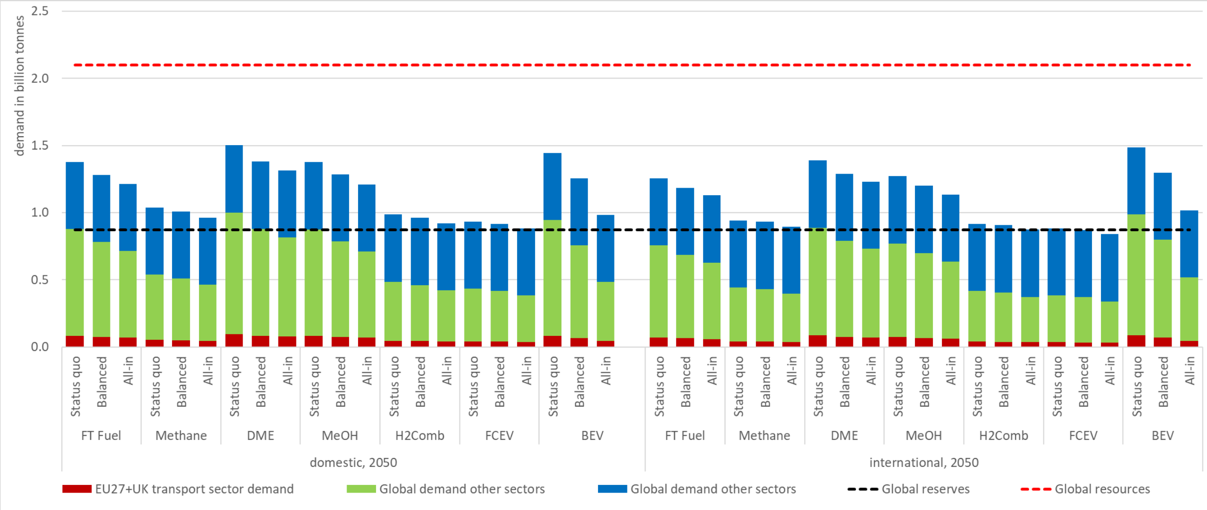

Figure 106: Cumulative primary copper demand 2021-2050 in the 100 % scenarios [Source: own compilation and (USGS, 2021b)].

11.3.3.3 Copper bottlenecks in the 100 % scenarios

Scenario results show that following the given assumptions on vehicle production, fuel supply technologies and economic development outside Europe, copper supply can be a bottleneck particularly in BEV and hydrocarbon fuel pathways with Status Quo vehicle technology. However, as demand from other sectors is high, the overall copper demand of all sectors exceeds current production in all scenarios in both years, 2030 and 2050.

Together with high copper demand for climate-mitigation strategies in non-transport sectors, cumulative primary copper demand exceeds currently known global reserves in nearly all pathways (except FCEV Balanced and All-In). Overall primary copper demand is below currently known global resources, but still very high in hydrocarbon fuel pathways with Balanced or Status Quo vehicle technology and BEV pathways with Status Quo technology. Hydrogen pathways have the lowest copper demand. In scenarios with international energy sourcing, fewer wind and PV power plants are required and, thus, the copper demand for the fuel supply chain is lower in all scenarios with hydrocarbon fuels or hydrogen.

The results in this study confirm other studies on critical materials. Although particular assumptions on mobility demand, battery types and technology mixtures are different, several studies such as Dittrich et al. (2020); IEA (2021); Schipper et al. (2018); UBA (2019); World Bank (2017) have shown that future copper demand can be a critical material in a transformation pathway. At the same time, several substitution options are available in order to lower overall copper demand, e.g. using aluminium for power cables, titanium and steel in heat exchangers or plastics in water pipes (see also Annex 16.7.4). Copper exploration activities have discovered additional sources in recent years, e.g. in Ecuador or Mongolia. However, it could take up to 20 years until copper mines starts the production; furthermore, copper mining is linked to serious environmental impacts (see Annex 6.2.4). Furthermore, there is still a potential to increase secondary copper production, which should be fostered systematically.

11.3.4 Further raw materials

For the following raw materials, we have calculated the material demands for EU27+UK in the 100% scenarios and compared them with the global reserves and resources. In contrast to the in-depth analysed critical materials, there is no extrapolation of global demand in transport and other sectors and no assessment of possible absolute or temporary bottlenecks.

11.3.4.1 Nickel

Figure 107 shows the annual nickel demand associated with the European transport sector in the year 2050 for the domestic and the international scenarios. Nickel demand is driven by material demand for supply chain infrastructure in most technology pathways. It arises from use of nickel in wind turbines in alloys and stainless steel for different components of the turbine and in solar PV panels in electroplating or in stainless steel frames, fasteners and connectors (European Commission, 2020c). In all scenarios with hydrocarbon fuels, nickel demand for the fuel supply chain infrastructure makes up 90 % or higher of the total nickel demand associated with the transport sector. Only in BEV scenarios, nickel is mainly used for the vehicle fleet due to its use as hydroxide or intermetallic compounds in NMC batteries. Here, in 2050 the supply chain infrastructure only accounts for 23–33 % of the nickel demand.

In all fuel pathways, nickel demand decreases with higher vehicle technology levels. In the fuel pathways, this is driven by the higher vehicle efficiencies in Balanced and All-In scenarios and, thus, lower required fuel production capacities. In the BEV scenarios, main driver is the specific nickel reduction in batteries with higher energy densities and changed cell chemistry (NMC811 in Balanced and All-In compared to NMC622 in Status Quo).

Scenarios with international energy sourcing need slightly less nickel than scenarios with domestic sourcing due to changes in material demand for the fuel supply chain.

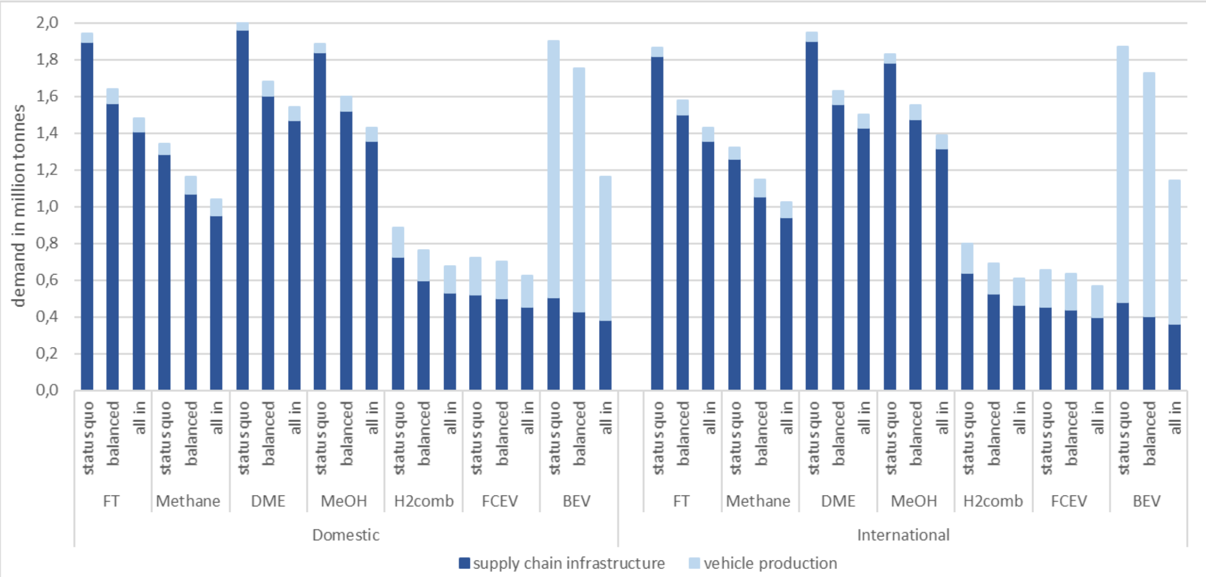

Figure 107: Annual nickel demand in 2050 associated with the EU27+UK transport sector in the 100% scenarios.

The cumulative demand for primary nickel results from annual nickel demand and the share of it satisfied by secondary nickel supply. In our calculations, we consider an ambitious and very optimistic recycling rate for end of life vehicles of 95 % with a collection rate of 90 % (based on Dominish et al. 2021). However, apart from the BEV scenarios, nickel demand is mainly attributable to the fuel supply chain infrastructure. Accordingly, secondary nickel from car fleet production plays no essential role, but still is important to decrease demand of primary nickel.

Figure 108 shows the cumulative primary nickel demand associated with the EU27+UK transport sector for all domestic and international scenarios and in comparison to currently known global reserves and resources. Domestic Status Quo scenarios with hydrocarbon fuels and electric mobility have the highest cumulative nickel demand requiring 33 % to 46 % of the global reserves. In the hydrogen pathways, cumulative primary nickel demand is considerably lower. Furthermore, higher technology levels and international energy sourcing lead to lower cumulative nickel demand. H_2 combustion and FCEV Balanced and All-In scenarios with international energy sourcing require only 14 % to 17 % of global nickel reserves.

Compared with the global terrestric resources, the cumulative primary nickel demand of the EU27+UK transport sector in the 100 % scenarios is in a bandwidth of 10 % to 33 % and, thus, even in the scenario with lowest nickel demand higher than the share of EU27+UK countries in the world population. As a consequence, it can be projected that in case of the rest of the world following the transport sector development in EU27+UK Nickel can become an absolute bottleneck in all scenarios and technology pathways. This is even aggravated when including global demand for Nickel in other, non-transport sectors and applications (e.g. for stainless and alloy steels, non-ferrous alloys and superalloys or electroplating).

Against this, backdrop substitution possibilities for nickel become more important. In the application as steel alloy element; Nickel can be replaced by titanium, chromium, manganese and cobalt (European Commission, 2020c; M. Karhu et al., 2019). In construction, steel with high nickel content may be replaced with low-nickel, duplex, or ultrahigh-chromium stainless steels. In the power generating and petrochemical industries nickel-free specialty steels can be used instead of stainless steel (containing nickel).

In the application of batteries, Lithium-ion batteries can serve as a substitute of nickel metal hydride batteries in certain applications. In the EV market, the recent tendency is reverse; nickel contents are expected to increase further in NMC batteries (e.g. NMC 9.5.5 battery) and Nickel is more and more used as a substitute for cobalt. (Azevedo et al., 2018; European Commission, 2020c). However, alternative battery technologies (LFP, SIB, see sensitivity analysis for lithium and cobalt in section 11.3.1.6) come also without nickel.

The exploitation of further oceanic nickel resources might win in importance. USGS reports extensive nickel resources in manganese crusts and nodules on the ocean floor. Already, the decline in the discovery of new sulfide deposits in traditional mining districts has led to exploration in more difficult and sensitive areas such as East Central Africa and the Subarctic. (European Commission, 2020c; USGS, 2021f)

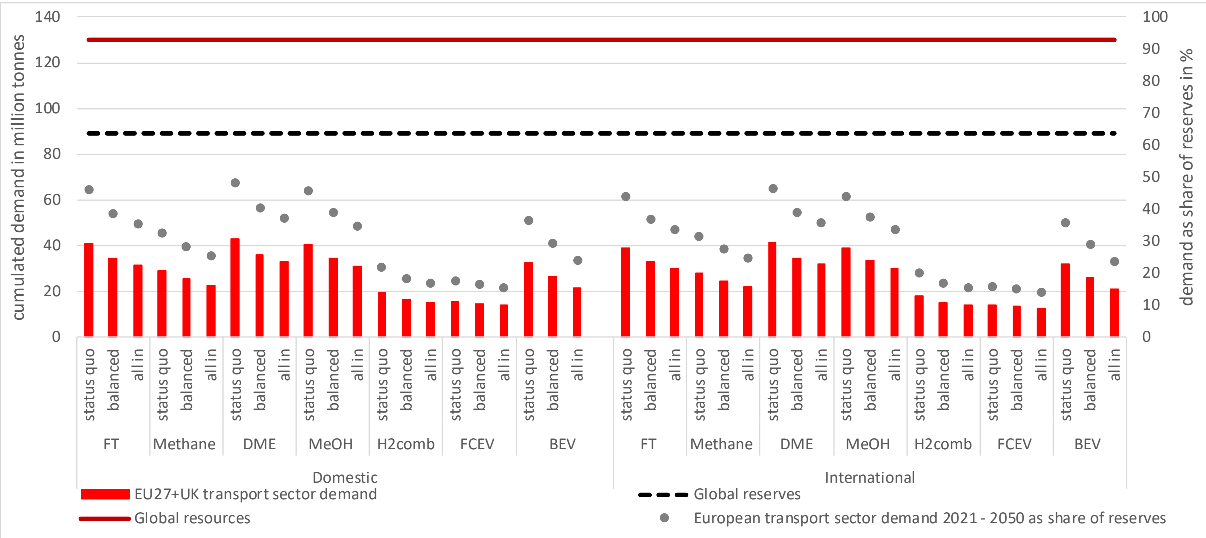

Figure 108: Cumulative primary nickel demand 2021-2050 associated with the EU27+UK transport sector in the 100% scenarios [Source: own compilation and (USGS, 2021f)].

11.3.4.2 Silver

Silver is not needed in vehicle production. Therefore, the silver demand in the 100 % scenarios results exclusively from the material demand of the fuel supply chain infrastructure. Due to the long lifetime of the infrastructure, the total silver demand can be directly compared to the primary silver supply, we have accordingly not considered recycling in our analysis.

In all scenarios, silver is mainly used for power generation from solar panels. According to the demand of power generation in the different pathways, BEV scenarios with direct use of electricity in the vehicles have considerably lower silver demand compared to scenarios with use of electricity for fuel production. All-In scenarios need less silver than Balanced and Status Quo scenarios. International scenarios with higher full load hours of PV plants and accordingly lower installed capacities have a lower annual silver demand for the ramp-up of power generation capacities than domestic scenarios (Figure 109).

The total bandwidth of annual silver demand in 2050 associated with the EU27+UK transport sector is from 2,500 tonnes per year (BEV All-In International) up to 16,400 tonnes per year (DME Status Quo Domestic). This corresponds to a share of 10 % to more than 60 % of today's global primary silver production.

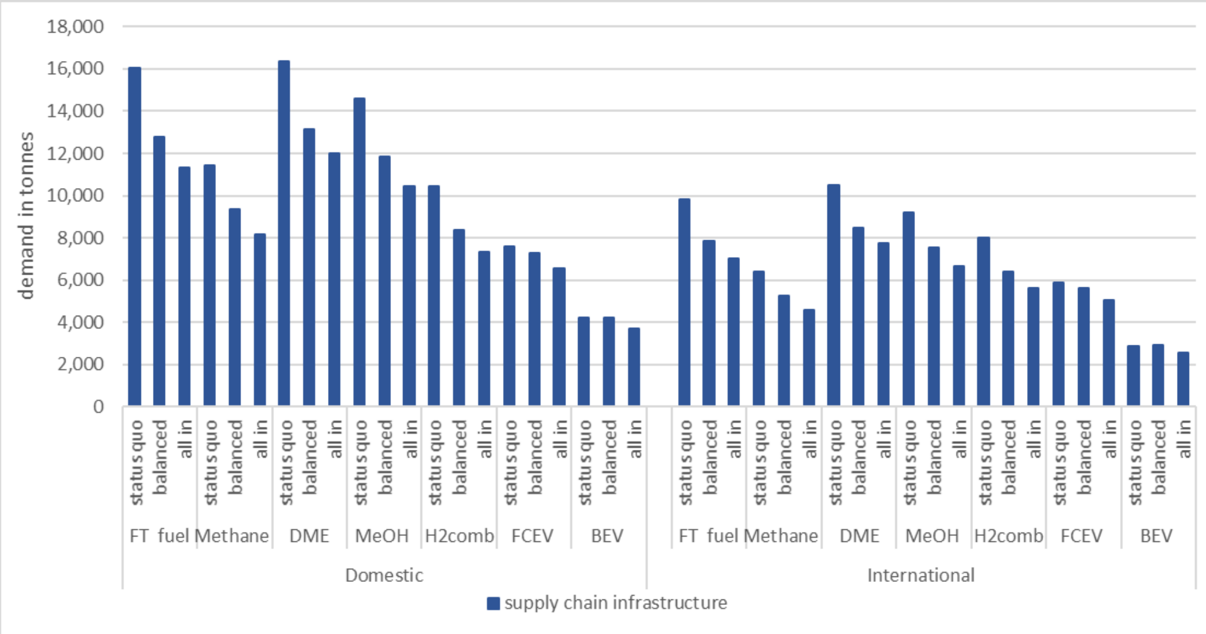

Figure 109: Annual silver demand in 2050 associated with the EU27+UK transport sector in the 100% scenarios [Source: own compilation and (USGS, 2021e)].

Figure 110 shows the cumulative primary silver demand associated with the EU27+UK transport sector for all domestic and international scenarios and in comparison to currently known global reserves and resources. European cumulative demand of the mobility sector for primary silver until 2050 requires between 12 % and 79 % of total reserves. As already shown for the annual silver demand, scenarios with direct electricity use have the lowest silver demand (12-24 % of reserves). Silver demand is highest in the scenarios with hydrocarbon fuels, today's vehicle efficiencies (Status Quo) and domestic fuel production (71-79 % of reserves).

Compared with the global resources, the cumulative primary silver demand of the EU27+UK transport sector in the 100 % scenarios is in a bandwidth of 9 % to 55 % and, thus, even in the scenario with lowest silver demand higher than the share of EU27+UK countries in the world population. As a consequence, and likewise for nickel, it can be projected that in case of the rest of the world following the transport sector development in EU27+UK silver can become an absolute bottleneck in all scenarios and technology pathways. This is even aggravated when including global demand for silver in other, non-transport sectors and applications (e.g. electrical and electronics, brazing alloys, jewellery, silverware and bar coins)

Against this, backdrop substitution possibilities for silver or alternative technologies gain importance. In many electrical and electronic uses where a high conductivity over a small distance is not prioritized, copper, aluminium and other precious metals can replace silver completely or partially. Substitution of silver from brazing alloys, such as tin is possible, and is occurring more frequently due to the cost of silver. (European Commission, 2020c; USGS, 2021e)

Silver's use in PV solar cells is mainly as a conductive paste for thick film crystalline silicon cells; VDMA estimate that hat silver intensity can be declined by 8 % annually up to 2027. Alternatively, silver can be replaced entirely by e.g. nickel-copper platin. Also the use of Concentrating Solar Power (CSP) might play a role in the diversification of power generation; silver intensity per GW is slightly higher compared to Solar PV, yet, silver used in the reflector and can be replaced with aluminium Månberger / Stenqvist (2018). For both alternatives however, demand for nickel and copper might increase and strengthen the bottleneck for these metals.

Recent silver discoveries have been associated with gold deposits; however, also copper and lead-zinc deposits, which contain silver as a by-product, might gain further importance in the portion of reserves and resources in the future. (USGS, 2021e)

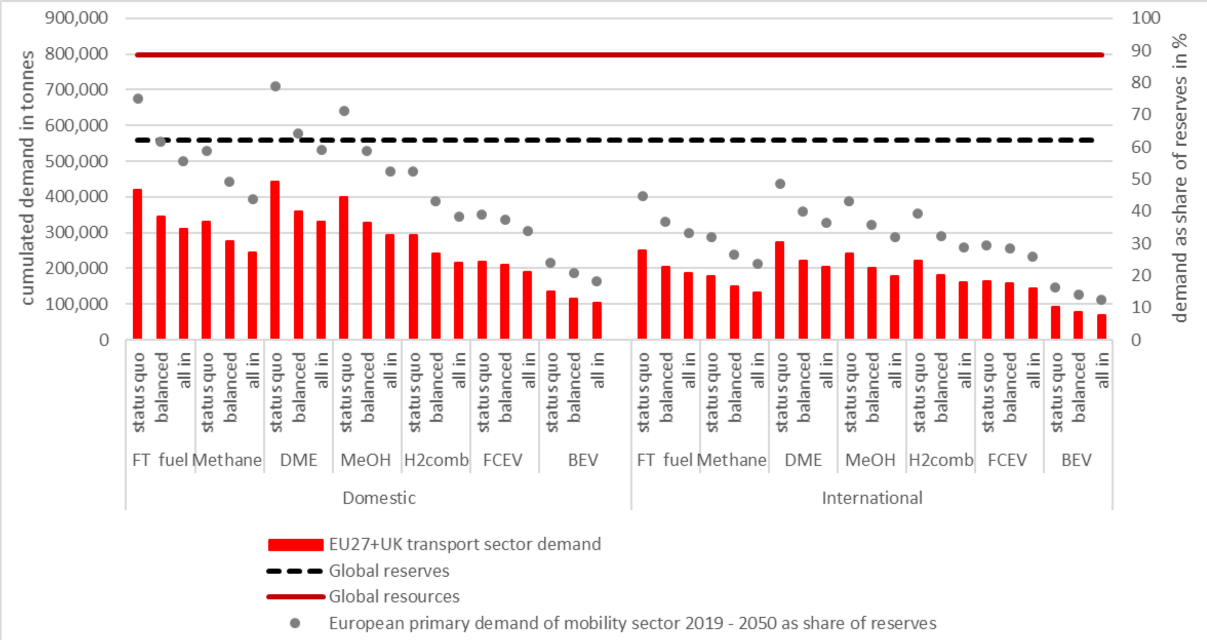

Figure 110: Cumulative primary silver demand 2021-2050 associated with the EU27+UK transport sector in the 100% scenarios [Source: own compilation and (USGS, 2021e)].

11.3.4.3 Neodymium and other Rare Earth Elements (REE)

In the following, yearly demand of several Rare Earth elements is evaluated; first a group of Rare Earth elements including lanthanum, cerium and gadolinium and in addition neodymium.

European Rare Earth demand (lanthanum, cerium and gadolinium) arises solely from material demand of supply chain infrastructure. Lanthanum and cerium are amongst other elements used for catalysts (e.g. lanthanum for water electrolysis), in metallurgy and batteries (BGR, 2021b; Marscheider-Weidemann et al., 2021), Gadolinium is used in metallurgy, e.g. to increase the machinability and the high temperature and oxidation resistance of iron and chromium alloys. It is also used to produce magnetic bubble stores (Institute for rare earths and metals AG, n.d.). Lanthanum, cerium and gadolinium are used for the generation of fuel supply chain. Lanthanum, cerium and gadolinium are not used for car fleet production, thus, no secondary flows from these rare earth elements are considered.

For neodymium, demand also mostly arises from fuel supply infrastructure in most technology pathways. Yet for BEV and FCEV technology pathway neodymium-oxide is also relevant for car fleet production and comprises roughly 40 - 60 % of cumulative demand in the transport sector depending on technology level. Neodymium is used in NdFeB permanent magnets in wind turbines for electricity generation. In cars, neodymium can also be used as magnetic material in auto-electronics (Groke et al., 2017). For neodymium, due to its importance for FSC, both, domestic and international scenarios, are depicted graphically.

Figure 111 shows rare earth (La, Ce, Gd) and Neodymium demand of European mobility sector in 2050 for domestic and international scenarios. With regard to neodymium, all technology pathways, except for BEV, exceed 2019 production levels of neodymium (30,687 tonnes). In the international scenario, however, due to more efficient wind turbines, demand exceeded by fewer technology pathways. Yet most pathways still require almost the entire production amount of 2019. BEV All-In scenario is least neodymium demanding, yet still requiring approximately 20,000 tonnes.

For other Rare Earths (RE), in 2050, generally a higher demand compared to 2030 is expected; lowest Rare Earth demand, is in the BEV technology pathway, whereas the DME pathways result in the highest RE demand (40-53 %) of current production levels of other Rare Earths (other than Pt and Pd). Due to lower material demand in the fuel supply chain, because of higher working hours of wind and PV plants, the demand of Rare Earths is lower in the international scenario. Overall, the technology level All-In shows the lowest values compared to the other pathways for all technologies with regard to European demand.

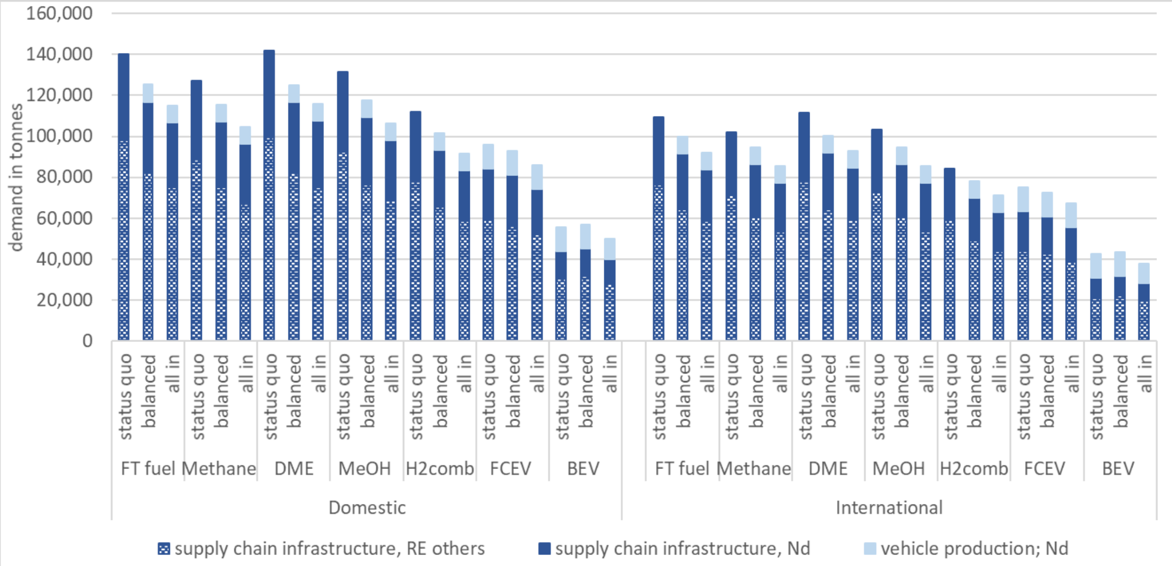

Figure 111: Annual Rare Earth others and Neodymium demand in 2050 associated with the EU27+UK transport sector in the 100% scenarios.

Figure 112 shows the total cumulative European demand for lanthanum, cerium, gadolinium and neodymium of the mobility sectors for all technology pathways and levels from 2021 to 2050 depicted against current reserves (in 2019). Overall, with regard to reserves rare earths (La, Ce, Gd) and neodymium do not result as a bottleneck for the European mobility sector. Highest cumulative demand for Rare Earth (La, Ce and Gd) reach 1.6 million tonnes (in DME Status Quo); for neodymium, highest cumulative demand reaches 0.8 million tonnes in FT Balanced. Together the total cumulative demand 2021 to 2050 amounts to less than 2 % of currently known rare earth reserves (120 million tonnes).

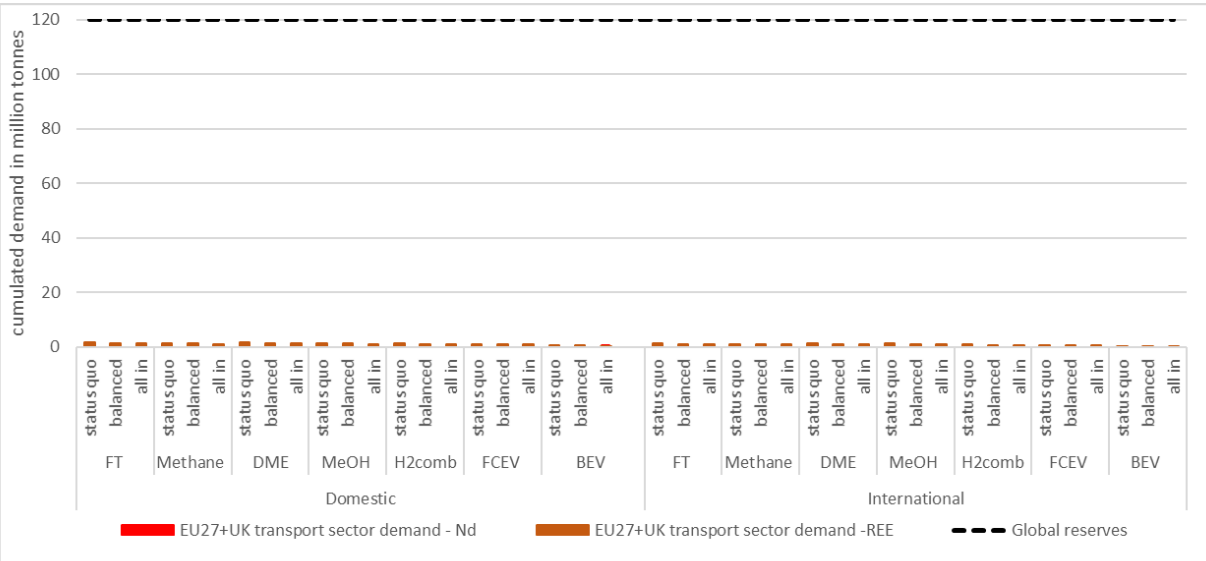

Figure 112: Total cumulative European Rare Earths (others) and Neodymium demand of mobility sector 2021 – 2050 and global reserves [Source: own compilation and (European Commission, 2020a; USGS, 2021g)].

11.3.4.4 Silicon metal

Silicon metal is more and more being used for solar plants, and thus, an important material for the fuel supply infrastructure. Demand for car fleet production is less significant, almost the entire demand for silicon metal arises from material demand for supply chain infrastructure for PV plants. Only in the BEV technology pathway, a very small share of demand is driven by car fleet production (especially in BEV technology pathway). In Li-ion batteries silicon can be used in anodes to enhance energy densities (European Commission, 2020b). Due to its importance for the supply chain infrastructure, the demand for silicon metal is differentiated for domestic and international scenario.

To estimate the demand of silicon metal for PV plants, we used the methodological approach of combining specific material intensity of silicon in c-Si panel (t/MW) with the assumed development of installed capacity of standalone and slanted PV panels in 2050. C-Si panels were used because it's the dominating technology on the market (approx. 95.4 % in 2017, (Carrara et al., 2020)) and it was also the chosen PV technology in GreenEe (Dittrich et al. 2020). For the specific material demand per MW, the study from Carrara et al. (2020) is used. According to the authors, in 2018, the specific material demand for a c-Si solar panel was 4 t/MW (compared to 16 t/MW in 2004). To assess future demands for several essential materials needed for the deployment of solar PV (and wind) systems until 2050, different policy-relevant electricity generation scenarios for the EU and the world were considered. For our study, we use the baseline scenario (Medium Demand Scenario – MDS). According to the MDS, in 2030 the specific material demand is 2.75 t/MW, in 2050 it decreases to 2 t/MW (Carrara et al., 2020). For the years in between a linear development was assumed.

Figure 113 shows the silicon metal demand of European mobility in 2050. It can be noticed for both, domestic and international scenario, that the main demand of silicon metal comes from PV plants. Vehicle fleet production has a negligible small demand compared to supply chain infrastructure. Domestic scenarios of hydrocarbon fuel pathways (FT fuel, DME, MeOH) with Status Quo vehicle technology have the highest silicon metal demand. Improved vehicle technologies reduce silicon metal demand.

In international scenarios, total silicon metal demand differs due to changes in material demand for fuel supply chain. Compared to the domestic scenario, in 2050 demand drops by 23 to 48 % for most technology pathways. Highest demand is reached in H_2 Comb with approximately 158,000 tonnes. Lowest demand, in contrast, is achieved in BEV All-In with 49,000 tonnes of which 48,000 tonnes is attributable to supply chain infrastructure.

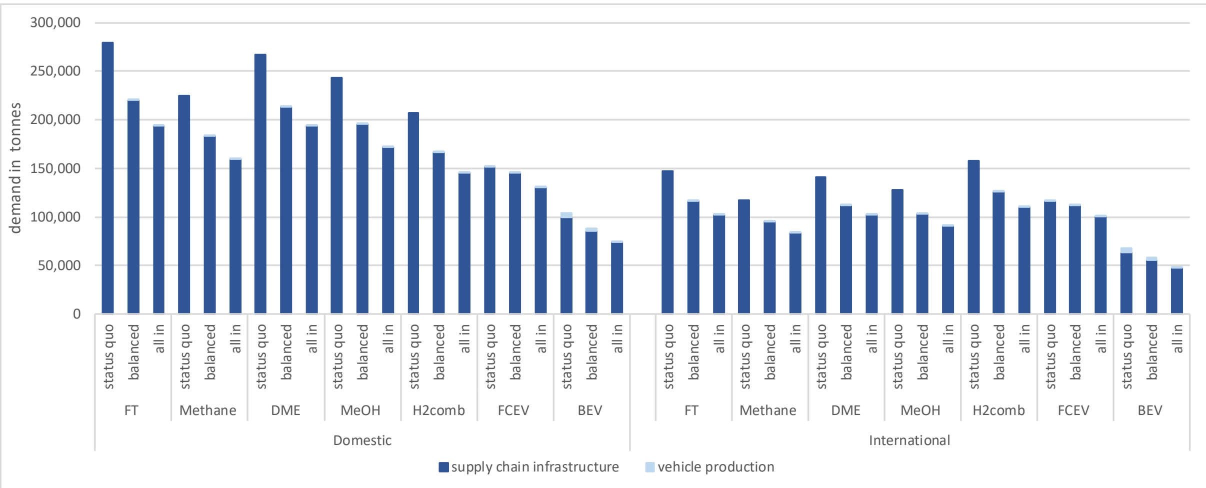

Figure 113: Annual silicon metal demand in 2050 associated with the EU27+UK transport sector in the 100% scenarios.

Figure 114 shows the total cumulative European silicon metal demand (domestic and international scenario) of the mobility sectors for different technology pathways and scenarios from 2021 to 2050 and current production[32] (in 2018).

The cumulative silicon metal demand associated with the EU27+UK transport in domestic scenario in the next 30 years varies around 100 % (BEV All-in) and 300 % (FT Status quo) of today's total global production of one year, depending on the technology pathways and the respective technology level. In the international scenarios, the cumulative demand until 2050 is considerably lower due to higher working hours of PV plants. Silicon metal demand for European mobility sector for the supply chain infrastructure as well as the car fleet production is therefore no bottleneck in any of the fuel pathways. This finding is reinforced against the backdrop of abundant (but unquantified) silicon metal reserves.

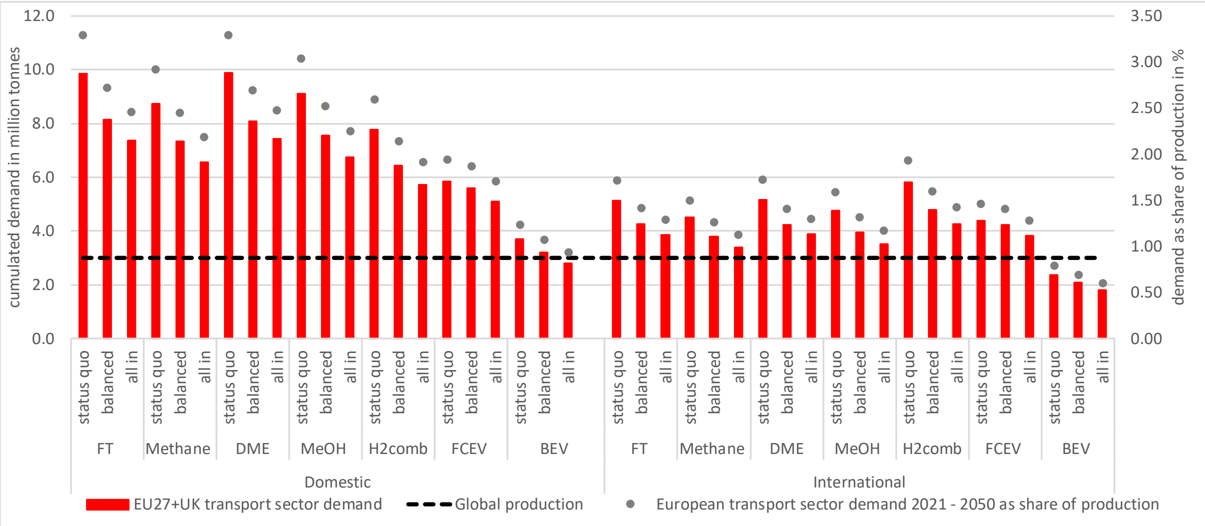

Figure 114: Total cumulative European silicon metal demand of mobility sector 2021 – 2050 and global production level in 2018 [Source: own compilation and Boubault (2019)].

11.3.5 Summary for critical raw materials

In all fuel pathways for the defossilisation of the transport sector, availability of selected raw materials can be a limiting factor for a fast market ramp-up and for achieving 100 % penetration of Europe's transport sector in 2050. Analyses of potential raw material bottlenecks include the annual demand for the transport sector in Europe amended by extrapolations of potential global demands (transport + stationary) in case of a catch-up development of the rest of the world up to 2050. Material demands are compared to global material availability (resources, reserves, annual global primary and secondary material supply).

Lithium and cobalt are key materials for electric mobility. Platinum is a key material for fuel cell vehicles. Identified bottlenecks result mainly by vehicle configurations, particulary by battery types, energy density and battery sizes and cell chemistry in the scenarios and by the assumed strong future motorisation increase in non-European countries.

- A worldwide ramp-up of electric mobility can be affected by absolute and temporary **lithium** or **cobalt** bottlenecks. With the specific battery configurations assumed in our scenarios (one single battery technology per scenario, battery sizes) and the extrapolated global material demand (in the event of full economic catch-up and same per capita vehicle sales worldwide by the year 2050), 100 % worldwide electric mobility would not be possible.

[32] Global production was used as a reference value as no quantified values on current reserves are published.

However, this finding is only valid for the scenario configurations in this study with estimates of future material demands on the upper end. 100 % worldwide electric mobility will be possible if other development trends are achieved. Other battery technologies than considered in the scenarios are already on the market or close to market-entry, which can substantially reduce specific material demands. A mix of different battery technologies as well as different general development trends than assumed (slower increase of worldwide motorization,) will most probably lead to substantially lower raw material demand that does not exceed today known global resources. Furthermore, global lithium and cobalt resources and reserves have developed very dynamically in the last few years. Therefore, a considerable future increase of primary material supply can be expected, too.

- **Platinum** is a clear bottleneck in the "FCEV Status Quo" scenario as European demand alone exceeds current global supply. In the "FCEV balanced" and "FCEV All-In" scenario, global platinum supply could fulfil the demand of Europe's transport sector, only. However, assuming similar developments of FCEV fleets in the rest of the world, global demand will clearly exceed currently known reserves and lead to absolute bottlenecks. Platinum bottlenecks for 100% worldwide FCEV mobility can be reduced by slow down of worldwide motorisation increase, further exploration of resources and increase of platinum substitution possibilities in several applications.

Further materials such as copper, silver, nickel and neodymium are required in vehicle production and / or the fuel supply chain infrastructure and could therefore cause bottlenecks in all fuel pathways. However, primary material demand can be reduced in transport as well as other demand sectors by increase of recycling, substitution with other (less critical) materials or use of existing alternative technologies as shown in the sensitivity analysis with respect to Lithium and Cobalt and /or further research & development of more material efficient technologies. At the same time, supply has to be increased based on sustainable mining and supply-systems. Hence, proactive demand and supply strategies can prevent future bottlenecks of these materials.

12 Cost estimations

Aside from environmental impact and material demand, total incremental costs caused by the transformation of the road sector to carbon neutrality are another key factor to take into account when evaluating the potential of the different fuels.

The aim of 100% carbon neutrality by 2050 implies that by then, the entire fuel supply chain needs to be built and all vehicles need to be replaced with the respective drive train.

In this section, we therefore set out the approach taken to estimate the total costs associated with the various scenarios for a 100% supply of the European transport sector with the different renewable fuels. Further, we then compare the various drivetrain options and the related energy supply chains with regard to costs.

As outlined previously, rail aviation and shipping have a subordinate impact relative to the developments in the road sector. Therefore, we consider a simplified approach for these sectors. We briefly discuss the findings (exemplarily for the balanced scenario) in section 12.4.

Generally, we always account for costs in the year that they occur, following a cash flow approach, as opposed to depreciating them over time. Further, we aim to estimate economic costs, thus omitting any implications from potential taxes or subsidies as well as strategic pricing[33]. Note that the costs in this section always refer to Net Present Values (NPV) in real 2020 values.

Hence, the section is structured as follows:

- Section 12.1 illustrates our approach to assessing the costs for new road vehicles required until 2050 based on the modelled fleet (as set out in section 6) and compares the total vehicle costs across fuels and scenarios;
- Section 12.2 sets out how we calculate costs associated with the build-up of the required assets and infrastructure along the entire fuel supply chain (as presented in section 8) and again compares the results for different fuels for the road sector, exemplifying their respective (dis-)advantages;
- Section 12.3 then draws together the findings from sections 12.1 and 12.2, calculating and comparing the total costs for both, vehicles and the fuel in the road segment;
- Finally, section 12.4 outlines the simplified approach applied to the rail, aviation and shipping sectors and briefly outlines the results for these sectors.

12.1 Vehicle Costs

The total vehicle costs are driven by the number of vehicles and the cost per vehicle. While the number of vehicles are an outcome of the fleet modelling as described in section 6, the costs per vehicle needs to be determined for each vehicle segment, each 100% pathway scenario, each level of technological advancement (status quo, balanced and all in) and base year.

[33] “Strategic pricing” refers to price setting based on the item’s value to the consumer rather than the true cost

12.1.1 Modelling Approach and key assumptions

To determine the cost of each of the vehicles, we follow a building-kit approach, using the cost of currently manufactured "conventional" vehicles as starting point.

For passenger cars, a representative vehicle has been chosen for each segment. This representative vehicle is then used to determine the fuel efficiency as described in section 8 as well as the vehicle cost.

As the starting point to assess costs, we use publicly available list-prices in 2020 of the gasoline variant of each of the representative vehicles. However, these list prices include tax and a retail margin. To obtain the manufacturing costs for the OEM, we therefore deduct a VAT of 19% and a retail margin of 20%, following estimates made in the Roland Berger Study (2016). Table 31 summarizes list and base prices for the representative vehicles.

Table 31: List and base prices for representative vehicles.

Vehicle Segment	**Representative Vehicle**	**List Price 2020 [EUR]**	**Base Price 2020 [EUR]**
Small	Small gasoline Car (VW Up!) (€)	13,038	9,130
Medium (gasoline)	Ford Focus 1.0l Ecoboost 125 PS Trend (€)	22,600	15,826
Medium (diesel)	Ford Focus 1.5l EcoBlue 120 PS Trend (€)	24,900	17,437
Large	Large gasoline Car (BMW 520) (€)	47,862	33,517
SUV	SUV gasoline (Honda CR-V) (€)	28,844	20,199
LCV	Ford Transit Kastenwagen 320 L1 Trend, Nutzlast 1,0t, 96 kW, 12/2020: (€)	40,079	28,067

For the medium-sized vehicle, costs for both the gasoline and diesel variant are used to calculate a "diesel-cost premium", which is then applied to all other vehicle segments to determine prices for diesel vehicles. Based on the Ford Focus, we calculate this premium to be at 10%.

We then determine all vehicle costs for other 100% pathways, levels of technological advancement and future years following a "building-kit" approach:

For each of the drivetrain technologies, there are components of the vehicle which either need to be altered or added, causing additional costs or can be removed and thus save costs.

The relevant components are similar across the different drivetrains – particularly the tank system and the engine are affected. BEV and FCEV additionally require the addition of a battery or a fuel cell. Figure 115 below sets out the addition/removal of the respective elements for each of the drivetrains for the Status Quo scenario. With respect to cost, each of the relevant components is assigned a cost which is then either added to or deducted from the base price. The individual component costs are illustrated in Table 32.

	Additional Costs through the addition of…								Cost savings through removal of…	
Technology	Tank System	Cold Start System	Fuel Cell	Battery	E-System	Heat Pump	Alumi-nium	ICE Upgrade	ICE System	Steel
FT Fuel	BASE CASE									
BEV				✓	✓				✓	
FCEV	✓		✓	✓	✓				✓	
H2 ICEV	✓									
Methane	✓									
Methanol		✓								
DME	✓									

✓ Status Quo Scenario

Figure 115: Additional costs and/or cost savings per fuel with FT Fuel as base case for Status Quo [Source: Frontier Economics].

Table 32: Individual cost components for each photo year.

	2020	2030	2050	Source
CNG - Tank system oncost: (€/kg CNG)	50.00	40.00	32.00	EERE (2016)
DME - Tank system oncost (€/l DME)	3.30	2.64	2.15	Analogue to LPG
MeOH - Net cold start system oncost (€)	120.00	120.00	120.00	Frontier Estimate based on 1:1 supplier communication
H2 - Tank system oncost (€/kg H2)	666.00	533.00	433.00	Dynamis (2019)
H2 - Tank sensoric oncosts (€ / car)	80.00	80.00	80.00	Frontier Estimate based on 1:1 supplier communication
Cost ICE removal (€/kW)	-37.78	-39.67	-39.67	ICCT (2019)
On-cost electrical PT w/o battery constant (€)	377.24	377.24	377.24	Roland Berger (2016)
On-cost electrical PT w/o battery variable (€/KW)	16.25	16.25	16.25	Roland Berger (2016)
FC system oncost (€/kw)	98.00	78.40	63.70	ANL (2009)
FC System Power battery cost (€/kWh)	910.40	682.80	455.20	ANL (2009)
BEV Battery Module Cost (€/kWh)	160.00	120.00	80.00	VDMA (2018)

As set out in section 3, we consider different grades of technological advancement for each of the drivetrain technologies, leading to different fuel efficiencies. In order to achieve these improved efficiencies, additional modifications are required.

In the Balanced Scenario, all combustion drivetrains are hybridised aiming for technological improvements that can lead to an increased fuel efficiency with an optimal cost/benefit ratio. This implies that all combustion engine vehicles require an additional battery and e-system. Figure 116 shows an overview of the technological components in the “Balanced” Scenario.

Technology	Tank System	Cold Start System	Fuel Cell	Battery	E-System	Heat Pump	Alumi-nium	ICE Upgrade	ICE System	Steel
	Additional Costs through the addition of…								Cost savings through removal of…	
FT Fuel	BASE CASE			Balanced	Balanced					
BEV				Status Quo	Status Quo				Status Quo	
FCEV	Status Quo		Status Quo	Status Quo	Status Quo				Status Quo	
H2 ICEV	Status Quo			Balanced	Balanced					
Methane	Status Quo			Balanced	Balanced					
Methanol		Status Quo		Balanced	Balanced					
DME	Status Quo			Balanced	Balanced					

Status Quo Scenario
Balanced Scenario (Hybridisation)

Figure 116: Additional costs and/or cost savings per fuel with FT Fuel as base case for Balanced

In the All-In Scenario, all potential alterations that could possibly lower the fuel consumption are implemented. In addition to hybridization, that includes the introduction of a heat pump, increased engine efficiency and lightweight construction. These changes affect all drivetrains equally, with the exception of engine improvements for battery and fuel cell electric vehicles. Figure 117 illustrates the technical configuration of the different drivetrains in the All-In Scenario.

Technology	Tank System	Cold Start System	Fuel Cell	Battery	E-System	Heat Pump	Alumi-nium	ICE Upgrade	ICE System	Steel
	Additional Costs through the addition of…								Cost savings through removal of…	
FT Fuel	BASE CASE			Balanced	Balanced	All In	All In	All In		All In
BEV				Status Quo	Status Quo	All In	All In		Status Quo	All In
FCEV	Status Quo		Status Quo	Status Quo	Status Quo	All In	All In		Status Quo	All In
H2 ICEV	Status Quo			Balanced	Balanced	All In	All In	All In		All In
Methane	Status Quo			Balanced	Balanced	All In	All In	All In		All In
Methanol		Status Quo		Balanced	Balanced	All In	All In	All In		All In
DME	Status Quo			Balanced	Balanced	All In	All In	All In		All In

Status Quo Scenario
Balanced Scenario (Hybridization)
All In Scenario

Figure 117: Additional costs and/or cost savings per fuel with FT Fuel as base case for All-In.

Just like all other components, the costs of the components added in the “All-In” scenario needs to be added to the vehicle costs from the “Balanced” scenario. Table 33 provides an overview of the relevant costs. To account for light weighting, we determine the share of steel which can be replaced with aluminium for each vehicle and then deduct the cost of the steel and add the cost of the respective amount of aluminium.

Table 33: Relevant costs for the Balanced and All-In Scenarios.

Component	Cost	Source
On-Cost Heat Pump (€)	1,242.00	VW Price List (2020)
Steel Price (€/kg)	0.48	Current market value
Aluminium Price (€/kg)	1.65	Current market value

The costs for each of the individual components are obtained from literature and then adjusted to the actual costs for OEMs by applying an additional uplift to cover for additional OEM-costs (e.g. fix-costs such as R&D, logistics, …) of 50% based on the Roland Berger Study to the pure “material costs”.

Across all drivetrain technologies and levels of technological advancement, general future developments between 2020 and 2050 need to be taken into account.

Therefore, we introduce a general costs increase for the underlying base vehicle of 6% for diesel vehicles and 5% for gasoline vehicles from 2020 to 2030, e.g. to account for additional costs through rising environmental standards.

Similarly and as illustrated by the previous tables, the costs for additional components are also set for each of the base years (2020/2030/2050) to account for aspects such as improved technological maturity.

Following this approach, we retrieve the total vehicle costs across all drivetrain technologies, levels of technological advancement and base years for each of the vehicle segments. Figure 118 illustrates the total vehicle costs across these different combination for the medium size vehicle. Annex 15.3.1 summarizes all light duty vehicle costs.

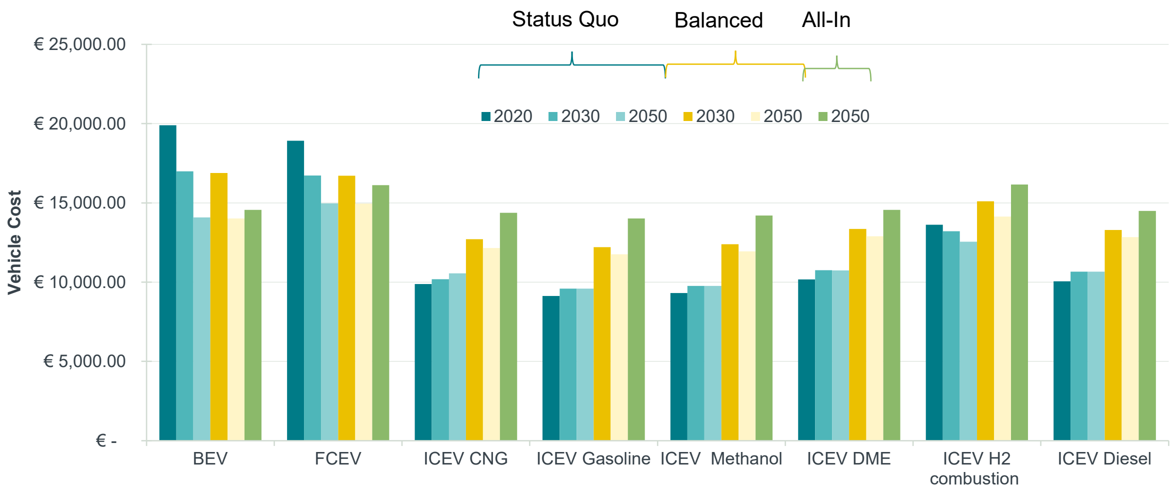

Figure 118: Vehicle costs for all pathway scenarios and fuel types exemplary for small segment.

For heavy duty vehicles, we follow an analogue approach, making minimal alterations: Other than for the light duty vehicles, diesel vehicles are used as the underlying base vehicle due to the limited role of gasoline vehicles in the heavy duty sector.

In the 100% electric scenario, we further assume that large HD vehicles (>16t) are electrified via catenary rather than solely battery, due to the requirements for heavy duty transport. Therefore, a pantograph has to be added as an additional component for the electrified drivetrains. The respective costs are summarized in Table 34.

Table 34: Costs for pantograph for each photo year [Source: Frontier based on ICCT (2013)].

	2020	2030	2050
Pantograph (€)	30,858.00	15,950.00	12,760.00

As for the light duty vehicles, the costs per vehicle are then determined for each technology, each level of technological advancement and each year. By way of example, Figure 119 illustrates the costs for a long haul truck. Annex provides details on the heavy duty vehicle costs.

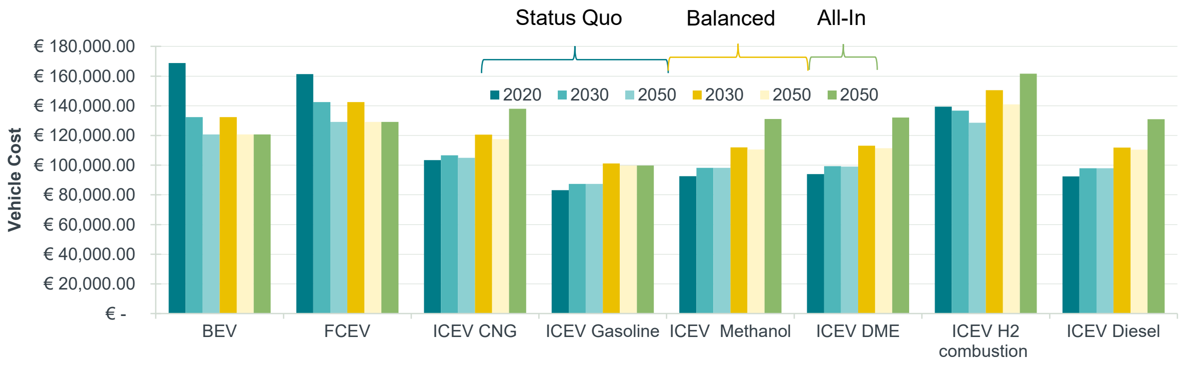

Figure 119: Vehicle costs for all pathway scenarios and fuel types exemplary for the long haul segment [Source: Frontier Economics].

Based on the costs per vehicle, we then determine the total expenses associated with vehicles by multiplying the costs per vehicle with the number of new registrations for each segment and in each year.

12.1.2 Estimations of vehicle costs

Costs on the vehicle side are caused through the construction of new vehicles. To obtain the total vehicle costs that accrue from 2020 to 2050, the number of newly registered cars of each technology therefore has to be multiplied with the respective costs. However, particularly in the beginning, the bulk part of the new registrations is still made up of conventional vehicles. These are the same across all technology pathways and would further occur independent from any defossilisation efforts. Therefore, we express the results in terms of incremental costs – so costs for vehicles that have been newly registered between 2020 until 2050 (omitting the value of the fleet today). This approach focusses on the differences between different fuels and thereby provides a clearer picture of the cost effects of choosing different drivetrain technologies.

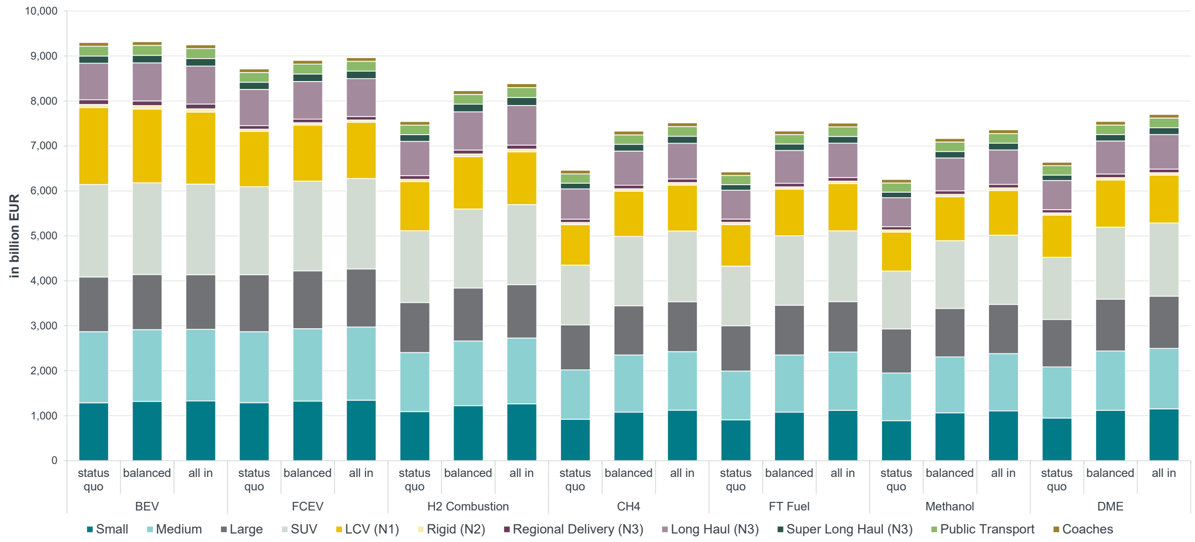

Figure 120: NPV vehicle costs of newly registered vehicles for all scenarios from 2020 to 2050 [Source: Frontier Economics].

Additionally, vehicles will be purchased in any case, irrespectively of whether the transport sector is transformed to a new, carbon neutral fuel or not. As we are aiming to express the additional economic costs caused by the defossilisation of the transport sector, we express the vehicle costs in incremental terms, relative to a benchmark scenario. We set this benchmark as the total vehicle costs for FT Fuel in the status quo scenario, assuming that this is a close approximation of the vehicle costs which would occur in an "unchanged world" which is dominated by ICEV. To determine incremental vehicle costs, we subtract the costs of the benchmark scenario from the total vehicle costs of a 100% scenario. Figure 121 shows this by way of example for the Status Quo scenario.

The highest incremental vehicle costs occur for BEVs, followed by FCEVs and H2 combustion vehicles, where the addition of supplementary components causes additional costs. The high costs for BEV are primarily driven by additional costs for batteries. Similarly, FCEVs require the addition of a specific tank and an additional fuel cell.

Total vehicle costs in the MeOH scenario are actually lower than in the FT Fuel scenario (and hence are shown as negative incremental costs in the comparisons). This is driven by the fact that all vehicles in the MeOH scenario are similar to (cheaper) gasoline vehicles, while in the FT scenario, the current split between gasoline and (more expensive) diesel vehicles is kept unchanged.

There are also only small incremental costs for Methane and DME vehicles (again, caused by the alterations set out in section 12.1).

Generally, the outcome is consistent across all technology pathways – Status Quo, Balanced and All-In.

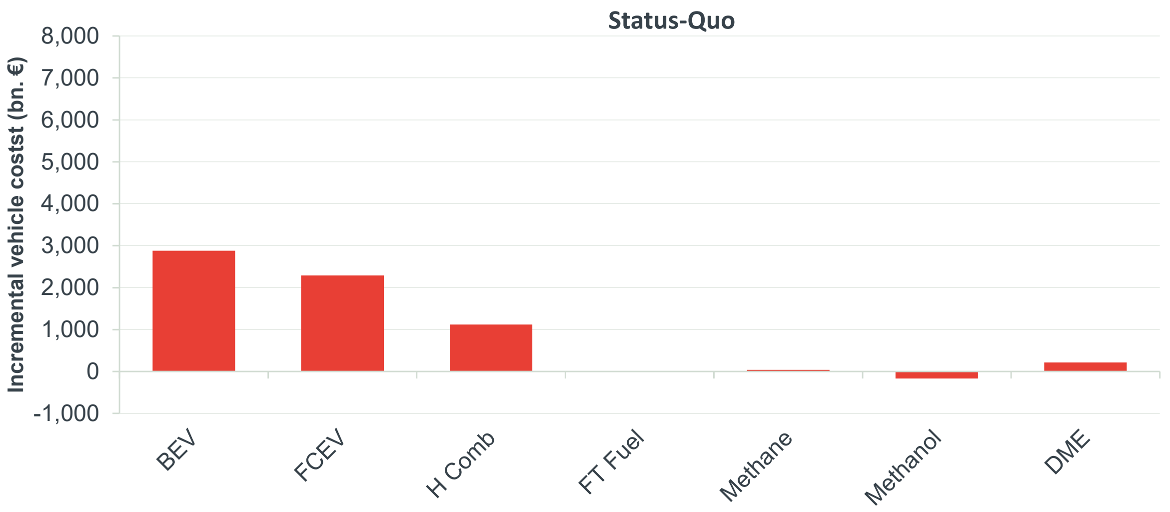

Figure 121: Incremental vehicle costs (NPV) in the Status Quo scenario compared to Benchmark FT Status Quo [Source: Frontier Economics].

12.2 Fuel Supply Chain Costs

Next to the vehicle costs, the costs associated with building the required infrastructure to produce fuel are the second cost driver of transforming the transport sector to be carbon neutral by 2050. Depending on the drivetrain technology and associated fuel supply chain, different elements are required to generate the fuel, as illustrated in section 8.

For each of these elements, there are two main components of costs which are taken into account:

1. Investment Costs: One off expenses for the construction of the relevant element of the Fuel Supply Chain and
2. O&M Costs: Recurring costs associated with operating and maintaining a certain element.

12.2.1 Modelling Approach and key assumptions

Investment Costs

Investment costs are the main component of the total fuel supply chain costs. The general approach to modelling them is similar to the assessment of the total vehicle costs.

As illustrated in section 7, we determine the required capacities for all elements of the respective fuel supply chain in 2020, 2030 and 2050, following from the fuel demand for the respective drivetrain in each of the base years. Following from these pillars, we then assess the build-up per year, by linearly interpolating the construction of fuel supply chain elements between the base years, so that the targets for the base years can be achieved.

Some elements, such as for example the chargers in the 100% electrified scenario ("BEV"), have a lifetime which is shorter than the time horizon of this study. They will therefore need replacement over the course of the examined period. Similarly to the vehicle fleet, the total build up per year is therefore determined by the increase required to achieve the necessary capacities and the replacements of outdated infrastructure.

We then determined the costs of each of the elements in the base years and sent a draft version to the expert group members, who commented confidentially back to Frontier. With this process we ensured the qualified feedback of the FVV focus group while making sure not to violate any compliance rules at the same time. These costs are shown in detail in Annex 15.3.2. They take into account learning curves, technological advancements and economies of scale for larger plants where applicable.

The total investment costs are then determined by multiplying the total annual build-up of each element of the fuel supply chain with the respective costs and finally summarizing across all required elements.

O&M Cost

Costs for operation and maintenance of equipment need to be accounted for on a recurring annual basis. Similarly to the investment costs, the O&M costs were set with the help of input from the FVV experts. in a confidential and compliant feedback process as described above. They are commonly expressed in relative terms of the total investment costs. By way of example: The O&M costs for a windfarm are assumed to be 3.5% of total investment cost per year. With increasing capital stock (i.e. larger capacities installed), the O&M costs thus also increase over time.

12.2.2 Estimations of fuel supply chain costs

As already set out in detail in section 8, the fuel supply chains partly use existing infrastructure where possible and partly require newly built infrastructure. Therefore, we only consider incremental fuel supply chain costs, as explained in section 12.1.2. By way of example, this implies that we do not consider the full cost of FT fuel station or an existing methane pipeline.

With regard to the time horizon, we only take into account costs accruing for the build-up during the transformation period from 2020 until 2050. Any recurring maintenance investments which will be necessary after 2050 are not considered.

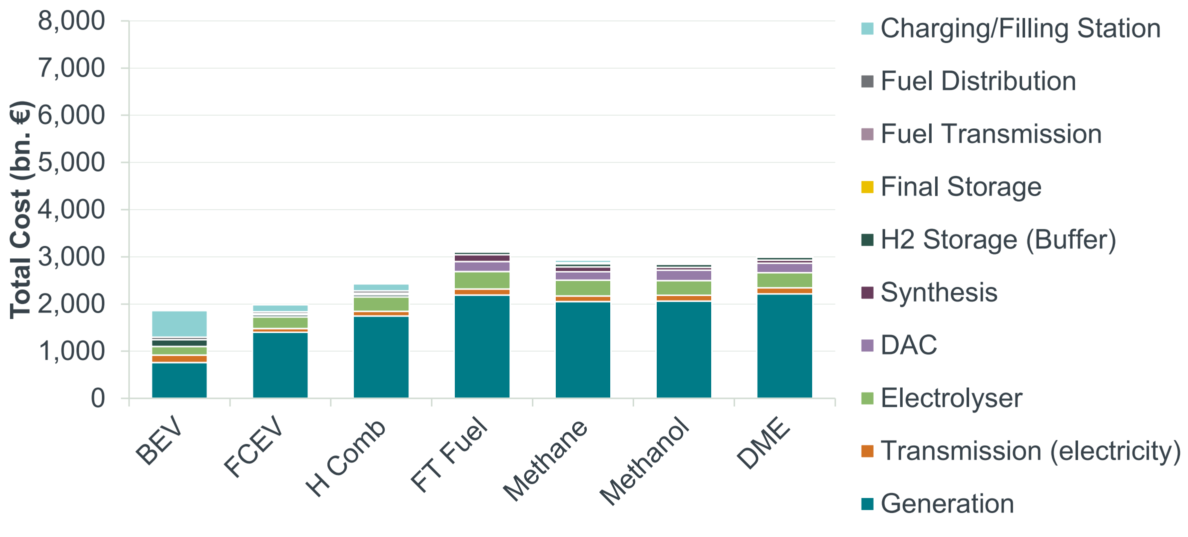

Figure 122: Fuel supply chain costs (in NPV) for the domestic balanced scenario for the road sector [Source: Frontier Econommics].

Figure 122 shows the costs for the infrastructure in the domestic Balanced scenario. The fuel supply chain costs are the highest for FT Fuel, followed by DME, Methane and MeOH – all in a similar range between 2,900 bn € and 3,150 bn €. The lowest fuel supply chain costs occur in the BEV scenario with less than 2,000 bn €, followed by the Hydrogen scenarios.

Generation costs dominate the costs of other stages of the fuel supply chains for all fuels with the exception of BEV. While generation still accounts for a large share of total costs here, charging costs are of similar importance. This is driven by the large quantities of chargers required for comprehensive coverage, together with high costs per unit and short lifetimes (e.g. 10 to 17 years depending on the type) and the resulting need for (multiple) replacements between 2020 and 2050.

Across all synthetic fuels, the second largest cost position are electrolysis costs, followed by costs for DAC and transmission of offshore generation to the coast. However, these positions are significantly smaller than costs associated with the required generation capacities.

For the hydrogen scenarios, costs for compression at the fuel stations account for the third largest position after generation and electrolysis.

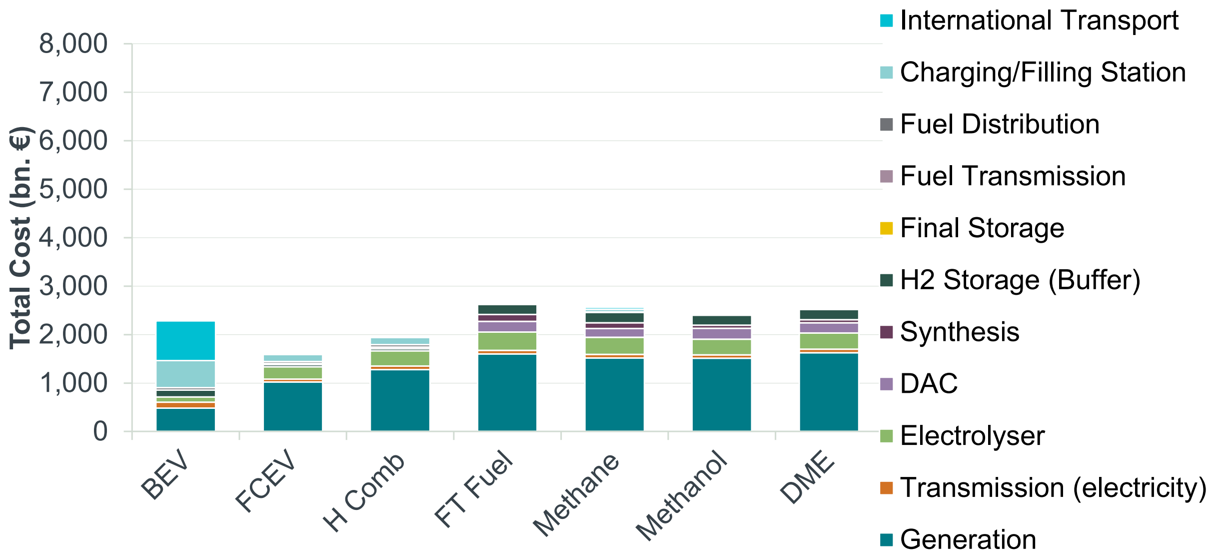

Figure 123: Fuel supply chain costs (in NPV) for the international balanced scenario for the road sector [Source: Frontier Economics].

Figure 123 shows the costs for the infrastructure in the international Balanced scenario. The fuel supply chain costs (NPV) are lower than in the domestic scenarios for all fuels except for BEV.

This general decrease in costs for most fuels is primarily driven by a decrease in total generation costs, which is in turn due to two reasons: First, the costs per unit for building generation capacities are assumed to be lower outside of Europe than within Europe. Second, lower generation capacities than in the domestic scenario are required. As already described in section 9.2, this is due to higher utilization of generation facilities outside Europe. Generation still accounts for the highest costs compared to all other components. However, the share is lower than in the domestic scenario.

The increase in costs in the BEV scenario is caused by relatively expensive power cables which are required to transport electricity from nearby international locations such as MENA to Europe. These import cables account for the highest cost component for the fuel supply chain, followed by the charging infrastructure and then generation costs.

Similar to the domestic scenario, the fuel supply chain costs are highest for FT Fuel, followed by DME, MeOH and Methane. Note that due to the high import costs in the BEV scenario, , the hydrogen scenarios have the lowest fuel supply chain costs of all international scenarios (see Figure 123).

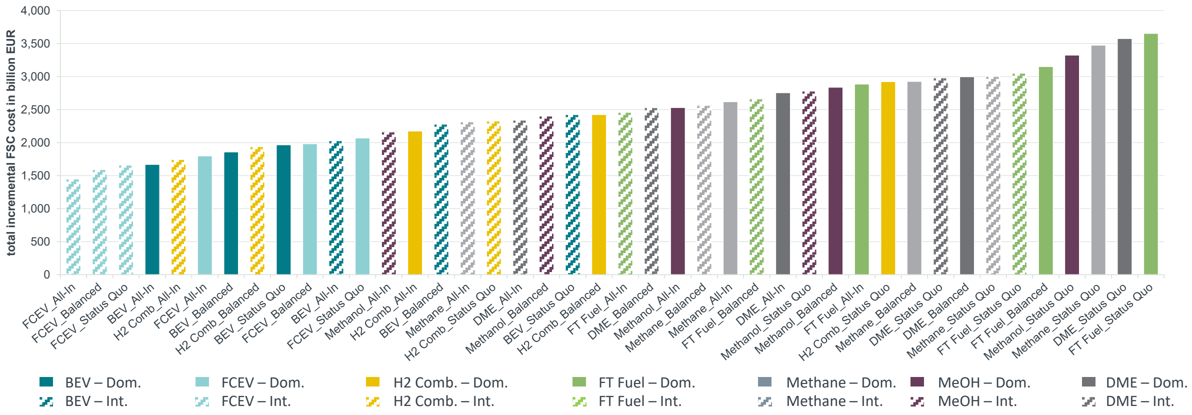

Figure 124: Fuel supply chain costs (NPV) in billion € for all 42 scenarios until 2050 [Source: Frontier Economics].

Figure 124 now compares the fuel supply chain costs across all possible 42 scenarios. Following the trend with regard to the WtW energy demand also costwise are the Status Quo scenarios the most expensive and the All-In scenarios the cheapest across all fuels. By definition, the TtW demand in the Status Quo scenarios is higher than the TtW demand for the All-In scenarios, as the respective fuel efficiencies of all vehicles increase. Thus, the total fuel demand decreases.

Comparing across all fuels, the costs associated with establishing the fuel supply chain are the highest for hydrocarbon fuels, although a large share of already existing infrastructure can be used. As set out in section 9.2, the higher costs for synthetic fuels are primarily driven by high costs for generation, in turn caused by high losses along the fuel supply chain (i.e. high WtW demands). Additional infrastructure requirements, such as DAC, further add to the total costs, as set out in detail in the previous section.

Across all hydrocarbon fuels, MeOH has the lowest fuel supply chain costs. This is due to small losses at the synthesis, but also relies on the assumption that because of the liquid nature existing infrastructure can be used.

In the international scenarios, the FCEV scenarios cause the lowest fuel supply chain costs amongst all, followed by the BEV and H2 combustion scenarios. As BEV and hydrogen scenarios do not require DAC or synthesis plants, the high costs are mainly driven by generation, electrolysis and, in the BEV scenario, by building a charging infrastructure.

In the international BEV scenarios, expensive power cables are required, which have a significant impact on the total fuel supply chain costs. This is the reason why the international BEV scenarios are placed in the midrange, as opposed to their positioning in the domestic scenarios.

For all other fuels, the effect of higher full load hours in generation outweighs the effect of additional import infrastructure costs, leading to lower overall costs. However, this affects all hydrocarbon fuels equally and does not cause any major changes in ranking among hydrocarbon fuels.

12.3 Total Cost

The total cost associated with transitioning to a 100% world are then defined as the sum of all incremental vehicle costs and the sum of all fuel supply chain costs (investment and O&M costs).

12.3.1 Modelling Approach

Adding up these elements then leads to a simple sum of the total cost, which gives a good indication of the total dimension.

However, it does not take into account at what point in time the respective investments are made. Therefore, total costs are commonly expressed by way of Net Present Value (NPV), to take into account the time value of money.

For societal expenditures, such as the transformation of the transport sector, it is common to use “social discount rates” to discount future cashflows. Within literature, there is textual dissent around how the social discount rate should be set.[34] On the one hand, it could be argued that societal expenditures should not be discounted, as that would lay a burden on future generations. On the other hand, given that the opportunity costs are similar, it could also be argued that the discount rates should be similar to those in the private sector.

We account for both viewpoints by calculating the simple sum of all costs (which is equal to setting a discount rate of zero) as well as an NPV, using a discount rate of 6%.

12.3.2 Estimations of total incremental costs

Since the relative cost comparison across the various drivetrain options show different rankings for vehicle costs (with electric vehicles showing highest costs) and the fuel supply chain (with electrification and hydrogen leading to the least costs), the overall advantageousness of the various options with regard to cost is not ex-ante obvious. We therefore calculate the total incremental costs as the sum of all costs across fleet and fuel supply chain (see Figure 125.

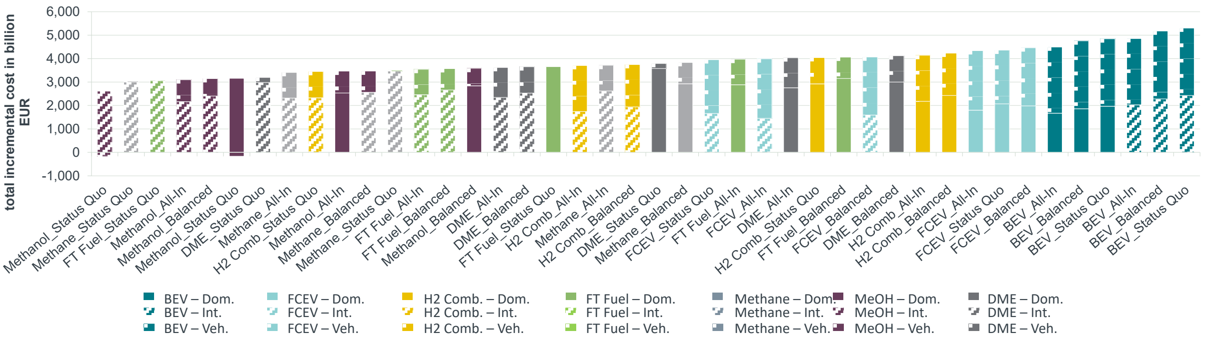

Figure 125: Total incremental costs (in NPV) – fuel supply chain and vehicles – until 2050 in billion € [Source: Frontier Economics].

When comparing the total incremental costs – fuel supply chain costs and incremental vehicle costs combined – it is striking that the vehicles costs for the BEV and FCEV scenarios outweigh the costs of the fuel supply chain. This dominance causes the scenarios with particularly high vehicle costs – BEV and FCEV – to have the highest total incremental costs across all scenarios. The BEV scenarios are most expensive, particularly the international scenarios due to additional import costs, followed by the hydrogen domestic scenarios.

The total incremental costs are the lowest for the international scenarios of MeOH, Methane, DME and some FT fuels.

Combining the lowest fuel supply chain costs for MeOH across all synthetic fuels and lower vehicle costs for MeOH relative to the benchmark FT fuel Status Quo, leads to the lowest overall incremental costs for MeOH. For synthetic fuels, the total costs are the lowest in the Status Quo scenarios compared to Balanced and All-In. The latter two scenarios are typically more expensive, albeit the lower fuel consumption and therefore lower fuel supply chain costs. However, this effect is outweighed by higher incremental vehicle costs, which again dominate the fuel supply chain cost savings.

[34] (European Commission, 2014)

12.4 Costs estimations for other segments

For the other segments, we follow a simplified approach and model only the segments of the fuel supply chain which overlap with the road sector (particularly generation to transmission). The main findings mimic those of the road sector. Nevertheless, we set out the results exemplarily for the balanced scenario below. Note that the findings for the other segments are primarily of indicative character, as costs for certain sector specific stages are excluded such as the expansion of the catenary grid for the electrification of the non-electrified share of the rail sector.

For aviation, the range of relevant fuels is limited for technical reasons, as set out in section 4.1. The highest costs accrue in the FCEV scenario. As mentioned in section 9.1, the fuel efficiency for aircrafts with fuel cell technology is lower than for aircrafts using a H2 combustion turbine, leading to higher fuel demands, capacities and thus costs. TheH2 Combustion scenario accounts for the lowest costs. Costs for the synthetic fuels (in the case of aviation: FT fuel and Methane) are quite similar. FT fuel has the slightly higher cost in the domestic scenario, while Methane has marginally higher costs in the international scenario. This is due to the more expensive import of LNG compared to FT Fuel.

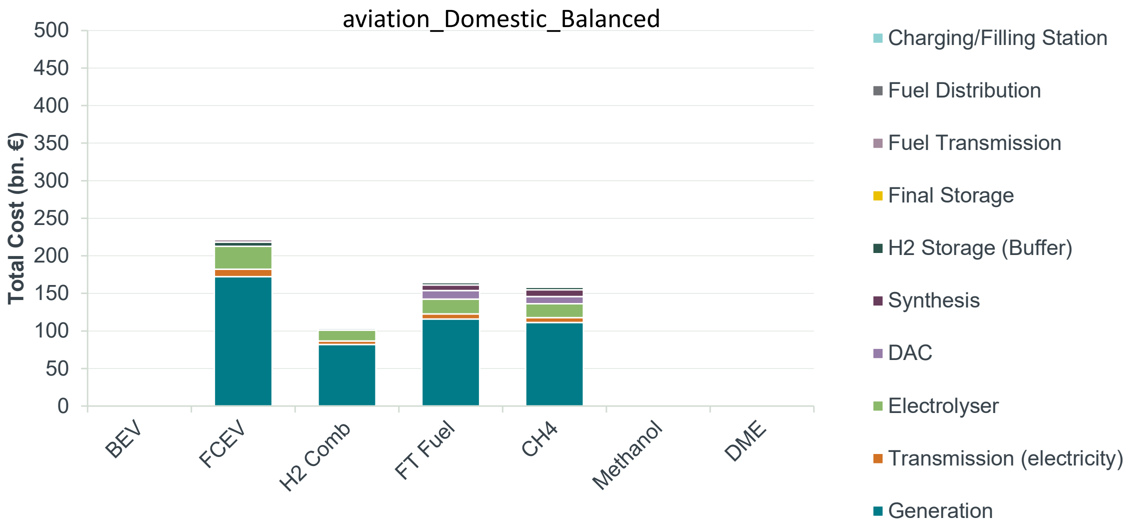

Figure 126: Fuel Supply Chain costs for aviation in 2050 exemplary for the domestic balanced scenario.

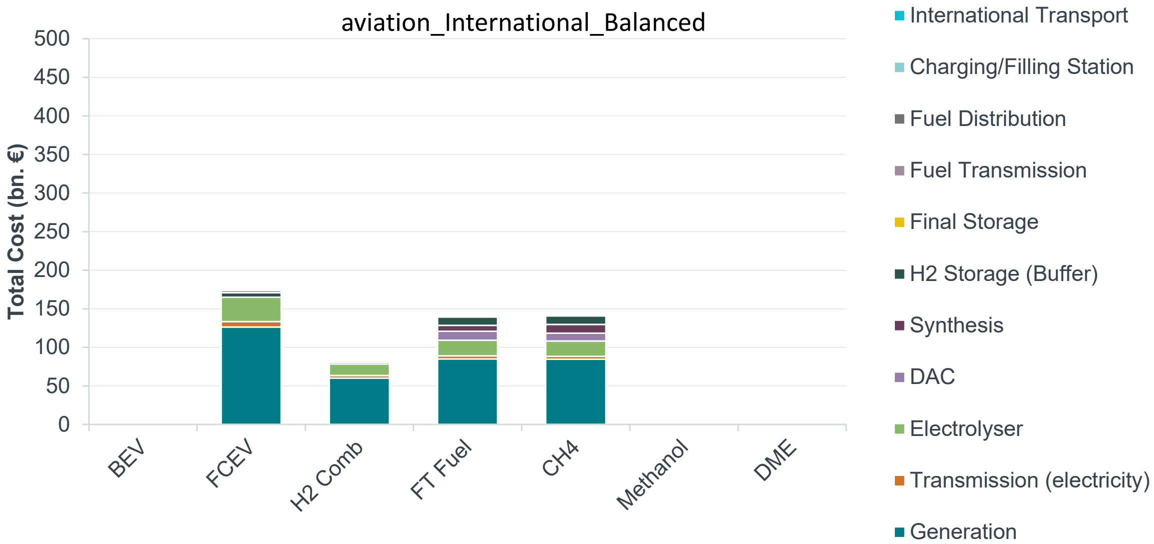

Figure 127: Fuel Supply Chain costs for aviation in 2050 exemplary for the international balanced scenario.

Several fuels, such as electrification and DME, are excluded for the shipping sector, as those are not considered to be a plausible option. Both Hydrogen scenarios have the lowest costs in both, the domestic and international scenarios, due to higher efficiencies and little losses along the fuel supply chain. Again, note that shipping-specific stages, such as liquefaction are not considered in this study. FT Fuel is the most expensive option in both the domestic and international scenario. The hydrocarbon fuels are on a similar cost level and significantly costlier than the hydrogen options.

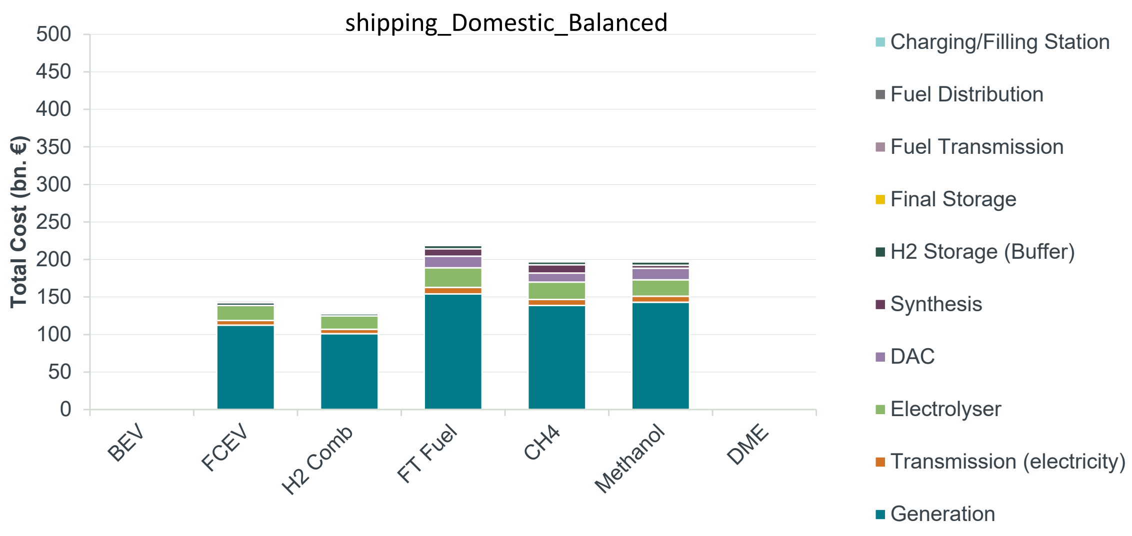

Figure 128: Fuel Supply Chain costs for shipping in 2050 exemplary for the domestic balanced scenario.

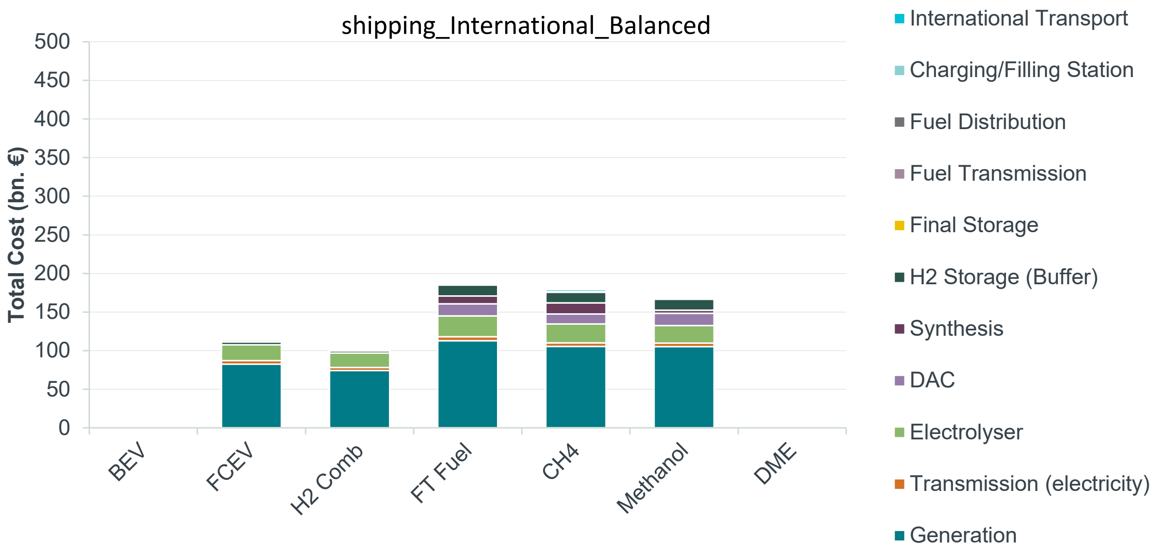

Figure 129: Fuel Supply Chain costs for shipping in 2050 exemplary for the international balanced scenario.

H2 combustion are excluded for the rail sector as this fuel is not considered to be a plausible option. Note that electrified routes will stay electrified for all fuel scenarios. For rail the electrified scenario has the lowest costs. Note that costs for stages of the fuel supply chain specific to rail are not reflected in these costs. For example, additional overhead lines are not included in this study. The highest costs have carbon fuels, especially FT Fuel and DME.

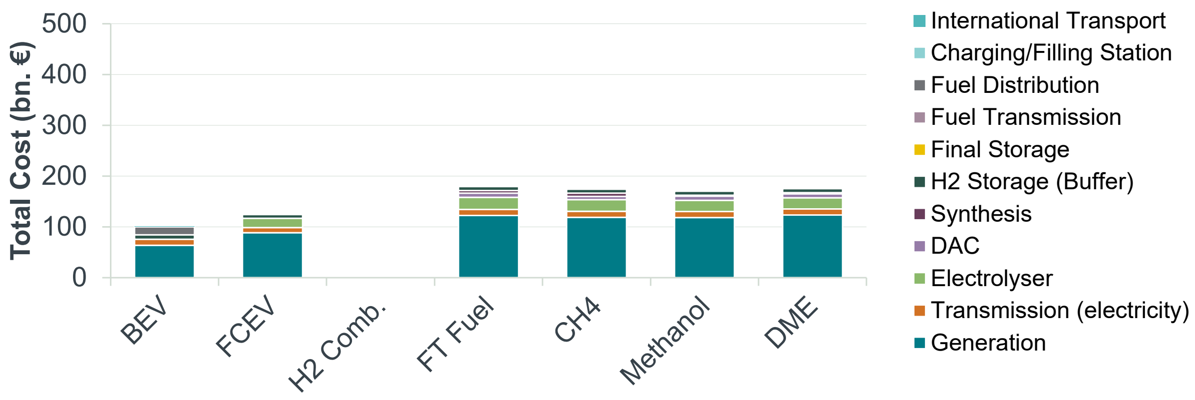

Figure 130: Fuel Supply Chain costs for rail in 2050 exemplary for the domestic balanced scenario.

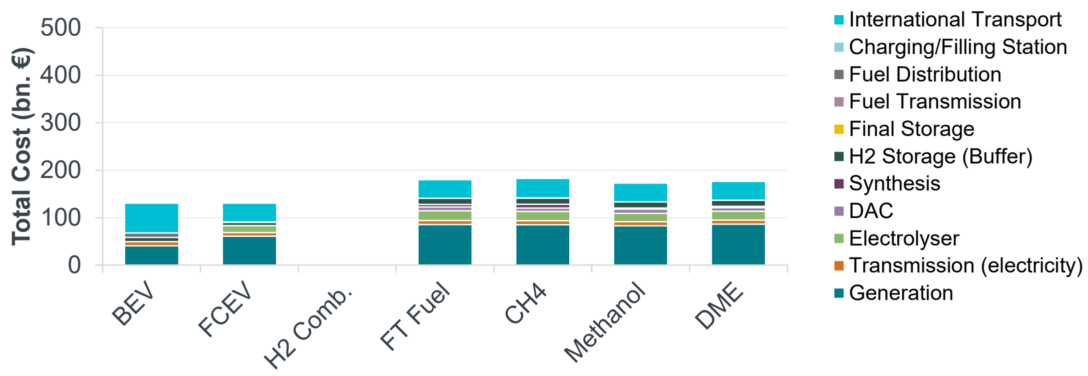

Figure 131: Fuel Supply Chain costs for rail in 2050 exemplary for the international balanced scenario.

13 Key findings and conclusions

The assumptions and results presented in the previous sections already allow to derive key findings with regard to the transition towards a full carbon neutral transport sector and the potential contribution of the different "fuel" (energy pathways) and drivetrain options. Across the various scenarios and different dimensions of evaluation, different fuels showed various advantages and disadvantages. Similarly, there are some results of our modelling which apply to all fuels.

In the following sections we provide a comprehensive overview of the most important outcomes and summarize a number of key findings for each of the areas of interest assessed in this study, i.e. with regard to

- Land use and renewable energy potential (see section 13.1)
- GHG Emissions (see section 13.2)
- Other environmental impacts (see section13.3)
- The availability of rare materials (see section 13.4)
- Energy demand and required infrastructure capacities (see section 13.5)
- And total costs (see section 13.6).

In the subsequent section 14 we summarize our main conclusions.

13.1 Land Use & Renewable Energy Potential

Land use and renewable energy potential are key metrics to determine whether Europe would be able to self-sustain a fully defossilised transport sector based on the modelled fuel paths. If available capacities of either are exceeded, this would constitute a significant limitation for the respective fuel. However, based on our modelling, neither land use nor renewable energy potential are likely to become a technically limiting factor, though the required resources are significant.

- In the domestic energy sourcing scenario power generation for European transportation requires 0.5% … 1.3% of EU27+UK land area, which is an area up to twice the size of Belgium.(wind/solar share: 68%/32% in terms of generation capacity).

- International energy sourcing requires about 1/3 less land use than energy sourcing only in Europe.

- **Land use of all other facilities in the defossilised fuel supply chain** (DAC, synthesis plants etc.) **is negligible** (e.g. DAC land use is max. 0.004% of EU27+UK land area)

- **Generally, land use is not believed to become a technical-ecological bottleneck for a defossilised transport sector.**

- For the domestic energy sourcing scenario, it was assumed that Europe can become energy independent in order to extrapolate the required land. As laid out in other studies this depends on the development of key technologies as "floating offshore wind".

13.2 GHG Emissions

While, by definition, all pathways considered will lead to 100% defossilisation by 2050, there are significant differences not only in the total emissions accumulated up to that point but also in the key drivers of the emissions across the different fuels. Nevertheless, there are also some general conclusions which apply across fuels and scenarios.

- In all 100% scenarios - with the assumed "linear" defossilisation ramp-ups until 2050 (determined by fleet exchange rate) – the GHG emissions associated with the transport sector (Cradle to Grave: including vehicle production and defossilised energy supply infrastructure) will exceed the total 1.5°C GHG budget[35] for Europe (EU27+UK, all sectors) in 2031 - 2032 and will require 43% - 51% of the total 1.75°C GHG budget for Europe[36]

- With the assumed ramp-ups of new vehicles (as BEV, FCEV, …), the cumulative GHG emissions 2021-2050 are dominated by emissions of vehicle operation of the remaining gasoline/diesel vehicle fleet with fossil fuels, which contributes 66% -74% to total cumulative GHG emissions.[37]
- In case of identical ramp-ups (as assumed) the bandwidth of cumulative GHG emissions in road transport 2021-2050 is relatively narrow in all 100% scenarios, in the range of 14%. Any change of the introduction gradient is likely to change the ranking of technologies. The most effective GHG pathways for LDV and HD trucks can be different.
- The ramp-up speed of complete sustainable transportation pathways is “the crucial factor” of “cumulative GHG emission minimisation”. The quickest applicable pathways of fossil fuel replacement are the most effective to minimize the cumulative GHG emissions. Faster introduction (e.g. enabled by mixed scenarios) of defossilised transportation pathways (GHG neutrality before 2050) can accelerate the ramp-up and thus reduce the use of fossil fuel.
- The fast introduction of each defossilised transportation pathway is determined by individual bottlenecks of each pathway (ramp-up of vehicle production and of all required facilities of fuel supply chain infrastructure, including renewable power generation capacities). The determination of those bottlenecks is a very complex task and will be covered in a follow-up study.
- For FCEV and all ICE pathways “balanced” technology scenarios (“balanced”: hybridisation for ICEV) offer lower cumulative GHG emissions than “All-in” scenarios (“All-in”: mainly aluminium light-weight measures for all pathways) as additional GHG from vehicle production outweighs GHG savings from efficiency improvements. Segregated energy efficiency optimization per sector is therefore not necessarily leading to the most efficient solution for overall GHG reduction.
- International fuel supply scenarios (i.e. importing 70% of final fuel demand) deliver slightly lower GHG emissions than domestic scenarios (energy sourcing only in Europe). For BEV the international GHG savings are 1% - 2% and for H2-based pathways (FCEV, H2-ICE) 2% - 3%. Highest GHG savings (4% - 6%) are observed for hydrocarbon e-fuel pathways when energy is sourced internationally. High political uncertainties have to be observed for international energy sourcing.

[35] 67% probability
[36] 50% probability
[37] Please note: for comparability reasons (same gradient) also in the FT scenario, only new vehicles are assumed to be operated with sustainable FT fuel, even if the existing vehicle stock is capable to be also operated with FT fuel.

- Worldwide defossilised background system reduces cumulative GHG emissions associated with the European transport sector by additional 3% - 4% compared to an incomplete defossilised background system.[38]

13.3 Other Environmental Impacts

Aside from GHG emissions, there are further environmental impacts which need to be evaluated to ensure that the defossilisation of the transport sector does not lead to other negative environmental effects. According to modelling results, this is likely not going to be the case.

- Eutrophication and PM formation 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" would not cause an environmental bottleneck.

13.4 Rare Materials

Both, vehicles and the fuel supply chain require certain rare materials, such as copper or lithium, which are only available in limited quantities. If demand from the transport sector exceeds its fair share of the worldwide supply, the ramp-up or even the long-term feasibility of the respective scenario would be threatened.

- In all investigated transport defossilisation pathways temporary restricted availability of raw materials can be a limiting factor for a fast market ramp-up.
- Lithium and cobalt are key materials for electric mobility.
    - With Li-NMC battery technology (as state of the art in Europe), lithium demand will become a bottleneck in a worldwide ramp-up of 100% BEV due to the assumed increase of motorization rates in the rest of the world (economic catch up to Europe by 2050). For cobalt the shortage is even more severe.
    - For solid state battery technology (i.e. pure lithium anode) (as assumed for future applications), lithium will become a severe bottleneck already in a pure European 100% BEV scenario by 2025.
- Platinum is a bottleneck in all FCEV scenarios.
    - Platinum demand will become a bottleneck in a worldwide ramp-up of 100% FCEV due to the assumed increase of motorization rates in the rest of the world (economic catch up to Europe by 2050). The global Pt demand will clearly exceed currently known reserves.
- Further materials, as copper, silver, nickel and neodymium are required in the fuel supply chain in all investigated energy pathways. However, primary material demand can be reduced in transport as well as in other demand sectors by increase of recycling, substitution with other materials or use of existing alternative technologies.

[38] "Incomplete defossilised background system": assuming only European production GHG free in 2050, but e.g. China production not GHG free before 2060. "Worldwide" defossilised background system: background system (material supply, production processes) of all countries defossilised in 2050.

13.5 Energy Demand & Required Infrastructure Capacity

WtW Energy Demand[39]

The WtW Energy demand determines the requirements for initial generation capacities (PV and wind plants), as well as any infrastructure requirements further down the supply chains. These capacities are then core drivers of environmental impacts as well as costs. Relative comparisons of the WtW energy demand across the different fuels are therefore a valuable indicator for further assessments.

- Lowest 2050 WtW energy* demand in the BEV scenario (~2,000 TWh/a which is still around 68% of U27+UK electricity demand in 2019 (2,900 TWh/a).
- H2-FCEV pathways require approx. 2x as much WtW energy* as BEV pathways
- H2-ICE pathways require approx. 2.5-3x as much WtW energy* as BEV pathways
- FT-ICE pathways require approx. 3-4x as much WtW energy* as BEV pathways

Installed Power Generation Capacity

Across all scenarios, large capacities of renewable energy generation are required. Therefore, irrespective of the fuel, generation capacities are a deciding factor regarding environmental impacts as well as costs. Similarly, electrolysis plays a role in all scenarios, albeit in varying forms.

- International scenarios require without exception much lower generation capacity
- Required installed power generation capacity is lowest for the most efficient "BEV International" (~750 GW) scenario, which assumes HV DC Power Lines from MENA to Europe. Domestic BEV scenarios require ~1200 GW installed generation capacity. For comparison: European wind and solar generation capacity is currently 340 GW (690 GW planned for 2030).
- The factor of required installed power generation capacity "FT-ICE / BEV" is ~3.25 for domestic energy sourcing. When FT is produced internationally the factor reduces to ~2.25 (for H2-FCEV it is ~1.5 and for H2-ICE ~2).
- Electrolysers are a key technology for all the investigated pathways, even for all BEV pathways, since they are required for energy buffering in the here assumed system without interaction of transport with other sectors. H2-FCEV pathways eventually (in 2050) require 1200 GW, H2-ICE 1600 GW and FT-ICE 1900 GW. In the BEV scenarios 600 GW (international) / 1000 GW (domestic) electrolyser capacity are required until 2050, in order to maximize the utilization of all renewable power generated. For comparison: 40 GW capacity are planned in Europe until 2030.

[39] WtW energy demand includes energy for all season vehicle operation (incl. cabin heating), loading losses and the required energy buffer in a fully sustainable energy supply.

13.6 Costs

While costs do not constitute a binding constraint, it is of common interest for consumers, manufacturers and governments to proceed with an economical pathway to transform the transport sector. Identifying core cost drivers and dependencies can also aid in determining which technological measures might have a particularly high cost benefit ratio.

- Cumulated costs to defossilise the complete European (EU27 + UK) total road transport sector are between 2,600 billion € and 5,300 billion € over 30 years, which is 17% to 34 % of the annual European GDP in 2020 (15,600 billion € in 2020)
- Incremental vehicle costs are dominating the total defossilization costs for the BEV and FCEV pathway and contribute more than 50% to the total costs
- Energy generation costs (i.e. investments in generation capacities) are the main driver of fuel supply chain costs
- While total costs for international energy sourcing are lower than for domestic energy sourcing for all ICEV and FCEV pathways, for BEV international energy sourcing costs are higher than domestic costs, because of the expensive transport and distribution infrastructure for BEV (i.a. the high voltage DC power line from MENA to Europe)
- Lowest total incremental costs (NPV[40]) for total road transport are for “E-Fuel-ICE international” pathways which carry over 2020 vehicle technology (“Status-Quo” pathway: without hybridization or light-weight measures) (from MeOH: ~2,600 billion over FT: ~3,000 billion € up to H2 ICE ~3,500 billion EUR). The increase of vehicle costs for hybridization or light-weight measures outweigh cost savings for reduced fuel supply infrastructure. Hence Energy efficiency optimization per sector is not necessarily leading to the cheapest solution for GHG reduction.
- Highest total incremental costs (NPV) for total road transport are found for BEV [NPV: ~4,500….5,300 billion €] because passenger car (LDV) vehicle costs are dominating the overall costs. BEV costs are dominated by battery costs determined by range assumptions (300 – 500km passenger car/LDV range assumed here) and specific cost assumptions. BEV costs are reduced with assumed battery technology development (as assumed in “balanced” and “all-in” technology pathways)[41]. Sensitivity analyses for different battery costs are planned in a follow up study.

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[40] We calculate total costs over time as a net present value (NPV) in 2020 €, assuming a real discount rate of 6%. The applicability and choice of a social discount rate is subject to controversia discussions. We therefore also calculated total costs based on a discount rate of 0% (i.e. the simple sum of costs over time): Absolute figures are in this case on average twice as high, with no significant changes in relativities.

[41] Battery system cost assumptions were: 160 €/kWh for 2020, 120 €/kWh for 2030, 80 €/kWh for 2050; range assumptions were 300 km for “Small Passenger Cars” and 500 km for all other passenger car segment and LDV (up to 3.5t) (range calculation on the basis of WLPT fuel consumption plus cabin heating penalty for winter operation).

14 Main Conclusions

While the analysed 100% scenarios, where a single drivetrain technology and fuel path is modelled to provide all of Europe's (road-)transport demands are obviously theoretical ones, this "all or nothing" approach nevertheless allows for a comprehensive comparison of technologies. While the most effective transformation will without doubt include a mix of technologies (which is recommended to be analysed in a follow-up study), based on the presented results already several conclusions might be drawn:

→ **Defossilisation of the complete European (EU27 + UK) transport sector is possible and affordable:** The total cost (NPV) are between 17% to 37 % of the annual European GDP (2020) over 30 years, which is an average of approx. 1% of GDP per year.

→ Depending on the applied metric and ignoring potential differences in ramp-up speeds, different technologies come out on top:

- With regard to cumulative GHG emissions, identical ramp-up speeds would lead to very similar cumulative GHG emissions for hydrocarbon synthetic fuels, H_2 (both for combustion engines as well as for fuel cells) and electric mobility. Any change of assumed ramp-up speed is likely to change the ranking of technologies.
- Regarding the lowest energy requirements, direct electrification (BEV) has the greatest advantage.
- Looking at total incremental costs, synthetic hydrocarbon fuels are the least expensive option.

These heterogeneous results further underline the expectations, that the most effective transformation pathway will have to include a mix of technologies.

→ In all investigated 100% scenarios (with the assumed "linear" defossilisation ramp-ups until 2050, determined by fleet exchange rate), **the GHG emissions associated with the transport sector** (including vehicle production and defossilised energy supply**) will exceed the total 1.5°C GHG budget for Europe** (EU27+UK, all sectors) and will require 43% - 51% of the total 1.75°C GHG budget for Europe.

→ In all fuel/powertrain pathways **the cumulative GHG emissions 2021-2050 are dominated by emissions of vehicle operation with fossil fuels** (remaining vehicle fleet), which contribute 66% -74% to total cumulative GHG emissions. A quick ramp down of fossil fuel usage is most important to meet the Paris climate targets. The ramp-up speed to a completely renewable energy supply of the transportation sector, is "the crucial factor" for cumulative GHG emissions minimisation"**.**

→ With the assumed ramp-up of new powertrain technology (passenger car 2033: 100% sales of new PT technology) it is probably difficult for the ramp-up of additional renewable energy supply to keep pace with the increasing demand. Technical feasible ramp-ups of powertrain and fuels supply are planned to be defined in a follow up study.

→ Availability of **critical raw materials** is a key factor for enabling 100% BEV or 100% FCEV pathways. Potential bottlenecks have to be assessed in the global context.

- All BEV scenarios lead to future bottlenecks in the supply of lithium or cobalt if the rest of the world is following a similar pathway. Main reason for the estimated high global Lithium and Cobalt demands are:
    - Assumptions of a worldwide economic catch-up to EU prosperity level of rest of the world within next 30 years with fair share. (~ 330 million vehicle sales worldwide in 2050, which is ~ 3x today's global production, ~ 50% higher than some global forecasts).

- Assumption of 1 single battery technology per scenario (NMC 622, NMC 811, Solid State)[42]

▪ Temporary lithium and cobalt bottlenecks can also constrain the ramp-up speed in a 100% BEV scenario (in addition to putting a limit to the total number of vehicles).

→ Platinum demand for a 100% FCEV scenario, leads to severe global platinum bottlenecks if the rest of the world is following this pathway. Main reason for estimated high global platinum demand is:

- Assumptions of a worldwide economic catch-up to EU prosperity level of rest of the world within next 30 years with fair share. (~ 330 million vehicle sales worldwide in 2050, which is ~ 3x today's global production, ~ 50% higher than some global forecasts).

▪ Slower increase of worldwide motorization than assumed can lead to lower platinum demand. Even though further explorations of vast platinum resources are required to avoid bottlenecks.

→ None of the investigated 100% pathways is restricted by technical-ecological **land use** bottlenecks or by other analysed environmental impacts as **eutrophication, PM formation and acidification**. Therefore, these environmental categories are no bottleneck for the supply of sufficient renewable energy for 100% defossilisation of the transport sector for all pathways.

→ Since alternative pathways limited by the regular vehicle fleet exchange rate are most likely not fast enough to meet the Paris 2050 targets, **carbon neutral drop-in fuels** are an option to additionally eliminate GHG emissions of the existing ICE powered vehicles. Therefore, significant efforts are required to defossilise gasoline and diesel fuel, which can be used in the existing vehicle fleet and non-electrifiable sectors. This will only work in case there is no effective limitation on additional renewable electricity ramp-up.

→ **Electrolysis** is a key technology for a carbon neutral mobility sector. All fuels require significant electrolysis capacity, also BEV, which in a fully renewable energy system requires a chemical buffer for dark doldrums. The required installed electrolysis capacity range in the domestic scenario is from 520 GW up to 2200 GW in 2050, while only 40 GW are planned for EU27+UK until 2030. Ramp-up of electrolysis capacity is likely to become a temporary bottleneck technology.

→ Certain key technologies are not at **industrial production level** (e.g. Direct air capturing, reverse water-gas-shift reactors) and thus can become a binding bottleneck. In that case bridging technologies (as PHEV, "blue" H2, biofuels, CO2 industry capture) could be options for the transition period to overcome those bottlenecks and thus to accelerate the ramp-down of fossil fuel use. Since those technologies have not been considered in this study a follow-up study is recommended, with the detailed assessment of bottlenecks and mixed scenarios.

→ **Incremental vehicle costs** (NPV) are dominating the total defossilisation costs for the BEV and FCEV pathway and contribute more than 50% to the total costs. Therefore,

[42] A different mix of battery technologies with lower specific lithium and cobalt content (e.g. lithium iron phosphate batteries, sodium-ion batteries), combined with slower increase of worldwide motorization and reduced battery sizes can lead to substantially lower Li and Co demand, which global resources might support. Strong expansion of global lithium and cobalt supply and development of closed-loop-recycling systems are required as well.

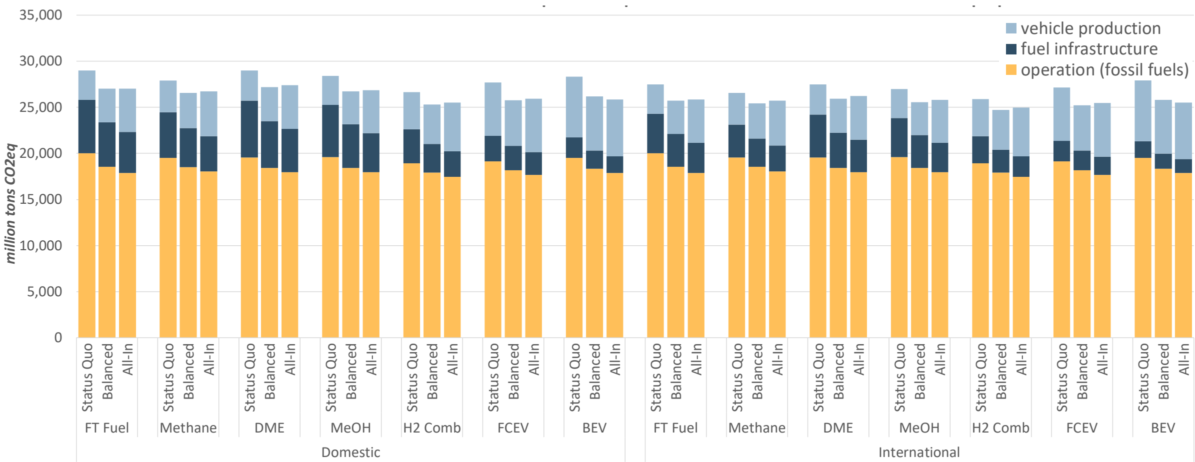
vehicle costs must be considered in any economic system optimization and GHG reduction strategy.

→ **Total incremental costs** are lower for international energy sourcing than for domestic energy sourcing for all ICEV and FCEV pathways, while domestic costs are lower for the BEV scenario. Therefore, mixed scenarios with domestic BEV and international FCEV/ICEV energy sourcing appear to be more cost efficient (to be analysed in follow up study).

→ Lowest **total incremental costs** (NPV) are achieved with e-fuel operated ICEV which carry over 2020 vehicle technology (without hybridization or light-weight measures) and international energy sourcing, while BEV (with the assumed battery costs and capacities[43]) is most expensive, 1.7 to 2 times the NPV for synthetic fuels.

→ Increasing **vehicle efficiency** is not always leading to an increase of overall GHG mitigation effectiveness. For FCEV and all ICE pathways e. g. light weight measures can increase the cumulative GHG emissions, if additional GHG from vehicle production outweighs GHG savings from efficiency improvements. Therefore, efficient GHG avoidance policy requires a Life Cycle GHG reduction approach. If (sub-)sector targets are set, they need to be well aligned with the life cycle approach. Furthermore, lowest total incremental costs (NPV), are achieved with state-of-the-art ICEV (no hybridization, light-weight measures etc.) operated with synthetic fuels, since total costs of sustainable fuel supply are lower than the cost of additional vehicle efficiency measures.

→ **Ramp-ups of all pathways** are likely to face temporary bottlenecks. A mix of technologies is likely to be better suited to overcome those restrictions and required to allow for quickest possible defossilisation and lowest cumulative GHG emissions. A technology open regulation, leaving room for a mix of different technologies (BEV, e-fuelled ICEV and FCEV) is required.



[43] Battery system cost assumptions were: 160 €/kWh for 2020, 120 €/kWh for 2030, 80 €/kWh for 2050; range assumptions were 300 km for "Small Passenger Cars" and 500 km for all other passenger car segment and LDV (up to 3.5t) (range calculation on the basis of WLTP fuel consumption plus cabin heating penalty for win-ter operation)

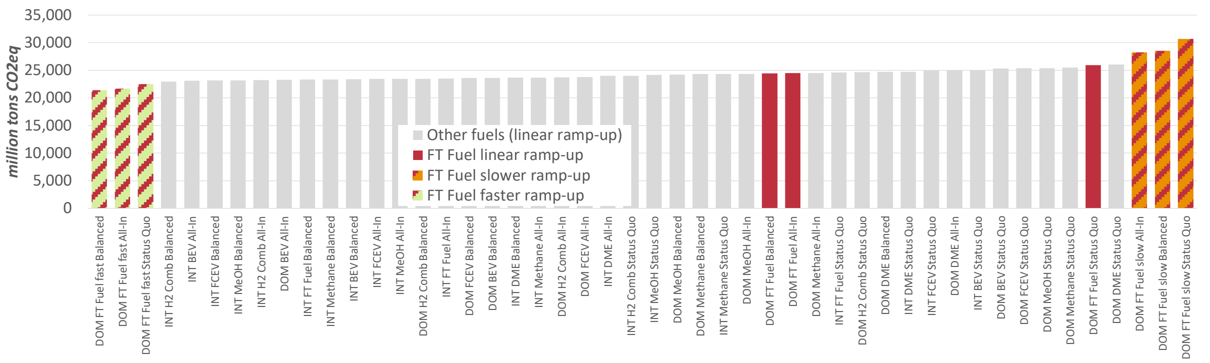


Figure 133: Sensitivity analysis for the impact of different market ramp-up speeds for FT fuels in road transport on cumulative GHG emissions 2021-2050 associated with the EU27+UK road transport [Source: ifeu].

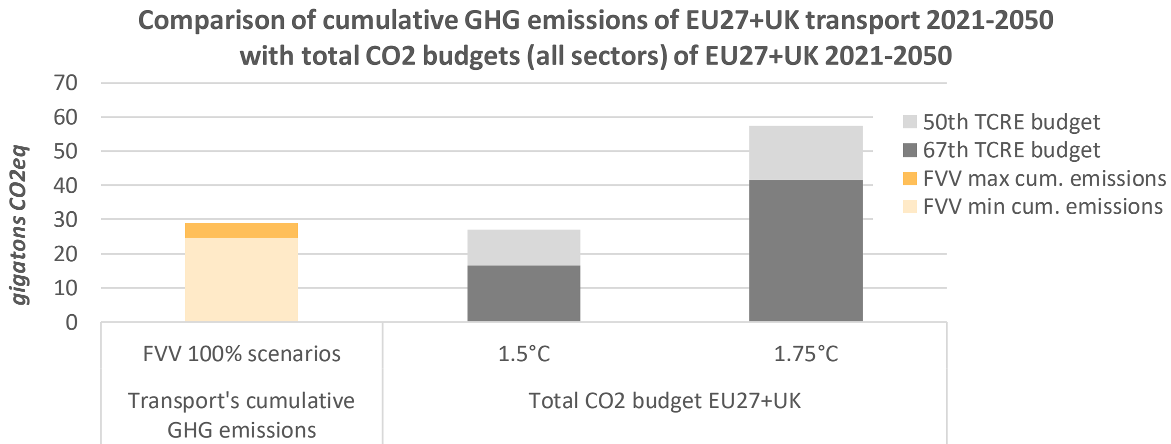


Figure 134: Comparison of cumulative GHG emissions of EU27+UK transport 2021-2050 with total CO_2 budgets (own estimates for all sectors) of EU27+UK 2021-2050 [Source: ifeu].

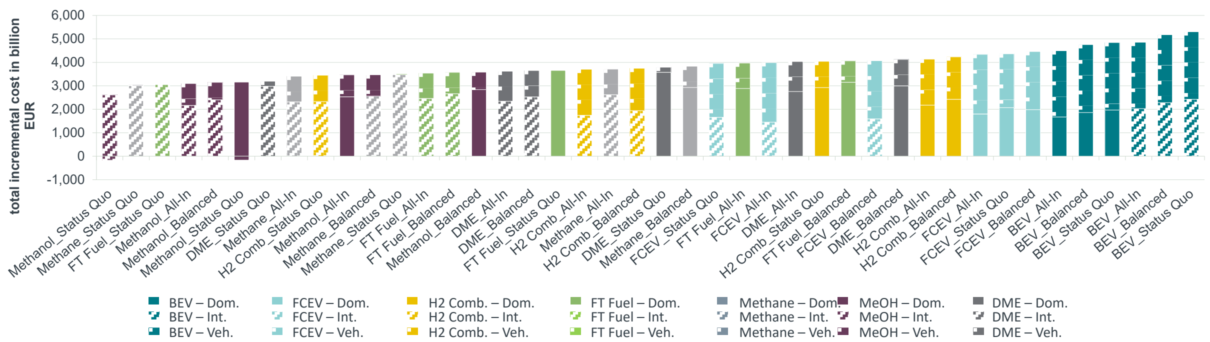


Figure 135 - Incremental costs (NPV) across all scenarios [Source: Frontier Economics].

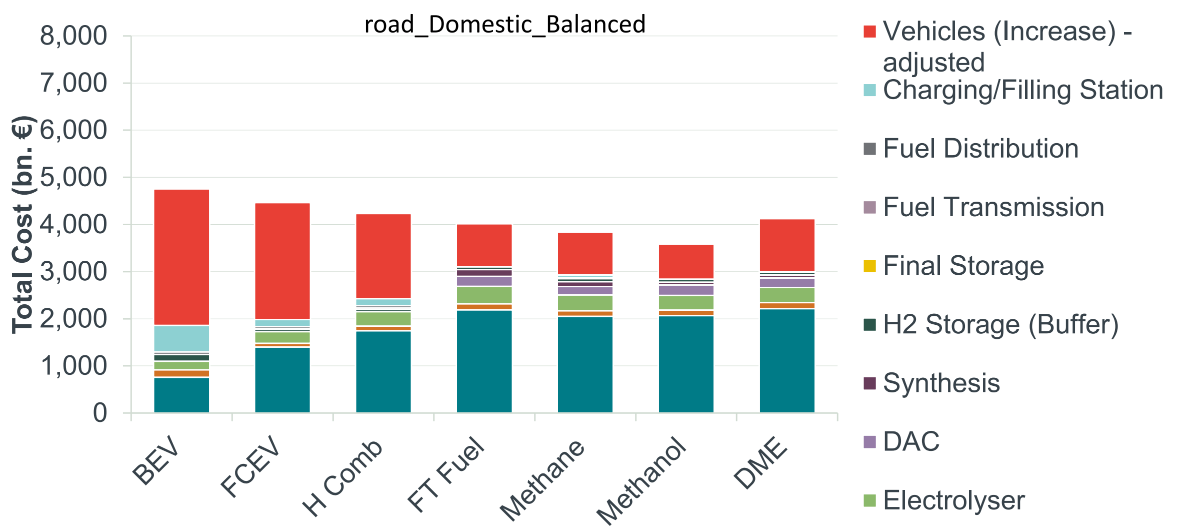


Figure 136: Total incremental costs for the domestic/balanced scenario.

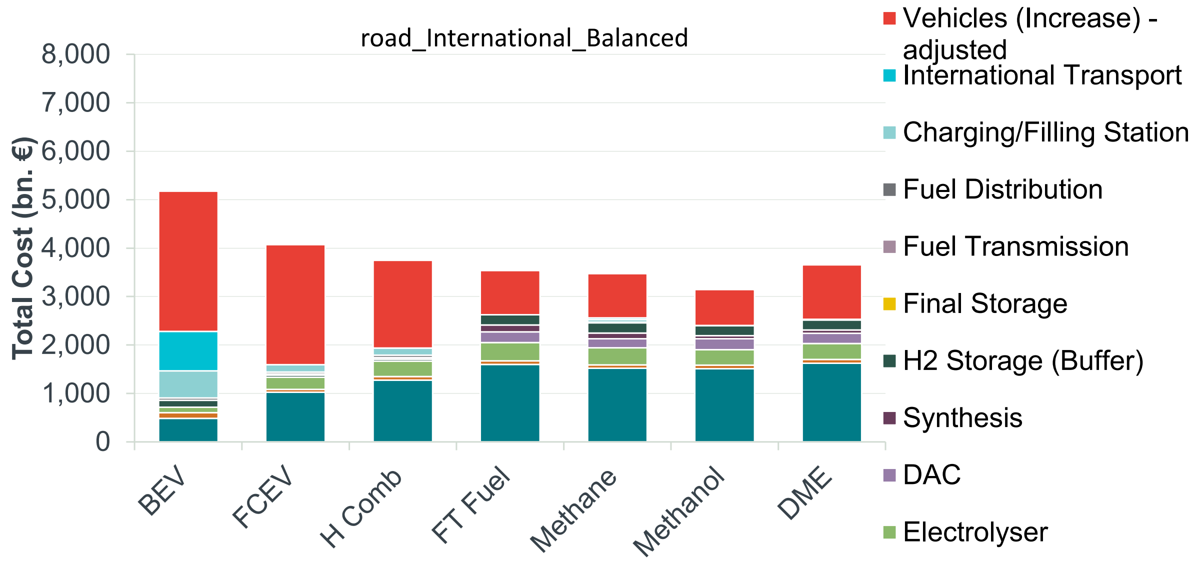


Figure 137: Total incremental costs for the international/b6alanced scenario.

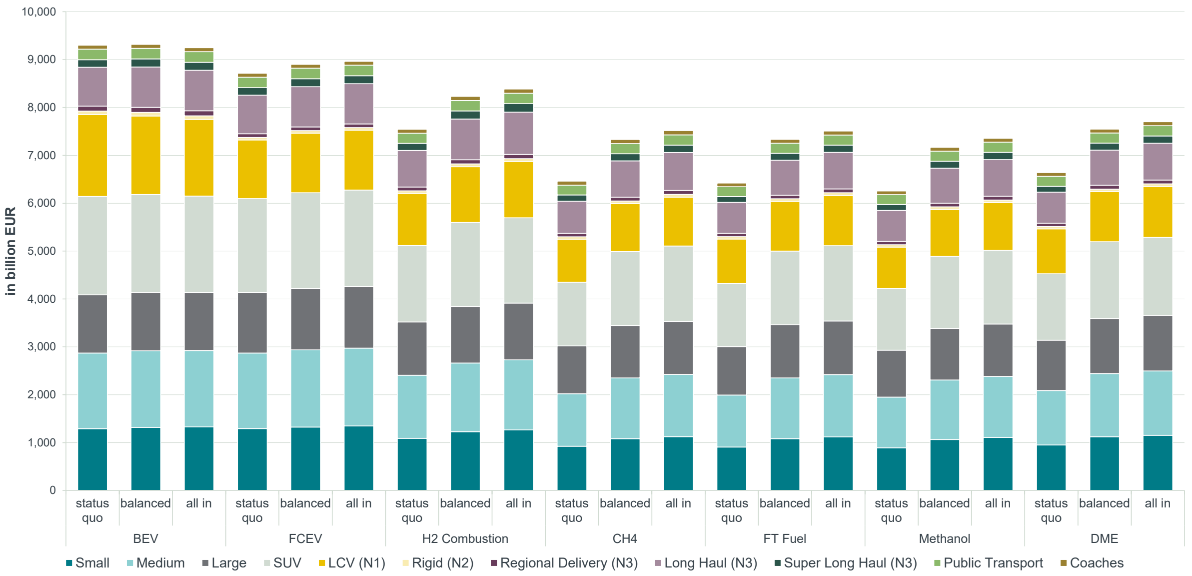


Figure 138: Vehicle Costs Across all Scenarios.

15 Annex I – Detailed Results

15.1 Capacities

15.1.1 Capacities Road

15.1.1.1 BEV

Table 35: Fuel supply chain requirements for the road segment – BEV, Domestic, Status Quo.

Segment	Type	unit	2020	2030	2050
Generation	Offshore	MW	0	70,564	287,472
	Onshore	MW	0	69,654	166,548
	PV Standalone	MW	0	197,219	674,374
	PV Slanted Roof	MW	0	84,522	289,017
Converter platform (Offshore)	Converter Station	unit	0	24	96
Transmission	Offshore - sea cable	km	0	3,716	19,165
	AC Overhead line	km	0	23,023	72,565
	AC cable	km	0	0	0
	DC cable	km	0	5,756	18,141
	Overhead line - poles	units	0	61,397	193,507
	HVDC Overhead line - poles	units	0	0	0
	cable - poles	units	0	5,757	18,143
Electrolyser	Electrolyser	MW	0	250,150	1,139,634
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	328	965
	Compressor (from Electrolyser to Storage)	MW	0	85	251
Storage	Battery	MWh	0	31,696	212,428
	Hydrogen Pressure Storage	m³	0	0	0
	Hydrogen Cavern storage	m³	0	185,788,041	686,936,937
Re-conversion	Gas Turbine (PtGtP)	MW	0	79,728	393,426
Distribution	HS	km	0	3,715	280,316
	MS	km	0	9,792	115,761
	NS	km	0	255,024	1,323,168
	Transformer HV-MV	units	0	569	6,718
	Transformer MV-LV	units	0	4,739	56,014
Charging	Wallboxes	units	0	98,938,979	398,043,480
	Depot Charger (trucks)	units	0	117,647	445,558
	Public Chargers (44kW)	units	0	5,373,419	21,630,900
	Fast Chargers (150kW)	units	0	537,342	2,163,090
Overhead Grid (trucks)	Expected total electrification	km	0	35,662	118,248

[Source: Frontier Economics].

Table 36: Fuel supply chain requirements for the road segment – BEV, Domestic, Balanced.

Segment	Type	unit	2020	2030	2050
Generation	Offshore	MW	0	65,639	263,450
	Onshore	MW	0	64,792	152,631
	PV Standalone	MW	0	183,452	618,020
	PV Slanted Roof	MW	0	78,622	264,866
Converter platform (Offshore)	Converter Station	unit	0	22	88
Transmission	Offshore - sea cable	km	0	3,457	17,563
	AC Overhead line	km	0	21,416	66,501
	AC cable	km	0	0	0
	DC cable	km	0	5,354	16,625
	Overhead line - poles	units	0	57,111	177,337
	HVDC Overhead line - poles	units	0	0	0
	cable - poles	units	0	5,356	16,627
Electrolyser	Electrolyser	MW	0	232,690	1,044,402
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	305	884
	Compressor (from Electrolyser to Storage)	MW	0	79	230
Storage	Battery	MWh	0	29,483	194,676
	Hydrogen Pressure Storage	m³	0	0	0
	Hydrogen Cavern storage	m³	0	188,588,336	686,936,937
Re-conversion	Gas Turbine (PtGtP)	MW	0	74,163	360,550
Distribution	HS	km	0	3,456	256,892
	MS	km	0	9,109	106,087
	NS	km	0	237,223	1,212,599
	Transformer HV-MV	units	0	529	6,156
	Transformer MV-LV	units	0	4,408	51,333
Charging	Wallboxes	units	0	98,938,979	398,043,480
	Depot Charger (trucks)	units	0	117,647	445,558
	Public Chargers (44kW)	units	0	5,373,419	21,630,900
	Fast Chargers (150kW)	units	0	537,342	2,163,090
Overhead Grid (trucks)	Expected total electrification	km	0	35,662	118,248

[Source: Frontier Economics].

Table 37: Fuel supply chain requirements for the road segment – BEV, Domestic, All-In.

Segment	Type	unit	2020	2030	2050
Generation	Offshore	MW	0	57,904	219,919
	Onshore	MW	0	57,158	127,411
	PV Standalone	MW	0	161,836	515,903
	PV Slanted Roof	MW	0	69,358	221,101
Converter platform (Offshore)	Converter Station	unit	0	19	73
Transmission	Offshore - sea cable	km	0	3,050	14,661
	AC Overhead line	km	0	18,893	55,513
	AC cable	km	0	0	0
	DC cable	km	0	4,723	13,878
	Overhead line - poles	units	0	50,382	148,035
	HVDC Overhead line - poles	units	0	0	0
	cable - poles	units	0	4,725	13,880
Electrolyser	Electrolyser	MW	0	205,271	871,832
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	269	738
	Compressor (from Electrolyser to Storage)	MW	0	70	192
Storage	Battery	MWh	0	26,009	162,509
	Hydrogen Pressure Storage	m³	0	0	0
	Hydrogen Cavern storage	m³	0	199,412,276	686,936,937
Re-conversion	Gas Turbine (PtGtP)	MW	0	65,424	300,975
Distribution	HS	km	0	3,048	214,445
	MS	km	0	8,035	88,558
	NS	km	0	209,270	1,012,237
	Transformer HV-MV	units	0	467	5,139
	Transformer MV-LV	units	0	3,889	42,851
Charging	Wallboxes	units	0	98,938,979	398,043,480
	Depot Charger (trucks)	units	0	117,647	445,558
	Public Chargers (44kW)	units	0	5,373,419	21,630,900
	Fast Chargers (150kW)	units	0	537,342	2,163,090
Overhead Grid (trucks)	Expected total electrification	km	0	35,662	118,248

[Source: Frontier Economics].

Table 38: Fuel supply chain requirements for the road segment – BEV, International, Status Quo.

				Europe		International (MENA)	
Segment	**Type**	**unit**	**2020**	**2030**	**2050**	**2030**	**2050**
Generation	Offshore	MW	0	19,007	78,289	32,353	97,972
	Onshore	MW	0	18,762	45,357	32,552	105,112
	PV Standalone	MW	0	53,121	183,656	107,603	394,170
	PV Slanted Roof	MW	0	22,766	78,710	0	0
Converter platform (Offshore)	Converter Station	unit	0	6	26	11	33
Transmission	Offshore - sea cable	km	0	1,001	5,219	1,704	6,531
	AC Overhead line	km	0	18,534	60,820	0	0
	AC cable	km	0	0	0	0	0
	DC cable	km	0	4,634	15,205	0	0
	Overhead line - poles	units	0	49,426	162,189	0	0
	HVDC Overhead line - poles	units	0	0	0	0	0
	cable - poles	units	0	4,635	15,207	0	0
Electrolyser	Electrolyser	MW	0	148,832	678,049	0	0
International Transport	Cable	km				100095.5813	330772.2429
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	76	235	0	0
	Compressor (from Electrolyser to Storage)	MW	0	20	61	0	0
Storage	Battery	MWh	0	29,483	194,676	0	0
	Hydrogen Pressure Storage	m³	0	0	0	0	0
	Hydrogen Cavern storage	m³	0	117,767,283	435,435,435	0	0
Re-conversion	Gas Turbine (PtGtP)	MW	0	90,560	446,874	0	0
Distribution	HS	km	0	3,362	253,488	0	0
	MS	km	0	8,862	104,681	0	0
	NS	km	0	230,804	1,196,532	0	0
	Transformer HV-MV	units	0	515	6,075	0	0
	Transformer MV-LV	units	0	4,289	50,653	0	0
Charging	Wallboxes	units	0	98,938,979	398,043,480	0	0
	Depot Charger (trucks)	units	0	117,647	445,558	0	0
	Public Chargers (44kW)	units	0	5,373,419	21,630,900	0	0
	Fast Chargers (150kW)	units	0	537,342	2,163,090	0	0
Overhead Grid		km	0	35,662	118,248	0	0

[Source: Frontier Economics].

Table 39: Fuel supply chain requirements for the road segment – BEV, International, Balanced.

				Europe		International (MENA)	
Segment	**Type**	**unit**	**2020**	**2030**	**2050**	**2030**	**2050**
Generation	Offshore	MW	0	17,680	71,747	30,094	89,785
	Onshore	MW	0	17,452	41,567	30,280	96,329
	PV Standalone	MW	0	49,414	168,309	100,092	361,232
	PV Slanted Roof	MW	0	21,177	72,133	0	0
Converter platform (Offshore)	Converter Station	unit	0	6	24	10	30
Transmission	Offshore - sea cable	km	0	931	4,783	1,585	5,986
	AC Overhead line	km	0	17,240	55,738	0	0
	AC cable	km	0	0	0	0	0
	DC cable	km	0	4,310	13,935	0	0
	Overhead line - poles	units	0	45,976	148,636	0	0
	HVDC Overhead line - poles	units	0	0	0	0	0
	cable - poles	units	0	4,312	13,936	0	0
Electrolyser	Electrolyser	MW	0	138,443	621,388	0	0
International Transport	Cable	km				93108.71565	303131.6554
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	70	216	0	0
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	18	56	0	0
Storage	Battery	MWh	0	29,483	194,676	0	0
	Hydrogen Pressure Storage	m³	0	0	0	0	0
	Hydrogen Cavern storage	m³	0	119,542,333	435,435,435	0	0
Re-conversion	Gas Turbine (PtGtP)	MW	0	84,239	409,531	0	0
Distribution	HS	km	0	3,127	232,306	0	0
	MS	km	0	8,243	95,934	0	0
	NS	km	0	214,693	1,096,545	0	0
	Transformer HV-MV	units	0	479	5,567	0	0
	Transformer MV-LV	units	0	3,989	46,420	0	0
Charging	Wallboxes	units	0	98,938,979	398,043,480	0	0
	Depot Charger (trucks)	units	0	117,647	445,558	0	0
	Public Chargers (44kW)	units	0	5,373,419	21,630,900	0	0
	Fast Chargers (150kW)	units	0	537,342	2,163,090	0	0
Overhead Grid (trucks)	Expected total electrification	km	0	35,662	118,248	0	0

[Source: Frontier Economics].

Table 40: Fuel supply chain requirements for the road segment – BEV, International, All-In.

			Europe			International (MENA)	
Segment	**Type**	**unit**	**2020**	**2030**	**2050**	**2030**	**2050**
Generation	Offshore	MW	0	15,597	59,892	26,548	74,950
	Onshore	MW	0	15,396	34,699	26,712	80,412
	PV Standalone	MW	0	43,591	140,499	88,298	301,544
	PV Slanted Roof	MW	0	18,682	60,214	0	0
Converter plat-form (Offshore)	Converter Station	unit	0	5	20	9	25
Transmission	Offshore - sea cable	km	0	821	3,993	1,398	4,997
	AC Overhead line	km	0	15,209	46,528	0	0
	AC cable	km	0	0	0	0	0
	DC cable	km	0	3,802	11,632	0	0
	Overhead line - poles	units	0	40,558	124,077	0	0
	HVDC Overhead line - poles	units	0	0	0	0	0
	cable - poles	units	0	3,804	11,634	0	0
Electrolyser	Electrolyser	MW	0	122,130	518,714	0	0
International Transport	Cable	km				82137.44117	253044.1671
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	62	180	0	0
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	16	47	0	0
Storage	Battery	MWh	0	29,483	194,676	0	0
	Hydrogen Pressure Storage	m^3	0	0	0	0	0
	Hydrogen Cavern storage	m^3	0	126,403,410	435,435,435	0	0
Re-conversion	Gas Turbine (PtGtP)	MW	0	74,312	341,863	0	0
Distribution	HS	km	0	2,759	193,921	0	0
	MS	km	0	7,272	80,082	0	0
	NS	km	0	189,395	915,359	0	0
	Transformer HV-MV	units	0	422	4,647	0	0
	Transformer MV-LV	units	0	3,519	38,750	0	0
Charging	Wallboxes	units	0	98,938,979	398,043,480	0	0
	Depot Charger (trucks)	units	0	117,647	445,558	0	0
	Public Chargers (44kW)	units	0	5,373,419	21,630,900	0	0
	Fast Chargers (150kW)	units	0	537,342	2,163,090	0	0
Overhead Grid (trucks)	Expected total electrification	km	0	35,662	118,248	0	0

[Source: Frontier Economics].

15.1.1.2 FCEV

Table 41: Fuel supply chain requirements for the road segment – FCEV, Domestic, Status Quo.

Segment	Type	unit	2020	2030	2050
Generation	Offshore	*in MW*	0	133,630	536,614
	Onshore	*in MW*	0	131,907	310,889
	PV Standalone	*in MW*	0	533,542	1,798,324
	PV Slanted Roof	*in MW*	0	0	0
Converter platform (Offshore)	Converter Station	*unit*	0	45	179
Transmission	Overhead line	*km*			
	HVDC Overhead line	*km*			
Transmission (Off-shore)	Offshore - sea cable	*km*	0	7,038	35,774
Transmission	Overhead line - poles	*units*			
	HVDC Overhead line - poles	*units*			
	cable - poles	*units*			
Electrolyser	Electrolyser	*MW*	0	387,649	1,246,673
H2 Pipeline	Pipeline (from Electrolyser to Storage)	*km*	0	267	882
	Compressor (from Electrolyser to Storage)	*MW*	0	69	229
Storage	Hydrogen Pressure Storage	*m³*	0	0	0
	Hydrogen Cavern storage	*m³*	0	288,114,913	1,058,558,559
Transmission Pipeline H2	H2 Pipeline - new built	km	0	2,036	6,735
	H2 Pipeline - retrofit	km	0	8,143	26,942
	Compressor - new built	MW	0	529	1,751
	Compressor - retrofit	MW	0	2,117	7,005
Compression	H2 Compressor	*kg/year*	0	1,687,753,183	6,200,947,943
Distribution	H2 Trucks (Container Trailer, 500bar, 900-1100kg)	*units*	0	0	0
Fueling	H2 car pumps	*units*	0	200,020	717,939
	H2 truck pumps	*units*	0	27,438	107,691

[Source: Frontier Economics].

Table 42: Fuel supply chain requirements for the road segment – FCEV, Domestic, Balanced.

Segment	**Type**	***unit***	**2020**	**2030**	**2050**
Generation	Offshore	*in MW*	0	127,815	511,333
	Onshore	*in MW*	0	126,167	296,243
	PV Standalone	*in MW*	0	510,324	1,713,603
	PV Slanted Roof	*in MW*	0	0	0
Converter platform (Offshore)	Converter Station	*unit*	0	43	170
Transmission	Overhead line	*km*			
	HVDC Overhead line	*km*			
Transmission (Off-shore)	Offshore - sea cable	*km*	0	6,732	34,089
Transmission	Overhead line - poles	*units*			
	HVDC Overhead line - poles	*units*			
	cable - poles	*units*			
Electrolyser	Electrolyser	*MW*	0	370,779	1,187,941
H2 Pipeline	Pipeline (from Electrolyser to Storage)	*km*	0	255	841
	Compressor (from Electrolyser to Storage)	*MW*	0	66	219
Storage	Hydrogen Pressure Storage	*m^3*	0	0	0
	Hydrogen Cavern storage	*m^3*	0	289,201,311	1,058,558,559
Transmission Pipeline H2	H2 Pipeline - new built	km	0	1,947	6,418
	H2 Pipeline - retrofit	km	0	7,789	25,673
	Compressor - new built	MW	0	506	1,669
	Compressor - retrofit	MW	0	2,025	6,675
Compression	H2 Compressor	*kg/year*	0	1,614,306,143	5,908,816,862
Distribution	H2 Trucks (Container Trailer, 500bar, 900-1100kg)	*units*	0	0	0
Fueling	H2 car pumps	*units*	0	200,020	717,939
	H2 truck pumps	*units*	0	27,438	107,691

[Source: Frontier Economics].

Table 43: Fuel supply chain requirements for the road segment – FCEV, Domestic, All-In.

Segment	**Type**	***unit***	**2020**	**2030**	**2050**
Generation	Offshore	*in MW*	0	116,716	453,553
	Onshore	*in MW*	0	115,211	262,767
	PV Standalone	*in MW*	0	466,009	1,519,966
	PV Slanted Roof	*in MW*	0	0	0
Converter platform (Offshore)	Converter Station	*unit*	0	39	151
Transmission	Overhead line	*km*			
	HVDC Overhead line	*km*			
Transmission (Off-shore)	Offshore - sea cable	*km*	0	6,147	30,237
Transmission	Overhead line - poles	*units*			
	HVDC Overhead line - poles	*units*			
	cable - poles	*units*			
Electrolyser	Electrolyser	*MW*	0	338,582	1,053,703
H2 Pipeline	Pipeline (from Electrolyser to Storage)	*km*	0	233	746
	Compressor (from Electrolyser to Storage)	*MW*	0	61	194
Storage	Hydrogen Pressure Storage	*m³*	0	0	0
	Hydrogen Cavern storage	*m³*	0	297,731,652	1,058,558,559
Transmission Pipeline H2	H2 Pipeline - new built	km	0	1,778	5,693
	H2 Pipeline - retrofit	km	0	7,112	22,772
	Compressor - new built	MW	0	462	1,480
	Compressor - retrofit	MW	0	1,849	5,921
Compression	H2 Compressor	*kg/year*	0	1,474,124,379	5,241,118,858
Distribution	H2 Trucks (Container Trailer, 500bar, 900-1100kg)	*units*	0	0	0
Fueling	H2 car pumps	*units*	0	200,020	717,939
	H2 truck pumps	*units*	0	27,438	107,691

[Source: Frontier Economics].

Table 44: Fuel supply chain requirements for the road segment – FCEV, International, Status Quo.

			Europe			International (MENA)	
Segment	**Type**	**unit**	**2020**	**2030**	**2050**	**2030**	**2050**
Generation	Offshore	*in MW*	0	40,152	161,214	68,988	203,641
	Onshore	*in MW*	0	39,634	93,400	69,413	218,482
	PV Standalone	*in MW*	0	160,313	540,266	229,447	819,308
	PV Slanted Roof	*in MW*	0	0	0	0	0
Converter platform (Offshore)	Converter Station	*unit*	0	13	54	23	68
Transmission	Overhead line	*km*					
	HVDC Overhead line	*km*					
Transmission (Offshore)	Offshore - sea cable	*km*	0	2,115	10,748	3,633	13,576
Transmission	Overhead line - poles	*units*					
	HVDC Overhead line - poles	*units*					
	cable - poles	*units*					
Electrolyser	Electrolyser	*MW*	0	116,476	374,535	284,585	916,709
International Transport (MENA)	H2 Pipelines	*km*				21,997	72,912
International Transport (MENA)	Compressors (international)	*MW*				5,719	18,957
H2 Pipeline	Pipeline (from Electrolyser to Storage)	*km*	0	267	882	0	0
H2 Pipeline	Compressor (from Electrolyser to Storage)	*MW*	0	69	229	0	0
Storage	Hydrogen Pressure Storage	*m^3*	0	0	0	0	0
Storage	Hydrogen Cavern storage	*m^3*	0	288,114,913	1,058,558,559	0	0
Transmission Pipeline H2	H2 Pipeline - new built	km	0	2,036	6,735	0	0
Transmission Pipeline H2	H2 Pipeline - retrofit	km	0	8,143	26,942	0	0
Transmission Pipeline H2	Compressor - new built	MW	0	529	1,751	0	0
Transmission Pipeline H2	Compressor - retrofit	MW	0	2,117	7,005	0	0
Compression	H2 Compressor	*Kg/ year*	0	1,687,753,183	6,200,947,943	0	0
Distribution	H2 Trucks (Container Trailer, 500bar, 900-1100kg)	*units*	0	0	0	0	0
Fueling	H2 car pumps	*units*	0	200,020	717,939	0	0
Fueling	H2 truck pumps	*units*	0	27,438	107,691	0	0

[Source: Frontier Economics].

Table 45: Fuel supply chain requirements for the road segment – FCEV, International, Balanced.

			Europe			International (MENA)	
Segment	**Type**	***unit***	**2020**	**2030**	**2050**	**2030**	**2050**
Generation	Offshore	*in MW*	0	38,404	153,619	65,985	194,048
	Onshore	*in MW*	0	37,909	89,000	66,392	208,189
	PV Standalone	*in MW*	0	153,336	514,814	219,462	780,710
	PV Slanted Roof	*in MW*	0	0	0	0	0
Converter plat-form (Offshore)	Converter Station	*unit*	0	13	51	22	65
Transmission	Overhead line	*km*					
	HVDC Overhead line	*km*					
Transmission (Offshore)	Offshore - sea cable	*km*	0	2,023	10,241	3,475	12,937
Transmission	Overhead line - poles	*units*					
	HVDC Overhead line - poles	*units*					
	cable - poles	*units*					
Electrolyser	Electrolyser	*MW*	0	111,407	356,890	272,201	873,522
International Transport (MENA)	H2 Pipelines	*km*				21,040	69,477
	Compressors (interna-tional)	*MW*				5,470	18,064
H2 Pipeline	Pipeline (from Electrolyser to Storage)	*km*	0	255	841	0	0
	Compressor (from Elec-trolyser to Storage)	*MW*	0	66	219	0	0
Storage	Hydrogen Pressure Stor-age	*m³*	0	0	0	0	0
	Hydrogen Cavern storage	*m³*	0	289,201,311	1,058,558,559	0	0
Transmission Pipeline H2	H2 Pipeline - new built	km	0	1,947	6,418	0	0
	H2 Pipeline - retrofit	km	0	7,789	25,673	0	0
	Compressor - new built	MW	0	506	1,669	0	0
	Compressor - retrofit	MW	0	2,025	6,675	0	0
Compression	H2 Compressor	*kg/year*	0	1,614,306,143	5,908,816,862	0	0
Distribution	H2 Trucks (Container Trailer, 500bar, 900-1100kg)	*units*	0	0	0	0	0
Fueling	H2 car pumps	*units*	0	200,020	717,939	0	0
	H2 truck pumps	*units*	0	27,438	107,691	0	0

[Source: Frontier Economics].

Table 46: Fuel supply chain requirements for the road segment – FCEV, International, All-In.

			Europe			International (MENA)	
Segment	**Type**	***unit***	**2020**	**2030**	**2050**	**2030**	**2050**
Generation	Offshore	*in MW*	0	35,069	136,260	60,255	172,120
Generation	Onshore	*in MW*	0	34,617	78,943	60,627	184,664
Generation	PV Standalone	*in MW*	0	140,021	456,640	200,404	692,490
Generation	PV Slanted Roof	*in MW*	0	0	0	0	0
Converter platform (Offshore)	Converter Station	*unit*	0	12	45	20	57
Transmis-sion	Overhead line	*km*					
Transmis-sion	HVDC Overhead line	*km*					
Transmis-sion (Off-shore)	Offshore - sea cable	*km*	0	1,847	9,084	3,173	11,475
Transmis-sion	Overhead line - poles	*units*					
Transmis-sion	HVDC Overhead line - poles	*units*					
Transmis-sion	cable - poles	*units*					
Electrolyser	Electrolyser	*MW*	0	101,733	316,562	248,564	774,814
Interna-tional Transport (MENA)	H2 Pipelines	*km*				19,213	61,626
Interna-tional Transport (MENA)	Compressors (international)	*MW*				4,995	16,023
H2 Pipeline	Pipeline (from Electrolyser to Storage)	*km*	0	233	746	0	0
H2 Pipeline	Compressor (from Electrolyser to Storage)	*MW*	0	61	194	0	0
Storage	Hydrogen Pressure Storage	*m³*	0	0	0	0	0
Storage	Hydrogen Cavern storage	*m³*	0	297,731,652	1,058,558,559	0	0
Transmis-sion Pipe-line H2	H2 Pipeline - new built	km	0	1,778	5,693	0	0
Transmis-sion Pipe-line H2	H2 Pipeline - retrofit	km	0	7,112	22,772	0	0
Transmis-sion Pipe-line H2	Compressor - new built	MW	0	462	1,480	0	0
Transmis-sion Pipe-line H2	Compressor - retrofit	MW	0	1,849	5,921	0	0
Compres-sion	H2 Compressor	*kg/year*	0	1,474,124,379	5,241,118,858	0	0
Distribution	H2 Trucks (Container Trailer, 500bar, 900-1100kg)	*units*	0	0	0	0	0
Fueling	H2 car pumps	*units*	0	200,020	717,939	0	0
Fueling	H2 truck pumps	*units*	0	27,438	107,691	0	0

[Source: Frontier Economics].

15.1.1.3 H2 Comb

Table 47: Fuel supply chain requirements for the road segment – H2 Comb, Domestic, Status Quo.

Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	*in MW*	0	191,551	787,692
Generation	Onshore	*in MW*	0	189,081	456,352
Generation	PV Standalone	*in MW*	0	764,802	2,639,749
Generation	PV Slanted Roof	*in MW*	0	0	0
Converter platform (Offshore)	Converter Station	*unit*	0	64	263
Transmission	Overhead line	*km*			
Transmission	HVDC Overhead line	*km*			
Transmission (Offshore)	Offshore - sea cable	*km*	0	10,088	52,513
Transmission	Overhead line - poles	*units*			
Transmission	HVDC Overhead line - poles	*units*			
Transmission	cable - poles	*units*			
Electrolyser	Electrolyser	*MW*	0	555,672	1,829,984
International Transport (RoW)	H2 Shipping	*units*			
International Transport (MENA)	H2 Pipelines	*km*			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	*km*	0	382	1,295
H2 Pipeline	Compressor (from Electrolyser to Storage)	*MW*	0	99	337
Storage	Hydrogen Pressure Storage	*m³*	0	0	0
Storage	Hydrogen Cavern storage	*m³*	0	281,352,666	1,058,558,559
Transmission Pipeline H2	H2 Pipeline - new built	km	0	2,918	9,887
Transmission Pipeline H2	H2 Pipeline - retrofit	km	0	11,673	39,548
Transmission Pipeline H2	Compressor - new built	MW	0	759	2,571
Transmission Pipeline H2	Compressor - retrofit	MW	0	3,035	10,282
Compression	H2 Compressor	*kg/year*	0	2,419,296,274	9,102,336,988
Distribution	H2 Trucks (Container Trailer, 500bar, 900-1100kg)	*units*	0	0	0
Fueling	H2 car pumps	*units*	0	200,020	717,939
Fueling	H2 truck pumps	*units*	0	27,438	107,691

[Source: Frontier Economics].

Table 48: Fuel supply chain requirements for the road segment – H2 Comb, Domestic, Balanced.

Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	*in MW*	0	162,064	630,212
Generation	Onshore	*in MW*	0	159,975	365,116
Generation	PV Standalone	*in MW*	0	647,072	2,111,994
Generation	PV Slanted Roof	*in MW*	0	0	0
Converter platform (Offshore)	Converter Station	*unit*	0	54	210
Transmission	Overhead line	*km*			
Transmission	HVDC Overhead line	*km*			
Transmission (Offshore)	Offshore - sea cable	*km*	0	8,535	42,014
Transmission	Overhead line - poles	*units*			
Transmission	HVDC Overhead line - poles	*units*			
Transmission	cable - poles	*units*			
Electrolyser	Electrolyser	*MW*	0	470,134	1,464,122
International Transport (RoW)	H2 Shipping	*units*			
International Transport (MENA)	H2 Pipelines	*km*			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	*km*	0	323	1,036
H2 Pipeline	Compressor (from Electrolyser to Storage)	*MW*	0	84	269
Storage	Hydrogen Pressure Storage	*m³*	0	0	0
Storage	Hydrogen Cavern storage	*m³*	0	297,525,716	1,058,558,559
Transmission Pipeline H2	H2 Pipeline - new built	km	0	2,469	7,910
Transmission Pipeline H2	H2 Pipeline - retrofit	km	0	9,876	31,641
Transmission Pipeline H2	Compressor - new built	MW	0	642	2,057
Transmission Pipeline H2	Compressor - retrofit	MW	0	2,568	8,227
Compression	H2 Compressor	*kg/year*	0	2,046,881,052	7,282,541,783
Distribution	H2 Trucks (Container Trailer, 500bar, 900-1100kg)	*units*	0	0	0
Fueling	H2 car pumps	*units*	0	200,020	717,939
Fueling	H2 truck pumps	*units*	0	27,438	107,691

[Source: Frontier Economics].

Table 49: Fuel supply chain requirements for the road segment – H2 Comb, Domestic, All-In.

Segment	**Type**	***unit***	**2020**	**2030**	**2050**
Generation	Offshore	*in MW*	0	147,121	551,398
Generation	Onshore	*in MW*	0	145,224	319,455
Generation	PV Standalone	*in MW*	0	587,410	1,847,871
Generation	PV Slanted Roof	*in MW*	0	0	0
Converter platform (Offshore)	Converter Station	*unit*	0	49	184
Transmission	Overhead line	*km*			
Transmission	HVDC Overhead line	*km*			
Transmission (Offshore)	Offshore - sea cable	*km*	0	7,748	36,760
Transmission	Overhead line - poles	*units*			
Transmission	HVDC Overhead line - poles	*units*			
Transmission	cable - poles	*units*			
Electrolyser	Electrolyser	*MW*	0	426,787	1,281,021
International Transport (RoW)	H2 Shipping	*units*			
International Transport (MENA)	H2 Pipelines	*km*			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	*km*	0	294	907
H2 Pipeline	Compressor (from Electrolyser to Storage)	*MW*	0	76	236
Storage	Hydrogen Pressure Storage	*m³*	0	0	0
Storage	Hydrogen Cavern storage	*m³*	0	308,698,348	1,058,558,559
Transmission Pipeline H2	H2 Pipeline - new built	km	0	2,241	6,921
Transmission Pipeline H2	H2 Pipeline - retrofit	km	0	8,965	27,684
Transmission Pipeline H2	Compressor - new built	MW	0	583	1,799
Transmission Pipeline H2	Compressor - retrofit	MW	0	2,331	7,198
Compression	H2 Compressor	*kg/year*	0	1,858,152,440	6,371,796,869
Distribution	H2 Trucks (Container Trailer, 500bar, 900-1100kg)	*units*	0	0	0
Fueling	H2 car pumps	*units*	0	200,020	717,939
Fueling	H2 truck pumps	*units*	0	27,438	107,691

[Source: Frontier Economics].

Table 50: Fuel supply chain requirements for the road segment – H2 Comb, International, Status Quo.

			Europe			International (MENA)	
Segment	**Type**	***unit***	**2020**	**2030**	**2050**	**2030**	**2050**
Generation	Offshore	*in MW*	0	57,555	236,645	98,890	298,924
Generation	Onshore	*in MW*	0	56,813	137,101	99,499	320,709
Generation	PV Standalone	*in MW*	0	229,799	793,054	328,899	1,202,658
Generation	PV Slanted Roof	*in MW*	0	0	0	0	0
Converter plat-form (Offshore)	Converter Station	*unit*	0	19	79	33	100
Transmission	Overhead line	*km*					
Transmission	HVDC Overhead line	*km*					
Transmission (Offshore)	Offshore - sea cable	*km*	0	3,031	15,776	5,208	19,928
Transmission	Overhead line - poles	*units*					
Transmission	HVDC Overhead line - poles	*units*					
Transmission	cable - poles	*units*					
Electrolyser	Electrolyser	*MW*	0	166,962	549,778	407,937	1,345,631
International Transport (MENA)	H2 Pipelines	*km*				31,532	107,027
International Transport (MENA)	Compressors (international)	*MW*			8,198	27,827	8,198
H2 Pipeline	Pipeline (from Electrolyser to Storage)	*km*	0	387	1,312	0	0
H2 Pipeline	Compressor (from Electrolyser to Storage)	*MW*	0	101	341	0	0
Storage	Hydrogen Pressure Storage	*m³*	0	0	0	0	0
Storage	Hydrogen Cavern storage	*m³*	0	281,352,666	1,058,558,559	0	0
Transmission Pipeline H2	H2 Pipeline - new built	km	0	2,952	10,014	0	0
Transmission Pipeline H2	H2 Pipeline - retrofit	km	0	11,808	40,055	0	0
Transmission Pipeline H2	Compressor - new built	MW	0	768	2,604	0	0
Transmission Pipeline H2	Compressor - retrofit	MW	0	3,070	10,414	0	0
Compression	H2 Compressor	*kg/year*	0	2,419,296,274	9,102,336,988	0	0
Distribution	H2 Trucks (Container Trailer, 500bar, 900-1100kg)	*units*	0	0	0	0	0
Fueling	H2 car pumps	*units*	0	200,020	717,939	0	0
Fueling	H2 truck pumps	*units*	0	27,438	107,691	0	0

[Source: Frontier Economics].

Table 51: Fuel supply chain requirements for the road segment – H2 Comb, International, Balanced.

			Europe			International (MENA)	
Segment	**Type**	**unit**	**2020**	**2030**	**2050**	**2030**	**2050**
Generation	Offshore	*in MW*	0	48,695	189,333	83,667	239,161
Generation	Onshore	*in MW*	0	48,067	109,691	84,182	256,591
Generation	PV Standalone	*in MW*	0	194,425	634,502	278,270	962,215
Generation	PV Slanted Roof	*in MW*	0	0	0	0	0
Converter plat-form (Offshore)	Converter Station	*unit*	0	16	63	28	80
Transmission	Overhead line	*km*					
Transmission	HVDC Overhead line	*km*					
Transmission (Offshore)	Offshore - sea cable	*km*	0	2,565	12,622	4,406	15,944
Transmission	Overhead line - poles	*units*					
Transmission	HVDC Overhead line - poles	*units*					
Transmission	cable - poles	*units*					
Electrolyser	Electrolyser	*MW*	0	141,261	439,863	345,141	1,076,604
International Transport (MENA)	H2 Pipelines	*km*				26,678	85,630
International Transport (MENA)	Compressors (international)	*MW*				6,936	22,264
H2 Pipeline	Pipeline (from Electrolyser to Storage)	*km*	0	327	1,050	0	0
H2 Pipeline	Compressor (from Electrolyser to Storage)	*MW*	0	85	273	0	0
Storage	Hydrogen Pressure Storage	*m³*	0	0	0	0	0
Storage	Hydrogen Cavern storage	*m³*	0	297,525,716	1,058,558,559	0	0
Transmission Pipeline H2	H2 Pipeline - new built	km	0	2,498	8,012	0	0
Transmission Pipeline H2	H2 Pipeline - retrofit	km	0	9,990	32,047	0	0
Transmission Pipeline H2	Compressor - new built	MW	0	649	2,083	0	0
Transmission Pipeline H2	Compressor - retrofit	MW	0	2,597	8,332	0	0
Compression	H2 Compressor	*kg/year*	0	2,046,881,052	7,282,541,783	0	0
Distribution	H2 Trucks (Container Trailer, 500bar, 900-1100kg)	*units*	0	0	0	0	0
Fueling	H2 car pumps	*units*	0	200,020	717,939	0	0
Fueling	H2 truck pumps	*units*	0	27,438	107,691	0	0

[Source: Frontier Economics].

Table 52: Fuel supply chain requirements for the road segment – H2 Comb, International, All-In.

				Europe		International (MENA)	
Segment	**Type**	***unit***	**2020**	**2030**	**2050**	**2030**	**2050**
Generation	Offshore	*in MW*	0	44,205	165,655	75,953	209,252
Generation	Onshore	*in MW*	0	43,635	95,973	76,421	224,502
Generation	PV Standalone	*in MW*	0	176,498	555,152	252,612	841,882
Generation	PV Slanted Roof	*in MW*	0	0	0	0	0
Converter plat-form (Offshore)	Converter Station	*unit*	0	15	55	25	70
Transmission	Overhead line	*km*					
Transmission	HVDC Overhead line	*km*					
Transmission (Offshore)	Offshore - sea cable	*km*	0	2,328	11,044	4,000	13,950
Transmission	Overhead line - poles	*units*					
Transmission	HVDC Overhead line - poles	*units*					
Transmission	cable - poles	*units*					
Electrolyser	Electrolyser	*MW*	0	128,236	384,854	313,318	941,966
International Transport (MENA)	H2 Pipelines	*km*				24,218	74,921
International Transport (MENA)	Compressors (international)	*MW*				6,297	19,479
H2 Pipeline	Pipeline (from Electrolyser to Storage)	*km*	0	297	918	0	0
H2 Pipeline	Compressor (from Electrolyser to Storage)	*MW*	0	77	239	0	0
Storage	Hydrogen Pressure Storage	*m³*	0	0	0	0	0
Storage	Hydrogen Cavern storage	*m³*	0	308,698,348	1,058,558,559	0	0
Transmission Pipeline H2	H2 Pipeline - new built	km	0	2,267	7,010	0	0
Transmission Pipeline H2	H2 Pipeline - retrofit	km	0	9,069	28,039	0	0
Transmission Pipeline H2	Compressor - new built	MW	0	589	1,823	0	0
Transmission Pipeline H2	Compressor - retrofit	MW	0	2,358	7,290	0	0
Compression	H2 Compressor	*kg/year*	0	1,858,152,440	6,371,796,869	0	0
Distribution	H2 Trucks (Container Trailer, 500bar, 900-1100kg)	*units*	0	0	0	0	0
Fueling	H2 car pumps	*units*	0	200,020	717,939	0	0
Fueling	H2 truck pumps	*units*	0	27,438	107,691	0	0

[Source: Frontier Economics].

15.1.1.4 FT Fuel

Table 53: Fuel supply chain requirements for the road segment – FT Fuel, Domestic, Status Quo.

Segment	**Type**	***unit***	**2020**	**2030**	**2050**
Generation	Offshore	MW	0	221,432	964,911
Generation	Onshore	MW	0	218,577	559,025
Generation	PV Standalone	MW	0	884,109	3,233,652
Generation	PV Slanted Roof	MW	0	0	0
Converter platform (Off-shore)	Converter station	unit	0	74	322
Transmission	Offshore - sea cable	km	0	11,662	64,327
Electrolyser	Electrolyser	MW	0	611,830	2,163,938
International Transport	FT Shipping	units			
International Transport	FT Pipelines	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	892	3,246
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	232	844
H2 Buffer Storage	Battery	MW			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	378,030,769	1,527,777,778
Direct Air Capture	Direct Air Capture	t CO2	0	300,240,287	1,213,394,454
Direct Air Capture	CO2 Buffer storage	t CO2	-	19,783,610	79,953,704
FT Synthesis	FT Synthese	MW	0	140,029	565,915
Transmission FT Fuel	Ship/Rail - analogue to today (O&M only)		0	0	0
FT Storage	Analogue to today (O&M only)		0	0	0
FT Distribution	Trucks - Analogue to today (O&M only)		0	0	0
FT Fueling	Car pumps - retrofit only	car pumps	0	258018	959368
FT Fueling	truck pumps - retrofit only	truck pumps	0	117,101	479,684

[Source: Frontier Economics].

Table 54: Fuel supply chain requirements for the road segment – FT Fuel, Domestic, Balanced.

Segment	**Type**	***unit***	**2020**	**2030**	**2050**
Generation	Offshore	MW	0	202,492	793,798
Generation	Onshore	MW	0	199,881	459,890
Generation	PV Standalone	MW	0	808,488	2,660,213
Generation	PV Slanted Roof	MW	0	0	0
Converter platform (Off-shore)	Converter station	unit	0	67	265
Transmission	Offshore - sea cable	km	0	10,665	52,920
Electrolyser	Electrolyser	MW	0	559,498	1,780,196
International Transport	FT Shipping	units			
International Transport	FT Pipelines	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	816	2,670
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	212	694
H2 Buffer Storage	Battery	MW			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	420,215,283	1,527,777,778
Direct Air Capture	Direct Air Capture	t CO2	0	274,559,678	998,217,323
Direct Air Capture	CO2 Buffer storage	t CO2	-	21,991,266	79,953,704
FT Synthesis	FT Synthese	MW	0	128,052	465,558
Transmission FT Fuel	Ship/Rail - analogue to today (O&M only)		0	0	0
FT Storage	Analogue to today (O&M only)		0	0	0
FT Distribution	Trucks - Analogue to today (O&M only)		0	0	0
FT Fueling	Car pumps - retrofit only	car pumps	0	258018	959368
FT Fueling	truck pumps - retrofit only	truck pumps	0	117,101	479,684

[Source: Frontier Economics].

Table 55: Fuel supply chain requirements for the road segment – FT Fuel, Domestic, All-In.

Segment	**Type**	***unit***	**2020**	**2030**	**2050**
Generation	Offshore	MW	0	192,127	705,898
Generation	Onshore	MW	0	189,649	408,965
Generation	PV Standalone	MW	0	767,101	2,365,637
Generation	PV Slanted Roof	MW	0	0	0
Converter platform (Off-shore)	Converter station	unit	0	64	235
Transmission	Offshore - sea cable	km	0	10,119	47,060
Electrolyser	Electrolyser	MW	0	530,857	1,583,068
International Transport	FT Shipping	units			
International Transport	FT Pipelines	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	774	2,375
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	201	617
H2 Buffer Storage	Battery	MW			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	448,351,660	1,527,777,778
Direct Air Capture	Direct Air Capture	t CO2	0	260,504,621	887,680,825
Direct Air Capture	CO2 Buffer storage	t CO2	-	23,463,737	79,953,704
FT Synthesis	FT Synthese	MW	0	121,497	414,005
Transmission FT Fuel	Ship/Rail - analogue to today (O&M only)		0	0	0
FT Storage	Analogue to today (O&M only)		0	0	0
FT Distribution	Trucks - Analogue to today (O&M only)		0	0	0
FT Fueling	Car pumps - retrofit only	car pumps	0	258018	959368
FT Fueling	truck pumps - retrofit only	truck pumps	0	117,101	479,684

[Source: Frontier Economics].

Table 56: Fuel supply chain requirements for the road segment – FT Fuel, International, Status Quo.

Segment	**Type**	***unit***			**Europe**
			2020	**2030**	**2050**
Generation	Offshore	MW	0	66,430	289,473
Generation	Onshore	MW	0	65,573	167,707
Generation	PV Standalone	MW	0	265,233	970,096
Generation	PV Slanted Roof	MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	22	96
Transmission	Offshore - sea cable	km	0	3,499	19,298
Electrolyser	Electrolyser	MW	0	183,549	649,181
International Transport	FT Shipping	units			
International Transport	FT Pipelines	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	268	974
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	70	253
H2 Buffer Storage	Battery	MW			
H2 Buffer Storage	Hydrogen Pressure Storage	m^3	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m^3	0	113,409,231	458,333,333
Direct Air Capture	Direct Air Capture	t CO2	0	90,072,086	364,018,336
Direct Air Capture	CO2 Buffer storage	t CO2	0	5,935,083	23,986,111
FT Synthesis	FT Synthese	MW	0	42,009	169,774
Transmission FT Fuel	Ship/Rail - analogue to today (O&M only)		0	0	0
FT Storage	Analogue to today (O&M only)		0	0	0
FT Distribution	Trucks - Analogue to today (O&M only)		0	0	0
FT Fueling	Car pumps - retrofit only	car pumps	0	258018	959368
FT Fueling	truck pumps - retrofit only	truck pumps	0	117,101	479,684
International Transport	Ship Import	tkm			

Nearby International Location		Far Off International Location	
2030	**2050**	**2030**	**2050**
55,626	178,133	22,571	72,127
55,969	191,115	204,390	696,455
185,009	716,682	0	0
0	0	0	0
19	59	8	24
2,930	11,876	1,189	4,808
218,575	774,092	215,408	738,798
		20	79
292	1,063	271	956
76	276	70	248
3,445,593	13,925,058	3,445,593	13,925,058
119,079,692	481,250,000	119,079,692	481,250,000
105,398,535	425,777,282	106,970,709	431,223,397
6,924,264	27,983,796	6,924,264	27,983,796
49,157	198,578	49,890	201,118
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0
83,799,550,168	338,668,439,235	502,797,301,006	2,032,010,635,411

[Source: Frontier Economics].

Table 57: Fuel supply chain requirements for the road segment – FT Fuel, International, Balanced.

Segment	**Type**	***unit***			**Europe**
			2020	**2030**	**2050**
Generation	Offshore	MW	0	60,748	238,140
Generation	Onshore	MW	0	59,964	137,967
Generation	PV Standalone	MW	0	242,546	798,064
Generation	PV Slanted Roof	MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	20	79
Transmission	Offshore - sea cable	km	0	3,199	15,876
Electrolyser	Electrolyser	MW	0	167,850	534,059
International Transport	FT Shipping	units			
International Transport	FT Pipelines	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	245	801
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	64	208
H2 Buffer Storage	Battery	MW			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	126,064,585	458,333,333
Direct Air Capture	Direct Air Capture	t CO2	0	82,367,903	299,465,197
Direct Air Capture	CO2 Buffer storage	t CO2	0	6,597,380	23,986,111
FT Synthesis	FT Synthese	MW	0	38,416	139,668
Transmission FT Fuel	Ship/Rail - analogue to today (O&M only)		0	0	0
FT Storage	Analogue to today (O&M only)		0	0	0
FT Distribution	Trucks - Analogue to today (O&M only)		0	0	0
FT Fueling	Car pumps - retrofit only	car pumps	0	258018	959368
FT Fueling	truck pumps - retrofit only	truck pumps	0	117,101	479,684
International Transport	Ship Import	tkm			

Nearby International Location		Far Off International Location	
2030	**2050**	**2030**	**2050**
50,869	146,544	20,640	59,337
51,182	157,224	186,908	572,949
169,185	589,589	0	0
0	0	0	0
17	49	7	20
2,679	9,770	1,087	3,956
199,879	636,819	196,984	607,784
		18	65
267	874	248	786
69	227	64	204
3,830,087	13,925,058	3,830,087	13,925,058
132,367,814	481,250,000	132,367,814	481,250,000
96,383,427	350,272,129	97,821,128	354,752,458
7,696,943	27,983,796	7,696,943	27,983,796
44,952	163,363	45,623	165,453
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0
76,631,879,580	278,610,720,303	459,791,277,478	1,671,664,321,819

[Source: Frontier Economics].

Table 58: Fuel supply chain requirements for the road segment – FT Fuel, International, All-In.

Segment	**Type**	***unit***			**Europe**
			2020	**2030**	**2050**
Generation	Offshore	MW	0	57,638	211,769
Generation	Onshore	MW	0	56,895	122,689
Generation	PV Standalone	MW	0	230,130	709,691
Generation	PV Slanted Roof	MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	19	71
Transmission	Offshore - sea cable	km	0	3,036	14,118
Electrolyser	Electrolyser	MW	0	159,257	474,920
International Transport	FT Shipping	units			
International Transport	FT Pipelines	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	232	712
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	60	185
H2 Buffer Storage	Battery	MW			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	134,505,498	458,333,333
Direct Air Capture	Direct Air Capture	t CO2	0	78,151,386	266,304,248
Direct Air Capture	CO2 Buffer storage	t CO2	0	7,039,121	23,986,111
FT Synthesis	FT Synthese	MW	0	36,449	124,202
Transmission FT Fuel	Ship/Rail - analogue to today (O&M only)		0	0	0
FT Storage	Analogue to today (O&M only)		0	0	0
FT Distribution	Trucks - Analogue to today (O&M only)		0	0	0
FT Fueling	Car pumps - retrofit only	car pumps	0	258018	959368
FT Fueling	truck pumps - retrofit only	truck pumps	0	117,101	479,684
International Transport	Ship Import	tkm			

Nearby International Location		Far Off International Location	
2030	**2050**	**2030**	**2050**
48,265	130,317	19,584	52,766
48,562	139,814	177,340	509,504
160,524	524,302	0	0
0	0	0	0
16	43	7	18
2,542	8,688	1,031	3,518
189,647	566,301	186,900	540,481
		17	58
253	778	235	699
66	202	61	182
4,086,539	13,925,058	4,086,539	13,925,058
141,230,773	481,250,000	141,230,773	481,250,000
91,449,438	311,485,130	92,813,541	315,469,335
8,212,308	27,983,796	8,212,308	27,983,796
42,651	145,274	43,287	147,132
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0
72,708,996,898	247,759,068,496	436,253,981,387	1,486,554,410,976

[Source: Frontier Economics].

15.1.1.5 Methane

Table 59: Fuel supply chain requirements for the road segment – Methane, Domestic, Status Quo.

Segment	**Type**	***unit***	**2020**	**2030**	**2050**
Generation	Offshore	in MW	0	231,019	880,758
Generation	Onshore	in MW	0	228,040	510,271
Generation	PV Standalone	in MW	0	922,384	2,951,637
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	77	294
Transmission (Offshore Connection)	Offshore - sea cable	km	0	12,167	58,717
Electrolyser	Electrolyser	MW	0	621,398	1,939,652
International Transport (RoW)	LNG Shipping	units			
International Transport (MENA)	CH4 Pipelines (costs for compressors included)	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	906	2,910
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	236	756
H2 Buffer Storage	Battery	MW			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	425,405,040	1,527,777,778
Direct Air Capture	Direct Air Capture	t CO2	0	266,755,092	951,449,741
Direct Air Capture	CO2 Buffer storage	t	0	18,068,055	64,888,683
Methanisation	Methanisation	MW	0	173,591	619,155
Liquefaction	Liquefaction for LNG	MW	0	75,060	237,331
Transmission Methane	New construction of pipeline	km	0	1375	4905
Transmission Methane	Compressors for pipeline	MW	0	612	2,183
Methane Storage	Methane Storage - new built	m³	0	101,913,582	366,007,194
Distribution	Pipeline	km	0	66772	224356
Distribution	LNG tank trucks - new built	units	0	2,069	6,613
Fueling	Car pumps (CNG) - new built	units	0	209,745	714,013
Fueling	Truck pumps (LNG) - new built	units	0	27,540	107,331

[Source: Frontier Economics].

Table 60: Fuel supply chain requirements for the road segment – Methane, Domestic, Balanced.

Segment	**Type**	***unit***	**2020**	**2030**	**2050**
Generation	Offshore	in MW	0	198,677	719,362
Generation	Onshore	in MW	0	196,115	416,765
Generation	PV Standalone	in MW	0	793,253	2,410,759
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	66	240
Transmission (Offshore Connection)	Offshore - sea cable	km	0	10,464	47,957
Electrolyser	Electrolyser	MW	0	534,405	1,584,217
International Transport (RoW)	LNG Shipping	units			
International Transport (MENA)	CH4 Pipelines (costs for compressors included)	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	779	2,376
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	203	618
H2 Buffer Storage	Battery	MW			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	448,158,051	1,527,777,778
Direct Air Capture	Direct Air Capture	t CO2	0	229,410,248	777,099,655
Direct Air Capture	CO2 Buffer storage	t	0	19,034,434	64,888,683
Methanisation	Methanisation	MW	0	149,289	505,697
Liquefaction	Liquefaction for LNG	MW	0	63,688	195,484
Transmission Methane	New construction of pipeline	km	0	1183	4006
Transmission Methane	Compressors for pipeline	MW	0	526	1,783
Methane Storage	Methane Storage - new built	m³	0	107,364,483	366,007,194
Distribution	Pipeline	km	0	66772	224356
Distribution	LNG tank trucks - new built	units	0	1,756	5,447
Fueling	Car pumps (CNG) - new built	units	0	209,745	714,013
Fueling	Truck pumps (LNG) - new built	units	0	27,540	107,331

[Source: Frontier Economics].

Table 61: Fuel supply chain requirements for the road segment – Methane, Domestic, All-In.

Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	in MW	0	180,552	628,544
Generation	Onshore	in MW	0	178,223	364,150
Generation	PV Standalone	in MW	0	720,886	2,106,406
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	60	210
Transmission (Offshore Connection)	Offshore - sea cable	km	0	9,509	41,903
Electrolyser	Electrolyser	MW	0	485,651	1,384,213
International Transport (RoW)	LNG Shipping	units			
International Transport (MENA)	CH4 Pipelines (costs for compressors included)	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	708	2,076
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	184	540
H2 Buffer Storage	Battery	MW			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	466,305,483	1,527,777,778
Direct Air Capture	Direct Air Capture	t CO2	0	208,481,419	678,992,465
Direct Air Capture	CO2 Buffer storage	t	0	19,805,203	64,888,683
Methanisation	Methanisation	MW	0	135,669	441,854
Liquefaction	Liquefaction for LNG	MW	0	57,637	173,437
Transmission Methane	New construction of pipeline	km	0	1075	3501
Transmission Methane	Compressors for pipeline	MW	0	478	1,558
Methane Storage	Methane Storage - new built	m³	0	111,712,033	366,007,194
Distribution	Pipeline	km	0	66772	224356
Distribution	LNG tank trucks - new built	units	0	1,589	4,833
Fueling	Car pumps (CNG) - new built	units	0	209,745	714,013
Fueling	Truck pumps (LNG) - new built	units	0	27,540	107,331

[Source: Frontier Economics].

Table 62: Fuel supply chain requirements for the road segment – Methane, International, Status Quo.

Segment	Type	unit		Europe	
			2020	2030	2050
Generation	Offshore	in MW	0	67,983	259,710
Generation	Onshore	in MW	0	67,107	150,464
Generation	PV Standalone	in MW	0	271,436	870,353
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	23	87
Transmission (Offshore Connection)	Offshore - sea cable	km	0	3,580	17,314
Electrolyser	Electrolyser	MW	0	182,863	571,948
International Transport (RoW)	LNG Shipping	units			
International Transport (MENA)	CH4 Pipelines (costs for compressors included)	km	0		
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	267	858
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	69	223
H2 Buffer Storage	Battery	MW			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	127,621,512	458,333,333
Direct Air Capture	Direct Air Capture	t CO2	0	78,499,816	280,555,355
Direct Air Capture	CO2 Buffer storage	t	0	5,420,417	19,466,605
Methanisation	Methanisation	MW	0	51,084	182,571
Liquefaction	Liquefaction for LNG	MW	0	12,412	14,709
Transmission Methane	New construction of pipeline	km	0	877	3133
Transmission Methane	Compressors for pipeline	MW	0	390	1,394
Methane Storage	Methane Storage - new built	m³	0	66,243,828	237,904,676
Distribution	Pipeline	km	0	66772	224356
Distribution	LNG tank trucks - new built	units	0	342	410
Fueling	Car pumps (CNG) - new built	units	0	209,745	714,013
Fueling	Truck pumps (LNG) - new built	units	0	27,540	107,331
International Transport (MENA)	Compressors for pipeline (international)	MW	0		
International Transport (RoW)	Export Storage (LNG)	m³			
International Transport (RoW)	Ship Import	tkm			
International Transport (RoW)	LNG Storage (Domestic)	m³			

Nearby International Location		**Far Off International Location**	
2030	**2050**	**2030**	**2050**
57,035	160,183	24,624	73,737
57,386	171,857	222,985	712,000
189,693	644,465	0	0
0	0	0	0
19	53	8	25
3,004	10,679	1,297	4,916
218,148	683,510	227,296	741,636
		54	194
2,554	9,129		
292	940	287	962
76	244	75	250
3,877,390	13,925,058	3,877,390	13,925,058
134,002,588	481,250,000	134,002,588	481,250,000
92,175,531	329,431,839	107,602,592	379,271,949
6,323,819	22,711,039	6,323,819	22,711,039
59,983	214,377	70,022	246,811
0	0	70,022	246,811
0	0	0	0
0	0	0	0
0	0		
0	0	0	0
0	0	8,636	31,016
0	0	0	0
0	0	0	0
383	1,369		
		107,827	387,244
		533,406,047,722	1,915,647,040,898
		3,170,645	11,386,890

[Source: Frontier Economics].

Table 63: Fuel supply chain requirements for the road segment – Methane, International, Balanced.

Segment	Type	unit		Europe	
			2020	2030	2050
Generation	Offshore	in MW	0	58,454	212,139
Generation	Onshore	in MW	0	57,700	122,904
Generation	PV Standalone	in MW	0	233,389	710,931
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	19	71
Transmission (Offshore Connection)	Offshore - sea cable	km	0	3,079	14,143
Electrolyser	Electrolyser	MW	0	157,231	467,184
International Transport (RoW)	LNG Shipping	units			
International Transport (MENA)	CH4 Pipelines (costs for compressors included)	km	0		
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	229	701
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	60	182
H2 Buffer Storage	Battery	MW			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	134,447,415	458,333,333
Direct Air Capture	Direct Air Capture	t CO2	0	67,496,409	229,165,962
Direct Air Capture	CO2 Buffer storage	t	0	5,710,330	19,466,605
Methanisation	Methanisation	MW	0	43,923	149,130
Liquefaction	Liquefaction for LNG	MW	0	9,792	13,686
Transmission Methane	New construction of pipeline	km	0	754	2559
Transmission Methane	Compressors for pipeline	MW	0	335	1,139
Methane Storage	Methane Storage - new built	m³	0	69,786,914	237,904,676
Distribution	Pipeline	km	0	66772	224356
Distribution	LNG tank trucks - new built	units	0	270	381
Fueling	Car pumps (CNG) - new built	units	0	209,745	714,013
Fueling	Truck pumps (LNG) - new built	units	0	27,540	107,331
International Transport (MENA)	Compressors for pipeline (international)	MW	0		
International Transport (RoW)	Export Storage (LNG)	m³			
International Transport (RoW)	Ship Import	tkm			
International Transport (RoW)	LNG Storage (Domestic)	m³			

Nearby International Location		Far Off International Location	
2030	2050	2030	2050
49,040	130,843	21,184	60,216
49,342	140,378	191,834	581,436
163,104	526,418	0	0
0	0	0	0
16	44	7	20
2,583	8,723	1,116	4,014
187,570	558,311	195,542	605,637
		47	159
2,196	7,456		
251	768	247	786
65	200	64	204
4,084,774	13,925,058	4,084,774	13,925,058
141,169,786	481,250,000	141,169,786	481,250,000
79,255,183	269,089,729	92,570,561	309,722,184
6,662,052	22,711,039	6,662,052	22,711,039
51,575	175,110	60,240	201,551
0	0	60,240	201,551
0	0	0	0
0	0	0	0
0	0		
0	0	0	0
0	0	7,430	25,328
0	0	0	0
0	0	0	0
329	1,118		
		92,764	316,232
		458,889,474,027	1,564,361,366,227
		3,340,228	11,386,890

[Source: Frontier Economics].

Table 64: Fuel supply chain requirements for the road segment – Methane, International, All-In.

Segment	**Type**	**unit**		**Europe**	
			2020	**2030**	**2050**
Generation	Offshore	in MW	0	53,118	185,389
Generation	Onshore	in MW	0	52,433	107,406
Generation	PV Standalone	in MW	0	212,084	621,284
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	18	62
Transmission (Offshore Connection)	Offshore - sea cable	km	0	2,798	12,359
Electrolyser	Electrolyser	MW	0	142,878	408,273
International Transport (RoW)	LNG Shipping	units			
International Transport (MENA)	CH4 Pipelines (costs for compressors included)	km	0		
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	208	612
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	54	159
H2 Buffer Storage	Battery	MW			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	139,891,645	458,333,333
Direct Air Capture	Direct Air Capture	t CO2	0	61,334,980	200,268,641
Direct Air Capture	CO2 Buffer storage	t	0	5,941,561	19,466,605
Methanisation	Methanisation	MW	0	39,914	130,325
Liquefaction	Liquefaction for LNG	MW	0	8,653	14,638
Transmission Methane	New construction of pipeline	km	0	685	2237
Transmission Methane	Compressors for pipeline	MW	0	305	995
Methane Storage	Methane Storage - new built	m³	0	72,612,821	237,904,676
Distribution	Pipeline	km	0	66772	224356
Distribution	LNG tank trucks - new built	units	0	239	408
Fueling	Car pumps (CNG) - new built	units	0	209,745	714,013
Fueling	Truck pumps (LNG) - new built	units	0	27,540	107,331
International Transport (MENA)	Compressors for pipeline (international)	MW	0		
International Transport (RoW)	Export Storage (LNG)	m³			
International Transport (RoW)	Ship Import	tkm			
International Transport (RoW)	LNG Storage (Domestic)	m³			

Nearby International Location		Far Off International Location	
2030	**2050**	**2030**	**2050**
44,564	114,344	19,254	52,598
44,838	122,677	174,352	507,882
148,215	460,038	0	0
0	0	0	0
15	38	6	18
2,347	7,623	1,014	3,507
170,447	487,909	177,722	529,022
		42	139
1,996	6,516		
228	671	224	687
59	174	58	178
4,250,180	13,925,058	4,250,180	13,925,058
146,886,227	481,250,000	146,886,227	481,250,000
72,020,351	235,158,109	84,134,359	270,541,248
6,931,821	22,711,039	6,931,821	22,711,039
46,867	153,029	54,750	176,054
0	0	54,750	176,054
0	0	0	0
0	0	0	0
0	0		
0	0	0	0
0	0	6,753	22,124
0	0	0	0
0	0	0	0
299	977		
		84,310	276,228
		417,069,654,191	1,366,464,202,063
		3,475,485	11,386,890

[Source: Frontier Economics].

15.1.1.6 MeOH

Table 65: Fuel supply chain requirements for the road segment – MeOH, Domestic, Status Quo.

Segment	Type	unit	2020	2030	2050
Generation	Offshore	in MW	0	222,220	887,798
Generation	Onshore	in MW	0	219,354	514,349
Generation	PV Standalone	in MW	0	887,254	2,975,229
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	74	296
Transmission	Offshore - sea cable	km	0	11,704	59,187
Electrolyser	Electrolyser	MW	0	548,306	1,800,126
International Transport	MeOH Shipping	units			
International Transport	MeOH Pipelines	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	799	2,700
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	208	702
H2 Buffer Storage	Battery	MWh			
H2 Buffer Storage	Hydrogen Pressure Storage	m^3	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m^3	0	407,250,170	1,527,777,778
Direct Air Capture	Direct Air Capture	t CO2	0	319,064,634	1,196,954,339
Direct Air Capture	CO2 Buffer storage	t		23,491,904.55	88,128,654.97
MeOH Synthese	MeOH Synthese	MW	0	157,786	591,924
Transmission MeOH	Ship/Rail - analogue to today (O&M only)		0	0	0
MeOH Storage	Analogue to today (O&M only)		0	0	0
MeOH Distribution	Trucks - Analogue to today (O&M only)		0	0	0
Fueling	retrofit car pumps MeOH	units	0	200,020	717,939
Fueling	retrofit truck pumps MeOH	units	0	27,438	107,691

[Source: Frontier Economics].

Table 66: Fuel supply chain requirements for the road segment – MeOH, Domestic, Balanced.

Segment	**Type**	***unit***	**2020**	**2030**	**2050**
Generation	Offshore	*in MW*	0	193,876	740,271
Generation	Onshore	*in MW*	0	191,377	428,879
Generation	PV Standalone	*in MW*	0	774,088	2,480,830
Generation	PV Slanted Roof	*in MW*	0	0	0
Converter platform (Offshore)	Converter station	*unit*	0	65	247
Transmission	Offshore - sea cable	*km*	0	10,211	49,351
Electrolyser	Electrolyser	*MW*	0	478,372	1,500,996
International Transport	MeOH Shipping	*units*			
International Transport	MeOH Pipelines	*MW*			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	*km*	0	697	2,252
H2 Pipeline	Compressor (from Electrolyser to Storage)	*MW*	0	181	585
H2 Buffer Storage	Battery	*MWh*			
H2 Buffer Storage	Hydrogen Pressure Storage	*m³*	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	*m³*	0	426,115,096	1,527,777,778
Direct Air Capture	Direct Air Capture	t CO2	0	278,369,033	998,054,344
Direct Air Capture	CO2 Buffer storage	t		24,580,112.90	88,128,654.97
MeOH Synthese	MeOH Synthese	*MW*	0	137,661	493,563
Transmission MeOH	Ship/Rail - analogue to today (O&M only)		0	0	0
MeOH Storage	Analogue to today (O&M only)		0	0	0
MeOH Distribution	Trucks - Analogue to today (O&M only)		0	0	0
Fueling	retrofit car pumps MeOH	*units*	0	200,020	717,939
Fueling	retrofit truck pumps MeOH	units	0	27,438	107,691

[Source: Frontier Economics].

Table 67: Fuel supply chain requirements for the road segment – MeOH, Domestic, All-In.

Segment	**Type**	***unit***	**2020**	**2030**	**2050**
Generation	Offshore	*in MW*	0	175,680	647,395
Generation	Onshore	*in MW*	0	173,415	375,071
Generation	PV Standalone	*in MW*	0	701,436	2,169,579
Generation	PV Slanted Roof	*in MW*	0	0	0
Converter platform (Offshore)	Converter station	*unit*	0	59	216
Transmission	Offshore - sea cable	*km*	0	9,252	43,160
Electrolyser	Electrolyser	*MW*	0	433,474	1,312,677
International Transport	MeOH Shipping	*units*			
International Transport	MeOH Pipelines	*MW*			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	*km*	0	632	1,969
H2 Pipeline	Compressor (from Electrolyser to Storage)	*MW*	0	164	512
H2 Buffer Storage	Battery	*MWh*			
H2 Buffer Storage	Hydrogen Pressure Storage	*m^3*	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	*m^3*	0	441,515,880	1,527,777,778
Direct Air Capture	Direct Air Capture	t CO2	0	252,242,839	872,836,113
Direct Air Capture	CO2 Buffer storage	t		25,468,494.96	88,128,654.97
MeOH Synthese	MeOH Synthese	*MW*	0	124,741	431,640
Transmission MeOH	Ship/Rail - analogue to today (O&M only)		0	0	0
MeOH Storage	Analogue to today (O&M only)		0	0	0
MeOH Distribution	Trucks - Analogue to today (O&M only)		0	0	0
Fueling	retrofit car pumps MeOH	*units*	0	200,020	717,939
Fueling	retrofit truck pumps MeOH	units	0	27,438	107,691

[Source: Frontier Economics].

Table 68: Fuel supply chain requirements for the road segment – MeOH, International, Status Quo.

Segment	Type	unit		Europe	
		unit	2020	2030	2050
Generation	Offshore	*in MW*	0	66,666	266,339
Generation	Onshore	*in MW*	0	65,806	154,305
Generation	PV Standalone	*in MW*	0	266,176	892,569
Generation	PV Slanted Roof	*in MW*	0	0	0
Converter platform (Offshore)	Converter station	*unit*	0	22	89
Transmission	Offshore - sea cable	*km*	0	3,511	17,756
Electrolyser	Electrolyser	*MW*	0	164,492	540,038
International Transport	MeOH Shipping	*units*			
International Transport	MeOH Pipelines	*MW*			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	*km*	0	240	810
H2 Pipeline	Compressor (from Electrolyser to Storage)	*MW*	0	62	211
H2 Buffer Storage	Battery	*MWh*			
H2 Buffer Storage	Hydrogen Pressure Storage	*m³*	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	*m³*	0	122,175,051	458,333,333
Direct Air Capture	Direct Air Capture	t CO2	0	95,719,390	359,086,302
Direct Air Capture	CO2 Buffer storage	t	-	7,047,571	26,438,596
MeOH Synthese	MeOH Synthese	*MW*	0	47,336	177,577
Transmission MeOH	Ship/Rail - analogue to today (O&M only)		0	0	0
MeOH Storage	Analogue to today (O&M only)		0	0	0
MeOH Distribution	Trucks - Analogue to today (O&M only)		0	0	0
Fueling	retrofit car pumps MeOH	*units*	0	200,020	717,939
Fueling	retrofit truck pumps MeOH	units	0	27,438	107,691
International Transport	Ship Import	tkm			

Nearby International Location		Far Off International Location	
2030	**2050**	**2030**	**2050**
55,833	163,830	22,809	67,320
56,177	175,770	206,550	650,034
185,696	659,136	0	0
0	0	0	0
19	55	8	22
2,941	10,922	1,201	4,488
195,822	643,436	195,238	623,194
9	33	48	179
260	880	244	803
68	229	64	209
3,711,916	13,925,058	3,711,916	13,925,058
128,283,804	481,250,000	128,283,804	481,250,000
112394909	421256552	111,672,622	432,869,217
8,222,166.59	30,845,029.24	8,222,167	30,845,029
55,582	208,322	55,225	214,065
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0
204,108,208,477	765,701,301,269	1,224,649,250,860	4,594,207,807,616

[Source: Frontier Economics].

Table 69: Fuel supply chain requirements for the road segment – MeOH, International, Balanced.

Segment	**Type**	**unit**		**Europe**	
		unit	**2020**	**2030**	**2050**
Generation	Offshore	*in MW*	0	58,163	222,081
Generation	Onshore	*in MW*	0	57,413	128,664
Generation	PV Standalone	*in MW*	0	232,226	744,249
Generation	PV Slanted Roof	*in MW*	0	0	0
Converter platform (Offshore)	Converter station	*unit*	0	19	74
Transmission	Offshore - sea cable	*km*	0	3,063	14,805
Electrolyser	Electrolyser	*MW*	0	143,511	450,299
International Transport	MeOH Shipping	*units*			
International Transport	MeOH Pipelines	*MW*			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	*km*	0	209	675
H2 Pipeline	Compressor (from Electrolyser to Storage)	*MW*	0	54	176
H2 Buffer Storage	Battery	*MWh*			
H2 Buffer Storage	Hydrogen Pressure Storage	*m³*	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	*m³*	0	127,834,529	458,333,333
Direct Air Capture	Direct Air Capture	t CO2	0	83,510,710	299,416,303
Direct Air Capture	CO2 Buffer storage	t	-	7,374,033.87	26,438,596.49
MeOH Synthese	MeOH Synthese	*MW*	0	41,298	148,069
Transmission MeOH	Ship/Rail - analogue to today (O&M only)		0	0	0
MeOH Storage	Analogue to today (O&M only)		0	0	0
MeOH Distribution	Trucks - Analogue to today (O&M only)		0	0	0
Fueling	retrofit car pumps MeOH	*units*	0	200,020	717,939
Fueling	retrofit truck pumps MeOH	units	0	27,438	107,691
International Transport	Ship Import	tkm			

Nearby International Location		Far Off International Location	
2030	**2050**	**2030**	**2050**
48,712	136,606	19,900	56,133
49,012	146,562	180,205	542,017
162,011	549,606	0	0
0	0	0	0
16	46	7	19
2,565	9,107	1,048	3,742
170,845	536,515	170,336	519,637
8	28	42	149
227	734	213	669
59	191	55	174
3,883,862	13,925,058	3,883,862	13,925,058
134,226,255	481,250,000	134,226,255	481,250,000
98,059,323	351,255,614	97,429,162	360,938,583
8,603,040	30,845,029	8,603,040	30,845,029
48,493	173,705	48,181	178,493
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0
178,074,905,489	638,463,377,537	1,068,449,432,936	3,830,780,265,220

[Source: Frontier Economics].

Table 70: Fuel supply chain requirements for the road segment – MeOH, International, All-In.

Segment	**Type**	**unit**		**Europe**	
		unit	**2020**	**2030**	**2050**
Generation	Offshore	*in MW*	0	52,704	194,219
Generation	Onshore	*in MW*	0	52,024	112,521
Generation	PV Standalone	*in MW*	0	210,431	650,874
Generation	PV Slanted Roof	*in MW*	0	0	0
Converter platform (Offshore)	Converter station	*unit*	0	18	65
Transmission	Offshore - sea cable	*km*	0	2,776	12,948
Electrolyser	Electrolyser	*MW*	0	130,042	393,803
International Transport	MeOH Shipping	*units*			
International Transport	MeOH Pipelines	*MW*			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	*km*	0	190	591
H2 Pipeline	Compressor (from Electrolyser to Storage)	*MW*	0	49	154
H2 Buffer Storage	Battery	*MWh*			
H2 Buffer Storage	Hydrogen Pressure Storage	*m³*	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	*m³*	0	132,454,764	458,333,333
Direct Air Capture	Direct Air Capture	t CO2	0	75,672,852	261,850,834
Direct Air Capture	CO2 Buffer storage	t	-	7,640,548.49	26,438,596.49
MeOH Synthese	MeOH Synthese	*MW*	0	37,422	129,492
Transmission MeOH	Ship/Rail - analogue to today (O&M only)		0	0	0
MeOH Storage	Analogue to today (O&M only)		0	0	0
MeOH Distribution	Trucks - Analogue to today (O&M only)		0	0	0
Fueling	retrofit car pumps MeOH	*units*	0	200,020	717,939
Fueling	retrofit truck pumps MeOH	units	0	27,438	107,691
International Transport	Ship Import	tkm			

Nearby International Location		Far Off International Location	
2030	**2050**	**2030**	**2050**
44,140	119,467	18,032	49,091
44,412	128,174	163,292	474,014
146,806	480,651	0	0
0	0	0	0
15	40	6	16
2,325	7,964	950	3,273
154,811	469,202	154,349	454,442
7	24	38	130
206	642	193	585
53	167	50	152
4,024,233	13,925,058	4,024,233	13,925,058
139,077,502	481,250,000	139,077,502	481,250,000
88,856,012	307,186,264	88,284,994	315,654,384
8,913,973	30,845,029	8,913,973	30,845,029
43,942	151,911	43,659	156,099
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0
161,361,769,494	558,360,269,378	968,170,616,964	3,350,161,616,268

[Source: Frontier Economics].

15.1.1.7 DME

Table 71: Fuel supply chain requirements for the road segment – DME, Domestic, Status Quo.

Segment	**Type**	***unit***	**2020**	**2030**	**2050**
Generation	Offshore	*in MW*	0	242,139	971,457
Generation	Onshore	*in MW*	0	239,017	562,817
Generation	PV Standalone	*in MW*	0	966,784	3,255,590
Generation	PV Slanted Roof	*in MW*	0	0	0
Converter platform (Offshore)	Converter station	*unit*	0	81	324
Transmission	Offshore - sea cable	*km*	0	12,753	64,764
Electrolyser	Electrolyser	*MW*	0	573,797	1,881,397
International Transport	DME Shipping	*units*			
International Transport	DME Pipelines	*MW*			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	*km*	0	836	2,822
H2 Pipeline	Compressor (from Electrolyser to Storage)	*MW*	0	217	734
H2 Buffer Storage	Battery	*MW*			
H2 Buffer Storage	Hydrogen Pressure Storage	*m^3*	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	*m^3*	0	407,772,987	1,527,777,778
Direct Air Capture	Direct Air Capture	t CO2	0	296,402,748	1,110,513,806
Direct Air Capture	CO2 Buffer storage	t	-	23,703,549	88,808,619
DME Synthesis	DME Synthesis	*MW*	0	150,893	565,343
Transmission FT Fuel	Ship/Rail - analogue to today (O&M only)		0	0	0
DME Storage	Analogue to today (O&M only)		0	0	0
DME Distribution	Trucks - Analogue to today (O&M only)		0	0	0
Fueling	Car pumps – new built	*units*	0	200,020	717,939
Fueling	truck pumps – new built	units	0	27,438	107,691
Liquefaction	Liquefaction	MW	0	148,705	557,146

[Source: Frontier Economics].

Table 72: Fuel supply chain requirements for the road segment – DME, Domestic, Balanced.

Segment	**Type**	***unit***	**2020**	**2030**	**2050**
Generation	Offshore	*in MW*	0	207,655	794,274
Generation	Onshore	*in MW*	0	204,977	460,166
Generation	PV Standalone	*in MW*	0	829,101	2,661,806
Generation	PV Slanted Roof	*in MW*	0	0	0
Converter platform (Offshore)	Converter station	*unit*	0	69	265
Transmission	Offshore - sea cable	*km*	0	10,937	52,952
Electrolyser	Electrolyser	*MW*	0	492,080	1,538,251
International Transport	DME Shipping	*units*			
International Transport	DME Pipelines	*MW*			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	*km*	0	717	2,307
H2 Pipeline	Compressor (from Electrolyser to Storage)	*MW*	0	187	600
H2 Buffer Storage	Battery	*MW*			
H2 Buffer Storage	Hydrogen Pressure Storage	*m^3*	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	*m^3*	0	427,710,293	1,527,777,778
Re-conversion	Gas Turbine (PtGtP)	*MW*			
Direct Air Capture	CO2 Buffer storage	t	-	24,862,490	88,808,619
DME Synthesis	DME Synthesis	*MW*	0	129,404	462,231
Transmission FT Fuel	Ship/Rail - analogue to today (O&M only)		0	0	0
DME Storage	Analogue to today (O&M only)		0	0	0
DME Distribution	Trucks - Analogue to today (O&M only)		0	0	0
Fueling	Car pumps – new built	*units*	0	200,020	717,939
Fueling	truck pumps – new built	units	0	27,438	107,691
Liquefaction	Liquefaction	MW	0	127,528	455,528

[Source: Frontier Economics].

Table 73: Fuel supply chain requirements for the road segment – DME, Domestic, All-In.

Segment	**Type**	***unit***	**2020**	**2030**	**2050**
Generation	Offshore	*in MW*	0	192,948	720,731
Generation	Onshore	*in MW*	0	190,460	417,558
Generation	PV Standalone	*in MW*	0	770,380	2,415,345
Generation	PV Slanted Roof	*in MW*	0	0	0
Converter platform (Offshore)	Converter station	*unit*	0	64	240
Transmission	Offshore - sea cable	*km*	0	10,162	48,049
Electrolyser	Electrolyser	*MW*	0	457,229	1,395,822
International Transport	DME Shipping	*units*			
International Transport	DME Pipelines	*MW*			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	*km*	0	667	2,094
H2 Pipeline	Compressor (from Electrolyser to Storage)	*MW*	0	173	544
H2 Buffer Storage	Battery	*MW*			
H2 Buffer Storage	Hydrogen Pressure Storage	*m³*	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	*m³*	0	437,969,903	1,527,777,778
Direct Air Capture	Direct Air Capture	t CO2	0	236,187,834	823,897,993
Direct Air Capture	CO2 Buffer storage	t	-	25,458,874	88,808,619
DME Synthesis	DME Synthesis	*MW*	0	120,239	419,432
Transmission FT Fuel	Ship/Rail - analogue to today (O&M only)		0	0	0
DME Storage	Analogue to today (O&M only)		0	0	0
DME Distribution	Trucks - Analogue to today (O&M only)		0	0	0
Fueling	Car pumps – new built	*units*	0	200,020	717,939
Fueling	truck pumps – new built	units	0	27,438	107,691
Liquefaction	Liquefaction	MW	0	118,496	413,350

[Source: Frontier Economics].

Table 74: Fuel supply chain requirements for the road segment – DME, International, Status Quo.

Segment	**Type**	**unit**		**Europe**	
		unit	**2020**	**2030**	**2050**
Generation	Offshore	*in MW*	0	72,642	291,437
Generation	Onshore	*in MW*	0	71,705	168,845
Generation	PV Standalone	*in MW*	0	290,035	976,677
Generation	PV Slanted Roof	*in MW*	0	0	0
Converter platform (Offshore)	Converter station	*unit*	0	24	97
Transmission	Offshore - sea cable	*km*	0	3,826	19,429
Electrolyser	Electrolyser	*MW*	0	172,139	564,419
International Transport	DME Shipping	*units*			
International Transport	DME Pipelines	*MW*			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	*km*	0	251	847
H2 Pipeline	Compressor (from Electrolyser to Storage)	*MW*	0	65	220
H2 Buffer Storage	Battery	*MW*			
H2 Buffer Storage	Hydrogen Pressure Storage	*m^3*	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	*m^3*	0	122,331,896	458,333,333
Direct Air Capture	Direct Air Capture	t CO2	0	88,920,824	333,154,142
Direct Air Capture	CO2 Buffer storage	t	-	7,111,065	26,642,586
DME Synthesis	DME Synthesis	*MW*	0	45,268	169,603
Transmission FT Fuel	Ship/Rail - analogue to today (O&M only)		0	0	0
DME Storage	Analogue to today (O&M only)		0	0	0
DME Distribution	Trucks - Analogue to today (O&M only)		0	0	0
Fueling	Car pumps – new built	*units*	0	200,020	717,939
Fueling	truck pumps – new built	units	0	27,438	107,691
Liquefaction	Liquefaction	MW	0	44,612	167,144
International Transport	Ship	tkm			

Nearby International Location		Far Off International Location	
2030	**2050**	**2030**	**2050**
60,944	179,592	25,146	73,775
61,320	192,680	227,707	712,362
202,696	722,552	0	0
0	0	0	0
20	60	8	25
3,210	11,973	1,324	4,918
205,344	673,863	205,771	652,449
8	31	45	167
274	927	259	845
71	241	67	220
3,716,681	13,925,058	3,716,681	13,925,058
128,448,491	481,250,000	128,448,491	481,250,000
104,406,683	390,817,730	107,735,286	401,507,221
8,296,242	31,083,016	8,296,242	31,083,016
53,152	198,958	54,846	204,400
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0
52,047	195,001	52,047	195,001
190,852,876,453	715,056,643,301	1,145,117,258,716	4,290,339,859,809

[Source: Frontier Economics].

Table 75: Fuel supply chain requirements for the road segment – DME, International, Balanced.

Segment	**Type**	**unit**		**Europe**	
		unit	**2020**	**2030**	**2050**
Generation	Offshore	*in MW*	0	62,297	238,282
Generation	Onshore	*in MW*	0	61,493	138,050
Generation	PV Standalone	*in MW*	0	248,730	798,542
Generation	PV Slanted Roof	*in MW*	0	0	0
Converter platform (Offshore)	Converter station	*unit*	0	21	79
Transmission	Offshore - sea cable	*km*	0	3,281	15,885
Electrolyser	Electrolyser	*MW*	0	147,624	461,475
International Transport	DME Shipping	*units*			
International Transport	DME Pipelines	*MW*			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	*km*	0	215	692
H2 Pipeline	Compressor (from Electrolyser to Storage)	*MW*	0	56	180
H2 Buffer Storage	Battery	*MW*			
H2 Buffer Storage	Hydrogen Pressure Storage	*m^3*	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	*m^3*	0	128,313,088	458,333,333
Direct Air Capture	Direct Air Capture	t CO2	0	76,257,317	272,390,531
Direct Air Capture	CO2 Buffer storage	t	-	7,458,747	26,642,586
DME Synthesis	DME Synthesis	*MW*	0	38,821	138,669
Transmission FT Fuel	Ship/Rail - analogue to today (O&M only)		0	0	0
DME Storage	Analogue to today (O&M only)		0	0	0
DME Distribution	Trucks - Analogue to today (O&M only)		0	0	0
Fueling	Car pumps – new built	*units*	0	200,020	717,939
Fueling	truck pumps – new built	units	0	27,438	107,691
Liquefaction	Liquefaction	MW	0	38,258	136,659
International Transport	Ship	tkm			

Nearby International Location		Far Off International Location	
2030	**2050**	**2030**	**2050**
52,265	146,837	21,565	60,319
52,587	157,538	195,279	582,435
173,829	590,766	0	0
0	0	0	0
17	49	7	20
2,753	9,789	1,136	4,021
176,100	550,958	176,467	533,449
7	25	38	136
235	758	222	691
61	197	58	180
3,898,401	13,925,058	3,898,401	13,925,058
134,728,742	481,250,000	134,728,742	481,250,000
89,537,783	319,536,922	92,392,349	328,276,768
8,701,872	31,083,016	8,701,872	31,083,016
45,582	162,671	47,035	167,120
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0
44,635	159,435	44,635	159,435
163,672,888,985	584,638,262,204	982,037,333,907	3,507,829,573,223

[Source: Frontier Economics].

Table 76: Fuel supply chain requirements for the road segment – DME, International, All-In.

Segment	Type	unit		Europe	
			2020	2030	2050
Generation	Offshore	*in MW*	0	57,884	216,219
Generation	Onshore	*in MW*	0	57,138	125,267
Generation	PV Standalone	*in MW*	0	231,114	724,603
Generation	PV Slanted Roof	*in MW*	0	0	0
Converter platform (Offshore)	Converter station	*unit*	0	19	72
Transmission	Offshore - sea cable	*km*	0	3,049	14,415
Electrolyser	Electrolyser	*MW*	0	137,169	418,747
International Transport	DME Shipping	*units*			
International Transport	DME Pipelines	*MW*			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	*km*	0	200	628
H2 Pipeline	Compressor (from Electrolyser to Storage)	*MW*	0	52	163
H2 Buffer Storage	Battery	*MW*			
H2 Buffer Storage	Hydrogen Pressure Storage	*m³*	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	*m³*	0	131,390,971	458,333,333
Direct Air Capture	Direct Air Capture	t CO2	0	70,856,350	247,169,398
Direct Air Capture	CO2 Buffer storage	t	-	7,637,662	26,642,586
DME Synthesis	DME Synthesis	*MW*	0	36,072	125,830
Transmission FT Fuel	Ship/Rail - analogue to today (O&M only)		0	0	0
DME Storage	Analogue to today (O&M only)		0	0	0
DME Distribution	Trucks - Analogue to today (O&M only)		0	0	0
Fueling	Car pumps – new built	*units*	0	200,020	717,939
Fueling	truck pumps – new built	units	0	27,438	107,691
Liquefaction	Liquefaction	MW	0	35,549	124,005
International Transport	Ship	tkm			

Nearby International Location		Far Off International Location	
2030	**2050**	**2030**	**2050**
48,563	133,241	20,037	54,734
48,862	142,951	181,448	528,506
161,518	536,066	0	0
0	0	0	0
16	44	7	18
2,558	8,883	1,055	3,649
163,628	499,944	163,968	484,056
7	23	35	124
219	688	206	627
57	179	54	163
3,991,913	13,925,058	3,991,913	13,925,058
137,960,520	481,250,000	137,960,520	481,250,000
83,196,220	289,950,419	85,848,610	297,881,027
8,910,606	31,083,016	8,910,606	31,083,016
42,354	147,609	43,704	151,646
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0
41,473	144,673	41,473	144,673
152,080,666,501	530,505,545,957	912,483,999,007	3,183,033,275,743

[Source: Frontier Economics].

15.1.2 Capacities Aviation

15.1.2.1 FCEV

Table 77: Fuel supply chain requirements for the aviation segment – FCEV, Domestic, Status Quo.

Segment	**Type**	unit	2020	2030	2050
Generation	Offshore	in MW	0	17,674	57,950
	Onshore	in MW	0	17,446	33,574
	PV Standalone	in MW	0	70,565	194,205
	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter Station	unit	0	6	19
Transmission (Off-shore)	Offshore - sea cable	km	0	931	3,863
Electrolyser	Electrolyser	MW	0	51,269	134,631
H2 Pipeline Storage	Pipeline (from Electrolyser to Storage)	km	0	35	95
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	9	25
Storage	Hydrogen Pressure Storage	m³	0	0	0
Storage	Hydrogen Cavern storage	m³	0	45,190,545	135,571,636
Pipeline H2	H2 Pipeline - new built	km	0	269	727
Transmission Pipe-line H2	H2 Pipeline - retrofit	km	0	1,077	2,909
	Compressor - new built	MW	0	70	189
Transmission Pipe-line H2	Compressor - retrofit	MW	0	280	756

[Source: Frontier Economics].

Table 78: Fuel supply chain requirements for the aviation segment – FCEV, Domestic, Balanced.

Segment	Type	unit	2020	2030	2050
Generation	Offshore	in MW	0	17,674	57,950
	Onshore	in MW	0	17,446	33,574
	PV Standalone	in MW	0	70,565	194,205
	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter Station	unit	0	6	19
Transmission (Off-shore)	Offshore - sea cable	km	0	931	3,863
Electrolyser	Electrolyser	MW	0	51,269	134,631
H2 Pipeline Storage	Pipeline (from Electrolyser to Storage)	km	0	35	95
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	9	25
Storage	Hydrogen Pressure Storage	m³	0	0	0
Storage	Hydrogen Cavern storage	m³	0	45,190,545	135,571,636
Transmission Pipeline H2	H2 Pipeline - new built	km	0	269	727
Transmission Pipeline H2	H2 Pipeline - retrofit	km	0	1,077	2,909
	Compressor - new built	MW	0	70	189
Transmission Pipeline H2	Compressor - retrofit	MW	0	280	756

[Source: Frontier Economics].

Table 79: Fuel supply chain requirements for the aviation segment – FCEV, Domestic, All-In.

Segment	Type	unit	2020	2030	2050
Generation	Offshore	in MW	0	17,674	57,950
	Onshore	in MW	0	17,446	33,574
	PV Standalone	in MW	0	70,565	194,205
	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter Station	unit	0	6	19
Transmission (Off-shore)	Offshore - sea cable	km	0	931	3,863
Electrolyser	Electrolyser	MW	0	51,269	134,631
H2 Pipeline Storage	Pipeline (from Electrolyser to Storage)	km	0	35	95
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	9	25
Storage	Hydrogen Pressure Storage	m³	0	0	0
Storage	Hydrogen Cavern storage	m³	0	45,190,545	135,571,636
Transmission Pipe-line H2	H2 Pipeline - new built	km	0	269	727
Transmission Pipe-line H2	H2 Pipeline - retrofit	km	0	1,077	2,909
	Compressor - new built	MW	0	70	189
Transmission Pipe-line H2	Compressor - retrofit	MW	0	280	756

[Source: Frontier Economics].

Table 80: Fuel supply chain requirements for the aviation segment – FCEV, International, Status Quo.

			Europe			International (MENA)	
Segment	**Type**	**unit**	**2020**	**2030**	**2050**	**2030**	**2050**
Generation	Offshore	in MW	0	5,310	17,410	9,124	21,992
	Onshore	in MW	0	5,242	10,086	9,180	23,594
	PV Standalone	in MW	0	21,203	58,345	30,346	88,479
	PV Slanted Roof	in MW	0	0	0	0	0
Converter platform (Offshore)	Converter Station	unit	0	2	6	3	7
Transmission (Off-shore)	Offshore - sea cable	km	0	280	1,161	481	1,466
Electrolyser	Electrolyser	MW	0	15,405	40,447	37,639	98,997
International Transport (MENA)	H2 Pipelines	km				2,909	7,874
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	35	95	0	0
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	9	25	0	0
Storage	Hydrogen Pressure Storage	m³	0	0	0	0	0
Storage	Hydrogen Cavern storage	m³	0	45,190,545	135,571,636	0	0
Transmission Pipe-line H2	H2 Pipeline - new built	km	0	269	727	0	0
Transmission Pipe-line H2	H2 Pipeline - retrofit	km	0	1,077	2,909	0	0
Transmission Pipe-line H2	Compressor - new built	MW	0	70	189	0	0
Transmission Pipe-line H2	Compressor - retrofit	MW	0	280	756	0	0
International Transport (MENA)	Compressors (international)	MW				756	2,047

[Source: Frontier Economics].

Table 81: Fuel supply chain requirements for the aviation segment – FCEV, International, Balanced.

					Europe	International (MENA)	
Segment	**Type**	**unit**	**2020**	**2030**	**2050**	**2030**	**2050**
Generation	Offshore	in MW	0	5,310	17,410	9,124	21,992
	Onshore	in MW	0	5,242	10,086	9,180	23,594
	PV Standalone	in MW	0	21,203	58,345	30,346	88,479
	PV Slanted Roof	in MW	0	0	0	0	0
Converter platform (Off-shore)	Converter Station	unit	0	2	6	3	7
Transmission (Offshore)	Offshore - sea cable	km	0	280	1,161	481	1,466
Electrolyser	Electrolyser	MW	0	15,405	40,447	37,639	98,997
International Transport (MENA)	H2 Pipelines	km				2,909	7,874
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	35	95	0	0
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	9	25	0	0
Storage	Hydrogen Pressure Storage	m³	0	0	0	0	0
Storage	Hydrogen Cavern storage	m³	0	45,190,545	135,571,636	0	0
Transmission Pipeline H2	H2 Pipeline - new built	km	0	269	727	0	0
Transmission Pipeline H2	H2 Pipeline - retrofit	km	0	1,077	2,909	0	0
Transmission Pipeline H2	Compressor - new built	MW	0	70	189	0	0
Transmission Pipeline H2	Compressor - retrofit	MW	0	280	756	0	0
International Transport (MENA)	Compressors (international)	MW				756	2,047

[Source: Frontier Economics].

Table 82: Fuel supply chain requirements for the aviation segment – FCEV, International, All-In.

				Europe		International (MENA)	
Segment	**Type**	**unit**	**2020**	**2030**	**2050**	**2030**	**2050**
Generation	Offshore	in MW	0	5,310	17,410	9,124	21,992
	Onshore	in MW	0	5,242	10,086	9,180	23,594
	PV Standalone	in MW	0	21,203	58,345	30,346	88,479
	PV Slanted Roof	in MW	0	0	0	0	0
Converter platform (Off-shore)	Converter Station	unit	0	2	6	3	7
Transmission (Offshore)	Offshore - sea cable	km	0	280	1,161	481	1,466
Electrolyser	Electrolyser	MW	0	15,405	40,447	37,639	98,997
International Transport (MENA)	H2 Pipelines	km				2,909	7,874
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	35	95	0	0
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	9	25	0	0
Storage	Hydrogen Pressure Storage	m³	0	0	0	0	0
Storage	Hydrogen Cavern storage	m³	0	45,190,545	135,571,636	0	0
Transmission Pipeline H2	H2 Pipeline - new built	km	0	269	727	0	0
Transmission Pipeline H2	H2 Pipeline - retrofit	km	0	1,077	2,909	0	0
Transmission Pipeline H2	Compressor - new built	MW	0	70	189	0	0
Transmission Pipeline H2	Compressor - retrofit	MW	0	280	756	0	0
International Transport (MENA)	Compressors (international)	MW				756	2,047

15.1.2.2 H2 Combustion

Table 83: Fuel supply chain requirements for the aviation segment – H2 Comb, Domestic, Status Quo.

Segment	Type	unit	2020	2030	2050
Generation	Offshore	in MW	0	8,409	27,572
Generation	Onshore	in MW	0	8,300	15,974
Generation	PV Standalone	in MW	0	33,574	92,399
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter Station	unit	0	3	9
Transmission (Offshore)	Offshore - sea cable	km	0	443	1,838
Electrolyser	Electrolyser	MW	0	24,393	64,055
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	17	45
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	4	12
Storage	Hydrogen Pressure Storage	m³	0	0	0
Storage	Hydrogen Cavern storage	m³	0	17,445,141	52,335,423
Transmission Pipeline H2	H2 Pipeline - new built	km	0	128	346
Transmission Pipeline H2	H2 Pipeline - retrofit	km	0	512	1,384
Transmission Pipeline H2	Compressor - new built	MW	0	33	90
Transmission Pipeline H2	Compressor - retrofit	MW	0	133	360

[Source: Frontier Economics].

Table 84: Fuel supply chain requirements for the aviation segment – H2 Comb, Domestic, Balanced.

Segment	Type	unit	2020	2030	2050
Generation	Offshore	in MW	0	8,409	27,572
Generation	Onshore	in MW	0	8,300	15,974
Generation	PV Standalone	in MW	0	33,574	92,399
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter Station	unit	0	3	9
Transmission (Offshore)	Offshore - sea cable	km	0	443	1,838
Electrolyser	Electrolyser	MW	0	24,393	64,055
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	17	45
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	4	12
Storage	Hydrogen Pressure Storage	m^3	0	0	0
Storage	Hydrogen Cavern storage	m^3	0	17,445,141	52,335,423
Transmission Pipeline H2	H2 Pipeline - new built	km	0	128	346
Transmission Pipeline H2	H2 Pipeline - retrofit	km	0	512	1,384
Transmission Pipeline H2	Compressor - new built	MW	0	33	90
Transmission Pipeline H2	Compressor - retrofit	MW	0	133	360

[Source: Frontier Economics].

Table 85: Fuel supply chain requirements for the aviation segment – H2 Comb, Domestic, All-In.

Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	in MW	0	8,409	27,572
Generation	Onshore	in MW	0	8,300	15,974
Generation	PV Standalone	in MW	0	33,574	92,399
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter Station	unit	0	3	9
Transmission (Offshore)	Offshore - sea cable	km	0	443	1,838
Electrolyser	Electrolyser	MW	0	24,393	64,055
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	17	45
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	4	12
Storage	Hydrogen Pressure Storage	m³	0	0	0
Storage	Hydrogen Cavern storage	m³	0	17,445,141	52,335,423
Transmission Pipeline H2	H2 Pipeline - new built	km	0	128	346
Transmission Pipeline H2	H2 Pipeline - retrofit	km	0	512	1,384
Transmission Pipeline H2	Compressor - new built	MW	0	33	90
Transmission Pipeline H2	Compressor - retrofit	MW	0	133	360

[Source: Frontier Economics].

Table 86: Fuel supply chain requirements for the aviation segment – H2 Comb, International, Status Quo.

			Europe			International (MENA)	
Segment	**Type**	**unit**	**2020**	**2030**	**2050**	**2030**	**2050**
Generation	Offshore	in MW	0	2,527	8,283	4,341	10,463
Generation	Onshore	in MW	0	2,494	4,799	4,368	11,226
Generation	PV Standalone	in MW	0	10,088	27,759	14,438	42,097
Generation	PV Slanted Roof	in MW	0	0	0	0	0
Converter platform (Off-shore)	Converter Station	unit	0	1	3	1	3
Transmission (Offshore)	Offshore - sea cable	km	0	133	552	229	698
Electrolyser	Electrolyser	MW	0	7,329	19,244	17,908	47,101
International Transport (MENA)	H2 Pipelines	km				1,384	3,746
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	17	46	0	0
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	4	12	0	0
Storage	Hydrogen Pressure Storage	m³	0	0	0	0	0
Storage	Hydrogen Cavern storage	m³	0	17,445,141	52,335,423	0	0
Transmission Pipeline H2	H2 Pipeline - new built	km	0	130	351	0	0
Transmission Pipeline H2	H2 Pipeline - retrofit	km	0	518	1,402	0	0
Transmission Pipeline H2	Compressor - new built	MW	0	34	91	0	0
Transmission Pipeline H2	Compressor - retrofit	MW	0	135	365	0	0
International Transport (MENA)	Compressors (international)	MW				360	974

[Source: Frontier Economics].

Table 87: Fuel supply chain requirements for the aviation segment – H2 Comb, International, Status Quo.

			Europe			**International (MENA)**	
Segment	**Type**	**unit**	**2020**	**2030**	**2050**	**2030**	**2050**
Generation	Offshore	in MW	0	2,527	8,283	4,341	10,463
Generation	Onshore	in MW	0	2,494	4,799	4,368	11,226
Generation	PV Standalone	in MW	0	10,088	27,759	14,438	42,097
Generation	PV Slanted Roof	in MW	0	0	0	0	0
Converter platform (Offshore)	Converter Station	unit	0	1	3	1	3
Transmis-sion (Off-shore)	Offshore - sea cable	km	0	133	552	229	698
Electrolyser	Electrolyser	MW	0	7,329	19,244	17,908	47,101
International Transport (MENA)	H2 Pipelines	km				1,384	3,746
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	17	46	0	0
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	4	12	0	0
Storage	Hydrogen Pressure Storage	m³	0	0	0	0	0
Storage	Hydrogen Cavern storage	m³	0	17,445,141	52,335,423	0	0
Transmis-sion Pipe-line H2	H2 Pipeline - new built	km	0	130	351	0	0
Transmis-sion Pipe-line H2	H2 Pipeline - retrofit	km	0	518	1,402	0	0
Transmis-sion Pipe-line H2	Compressor - new built	MW	0	34	91	0	0
Transmis-sion Pipe-line H2	Compressor - retrofit	MW	0	135	365	0	0
International Transport (MENA)	Compressors (international)	MW				360	974

[Source: Frontier Economics].

Table 88: Fuel supply chain requirements for the aviation segment – H2 Comb, International, All-In.

			Europe			International (MENA)	
Segment	**Type**	**unit**	**2020**	**2030**	**2050**	**2030**	**2050**
Generation	Offshore	in MW	0	2,527	8,283	4,341	10,463
Generation	Onshore	in MW	0	2,494	4,799	4,368	11,226
Generation	PV Standalone	in MW	0	10,088	27,759	14,438	42,097
Generation	PV Slanted Roof	in MW	0	0	0	0	0
Converter platform (Off-shore)	Converter Station	unit	0	1	3	1	3
Transmission (Offshore)	Offshore - sea cable	km	0	133	552	229	698
Electrolyser	Electrolyser	MW	0	7,329	19,244	17,908	47,101
International Transport (MENA)	H2 Pipelines	km				1,384	3,746
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	17	46	0	0
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	4	12	0	0
Storage	Hydrogen Pressure Storage	m³	0	0	0	0	0
Storage	Hydrogen Cavern storage	m³	0	17,445,141	52,335,423	0	0
Transmission Pipeline H2	H2 Pipeline - new built	km	0	130	351	0	0
Transmission Pipeline H2	H2 Pipeline - retrofit	km	0	518	1,402	0	0
Transmission Pipeline H2	Compressor - new built	MW	0	34	91	0	0
Transmission Pipeline H2	Compressor - retrofit	MW	0	135	365	0	0
International Transport (MENA)	Compressors (international)	MW				360	974

[Source: Frontier Economics].

15.1.2.3 FT Fuel

Table 89: Fuel supply chain requirements for the aviation segment – FT Fuel, Domestic, Status Quo.

Segment	**Type**	***unit***	**2020**	**2030**	**2050**
Generation	Offshore	MW	0	21,582	71,243
Generation	Onshore	MW	0	21,304	41,275
Generation	PV Standalone	MW	0	86,170	238,752
Generation	PV Slanted Roof	MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	7	24
Transmission	Offshore - sea cable	km	0	1,137	4,750
Electrolyser	Electrolyser	MW	0	59,632	159,771
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	87	240
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	23	62
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	44,206,576	135,339,161
Direct Air Capture	Direct Air Capture	t CO2	0	29,263,016	89,589,204
Direct Air Capture	CO2 Buffer storage	t CO2	-	2,313,477	7,082,749
FT Synthesis	FT Synthese	MW	0	13,648	41,784
Transmission FT Fuel	Ship/Rail - analogue to today (O&M only)		0	0	0
FT Storage	Analogue to today (O&M only)		0	0	0

[Source: Frontier Economics].

Table 90: Fuel supply chain requirements for the aviation segment – FT Fuel, Domestic, Balanced.

Segment	**Type**	***unit***	**2020**	**2030**	**2050**
Generation	Offshore	MW	0	11,855	39,133
Generation	Onshore	MW	0	11,702	22,672
Generation	PV Standalone	MW	0	47,333	131,145
Generation	PV Slanted Roof	MW	0	0	0
Converter platform (Off-shore)	Converter station	unit	0	4	13
Transmission	Offshore - sea cable	km	0	624	2,609
Electrolyser	Electrolyser	MW	0	32,756	87,762
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	48	132
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	12	34
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	24,282,486	74,341,229
Direct Air Capture	Direct Air Capture	t CO2	0	16,074,051	49,210,971
Direct Air Capture	CO2 Buffer storage	t CO2	-	1,270,783	3,890,524
FT Synthesis	FT Synthese	MW	0	7,497	22,952
Transmission FT Fuel	Ship/Rail - analogue to today (O&M only)		0	0	0
FT Storage	Analogue to today (O&M only)		0	0	0

[Source: Frontier Economics].

Table 91: Fuel supply chain requirements for the aviation segment – FT Fuel, Domestic, All-In.

Segment	**Type**	***unit***	**2020**	**2030**	**2050**
Generation	Offshore	MW	0	11,855	39,133
Generation	Onshore	MW	0	11,702	22,672
Generation	PV Standalone	MW	0	47,333	131,145
Generation	PV Slanted Roof	MW	0	0	0
Converter platform (Off-shore)	Converter station	unit	0	4	13
Transmission	Offshore - sea cable	km	0	624	2,609
Electrolyser	Electrolyser	MW	0	32,756	87,762
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	48	132
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	12	34
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	24,282,486	74,341,229
Direct Air Capture	Direct Air Capture	t CO2	0	16,074,051	49,210,971
Direct Air Capture	CO2 Buffer storage	t CO2	-	1,270,783	3,890,524
FT Synthesis	FT Synthese	MW	0	7,497	22,952
Transmission FT Fuel	Ship/Rail - analogue to today (O&M only)		0	0	0
FT Storage	Analogue to today (O&M only)		0	0	0

[Source: Frontier Economics].

Table 92: Fuel supply chain requirements for the aviation segment – FT Fuel, International, Status Quo.

Segment	Type	***unit***			**Europe**
			2020	**2030**	**2050**
Generation	Offshore	MW	0	6,475	21,373
Generation	Onshore	MW	0	6,391	12,382
Generation	PV Standalone	MW	0	25,851	71,626
Generation	PV Slanted Roof	MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	2	7
Transmission	Offshore - sea cable	km	0	341	1,425
Electrolyser	Electrolyser	MW	0	17,890	47,931
International Transport	FT Shipping	units			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	26	72
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	7	19
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	13,261,973	40,601,748
Direct Air Capture	Direct Air Capture	t CO2	0	8,778,905	26,876,761
Direct Air Capture	CO2 Buffer storage	t CO2	-	694,043	2,124,825
FT Synthesis	FT Synthese	MW	0	4,094	12,535
Transmission FT Fuel	Ship/Rail - analogue to today (O&M only)		0	0	0
FT Storage	Analogue to today (O&M only)		0	0	0
International Transport	Ship Import	tkm			

Nearby International Location		**Far Off International Location**	
2030	2050	2030	2050
5,422	13,152	2,200	5,325
5,455	14,111	19,921	51,422
18,032	52,915	0	0
0	0	0	0
2	4	1	2
286	877	116	355
21,303	57,154	20,995	54,548
		2	6
28	78	26	71
7	20	7	18
402,925	1,233,560	402,925	1,233,560
13,925,072	42,631,836	13,925,072	42,631,836
10,272,702	31,436,643	10,425,934	31,838,749
809,717	2,478,962	809,717	2,478,962
4,791	14,662	4,863	14,849
0	0	0	0
0	0	0	0
8,167,550,009	25,005,088,726	49,005,300,054	150,030,532,355

[Source: Frontier Economics].

Table 93: Fuel supply chain requirements for the aviation segment – FT Fuel, International, Balanced.

Segment	Type	*unit*			Europe
			2020	2030	2050
Generation	Offshore	MW	0	3,556	11,740
Generation	Onshore	MW	0	3,511	6,802
Generation	PV Standalone	MW	0	14,200	39,344
Generation	PV Slanted Roof	MW	0	0	0
Converter plat-form (Offshore)	Converter station	unit	0	1	4
Transmission	Offshore - sea cable	km	0	187	783
Electrolyser	Electrolyser	MW	0	9,827	26,328
International Transport	FT Shipping	units			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	14	39
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	4	10
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	7,284,746	22,302,369
Direct Air Capture	Direct Air Capture	t CO2	0	4,822,215	14,763,291
Direct Air Capture	CO2 Buffer storage	t CO2	-	381,235	1,167,157
FT Synthesis	FT Synthese	MW	0	2,249	6,885
Transmission FT Fuel	Ship/Rail - analogue to today (O&M only)		0	0	0
FT Storage	Analogue to today (O&M only)		0	0	0
International Transport	Ship Import	tkm			

Nearby International Location		Far Off International Location	
2030	2050	2030	2050
2,978	7,224	1,208	2,925
2,996	7,751	10,943	28,246
9,905	29,066	0	0
0	0	0	0
1	2	0	1
157	482	64	195
11,702	31,394	11,532	29,963
		1	3
16	43	14	39
4	11	4	10
221,325	677,589	221,325	677,589
7,648,983	23,417,487	7,648,983	23,417,487
5,642,752	17,268,015	5,726,922	17,488,890
444,774	1,361,684	444,774	1,361,684
2,632	8,054	2,671	8,157
0	0	0	0
0	0	0	0
4,486,400,709	13,735,189,582	26,918,404,255	82,411,137,491

[Source: Frontier Economics].

Table 94: Fuel supply chain requirements for the aviation segment – FT Fuel, International, All-In.

Segment	Type	*unit*		Europe	
			2020	2030	2050
Generation	Offshore	MW	0	3,556	11,740
Generation	Onshore	MW	0	3,511	6,802
Generation	PV Standalone	MW	0	14,200	39,344
Generation	PV Slanted Roof	MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	1	4
Transmission	Offshore - sea cable	km	0	187	783
Electrolyser	Electrolyser	MW	0	9,827	26,328
International Transport	FT Shipping	units			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	14	39
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	4	10
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	7,284,746	22,302,369
Direct Air Capture	Direct Air Capture	t CO2	0	4,822,215	14,763,291
Direct Air Capture	CO2 Buffer storage	t CO2	-	381,235	1,167,157
FT Synthesis	FT Synthese	MW	0	2,249	6,885
Transmission FT Fuel	Ship/Rail - analogue to today (O&M only)		0	0	0
FT Storage	Analogue to today (O&M only)		0	0	0
International Transport	Ship Import	tkm			

Nearby International Location		Far Off International Location	
2030	2050	2030	2050
2,978	7,224	1,208	2,925
2,996	7,751	10,943	28,246
9,905	29,066	0	0
0	0	0	0
1	2	0	1
157	482	64	195
11,702	31,394	11,532	29,963
		1	3
16	43	14	39
4	11	4	10
221,325	677,589	221,325	677,589
7,648,983	23,417,487	7,648,983	23,417,487
5,642,752	17,268,015	5,726,922	17,488,890
444,774	1,361,684	444,774	1,361,684
2,632	8,054	2,671	8,157
0	0	0	0
0	0	0	0
4,486,400,709	13,735,189,582	26,918,404,255	82,411,137,491

[Source: Frontier Economics].

15.1.2.4 Methane

Table 95: Fuel supply chain requirements for the aviation segment – Methane, International, Status Quo / Balanced / All-In.

Segment	Type	***unit***	**2020**	**2030**	**2050**
Generation	Offshore	in MW	0	11,637	36,924
Generation	Onshore	in MW	0	11,487	21,392
Generation	PV Standalone	in MW	0	46,463	123,741
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	4	12
Transmission (Offshore Connection)	Offshore - sea cable	km	0	613	2,462
Electrolyser	Electrolyser	MW	0	31,302	81,316
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	46	122
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	12	32
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	25,570,080	76,710,241
Direct Air Capture	Direct Air Capture	t CO2	0	13,437,172	39,887,384
Direct Air Capture	CO2 Buffer storage	t	0	1,086,028	3,258,083
Methanisation	Methanisation	MW	0	8,744	25,957
Liquefaction	Liquefaction for LNG	MW	0	8,713	25,863
Transmission Methane	New construction of pipeline	km	0	69	206
Transmission Methane	Compressors for pipeline	MW	0	31	92
Methane Storage	Methane Storage - new built	m³	0	6,125,782	18,377,346

[Source: Frontier Economics].

Table 96: Fuel supply chain requirements for the aviation segment – Methane, International, Status Quo / Balanced / All-In.

Segment	Type	unit	Europe		
			2020	2030	2050
Generation	Offshore	in MW	0	3,605	11,378
Generation	Onshore	in MW	0	3,558	6,592
Generation	PV Standalone	in MW	0	14,393	38,130
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	1	4
Transmission (Off-shore Connection)	Offshore - sea cable	km	0	190	759
Electrolyser	Electrolyser	MW	0	9,696	25,057
International Transport (RoW)	LNG Shipping	units			
International Transport (MENA)	CH4 Pipelines (costs for compressors included)	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	14	38
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	4	10
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	7,671,024	23,013,072
Direct Air Capture	Direct Air Capture	t CO2	0	4,162,407	12,291,197
Direct Air Capture	CO2 Buffer storage	t	0	325,808	977,425
Methanisation	Methanisation	MW	0	2,709	7,998
Liquefaction	Liquefaction for LNG	MW	0	8,713	25,863
Transmission Me-thane	New construction of pipeline	km	0	46	137
Transmission Me-thane	Compressors for pipeline	MW	0	21	61
Methane Storage	Methane Storage - new built	m³	0	3,981,758	11,945,275
International Transport (MENA)	Compressors for pipeline (international)	MW			
International Transport (RoW)	Export Storage (LNG)	m³			
International Transport (RoW)	Ship Import	tkm			
International Transport (RoW)	LNG Storage (Domestic)	m³			

Nearby International Location		Far Off International Location	
2030	**2050**	**2030**	**2050**
3,024	7,018	1,199	2,998
3,043	7,529	10,854	28,951
10,058	28,234	0	0
0	0	0	0
1	2	0	1
159	468	63	200
11,567	29,945	11,064	30,156
		3	8
135	400		
15	41	14	39
4	11	4	10
233,061	699,182	233,061	699,182
8,054,575	24,163,726	8,054,575	24,163,726
4,887,554	14,432,488	5,237,686	15,421,662
380,110	1,140,329	380,110	1,140,329
3,181	9,392	3,408	10,036
0	0	3,408	10,036
0	0	0	0
0	0	0	0
0	0		
20	60		
		5,249	15,746
		25,964,185,385	77,892,556,155
		190,580	571,740

[Source: Frontier Economics].

15.1.3 Capacities Shipping

15.1.3.1 FCEV

Table 97: Fuel supply chain requirements for the shipping segment – FCEV, Domestic, Status Quo / Balanced / All-In.

Segment	Type	unit	2020	2030	2050
Generation	Offshore	in MW	0	11,534	37,820
Generation	Onshore	in MW	0	11,385	21,911
Generation	PV Standalone	in MW	0	46,052	126,742
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter Station	unit	0	4	13
Transmission (Offshore)	Offshore - sea cable	km	0	607	2,521
Electrolyser	Electrolyser	MW	0	33,460	87,863
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	23	62
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	6	16
Storage	Hydrogen Pressure Storage	m^3	0	0	0
Storage	Hydrogen Cavern storage	m^3	0	29,492,369	88,477,108
Transmission Pipeline H2	H2 Pipeline - new built	km	0	176	475
Transmission Pipeline H2	H2 Pipeline - retrofit	km	0	703	1,899
Transmission Pipeline H2	Compressor - new built	MW	0	46	123
Transmission Pipeline H2	Compressor - retrofit	MW	0	183	494

[Source: Frontier Economics].

Table 98: Fuel supply chain requirements for the Shipping segment – FCEV, International, Status Quo / Balanced / All-In.

			Europe			**International (MENA)**	
Segment	**Type**	***unit***	**2020**	**2030**	**2050**	**2030**	**2050**
Generation	Offshore	in MW	0	3,466	11,362	5,955	14,352
Generation	Onshore	in MW	0	3,421	6,583	5,991	15,398
Generation	PV Standalone	in MW	0	13,837	38,077	19,805	57,743
Generation	PV Slanted Roof	in MW	0	0	0	0	0
Converter platform (Offshore)	Converter Station	unit	0	1	4	2	5
Transmission (Offshore)	Offshore - sea cable	km	0	183	757	314	957
Electrolyser	Electrolyser	MW	0	10,054	26,397	24,564	64,608
International Transport (MENA)	H2 Pipelines	km				1,899	5,139
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	23	62	0	0
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	6	16	0	0
Storage	Hydrogen Pressure Storage	m³	0	0	0	0	0
Storage	Hydrogen Cavern storage	m³	0	29,492,369	88,477,108	0	0
Transmission Pipeline H2	H2 Pipeline - new built	km	0	176	475	0	0
Transmission Pipeline H2	H2 Pipeline - retrofit	km	0	703	1,899	0	0
Transmission Pipeline H2	Compressor - new built	MW	0	46	123	0	0
Transmission Pipeline H2	Compressor - retrofit	MW	0	183	494	0	0
International Transport (MENA)	Compressors (international)	MW				494	1,336

[Source: Frontier Economics].

15.1.3.2 H2 Combustion

Table 99: Fuel supply chain requirements for the shipping segment – H2 Comb, Domestic, Status Quo / Balanced / All-In.

Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	in MW	0	10,377	34,024
Generation	Onshore	in MW	0	10,243	19,712
Generation	PV Standalone	in MW	0	41,430	114,022
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter Station	unit	0	3	11
Transmission (Offshore)	Offshore - sea cable	km	0	546	2,268
Electrolyser	Electrolyser	MW	0	30,101	79,045
H2 Pipeline	Pipeline (from Electrolyser to Storage)	MW	0	21	56
H2 Pipeline	Compressor (from Electrolyser to Storage)		0	5	15
Storage	Hydrogen Pressure Storage		0	0	0
Storage	Hydrogen Cavern storage		0	21,527,499	64,582,496
Transmission Pipeline H2	H2 Pipeline - new built	MW	0	158	427
Transmission Pipeline H2	H2 Pipeline - retrofit	km	0	632	1,708
Transmission Pipeline H2	Compressor - new built	km	0	41	111
Transmission Pipeline H2	Compressor - retrofit	MW	0	164	444

[Source: Frontier Economics].

Table 100: Fuel supply chain requirements for the shipping segment – H2 Comb, International, Status Quo / Balanced / All-In.

			Europe			International (MENA)	
Segment	**Type**	**unit**	**2020**	**2030**	**2050**	**2030**	**2050**
Generation	Offshore	in MW	0	3,118	10,222	5,357	12,912
Generation	Onshore	in MW	0	3,078	5,922	5,390	13,853
Generation	PV Standalone	in MW	0	12,448	34,255	17,817	51,948
Generation	PV Slanted Roof	in MW	0	0	0	0	0
Converter platform (Offshore)	Converter Station	unit	0	1	3	2	4
Transmission	Overhead line	km					
Transmission	HVDC Overhead line	km					
Transmission (Offshore)	Offshore - sea cable	km	0	164	681	282	861
Transmission	Overhead line - poles	units					
Transmission	HVDC Overhead line - poles	units					
Transmission	cable - poles	units					
Electrolyser	Electrolyser	MW	0	9,045	23,747	22,098	58,124
International Transport (RoW)	H2 Shipping	units					
International Transport (MENA)	H2 Pipelines	km				1,708	4,623
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	21	57	0	0
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	5	15	0	0
Storage	Hydrogen Pressure Storage	m³	0	0	0	0	0
Storage	Hydrogen Cavern storage	m³	0	21,527,499	64,582,496	0	0
Transmission Pipeline H2	H2 Pipeline - new built	km	0	160	433	0	0
Transmission Pipeline H2	H2 Pipeline - retrofit	km	0	640	1,730	0	0
Transmission Pipeline H2	Compressor - new built	MW	0	42	112	0	0
Transmission Pipeline H2	Compressor - retrofit	MW	0	166	450	0	0
International Transport (MENA)	Compressors (international)	MW				444	1,202

[Source: Frontier Economics].

15.1.3.3 FT Fuel

Table 101: Fuel supply chain requirements for the shipping segment – FT Fuel, Domestic, Status Quo / Balanced / All-In.

Segment	Type	unit	2020	2030	2050
Generation	Offshore	MW	0	15,864	51,696
Generation	Onshore	MW	0	15,659	29,950
Generation	PV Standalone	MW	0	63,339	173,246
Generation	PV Slanted Roof	MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	5	17
Transmission	Offshore - sea cable	km	0	835	3,446
Electrolyser	Electrolyser	MW	0	43,832	115,935
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	64	174
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	17	45
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	32,493,789	98,206,605
Direct Air Capture	Direct Air Capture	t CO2	0	21,509,611	65,008,912
Direct Air Capture	CO2 Buffer storage	t CO2	-	1,700,508	5,139,479
FT Synthesis	FT Synthese	MW	0	10,032	30,320
Transmission FT Fuel	Ship/Rail - analogue to today (O&M only)		0	0	0
FT Storage	Analogue to today (O&M only)		0	0	0

[Source: Frontier Economics].

Table 102: Fuel supply chain requirements for the shipping segment – FT Fuel, International, Status Quo / Balanced / All-In.

Segment	**Type**	**unit**		**Europe**	
			2020	**2030**	**2050**
Generation	Offshore	MW	0	4,759	15,509
Generation	Onshore	MW	0	4,698	8,985
Generation	PV Standalone	MW	0	19,002	51,974
Generation	PV Slanted Roof	MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	2	5
Transmission	Offshore - sea cable	km	0	251	1,034
Electrolyser	Electrolyser	MW	0	13,150	34,781
International Transport	FT Shipping	units			
International Transport	FT Pipelines	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	19	52
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	5	14
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	9,748,137	29,461,981
Direct Air Capture	Direct Air Capture	t CO2	0	6,452,883	19,502,674
Direct Air Capture	CO2 Buffer storage	t CO2	-	510,152	1,541,844
FT Synthesis	FT Synthese	MW	0	3,010	9,096
Transmission FT Fuel	Ship/Rail - analogue to today (O&M only)		0	0	0
FT Storage	Analogue to today (O&M only)		0	0	0
International Transport	Ship Import	tkm			

Nearby International Location		Far Off International Location	
2030	2050	2030	2050
3,985	9,544	1,617	3,864
4,010	10,239	14,643	37,313
13,254	38,397	0	0
0	0	0	0
1	3	1	1
210	636	85	258
15,659	41,473	15,432	39,582
		1	4
21	57	19	51
5	15	5	13
296,167	895,112	296,167	895,112
10,235,543	30,935,081	10,235,543	30,935,081
7,550,890	22,811,476	7,663,523	23,103,257
595,178	1,798,818	595,178	1,798,818
3,522	10,639	3,574	10,775
0	0	0	0
0	0	0	0
6,003,510,509	18,144,525,653	36,021,063,054	108,867,153,918

[Source: Frontier Economics].

15.1.3.4 Methane

Table 103: Fuel supply chain requirements for the shipping segment – Methane, Domestic, Status Quo / Balanced / All-In.

Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	in MW	0	14,506	46,027
Generation	Onshore	in MW	0	14,319	26,666
Generation	PV Standalone	in MW	0	57,917	154,246
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	5	15
Transmission (Offshore Connection)	Offshore - sea cable	km	0	764	3,068
Electrolyser	Electrolyser	MW	0	39,018	101,362
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	57	152
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	15	40
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	31,873,782	95,621,347
Direct Air Capture	Direct Air Capture	t CO2	0	16,749,791	49,720,681
Direct Air Capture	CO2 Buffer storage	t	0	1,353,762	4,061,287
Methanisation	Methanisation	MW	0	10,900	32,356
Liquefaction	Liquefaction for LNG	MW	0	10,861	32,239
Transmission Methane	New construction of pipeline	km	0	86	256
Transmission Methane	Compressors for pipeline	MW	0	38	114
Methane Storage	Methane Storage - new built	m³	0	7,635,949	22,907,848

[Source: Frontier Economics].

Table 104: Fuel supply chain requirements for the shipping segment – Methane, International, Status Quo / Balanced / All-In.

Segment	Type	unit		Europe	
			2020	2030	2050
Generation	Offshore	in MW	0	4,493	14,183
Generation	Onshore	in MW	0	4,436	8,217
Generation	PV Standalone	in MW	0	17,941	47,531
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	1	5
Transmission (Offshore Connection)	Offshore - sea cable	km	0	237	946
Electrolyser	Electrolyser	MW	0	12,087	31,234
International Transport (RoW)	LNG Shipping	units			
International Transport (MENA)	CH4 Pipelines (costs for compressors included)	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	18	47
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	5	12
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	9,562,135	28,686,404
Direct Air Capture	Direct Air Capture	t CO2	0	5,188,550	15,321,303
Direct Air Capture	CO2 Buffer storage	t	0	406,129	1,218,386
Methanisation	Methanisation	MW	0	3,376	9,970
Liquefaction	Liquefaction for LNG	MW	0	10,861	32,239
Transmission Methane	New construction of pipeline	km	0	58	171
Transmission Methane	Compressors for pipeline	MW	0	26	76
Methane Storage	Methane Storage - new built	m³	0	4,963,367	14,890,101
International Transport (MENA)	Compressors for pipeline (international)	MW			
International Transport (RoW)	Export Storage (LNG)	m³			
International Transport (RoW)	Ship Import	tkm			
International Transport (RoW)	LNG Storage (Domestic)	m³			

Nearby International Location		Far Off International Location	
2030	**2050**	**2030**	**2050**
3,770	8,748	1,494	3,737
3,793	9,385	13,530	36,088
12,538	35,195	0	0
0	0	0	0
1	3	0	1
199	583	79	249
14,419	37,327	13,791	37,590
		3	10
169	499		
19	51	17	49
5	13	5	13
290,516	871,549	290,516	871,549
10,040,241	30,120,724	10,040,241	30,120,724
6,092,465	17,990,478	6,528,915	19,223,510
473,817	1,421,450	473,817	1,421,450
3,965	11,707	4,249	12,510
0	0	4,249	12,510
0	0	0	0
0	0	0	0
0	0		
25	75		
		6,543	19,628
		32,365,044,828	97,095,134,483
		237,563	712,689

[Source: Frontier Economics].

15.1.3.5 Methanol

Table 105: Fuel supply chain requirements for the shipping segment – Methanol, Domestic, Status Quo / Balanced / All-In.

Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	in MW	0	14,877	47,531
Generation	Onshore	in MW	0	14,685	27,537
Generation	PV Standalone	in MW	0	59,400	159,286
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	5	16
Transmission	Offshore - sea cable	km	0	784	3,169
Electrolyser	Electrolyser	MW	0	36,708	96,374
International Transport	MeOH Shipping	units			
International Transport	MeOH Pipelines	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	54	145
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	14	38
H2 Buffer Storage	Battery	MWh			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	32,809,508	98,428,523
Direct Air Capture	Direct Air Capture	t CO2	0	21360656	64081969
Direct Air Capture	CO2 Buffer storage	t	-	1,892,590.54	5,677,771.62
MeOH Synthese	MeOH Synthese	MW	0	10,563	31,690
Transmission MeOH	Ship/Rail - analogue to today (O&M only)		0	0	0
MeOH Storage	Analogue to today (O&M only)		0	0	0

[Source: Frontier Economics].

Table 106: Fuel supply chain requirements for the shipping segment – Methanol, International, Status Quo / Balanced / All-In.

			Europe		
Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	in MW	0	4,463	14,259
Generation	Onshore	in MW	0	4,406	8,261
Generation	PV Standalone	in MW	0	17,820	47,786
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	1	5
Transmission	Offshore - sea cable	km	0	235	951
Electrolyser	Electrolyser	MW	0	11,012	28,912
International Transport	MeOH Shipping	units	0		
International Transport	MeOH Pipelines	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	16	43
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	4	11
H2 Buffer Storage	Battery	MWh			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	9,842,852	29,528,557
Direct Air Capture	Direct Air Capture	t CO2	0	6408197	19224591
Direct Air Capture	CO2 Buffer storage	t	-	567,777.16	1,703,331.49
MeOH Synthese	MeOH Synthese	MW	0	3,169	9,507
Transmission MeOH	Ship/Rail - analogue to today (O&M only)		0	0	0
MeOH Storage	Analogue to today (O&M only)		0	0	0
International Transport	Ship Import	tkm			

Nearby International Location		Far Off International Location	
2030	2050	2030	2050
3,738	8,771	1,527	3,604
3,761	9,410	13,828	34,801
12,432	35,289	0	0
0	0	0	0
1	3	1	1
197	585	80	240
13,110	34,448	13,071	33,364
1	2	3	10
17	47	16	43
5	12	4	11
299,045	897,135	299,045	897,135
10,334,995	31,004,985	10,334,995	31,004,985
7524585	22553032	7476230	23174745
662,406.69	1,987,220.07	662,406.69	1,987,220.07
3,721	11,153	3,697	11,461
0	0	0	0
0	0	0	0
13,664,583,445	40,993,750,334	81,987,500,669	245,962,502,006

[Source: Frontier Economics].

15.1.4 Capacities Rail

15.1.4.1 BEV

Table 107: Fuel supply chain requirements for the rail segment – BEV, Domestic, Status Quo.

			Europe		
Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	MW	0	8,040	15,449
Generation	Onshore	MW	0	7,936	8,950
Generation	PV Standalone	MW	0	22,471	36,240
Generation	PV Slanted Roof	MW	0	9,630	15,532
Converter platform (Offshore)	Converter Station	unit	0	3	5
Transmission	Offshore - sea cable	km	0	423	1,030
Transmission	AC Overhead line	km	0	2,623	3,900
Transmission	AC cable	km	0	0	0
Transmission	DC cable	km	0	656	975
Transmission	Overhead line - poles	units	0	6,997	10,400
Transmission	HVDC Overhead line - poles	units	0	0	0
Transmission	cable - poles	units	0	657	976
Electrolyser	Electrolyser	MW	0	28,496	61,232
International Transport	Cable	km			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	37	52
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	10	13
Storage	Battery	MWh	0	0	0
Storage	Hydrogen Pressure Storage	m³	0	0	0
Storage	Hydrogen Cavern storage	m³	0	25,962,062	45,155,844
Re-conversion	Gas Turbine (PtGtP)	MW	0	9,082	21,138

[Source: Frontier Economics].

Table 108: Fuel supply chain requirements for the rail segment – BEV, Domestic, Balanced.

			Europe		
Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	MW	0	7,820	15,025
Generation	Onshore	MW	0	7,719	8,705
Generation	PV Standalone	MW	0	21,857	35,247
Generation	PV Slanted Roof	MW	0	9,367	15,106
Converter platform (Offshore)	Converter Station	unit	0	3	5
Transmission	Offshore - sea cable	km	0	412	1,002
Transmission	AC Overhead line	km	0	2,552	3,793
Transmission	AC cable	km	0	0	0
Transmission	DC cable	km	0	638	948
Transmission	Overhead line - poles	units	0	6,806	10,115
Transmission	HVDC Overhead line - poles	units	0	0	0
Transmission	cable - poles	units	0	639	950
Electrolyser	Electrolyser	MW	0	27,718	59,553
International Transport	Cable	km			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	36	50
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	9	13
Storage	Battery	MWh	0	0	0
Storage	Hydrogen Pressure Storage	m³	0	0	0
Storage	Hydrogen Cavern storage	m³	0	25,252,777	43,918,004
Re-conversion	Gas Turbine (PtGtP)	MW	0	8,834	20,559

[Source: Frontier Economics].

Table 109: Fuel supply chain requirements for the rail segment – BEV, Domestic, All-In.

			Europe		
Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	MW	0	7,688	14,771
Generation	Onshore	MW	0	7,589	8,558
Generation	PV Standalone	MW	0	21,488	34,651
Generation	PV Slanted Roof	MW	0	9,209	14,850
Converter platform (Offshore)	Converter Station	unit	0	3	5
Transmission	Offshore - sea cable	km	0	405	985
Transmission	AC Overhead line	km	0	2,509	3,729
Transmission	AC cable	km	0	0	0
Transmission	DC cable	km	0	627	932
Transmission	Overhead line - poles	units	0	6,691	9,944
Transmission	HVDC Overhead line - poles	units	0	0	0
Transmission	cable - poles	units	0	629	934
Electrolyser	Electrolyser	MW	0	27,251	58,546
International Transport	Cable	km			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	36	50
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	9	13
Storage	Battery	MWh	0	0	0
Storage	Hydrogen Pressure Storage	m³	0	0	0
Storage	Hydrogen Cavern storage	m³	0	24,827,207	43,175,301
Re-conversion	Gas Turbine (PtGtP)	MW	0	8,685	20,211

[Source: Frontier Economics].

Table 110: Fuel supply chain requirements for the rail segment – BEV, International, Status Quo.

			Europe			International (MENA)	
Segment	**Type**	**unit**	**2020**	**2030**	**2050**	**2030**	**2050**
Generation	Offshore	MW	0	2,166	4,207	3,686	5,265
Generation	Onshore	MW	0	2,138	2,438	3,709	5,649
Generation	PV Standalone	MW	0	6,053	9,870	12,260	21,183
Generation	PV Slanted Roof	MW	0	2,594	4,230	0	0
Converter plat-form (Offshore)	Converter Station	unit	0	1	1	1	2
Transmission	Offshore - sea cable	km	0	114	280	194	351
Transmission	AC Overhead line	km	0	2,112	3,269	0	0
Transmission	AC cable	km	0	0	0	0	0
Transmission	DC cable	km	0	528	817	0	0
Transmission	Overhead line - poles	units	0	5,633	8,718	0	0
Transmission	HVDC Overhead line - poles	units	0	0	0	0	0
Transmission	cable - poles	units	0	529	819	0	0
Electrolyser	Electrolyser	MW	0	16,954	36,431	0	0
International Transport	Cable	km				11,405	17,776
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	9	13	0	0
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	2	3	0	0
Storage	Battery	MWh	0	0	0	0	0
Storage	Hydrogen Pressure Storage	m³	0	0	0	0	0
Storage	Hydrogen Cavern storage	m³	0	16,456,826	28,623,377	0	0
Re-conversion	Gas Turbine (PtGtP)	MW	0	10,316	24,010	0	0

[Source: Frontier Economics].

Table 111: Fuel supply chain requirements for the rail segment – BEV, International, Balanced.

			Europe			International (MENA)	
Segment	**Type**	**unit**	**2020**	**2030**	**2050**	**2030**	**2050**
Generation	Offshore	MW	0	2,106	4,092	3,586	5,121
Generation	Onshore	MW	0	2,079	2,371	3,608	5,494
Generation	PV Standalone	MW	0	5,887	9,599	11,925	20,602
Generation	PV Slanted Roof	MW	0	2,523	4,114	0	0
Converter plat-form (Offshore)	Converter Station	unit	0	1	1	1	2
Transmission	Offshore - sea cable	km	0	111	273	189	341
Transmission	AC Overhead line	km	0	2,054	3,179	0	0
Transmission	AC cable	km	0	0	0	0	0
Transmission	DC cable	km	0	514	795	0	0
Transmission	Overhead line - poles	units	0	5,479	8,479	0	0
Transmission	HVDC Overhead line - poles	units	0	0	0	0	0
Transmission	cable - poles	units	0	515	796	0	0
Electrolyser	Electrolyser	MW	0	16,491	35,432	0	0
International Transport	Cable	km				11,093	17,289
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	8	12	0	0
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	2	3	0	0
Storage	Battery	MWh	0	0	0	0	0
Storage	Hydrogen Pressure Storage	m³	0	0	0	0	0
Storage	Hydrogen Cavern storage	m³	0	16,007,225	27,838,735	0	0
Re-conversion	Gas Turbine (PtGtP)	MW	0	10,034	23,352	0	0

[Source: Frontier Economics].

Table 112: Fuel supply chain requirements for the rail segment – BEV, International, All-In.

			Europe			International (MENA)	
Segment	**Type**	**unit**	**2020**	**2030**	**2050**	**2030**	**2050**
Generation	Offshore	MW	0	2,071	4,023	3,525	5,034
Generation	Onshore	MW	0	2,044	2,331	3,547	5,401
Generation	PV Standalone	MW	0	5,788	9,437	11,724	20,254
Generation	PV Slanted Roof	MW	0	2,481	4,044	0	0
Converter plat-form (Offshore)	Converter Station	unit	0	1	1	1	2
Transmission	Offshore - sea cable	km	0	109	268	186	336
Transmission	AC Overhead line	km	0	2,019	3,125	0	0
Transmission	AC cable	km	0	0	0	0	0
Transmission	DC cable	km	0	505	781	0	0
Transmission	Overhead line - poles	units	0	5,387	8,335	0	0
Transmission	HVDC Overhead line - poles	units	0	0	0	0	0
Transmission	cable - poles	units	0	506	783	0	0
Electrolyser	Electrolyser	MW	0	16,213	34,833	0	0
International Transport	Cable	km				10,906	16,996
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	8	12	0	0
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	2	3	0	0
Storage	Battery	MWh	0	0	0	0	0
Storage	Hydrogen Pressure Storage	m³	0	0	0	0	0
Storage	Hydrogen Cavern storage	m³	0	15,737,464	27,367,950	0	0
Re-conversion	Gas Turbine (PtGtP)	MW	0	9,865	22,957	0	0

[Source: Frontier Economics].

15.1.4.2 Partly BEV (required for all hydrogen and carbon-fuels scenarios)

Note that electrified rail will stay electrified, therefore all hydrogen carbon-fuels scenarios require the following infrastructure.

Table 113: Fuel supply chain requirements for the rail segment – Partly BEV, Domestic, Status Quo.

			Europe		
Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	MW	0	5,896	8,342
Generation	Onshore	MW	0	5,820	4,833
Generation	PV Standalone	MW	0	16,478	19,570
Generation	PV Slanted Roof	MW	0	7,062	8,387
Converter platform (Offshore)	Converter Station	unit	0	2	3
Transmission	Offshore - sea cable	km	0	311	556
Transmission	AC Overhead line	km	0	1,924	2,106
Transmission	AC cable	km	0	0	0
Transmission	DC cable	km	0	481	526
Transmission	Overhead line - poles	units	0	5,131	5,617
Transmission	HVDC Overhead line - poles	units	0	0	0
Transmission	cable - poles	units	0	482	528
Electrolyser	Electrolyser	MW	0	20,897	33,065
International Transport	Cable	km			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	27	28
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	7	7
Storage	Battery	MWh	0	0	0
Storage	Hydrogen Pressure Storage	m³	0	0	0
Storage	Hydrogen Cavern storage	m³	0	19,038,166	24,384,156
Re-conversion	Gas Turbine (PtGtP)	MW	0	6,660	11,415

[Source: Frontier Economics].

Table 114: Fuel supply chain requirements for the rail segment – Partly BEV, Domestic, Balanced.

			Europe		
Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	MW	0	5,735	8,114
Generation	Onshore	MW	0	5,661	4,701
Generation	PV Standalone	MW	0	16,028	19,033
Generation	PV Slanted Roof	MW	0	6,869	8,157
Converter platform (Offshore)	Converter Station	unit	0	2	3
Transmission	Offshore - sea cable	km	0	302	541
Transmission	AC Overhead line	km	0	1,871	2,048
Transmission	AC cable	km	0	0	0
Transmission	DC cable	km	0	468	512
Transmission	Overhead line - poles	units	0	4,991	5,463
Transmission	HVDC Overhead line - poles	units	0	0	0
Transmission	cable - poles	units	0	469	514
Electrolyser	Electrolyser	MW	0	20,326	32,159
International Transport	Cable	km			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	27	27
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	7	7
Storage	Battery	MWh	0	0	0
Storage	Hydrogen Pressure Storage	m³	0	0	0
Storage	Hydrogen Cavern storage	m³	0	18,518,683	23,715,722
Re-conversion	Gas Turbine (PtGtP)	MW	0	6,478	11,102

[Source: Frontier Economics].

Table 115: Fuel supply chain requirements for the rail segment – Partly BEV, Domestic, All-In.

			Europe		
Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	MW	0	5,638	7,976
Generation	Onshore	MW	0	5,566	4,621
Generation	PV Standalone	MW	0	15,758	18,711
Generation	PV Slanted Roof	MW	0	6,754	8,019
Converter platform (Offshore)	Converter Station	unit	0	2	3
Transmission	Offshore - sea cable	km	0	297	532
Transmission	AC Overhead line	km	0	1,840	2,013
Transmission	AC cable	km	0	0	0
Transmission	DC cable	km	0	460	503
Transmission	Overhead line - poles	units	0	4,907	5,371
Transmission	HVDC Overhead line - poles	units	0	0	0
Transmission	cable - poles	units	0	461	505
Electrolyser	Electrolyser	MW	0	19,984	31,615
International Transport	Cable	km			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	26	27
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	7	7
Storage	Battery	MWh	0	0	0
Storage	Hydrogen Pressure Storage	m³	0	0	0
Storage	Hydrogen Cavern storage	m³	0	18,206,994	23,314,662
Re-conversion	Gas Turbine (PtGtP)	MW	0	6,369	10,914

[Source: Frontier Economics].

Table 116: Fuel supply chain requirements for the rail segment – Partly BEV, International, Status Quo.

			Europe			International (MENA)	
Segment	**Type**	**unit**	**2020**	**2030**	**2050**	**2030**	**2050**
Generation	Offshore	MW	0	1,545	2,210	2,629	2,765
Generation	Onshore	MW	0	1,525	1,280	2,646	2,967
Generation	PV Standalone	MW	0	4,317	5,184	8,745	11,125
Generation	PV Slanted Roof	MW	0	1,850	2,222	0	0
Converter platform (Off-shore)	Converter Station	unit	0	1	1	1	1
Transmission	Offshore - sea cable	km	0	81	147	138	184
Transmission	AC Overhead line	km	0	1,506	1,717	0	0
Transmission	AC cable	km	0	0	0	0	0
Transmission	DC cable	km	0	377	429	0	0
Transmission	Overhead line - poles	units	0	4,018	4,579	0	0
Transmission	HVDC Overhead line - poles	units	0	0	0	0	0
Transmission	cable - poles	units	0	378	431	0	0
Electrolyser	Electrolyser	MW	0	12,094	19,133	0	0
International Transport	Cable	km				8,135	9,336
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	6	7	0	0
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	2	2	0	0
Storage	Battery	MWh	0	0	0	0	0
Storage	Hydrogen Pressure Storage	m³	0	0	0	0	0
Storage	Hydrogen Cavern storage	m³	0	11,738,619	15,032,917	0	0
Re-conversion	Gas Turbine (PtGtP)	MW	0	7,359	12,610	0	0

[Source: Frontier Economics].

Table 117: Fuel supply chain requirements for the rail segment – Partly BEV, International, Balanced.

			Europe			**International (MENA)**	
Segment	**Type**	**unit**	**2020**	**2030**	**2050**	**2030**	**2050**
Generation	Offshore	MW	0	1,545	2,210	2,629	2,765
Generation	Onshore	MW	0	1,525	1,280	2,646	2,967
Generation	PV Standalone	MW	0	4,317	5,184	8,745	11,125
Generation	PV Slanted Roof	MW	0	1,850	2,222	0	0
Converter platform (Off-shore)	Converter Station	unit	0	1	1	1	1
Transmission	Offshore - sea cable	km	0	81	147	138	184
Transmission	AC Overhead line	km	0	1,506	1,717	0	0
Transmission	AC cable	km	0	0	0	0	0
Transmission	DC cable	km	0	377	429	0	0
Transmission	Overhead line - poles	units	0	4,018	4,579	0	0
Transmission	HVDC Overhead line - poles	units	0	0	0	0	0
Transmission	cable - poles	units	0	378	431	0	0
Electrolyser	Electrolyser	MW	0	12,094	19,133	0	0
International Transport	Cable	km				8,135	9,336
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	6	7	0	0
H2 Pipeline	Compressor (from Electrolyser to Stor-age)	MW	0	2	2	0	0
Storage	Battery	MWh	0	0	0	0	0
Storage	Hydrogen Pressure Storage	m³	0	0	0	0	0
Storage	Hydrogen Cavern storage	m³	0	11,738,619	15,032,917	0	0
Re-conversion	Gas Turbine (PtGtP)	MW	0	7,359	12,610	0	0

[Source: Frontier Economics].

Table 118: Fuel supply chain requirements for the rail segment – Partly BEV, International, All-In.

			Europe			**International (MENA)**	
Segment	**Type**	**unit**	**2020**	**2030**	**2050**	**2030**	**2050**
Generation	Offshore	MW	0	1,519	2,172	2,585	2,718
Generation	Onshore	MW	0	1,499	1,259	2,601	2,917
Generation	PV Standalone	MW	0	4,245	5,096	8,598	10,937
Generation	PV Slanted Roof	MW	0	1,819	2,184	0	0
Converter platform (Offshore)	Converter Station	unit	0	1	1	1	1
Transmission	Offshore - sea cable	km	0	80	145	136	181
Transmission	AC Overhead line	km	0	1,481	1,688	0	0
Transmission	AC cable	km	0	0	0	0	0
Transmission	DC cable	km	0	370	422	0	0
Transmission	Overhead line - poles	units	0	3,951	4,502	0	0
Transmission	HVDC Overhead line - poles	units	0	0	0	0	0
Transmission	cable - poles	units	0	372	423	0	0
Electrolyser	Electrolyser	MW	0	11,890	18,810	0	0
International Transport	Cable	km				7,998	9,178
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	6	7	0	0
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	2	2	0	0
Storage	Battery	MWh	0	0	0	0	0
Storage	Hydrogen Pressure Storage	m³	0	0	0	0	0
Storage	Hydrogen Cavern storage	m³	0	11,541,045	14,778,693	0	0
Re-conversion	Gas Turbine (PtGtP)	MW	0	7,235	12,397	0	0

[Source: Frontier Economics].

15.1.4.3 FCEV

Note that the capacities in this section are those for the trains fuelled with FCEV only. To get the full required infrastructure one needs to add the required infrastructure for (partly) BEV as set out in 15.1.4.2.

Table 119: Fuel supply chain requirements for the rail segment – FCEV, Domestic, Status Quo.

			Europe		
Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	in MW	0	4,826	15,825
Generation	Onshore	in MW	0	4,764	9,168
Generation	PV Standalone	in MW	0	19,269	53,032
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter Station	unit	0	2	5
Transmission	Overhead line	km			
Transmission	HVDC Overhead line	km			
Transmission (Offshore)	Offshore - sea cable	km	0	254	1,055
Transmission	Overhead line - poles	units			
Transmission	HVDC Overhead line - poles	units			
Transmission	cable - poles	units			
Electrolyser	Electrolyser	MW	0	14,000	36,764
International Transport (RoW)	H2 Shipping	units			
International Transport (MENA)	H2 Pipelines	km			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	10	26
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	3	7
Storage	Hydrogen Pressure Storage	m³	0	0	0
Storage	Hydrogen Cavern storage	m³	0	12,340,288	37,020,863
Transmission Pipeline H2	H2 Pipeline - new built	km	0	74	199
Transmission Pipeline H2	H2 Pipeline - retrofit	km	0	294	795
Transmission Pipeline H2	Compressor - new built	MW	0	19	52
Transmission Pipeline H2	Compressor - retrofit	MW	0	76	207

[Source: Frontier Economics].

Table 120: Fuel supply chain requirements for the rail segment – FCEV, Domestic, Balanced.

			Europe		
Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	in MW	0	4,768	15,633
Generation	Onshore	in MW	0	4,706	9,057
Generation	PV Standalone	in MW	0	19,036	52,390
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter Station	unit	0	2	5
Transmission	Overhead line	km			
Transmission	HVDC Overhead line	km			
Transmission (Offshore)	Offshore - sea cable	km	0	251	1,042
Transmission	Overhead line - poles	units			
Transmission	HVDC Overhead line - poles	units			
Transmission	cable - poles	units			
Electrolyser	Electrolyser	MW	0	13,831	36,319
International Transport (RoW)	H2 Shipping	units			
International Transport (MENA)	H2 Pipelines	km			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	10	26
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	2	7
Storage	Hydrogen Pressure Storage	m³	0	0	0
Storage	Hydrogen Cavern storage	m³	0	12,190,851	36,572,553
Transmission Pipeline H2	H2 Pipeline - new built	km	0	73	196
Transmission Pipeline H2	H2 Pipeline - retrofit	km	0	291	785
Transmission Pipeline H2	Compressor - new built	MW	0	19	51
Transmission Pipeline H2	Compressor - retrofit	MW	0	76	204

[Source: Frontier Economics].

Table 121: Fuel supply chain requirements for the rail segment – FCEV, Domestic, All-In.

			Europe		
Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	in MW	0	4,545	14,903
Generation	Onshore	in MW	0	4,487	8,634
Generation	PV Standalone	in MW	0	18,148	49,945
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter Station	unit	0	2	5
Transmission	Overhead line	km			
Transmission	HVDC Overhead line	km			
Transmission (Offshore)	Offshore - sea cable	km	0	239	994
Transmission	Overhead line - poles	units			
Transmission	HVDC Overhead line - poles	units			
Transmission	cable - poles	units			
Electrolyser	Electrolyser	MW	0	13,185	34,624
International Transport (RoW)	H2 Shipping	units			
International Transport (MENA)	H2 Pipelines	km			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	9	25
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	2	6
Storage	Hydrogen Pressure Storage	m³	0	0	0
Storage	Hydrogen Cavern storage	m³	0	11,621,944	34,865,832
Transmission Pipeline H2	H2 Pipeline - new built	km	0	69	187
Transmission Pipeline H2	H2 Pipeline - retrofit	km	0	277	748
Transmission Pipeline H2	Compressor - new built	MW	0	18	49
Transmission Pipeline H2	Compressor - retrofit	MW	0	72	195

[Source: Frontier Economics].

Table 122: Fuel supply chain requirements for the rail segment – FCEV, International, Status Quo.

			Europe			International (MENA)	
Segment	**Type**	**unit**	**2020**	**2030**	**2050**	**2030**	**2050**
Generation	Offshore	in MW	0	1,450	4,754	2,492	6,005
Generation	Onshore	in MW	0	1,431	2,754	2,507	6,443
Generation	PV Standalone	in MW	0	5,790	15,932	8,287	24,161
Generation	PV Slanted Roof	in MW	0	0	0	0	0
Converter platform (Offshore)	Converter Station	unit	0	0	2	1	2
Transmission	Overhead line	km					
Transmission	HVDC Overhead line	km					
Transmission (Offshore)	Offshore - sea cable	km	0	76	317	131	400
Transmission	Overhead line - poles	units					
Transmission	HVDC Overhead line - poles	units					
Transmission	cable - poles	units					
Electrolyser	Electrolyser	MW	0	4,207	11,045	10,278	27,033
International Transport (RoW)	H2 Shipping	units					
International Transport (MENA)	H2 Pipelines	km				794	2,150
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	10	26	0	0
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	3	7	0	0
Storage	Hydrogen Pressure Storage	m³	0	0	0	0	0
Storage	Hydrogen Cavern storage	m³	0	12,340,288	37,020,863	0	0
Transmission Pipeline H2	H2 Pipeline - new built	km	0	74	199	0	0
Transmission Pipeline H2	H2 Pipeline - retrofit	km	0	294	795	0	0
Transmission Pipeline H2	Compressor - new built	MW	0	19	52	0	0
Transmission Pipeline H2	Compressor - retrofit	MW	0	76	207	0	0
International Transport (MENA)	Compressors (international)	MW				207	559

[Source: Frontier Economics].

Table 123: Fuel supply chain requirements for the rail segment – FCEV, International, Balanced.

			Europe			**International (MENA)**	
Segment	**Type**	**unit**	**2020**	**2030**	**2050**	**2030**	**2050**
Generation	Offshore	in MW	0	1,433	4,697	2,461	5,933
Generation	Onshore	in MW	0	1,414	2,721	2,477	6,365
Generation	PV Standalone	in MW	0	5,720	15,739	8,186	23,869
Generation	PV Slanted Roof	in MW	0	0	0	0	0
Converter platform (Offshore)	Converter Station	unit	0	0	2	1	2
Transmission	Overhead line	km					
Transmission	HVDC Overhead line	km					
Transmission (Offshore)	Offshore - sea cable	km	0	75	313	130	396
Transmission	Overhead line - poles	units					
Transmission	HVDC Overhead line - poles	units					
Transmission	cable - poles	units					
Electrolyser	Electrolyser	MW	0	4,156	10,911	10,154	26,706
International Transport (RoW)	H2 Shipping	units					
International Transport (MENA)	H2 Pipelines	km				785	2,124
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	10	26	0	0
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	2	7	0	0
Storage	Hydrogen Pressure Storage	m³	0	0	0	0	0
Storage	Hydrogen Cavern storage	m³	0	12,190,851	36,572,553	0	0
Transmission Pipeline H2	H2 Pipeline - new built	km	0	73	196	0	0
Transmission Pipeline H2	H2 Pipeline - retrofit	km	0	291	785	0	0
Transmission Pipeline H2	Compressor - new built	MW	0	19	51	0	0
Transmission Pipeline H2	Compressor - retrofit	MW	0	76	204	0	0
International Transport (MENA)	Compressors (international)	MW				204	552

[Source: Frontier Economics].

Table 124: Fuel supply chain requirements for the rail segment – FCEV, International, All-In.

			Europe			**International (MENA)**	
Segment	**Type**	**unit**	**2020**	**2030**	**2050**	**2030**	**2050**
Generation	Offshore	in MW	0	1,366	4,477	2,347	5,656
Generation	Onshore	in MW	0	1,348	2,594	2,361	6,068
Generation	PV Standalone	in MW	0	5,453	15,005	7,804	22,755
Generation	PV Slanted Roof	in MW	0	0	0	0	0
Converter platform (Offshore)	Converter Station	unit	0	0	1	1	2
Transmission	Overhead line	km					
Transmission	HVDC Overhead line	km					
Transmission (Offshore)	Offshore - sea cable	km	0	72	298	124	377
Transmission	Overhead line - poles	units					
Transmission	HVDC Overhead line - poles	units					
Transmission	cable - poles	units					
Electrolyser	Electrolyser	MW	0	3,962	10,402	9,680	25,460
International Transport (RoW)	H2 Shipping	units					
International Transport (MENA)	H2 Pipelines	km				748	2,025
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	9	25	0	0
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	2	6	0	0
Storage	Hydrogen Pressure Storage	m³	0	0	0	0	0
Storage	Hydrogen Cavern storage	m³	0	11,621,944	34,865,832	0	0
Transmission Pipeline H2	H2 Pipeline - new built	km	0	69	187	0	0
Transmission Pipeline H2	H2 Pipeline - retrofit	km	0	277	748	0	0
Transmission Pipeline H2	Compressor - new built	MW	0	18	49	0	0
Transmission Pipeline H2	Compressor - retrofit	MW	0	72	195	0	0
International Transport (MENA)	Compressors (international)	MW				195	526

[Source: Frontier Economics].

15.1.4.4 FT Fuel

Note that the capacities in this section are those for the trains fuelled with FT Fuel only. To get the full required infrastructure one needs to add the required infrastructure for (partly) BEV as set out in 15.1.4.2.

Table 125: Fuel supply chain requirements for the rail segment – FT Fuel, Domestic, Status Quo.

			Europe		
Segment	**Type**	***unit***	**2020**	**2030**	**2050**
Generation	Offshore	MW	0	8,610	26,422
Generation	Onshore	MW	0	8,499	15,308
Generation	PV Standalone	MW	0	34,375	88,547
Generation	PV Slanted Roof	MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	3	9
Transmission	Offshore - sea cable	km	0	453	1,761
Electrolyser	Electrolyser	MW	0	23,789	59,255
International Transport	FT Shipping	units			
International Transport	FT Pipelines	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	35	89
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	9	23
H2 Buffer Storage	Battery	MW			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	17,635,121	50,193,625
Direct Air Capture	Direct Air Capture	t CO2	0	11,673,757	33,226,207
Direct Air Capture	CO2 Buffer storage	t CO2	-	922,905	2,626,800
FT Synthesis	FT Synthese	MW	0	5,445	15,496
Transmission FT Fuel	Ship/Rail - analogue to today (O&M only)		0	0	0
FT Storage	Analogue to today (O&M only)		0	0	0

[Source: Frontier Economics].

Table 126: Fuel supply chain requirements for the rail segment – FT Fuel, Domestic, Balanced.

			Europe		
Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	MW	0	8,394	25,756
Generation	Onshore	MW	0	8,285	14,922
Generation	PV Standalone	MW	0	33,513	86,315
Generation	PV Slanted Roof	MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	3	9
Transmission	Offshore - sea cable	km	0	442	1,717
Electrolyser	Electrolyser	MW	0	23,192	57,761
International Transport	FT Shipping	units			
International Transport	FT Pipelines	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	34	87
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	9	23
H2 Buffer Storage	Battery	MW			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	17,192,909	48,928,636
Direct Air Capture	Direct Air Capture	t CO2	0	11,381,030	32,388,834
Direct Air Capture	CO2 Buffer storage	t CO2	-	899,762	2,560,599
FT Synthesis	FT Synthese	MW	0	5,308	15,106
Transmission FT Fuel	Ship/Rail - analogue to today (O&M only)		0	0	0
FT Storage	Analogue to today (O&M only)		0	0	0

[Source: Frontier Economics].

Table 127: Fuel supply chain requirements for the rail segment – FT Fuel, Domestic, All-In.

			Europe		
Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	MW	0	7,872	24,154
Generation	Onshore	MW	0	7,771	13,994
Generation	PV Standalone	MW	0	31,431	80,946
Generation	PV Slanted Roof	MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	3	8
Transmission	Offshore - sea cable	km	0	415	1,610
Electrolyser	Electrolyser	MW	0	21,751	54,169
International Transport	FT Shipping	units			
International Transport	FT Pipelines	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	32	81
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	8	21
H2 Buffer Storage	Battery	MW			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	16,124,781	45,885,153
Direct Air Capture	Direct Air Capture	t CO2	0	10,673,971	30,374,167
Direct Air Capture	CO2 Buffer storage	t CO2	-	843,864	2,401,323
FT Synthesis	FT Synthese	MW	0	4,978	14,166
Transmission FT Fuel	Ship/Rail - analogue to today (O&M only)		0	0	0
FT Storage	Analogue to today (O&M only)		0	0	0

[Source: Frontier Economics].

Table 128: Fuel supply chain requirements for the rail segment – FT Fuel, International, Status Quo.

			Europe		
Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	MW	0	2,583	7,927
Generation	Onshore	MW	0	2,550	4,592
Generation	PV Standalone	MW	0	10,313	26,564
Generation	PV Slanted Roof	MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	1	3
Transmission	Offshore - sea cable	km	0	136	528
Electrolyser	Electrolyser	MW	0	7,137	17,776
International Transport	FT Shipping	units			
International Transport	FT Pipelines	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	10	27
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	3	7
H2 Buffer Storage	Battery	MW			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	5,290,536	15,058,088
Direct Air Capture	Direct Air Capture	t CO2	0	3,502,127	9,967,862
Direct Air Capture	CO2 Buffer storage	t CO2	-	276,871	788,040
FT Synthesis	FT Synthese	MW	0	1,633	4,649
Transmission FT Fuel	Ship/Rail - analogue to today (O&M only)		0	0	0
FT Storage	Analogue to today (O&M only)		0	0	0
International Transport	Ship Import	tkm			

Nearby International Location		Far Off International Location	
2030	**2050**	**2030**	**2050**
2,163	4,878	878	1,975
2,176	5,233	7,947	19,071
7,193	19,625	0	0
0	0	0	0
1	2	0	1
114	325	46	132
8,498	21,197	8,375	20,230
		1	2
11	29	11	26
3	8	3	7
160,737	457,494	160,737	457,494
5,555,063	15,810,992	5,555,063	15,810,992
4,098,041	11,658,998	4,159,169	11,808,129
323,017	919,380	323,017	919,380
1,911	5,438	1,940	5,507
0	0	0	0
0	0	0	0
3,258,242,294	9,273,709,489	19,549,453,766	55,642,256,935

[Source: Frontier Economics].

Table 129: Fuel supply chain requirements for the rail segment – FT Fuel, International, Balanced.

			Europe		
Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	MW	0	2,518	7,727
Generation	Onshore	MW	0	2,486	4,477
Generation	PV Standalone	MW	0	10,054	25,895
Generation	PV Slanted Roof	MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	1	3
Transmission	Offshore - sea cable	km	0	133	515
Electrolyser	Electrolyser	MW	0	6,958	17,328
International Transport	FT Shipping	units			
International Transport	FT Pipelines	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	10	26
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	3	7
H2 Buffer Storage	Battery	MW			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	5,157,873	14,678,591
Direct Air Capture	Direct Air Capture	t CO2	0	3,414,309	9,716,650
Direct Air Capture	CO2 Buffer storage	t CO2	-	269,929	768,180
FT Synthesis	FT Synthese	MW	0	1,592	4,532
Transmission FT Fuel	Ship/Rail - analogue to today (O&M only)		0	0	0
FT Storage	Analogue to today (O&M only)		0	0	0
International Transport	Ship Import	tkm			

Nearby International Location		Far Off International Location	
2030	2050	2030	2050
2,109	4,755	856	1,925
2,122	5,101	7,748	18,590
7,013	19,130	0	0
0	0	0	0
1	2	0	1
111	317	45	128
8,285	20,663	8,165	19,721
		1	2
11	28	10	26
3	7	3	7
156,706	445,964	156,706	445,964
5,415,766	15,412,520	5,415,766	15,412,520
3,995,280	11,365,166	4,054,875	11,510,538
314,917	896,210	314,917	896,210
1,863	5,301	1,891	5,368
0	0	0	0
0	0	0	0
3,176,539,745	9,039,991,729	19,059,238,471	54,239,950,373

[Source: Frontier Economics].

Table 130: Fuel supply chain requirements for the rail segment – FT Fuel, International, All-In.

			Europe		
Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	MW	0	2,362	7,246
Generation	Onshore	MW	0	2,331	4,198
Generation	PV Standalone	MW	0	9,429	24,284
Generation	PV Slanted Roof	MW	0	0	0
Converter platform (Off-shore)	Converter station	unit	0	1	2
Transmission	Offshore - sea cable	km	0	124	483
Electrolyser	Electrolyser	MW	0	6,525	16,251
International Transport	FT Shipping	units			
International Transport	FT Pipelines	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	10	24
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	2	6
H2 Buffer Storage	Battery	MW			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	4,837,434	13,765,546
Direct Air Capture	Direct Air Capture	t CO2	0	3,202,191	9,112,250
Direct Air Capture	CO2 Buffer storage	t CO2	-	253,159	720,397
FT Synthesis	FT Synthese	MW	0	1,493	4,250
Transmission FT Fuel	Ship/Rail - analogue to today (O&M only)		0	0	0
FT Storage	Analogue to today (O&M only)		0	0	0
International Transport	Ship Import	tkm			

Nearby International Location		Far Off International Location	
2030	2050	2030	2050
1,978	4,459	802	1,806
1,990	4,784	7,266	17,434
6,577	17,940	0	0
0	0	0	0
1	1	0	1
104	297	42	120
7,771	19,377	7,658	18,494
		1	2
10	27	10	24
3	7	3	6
146,971	418,224	146,971	418,224
5,079,306	14,453,823	5,079,306	14,453,823
3,747,068	10,658,224	3,802,961	10,794,554
295,352	840,463	295,352	840,463
1,748	4,971	1,774	5,034
0	0	0	0
0	0	0	0
2,979,193,647	8,477,681,618	17,875,161,880	50,866,089,708

[Source: Frontier Economics].

15.1.4.5 Methane

Note that the capacities in this section are those for the trains fuelled with Methane only. To get the full required infrastructure one needs to add the required infrastructure for (partly) BEV as set out in 15.1.4.2.

Table 131: Fuel supply chain requirements for the rail segment – Methane, Domestic, Status Quo.

			Europe		
Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	in MW	0	8,073	25,617
Generation	Onshore	in MW	0	7,969	14,841
Generation	PV Standalone	in MW	0	32,235	85,848
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	3	9
Transmission (Offshore Connection)	Offshore - sea cable	km	0	425	1,708
Electrolyser	Electrolyser	MW	0	21,716	56,415
International Transport (RoW)	LNG Shipping	units			
International Transport (MENA)	CH4 Pipelines (costs for compressors included)	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	32	85
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	8	22
H2 Buffer Storage	Battery	MW			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	17,739,923	53,219,769
Direct Air Capture	Direct Air Capture	t CO2	0	9,322,395	27,672,934
Direct Air Capture	CO2 Buffer storage	t	0	753,461	2,260,382
Methanisation	Methanisation	MW	0	6,067	18,008
Liquefaction	Liquefaction for LNG	MW	0	6,045	17,943
Transmission Methane	New construction of pipeline	km	0	48	143
Transmission Methane	Compressors for pipeline	MW	0	21	63
Methane Storage	Methane Storage - new built	m³	0	4,249,924	12,749,772

[Source: Frontier Economics].

Table 132: Fuel supply chain requirements for the rail segment – Methane, Domestic, Balanced.

			Europe		
Segment	**Type**	***unit***	**2020**	**2030**	**2050**
Generation	Offshore	in MW	0	7,155	22,701
Generation	Onshore	in MW	0	7,062	13,152
Generation	PV Standalone	in MW	0	28,566	76,077
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Off-shore)	Converter station	unit	0	2	8
Transmission (Offshore Connection)	Offshore - sea cable	km	0	377	1,513
Electrolyser	Electrolyser	MW	0	19,245	49,994
International Transport (RoW)	LNG Shipping	units			
International Transport (MENA)	CH4 Pipelines (costs for com-pressors included)	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	28	75
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	7	19
H2 Buffer Storage	Battery	MW			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	15,720,762	47,162,286
Direct Air Capture	Direct Air Capture	t CO2	0	8,261,319	24,523,196
Direct Air Capture	CO2 Buffer storage	t	0	667,702	2,003,105
Methanisation	Methanisation	MW	0	5,376	15,958
Liquefaction	Liquefaction for LNG	MW	0	5,357	15,901
Transmission Methane	New construction of pipeline	km	0	43	126
Transmission Methane	Compressors for pipeline	MW	0	19	56
Methane Storage	Methane Storage - new built	m³	0	3,766,197	11,298,591

[Source: Frontier Economics].

Table 133: Fuel supply chain requirements for the rail segment – Methane, Domestic, All-In.

			Europe		
Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	in MW	0	6,710	21,289
Generation	Onshore	in MW	0	6,623	12,334
Generation	PV Standalone	in MW	0	26,789	71,345
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	2	7
Transmission (Offshore Connection)	Offshore - sea cable	km	0	353	1,419
Electrolyser	Electrolyser	MW	0	18,047	46,884
International Transport (RoW)	LNG Shipping	units			
International Transport (MENA)	CH4 Pipelines (costs for compressors included)	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	26	70
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	7	18
H2 Buffer Storage	Battery	MW			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	14,742,891	44,228,674
Direct Air Capture	Direct Air Capture	t CO2	0	7,747,444	22,997,791
Direct Air Capture	CO2 Buffer storage	t	0	626,169	1,878,506
Methanisation	Methanisation	MW	0	5,042	14,966
Liquefaction	Liquefaction for LNG	MW	0	5,023	14,912
Transmission Methane	New construction of pipeline	km	0	40	119
Transmission Methane	Compressors for pipeline	MW	0	18	53
Methane Storage	Methane Storage - new built	m³	0	3,531,930	10,595,790

[Source: Frontier Economics].

Table 134: Fuel supply chain requirements for the rail segment – Methane, International, Status Quo.

			Europe		
Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	in MW	0	2,501	7,894
Generation	Onshore	in MW	0	2,469	4,573
Generation	PV Standalone	in MW	0	9,985	26,454
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	1	3
Transmission (Offshore Connection)	Offshore - sea cable	km	0	132	526
Electrolyser	Electrolyser	MW	0	6,727	17,384
International Transport (RoW)	LNG Shipping	units			
International Transport (MENA)	CH4 Pipelines (costs for compressors included)	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	10	26
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	3	7
H2 Buffer Storage	Battery	MW			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	5,321,977	15,965,931
Direct Air Capture	Direct Air Capture	t CO2	0	2,887,780	8,527,345
Direct Air Capture	CO2 Buffer storage	t	0	226,038	678,114
Methanisation	Methanisation	MW	0	1,879	5,549
Liquefaction	Liquefaction for LNG	MW	0	6,045	17,943
Transmission Methane	New construction of pipeline	km	0	32	95
Transmission Methane	Compressors for pipeline	MW	0	14	42
Methane Storage	Methane Storage - new built	m³	0	2,762,451	8,287,352
International Transport (MENA)	Compressors for pipeline (international)	MW			
International Transport (RoW)	Export Storage (LNG)	m³			
International Transport (RoW)	Ship Import	tkm			
International Transport (RoW)	LNG Storage (Domestic)	m³			

Nearby International Location		**Far Off International Location**	
2030	**2050**	**2030**	**2050**
2,098	4,869	832	2,080
2,111	5,224	7,530	20,085
6,978	19,588	0	0
0	0	0	0
1	2	0	1
111	325	44	139
8,025	20,775	7,676	20,921
		2	5
94	277		
11	29	10	27
3	7	3	7
161,692	485,076	161,692	485,076
5,588,076	16,764,227	5,588,076	16,764,227
3,390,870	10,012,922	3,633,784	10,699,188
263,711	791,134	263,711	791,134
2,207	6,516	2,365	6,962
0	0	2,365	6,962
0	0	0	0
0	0	0	0
0	0		
14	42		
		3,641	10,924
		18,013,343,985	54,040,031,956
		132,220	396,660

[Source: Frontier Economics].

Table 135: Fuel supply chain requirements for the rail segment – Methane, International, Balanced.

			Europe		
Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	in MW	0	2,216	6,995
Generation	Onshore	in MW	0	2,188	4,053
Generation	PV Standalone	in MW	0	8,849	23,443
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	1	2
Transmission (Offshore Connection)	Offshore - sea cable	km	0	117	466
Electrolyser	Electrolyser	MW	0	5,961	15,405
International Transport (RoW)	LNG Shipping	units			
International Transport (MENA)	CH4 Pipelines (costs for compressors included)	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	9	23
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	2	6
H2 Buffer Storage	Battery	MW			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	4,716,229	14,148,686
Direct Air Capture	Direct Air Capture	t CO2	0	2,559,093	7,556,761
Direct Air Capture	CO2 Buffer storage	t	0	200,310	600,931
Methanisation	Methanisation	MW	0	1,665	4,918
Liquefaction	Liquefaction for LNG	MW	0	5,357	15,901
Transmission Methane	New construction of pipeline	km	0	29	84
Transmission Methane	Compressors for pipeline	MW	0	13	38
Methane Storage	Methane Storage - new built	m³	0	2,448,028	7,344,084
International Transport (MENA)	Compressors for pipeline (international)	MW			
International Transport (RoW)	Export Storage (LNG)	m³			
International Transport (RoW)	Ship Import	tkm			
International Transport (RoW)	LNG Storage (Domestic)	m³			

Nearby International Location		Far Off International Location	
2030	2050	2030	2050
1,859	4,315	737	1,843
1,871	4,629	6,673	17,799
6,184	17,359	0	0
0	0	0	0
1	1	0	1
98	288	39	123
7,112	18,410	6,802	18,540
		2	5
83	246		
10	25	9	24
2	7	2	6
143,288	429,865	143,288	429,865
4,952,040	14,856,120	4,952,040	14,856,120
3,004,921	8,873,250	3,220,186	9,481,405
233,696	701,087	233,696	701,087
1,955	5,774	2,096	6,170
0	0	2,096	6,170
0	0	0	0
0	0	0	0
0	0		
12	37		
		3,227	9,681
		15,963,062,111	47,889,186,334
		117,171	351,512

[Source: Frontier Economics].

Table 136: Fuel supply chain requirements for the rail segment – Methane, International, All-In.

			Europe		
Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	in MW	0	2,078	6,560
Generation	Onshore	in MW	0	2,052	3,801
Generation	PV Standalone	in MW	0	8,298	21,985
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	1	2
Transmission (Offshore Connection)	Offshore - sea cable	km	0	109	437
Electrolyser	Electrolyser	MW	0	5,591	14,447
International Transport (RoW)	LNG Shipping	units			
International Transport (MENA)	CH4 Pipelines (costs for compressors included)	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	8	22
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	2	6
H2 Buffer Storage	Battery	MW			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	4,422,867	13,268,602
Direct Air Capture	Direct Air Capture	t CO2	0	2,399,911	7,086,712
Direct Air Capture	CO2 Buffer storage	t	0	187,851	563,552
Methanisation	Methanisation	MW	0	1,562	4,612
Liquefaction	Liquefaction for LNG	MW	0	5,023	14,912
Transmission Methane	New construction of pipeline	km	0	27	79
Transmission Methane	Compressors for pipeline	MW	0	12	35
Methane Storage	Methane Storage - new built	m³	0	2,295,755	6,887,264
International Transport (MENA)	Compressors for pipeline (international)	MW			
International Transport (RoW)	Export Storage (LNG)	m³			
International Transport (RoW)	Ship Import	tkm			
International Transport (RoW)	LNG Storage (Domestic)	m³			

Nearby International Location		Far Off International Location	
2030	2050	2030	2050
1,744	4,046	691	1,729
1,754	4,341	6,258	16,692
5,799	16,279	0	0
0	0	0	0
1	1	0	1
92	270	36	115
6,669	17,265	6,379	17,387
		2	5
78	231		
9	24	8	23
2	6	2	6
134,375	403,126	134,375	403,126
4,644,011	13,932,032	4,644,011	13,932,032
2,818,007	8,321,311	3,019,883	8,891,638
219,159	657,477	219,159	657,477
1,834	5,415	1,965	5,786
0	0	1,965	5,786
0	0	0	0
0	0	0	0
0	0		
12	35		
		3,026	9,079
		14,970,119,696	44,910,359,087
		109,882	329,647

[Source: Frontier Economics].

15.1.4.6 Methanol

Note that the capacities in this section are those for the trains fuelled with MeOH only. To get the full required infrastructure one needs to add the required infrastructure for (partly) BEV as set out in 15.1.4.2.

Table 137: Fuel supply chain requirements for the rail segment – Methanol, Domestic, Status Quo.

			Europe		
Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	in MW	0	8,007	25,581
Generation	Onshore	in MW	0	7,904	14,820
Generation	PV Standalone	in MW	0	31,969	85,727
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	3	9
Transmission	Offshore - sea cable	km	0	422	1,705
Electrolyser	Electrolyser	MW	0	19,756	51,868
International Transport	MeOH Shipping	units			
International Transport	MeOH Pipelines	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	29	78
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	7	20
H2 Buffer Storage	Battery	MWh			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	17,657,937	52,973,810
Direct Air Capture	Direct Air Capture	t CO2	0	11496214	34488642
Direct Air Capture	CO2 Buffer storage	t	-	1,018,584.14	3,055,752.41
MeOH Synthese	MeOH Synthese	MW	0	5,685	17,056
Transmission MeOH	Ship/Rail - analogue to today (O&M only)		0	0	0
MeOH Storage	Analogue to today (O&M only)		0	0	0

[Source: Frontier Economics].

Table 138: Fuel supply chain requirements for the rail segment – Methanol, Domestic, Balanced.

			Europe		
Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	in MW	0	7,095	22,669
Generation	Onshore	in MW	0	7,004	13,133
Generation	PV Standalone	in MW	0	28,330	75,970
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	2	8
Transmission	Offshore - sea cable	km	0	374	1,511
Electrolyser	Electrolyser	MW	0	17,507	45,965
International Transport	MeOH Shipping	units			
International Transport	MeOH Pipelines	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	26	69
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	7	18
H2 Buffer Storage	Battery	MWh			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	15,648,107	46,944,322
Direct Air Capture	Direct Air Capture	t CO2	0	10187713	30563139
Direct Air Capture	CO2 Buffer storage	t	-	902,648.72	2,707,946.15
MeOH Synthese	MeOH Synthese	MW	0	5,038	15,114
Transmission MeOH	Ship/Rail - analogue to today (O&M only)		0	0	0
MeOH Storage	Analogue to today (O&M only)		0	0	0

[Source: Frontier Economics].

Table 139: Fuel supply chain requirements for the rail segment – Methanol, Domestic, All-In.

			Europe		
Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	in MW	0	6,654	21,259
Generation	Onshore	in MW	0	6,568	12,317
Generation	PV Standalone	in MW	0	26,568	71,244
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	2	7
Transmission	Offshore - sea cable	km	0	350	1,417
Electrolyser	Electrolyser	MW	0	16,418	43,105
International Transport	MeOH Shipping	units			
International Transport	MeOH Pipelines	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	24	65
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	6	17
H2 Buffer Storage	Battery	MWh			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	14,674,756	44,024,268
Direct Air Capture	Direct Air Capture	t CO2	0	9554012	28662035
Direct Air Capture	CO2 Buffer storage	t	-	846,501.71	2,539,505.12
MeOH Synthese	MeOH Synthese	MW	0	4,725	14,174
Transmission MeOH	Ship/Rail - analogue to today (O&M only)		0	0	0
MeOH Storage	Analogue to today (O&M only)		0	0	0

[Source: Frontier Economics].

Table 140: Fuel supply chain requirements for the rail segment – Methanol, International, Status Quo.

			Europe		
Segment	Type	*unit*	2020	2030	2050
Generation	Offshore	in MW	0	2,402	7,674
Generation	Onshore	in MW	0	2,371	4,446
Generation	PV Standalone	in MW	0	9,591	25,718
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	1	3
Transmission	Offshore - sea cable	km	0	127	512
Electrolyser	Electrolyser	MW	0	5,927	15,560
International Transport	MeOH Shipping	units			
International Transport	MeOH Pipelines	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	9	23
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	2	6
H2 Buffer Storage	Battery	MWh			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	5,297,381	15,892,143
Direct Air Capture	Direct Air Capture	t CO2	0	3448864	10346593
Direct Air Capture	CO2 Buffer storage	t	-	305,575	916,725
MeOH Synthese	MeOH Synthese	MW	0	1,706	5,117
Transmission MeOH	Ship/Rail - analogue to today (O&M only)		0	0	0
MeOH Storage	Analogue to today (O&M only)		0	0	0
International Transport	Ship Import	tkm			

Nearby International Location		Far Off International Location	
2030	2050	2030	2050
2,012	4,721	822	1,940
2,024	5,065	7,442	18,730
6,691	18,992	0	0
0	0	0	0
1	2	0	1
106	315	43	129
7,056	18,540	7,035	17,957
0	1	2	5
9	25	9	23
2	7	2	6
160,945	482,834	160,945	482,834
5,562,250	16,686,750	5,562,250	16,686,750
4049700	12137945	4023675	12472549
356,504.45	1,069,513.34	356,504.45	1,069,513.34
2,003	6,003	1,990	6,168
0	0	0	0
0	0	0	0
7,354,220,386	22,062,661,158	44,125,322,316	132,375,966,947

[Source: Frontier Economics].

Table 141: Fuel supply chain requirements for the rail segment – Methanol, International, Balanced.

			Europe		
Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	in MW	0	2,129	6,801
Generation	Onshore	in MW	0	2,101	3,940
Generation	PV Standalone	in MW	0	8,499	22,791
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	1	2
Transmission	Offshore - sea cable	km	0	112	453
Electrolyser	Electrolyser	MW	0	5,252	13,789
International Transport	MeOH Shipping	units			
International Transport	MeOH Pipelines	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	8	21
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	2	5
H2 Buffer Storage	Battery	MWh			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	4,694,432	14,083,297
Direct Air Capture	Direct Air Capture	t CO2	0	3056314	9168942
Direct Air Capture	CO2 Buffer storage	t	-	270,794	812,383
MeOH Synthese	MeOH Synthese	MW	0	1,511	4,534
Transmission MeOH	Ship/Rail - analogue to today (O&M only)		0	2,129	6,801
MeOH Storage	Analogue to today (O&M only)		0	0	0
International Transport	Ship Import	tkm			

Nearby International Location		Far Off International Location	
2030	**2050**	**2030**	**2050**
1,783	4,183	728	1,719
1,794	4,488	6,595	16,598
5,929	16,830	0	0
0	0	0	0
1	1	0	1
94	279	38	115
6,253	16,430	6,234	15,913
0	1	2	5
8	22	8	20
2	6	2	5
142,626	427,878	142,626	427,878
4,929,154	14,787,461	4,929,154	14,787,461
3588762	10756402	3565700	11052921
315,927.05	947,781.15	315,927.05	947,781.15
1,775	5,319	1,763	5,466
0	0	0	0
0	0	0	0
6,517,161,772	19,551,485,315	39,102,970,630	117,308,911,891

[Source: Frontier Economics].

Table 142: Fuel supply chain requirements for the rail segment – Methanol, International, All-In.

			Europe		
Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	in MW	0	1,996	6,378
Generation	Onshore	in MW	0	1,970	3,695
Generation	PV Standalone	in MW	0	7,970	21,373
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	1	2
Transmission	Offshore - sea cable	km	0	105	425
Electrolyser	Electrolyser	MW	0	4,926	12,932
International Transport	MeOH Shipping	units			
International Transport	MeOH Pipelines	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	7	19
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	2	5
H2 Buffer Storage	Battery	MWh			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	4,402,427	13,207,280
Direct Air Capture	Direct Air Capture	t CO2	0	2866204	8598611
Direct Air Capture	CO2 Buffer storage	t	-	253,950	761,851
MeOH Synthese	MeOH Synthese	MW	0	1,417	4,252
Transmission MeOH	Ship/Rail - analogue to today (O&M only)		0	1,996	6,378
MeOH Storage	Analogue to today (O&M only)		0	0	0
International Transport	Ship Import	tkm			

Nearby International Location		Far Off International Location	
2030	**2050**	**2030**	**2050**
1,672	3,923	683	1,612
1,682	4,209	6,185	15,566
5,560	15,784	0	0
0	0	0	0
1	1	0	1
88	262	36	107
5,864	15,408	5,846	14,923
0	1	1	4
8	21	7	19
2	5	2	5
133,754	401,263	133,754	401,263
4,622,548	13,867,644	4,622,548	13,867,644
3365532	10087327	3343904	10365402
296,275.60	888,826.79	296,275.60	888,826.79
1,664	4,988	1,654	5,126
0	0	0	0
0	0	0	0
6,111,777,998	18,335,333,995	36,670,667,990	110,012,003,970

[Source: Frontier Economics].

15.1.4.7 DME

Note that the capacities in this section are those for the trains fuelled with DME only. To get the full required infrastructure one needs to add the required infrastructure for (partly) BEV as set out in 15.1.4.2.

Table 143 : Fuel supply chain requirements for the rail segment – DME, Domestic, Status Quo.

			Europe		
Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	in MW	0	8,477	27,234
Generation	Onshore	in MW	0	8,368	15,778
Generation	PV Standalone	in MW	0	33,848	91,267
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	3	9
Transmission	Offshore - sea cable	km	0	446	1,816
Electrolyser	Electrolyser	MW	0	20,089	52,743
International Transport	DME Shipping	units			
International Transport	DME Pipelines	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	29	79
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	8	21
H2 Buffer Storage	Battery	MW			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	17,520,794	52,562,383
Direct Air Capture	Direct Air Capture	t CO2	0	10377321	31131962
Direct Air Capture	CO2 Buffer storage	t	-	1,018,471.11	3,055,413.33
DME Synthesis	DME Synthesis	MW	0	5,283	15,849
Transmission FT Fuel	Ship/Rail - analogue to today (O&M only)		0	0	0
DME Storage	Analogue to today (O&M only)		0	0	0
Liquefaction	Liquefaction	MW	0	5,206	15,619

[Source: Frontier Economics].

Table 144: Fuel supply chain requirements for the rail segment – DME, Domestic, Balanced.

			Europe		
Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	in MW	0	8,264	26,547
Generation	Onshore	in MW	0	8,157	15,380
Generation	PV Standalone	in MW	0	32,995	88,967
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	3	9
Transmission	Offshore - sea cable	km	0	435	1,770
Electrolyser	Electrolyser	MW	0	19,583	51,414
International Transport	DME Shipping	units			
International Transport	DME Pipelines	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	29	77
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	7	20
H2 Buffer Storage	Battery	MW			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	17,079,232	51,237,696
Direct Air Capture	Direct Air Capture	t CO2	0	10115789	30347368
Direct Air Capture	CO2 Buffer storage	t	-	992,803.41	2,978,410.23
DME Synthesis	DME Synthesis	MW	0	5,150	15,449
Transmission FT Fuel	Ship/Rail - analogue to today (O&M only)		0	0	0
DME Storage	Analogue to today (O&M only)		0	0	0
Liquefaction	Liquefaction	MW	0	5,075	15,225

[Source: Frontier Economics].

Table 145: Fuel supply chain requirements for the rail segment – DME, Domestic, All-In.

			Europe		
Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	in MW	0	7,750	24,896
Generation	Onshore	in MW	0	7,650	14,424
Generation	PV Standalone	in MW	0	30,943	83,433
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	3	8
Transmission	Offshore - sea cable	km	0	408	1,660
Electrolyser	Electrolyser	MW	0	18,365	48,215
International Transport	DME Shipping	units			
International Transport	DME Pipelines	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	27	72
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	7	19
H2 Buffer Storage	Battery	MW			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	16,016,861	48,050,583
Direct Air Capture	Direct Air Capture	t CO2	0	9486562	28459686
Direct Air Capture	CO2 Buffer storage	t	-	931,048.55	2,793,145.66
DME Synthesis	DME Synthesis	MW	0	4,829	14,488
Transmission FT Fuel	Ship/Rail - analogue to today (O&M only)		0	0	0
DME Storage	Analogue to today (O&M only)		0	0	0
Liquefaction	Liquefaction	MW	0	4,759	14,278

[Source: Frontier Economics].

Table 146: Fuel supply chain requirements for the rail segment – DME, International, Status Quo.

			Europe		
Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	in MW	0	2,543	8,170
Generation	Onshore	in MW	0	2,510	4,733
Generation	PV Standalone	in MW	0	10,154	27,380
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	1	3
Transmission	Offshore - sea cable	km	0	134	545
Electrolyser	Electrolyser	MW	0	6,027	15,823
International Transport	DME Shipping	units			
International Transport	DME Pipelines	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	9	24
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	2	6
H2 Buffer Storage	Battery	MW			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	5,256,238	15,768,715
Direct Air Capture	Direct Air Capture	t CO2	0	3113196	9339589
Direct Air Capture	CO2 Buffer storage	t	-	305,541.33	916,624.00
DME Synthesis	DME Synthesis	MW	0	1,585	4,755
Transmission FT Fuel	Ship/Rail - analogue to today (O&M only)		0	0	0
DME Storage	Analogue to today (O&M only)		0	0	0
Liquefaction	Liquefaction	MW	0	1,562	4,686
International Transport	Ship	tkm			

Nearby International Location		Far Off International Location	
2030	2050	2030	2050
2,134	5,035	880	2,068
2,147	5,402	7,972	19,970
7,097	20,256	0	0
0	0	0	0
1	2	0	1
112	336	46	138
7,189	18,891	7,204	18,291
0	1	2	5
10	26	9	24
2	7	2	6
159,695	479,084	159,695	479,084
5,519,050	16,557,151	5,519,050	16,557,151
3655370	10956120	3771907	11255788
356,464.89	1,069,394.67	356,464.89	1,069,394.67
1,861	5,578	1,920	5,730
0	0	0	0
0	0	0	0
1,822	5,467	1,822	5,467
6,681,926,860	20,045,780,580	40,091,561,160	120,274,683,479

[Source: Frontier Economics].

Table 147: Fuel supply chain requirements for the rail segment – DME, International, Balanced.

			Europe		
Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	in MW	0	2,479	7,964
Generation	Onshore	in MW	0	2,447	4,614
Generation	PV Standalone	in MW	0	9,898	26,690
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	1	3
Transmission	Offshore - sea cable	km	0	131	531
Electrolyser	Electrolyser	MW	0	5,875	15,424
International Transport	DME Shipping	units			
International Transport	DME Pipelines	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	9	23
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	2	6
H2 Buffer Storage	Battery	MW			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	5,123,770	15,371,309
Direct Air Capture	Direct Air Capture	t CO2	0	3034737	9104210
Direct Air Capture	CO2 Buffer storage	t	-	297,841.02	893,523.07
DME Synthesis	DME Synthesis	MW	0	1,545	4,635
Transmission FT Fuel	Ship/Rail - analogue to today (O&M only)		0	0	0
DME Storage	Analogue to today (O&M only)		0	0	0
Liquefaction	Liquefaction	MW	0	1,523	4,568
International Transport	Ship	tkm			

Nearby International Location		**Far Off International Location**	
2030	**2050**	**2030**	**2050**
2,080	4,908	858	2,016
2,093	5,265	7,771	19,467
6,918	19,745	0	0
0	0	0	0
1	2	0	1
110	327	45	134
7,008	18,415	7,023	17,830
0	1	2	5
9	25	9	23
2	7	2	6
155,670	467,010	155,670	467,010
5,379,958	16,139,874	5,379,958	16,139,874
3563246	10680002	3676847	10972117
347,481.19	1,042,443.58	347,481.19	1,042,443.58
1,814	5,437	1,872	5,586
0	0	0	0
0	0	0	0
1,776	5,329	1,776	5,329
6,513,527,690	19,540,583,070	39,081,166,140	117,243,498,421

[Source: Frontier Economics].

Table 148: Fuel supply chain requirements for the rail segment – DME, International, All-In.

			Europe		
Segment	**Type**	**unit**	**2020**	**2030**	**2050**
Generation	Offshore	in MW	0	2,325	7,469
Generation	Onshore	in MW	0	2,295	4,327
Generation	PV Standalone	in MW	0	9,283	25,030
Generation	PV Slanted Roof	in MW	0	0	0
Converter platform (Offshore)	Converter station	unit	0	1	2
Transmission	Offshore - sea cable	km	0	122	498
Electrolyser	Electrolyser	MW	0	5,509	14,465
International Transport	DME Shipping	units			
International Transport	DME Pipelines	MW			
H2 Pipeline	Pipeline (from Electrolyser to Storage)	km	0	8	22
H2 Pipeline	Compressor (from Electrolyser to Storage)	MW	0	2	6
H2 Buffer Storage	Battery	MW			
H2 Buffer Storage	Hydrogen Pressure Storage	m³	0	0	0
H2 Buffer Storage	Hydrogen Cavern storage	m³	0	4,805,058	14,415,175
Direct Air Capture	Direct Air Capture	t CO2	0	2845969	8537906
Direct Air Capture	CO2 Buffer storage	t	-	279,314.57	837,943.70
DME Synthesis	DME Synthesis	MW	0	1,449	4,346
Transmission FT Fuel	Ship/Rail - analogue to today (O&M only)		0	0	0
DME Storage	Analogue to today (O&M only)		0	0	0
Liquefaction	Liquefaction	MW	0	1,428	4,283
International Transport	Ship	tkm			

Nearby International Location		Far Off International Location	
2030	2050	2030	2050
1,951	4,602	805	1,891
1,963	4,938	7,288	18,256
6,487	18,517	0	0
0	0	0	0
1	2	0	1
103	307	42	126
6,572	17,269	6,586	16,721
0	1	1	4
9	24	8	22
2	6	2	6
145,987	437,961	145,987	437,961
5,045,311	15,135,934	5,045,311	15,135,934
3341604	10015679	3448138	10289624
325,866.99	977,600.98	325,866.99	977,600.98
1,701	5,099	1,755	5,238
0	0	0	0
0	0	0	0
1,666	4,997	1,666	4,997
6,108,369,966	18,325,109,897	36,650,219,794	109,950,659,381

[Source: Frontier Economics].

15.2 Environmental analysis

15.2.1 Specific environmental impacts: Build-up of fuel supply chain infrastructure

Table 149: Specific GHG emissions from build-up of fuel supply chain infrastructure.

Section	Category	Type	Unit	Greenhouse gases kg CO_2eq / unit		
				2020	2050a	2050b
Generation	PV standalone	5 MW	MW	1,721,703	440,933	105,111
	PV slanted roof	0.005 MW	MW	1,344,849	423,818	85,756
	Wind onshore	2020 (2.9 MW)	MW	847,220	277,625	91,691
		2030 (3.8 MW)	MW	901,298	298,447	98,567
		2050 (6 MW)	MW	1,054,519	347,032	114,613
	Wind offshore	2020 (4.15 MW)	MW	748,146	268,662	71,480
		2030 (8.5 MW)	MW	930,620	331,876	88,298
		2050 (15 MW)	MW	1,103,971	395,091	105,117
Transmis-sion & Dis-tribution	Lines/cables	Transmission line	km	425,285	77,105	102,816
		Transmission cable	km	362,006	132,672	71,994
		AC cable	km	262,751	92,613	52,935
		HV line (0.660 GW)	km	123,060	78,019	37,560
		MV line (0.216 GW)	km	27,697	11,381	7,621
		LV line (0.002 GW)	km	18,326	6,150	3,878
	Pipeline	1000mm diameter	km	1,366,177	612,864	221,865
		500 mm diameter	km	1,009,710	528,872	149,425
Hydrogen	Electrolyser	2020 (10 MW)	MW	118,094	68,435	16,457
		2030 (250 MW)	MW	93,232	54,028	12,992
		2050 (1000 MW)	MW	93,232	54,028	12,992
	Reconversion gas turbine (500 MW)		MW	12,668	1,875	625
Synthesis	DAC	Direct Air Capture	t CO_2/a	607.2	362.4	89.0
		CO_2 storage	t CO_2/a	4.6	0.5	0.2
	FT synthesis	2020 (90 MW)	MW	3,444,344	345,428	130,605
		2030 (493 MW)	MW	1,946,803	195,242	73,820
		2050 (1300 MW)	MW	1,534,980	153,941	58,205
	CH4 synthesis	2020 (20 MW)	MW	24,489	3,855	3,554
		2030 (180 MW)	MW	14,136	2,225	2,051
		2050 (500 MW)	MW	14,136	2,225	2,051
	MeOH synthesis	2020 (90 MW)	MW	3,862,907	387,405	146,477
		2030 (393 MW)	MW	2,372,929	237,977	89,979
		2050 (1000 MW)	MW	1,710,716	171,565	64,868
	DME synthesis	2020 (90 MW)	MW	5,375,054	539,056	203,816
		2030 (393 MW)	MW	3,291,702	330,120	124,817
		2050 (1000 MW)	MW	2,380,655	238,752	90,272
Storage	Methane	Cavern (500,000 m³)	m³	0.0013	0.0003	0.0002
		LNG storage (110 m³)	m³	7.0	3.0	1.0
		LNG liquefaction	MW	8,547	1,417	472
	Household battery	2020 (40 kWh)	MWh	3,420	2,025	525
		2030 (50 kWh)	MWh	3,271	1,932	517
		2050 (70 kWh)	MWh	3,523	2,307	585
Charging / Fueling	Charging Points	AC charger 11 kW	number	197	161	27
		AC charger 44 kW	number	4,758	3,829	679
	Overhead line		km	264,174	71,176	58,367
	H_2 filling station	car pump	number	21,980	9,230	4,308
		truck pump	number	146,535	61,533	28,721

Table 150 – Other specific environmental impacts from build-up of fuel supply chain infrastructure.

Section	Category	Type	Unit	Acidification kg SO_2eq/unit		Eutrophication kg PO_4eq/unit		PM formation kg $PM_{2.5}$eq/unit	
				2020	2050	2020	2050	2020	2050
Generation	PV standalone	5 MW	*MW*	11,006	5,563	789	381	9,374	4,575
	PV slanted roof	0.005 MW	*MW*	9,833	5,285	635	318	8,048	4,292
	Wind onshore	2020 (2.9 MW)	*MW*	7,872	2,855	389	201	6,014	2,480
		2030 (3.8 MW)	*MW*	8,375	3,069	414	216	6,397	2,666
		2050 (6 MW)	*MW*	9,798	3,568	485	251	7,485	3,100
	Wind offshore	2020 (4.15 MW)	*MW*	5,826	2,890	314	194	4,860	2,616
		2030 (8.5 MW)	*MW*	7,247	3,569	390	240	6,046	3,232
		2050 (15 MW)	*MW*	8,596	4,249	463	286	7,172	3,848
Transmission & Distribution	Lines/cables	Transmission line	*km*	2,103	774	220	63	2,015	746
		Transmission cable	*km*	13,541	3,308	847	163	9,366	2,312
		AC cable	*km*	13,429	2,680	812	115	9,120	1,832
		HV line (0.660 GW)	*km*	697	482	72	49	644	457
		MV line (0.216 GW)	*km*	967	188	60	9	665	135
		LV line (0.002 GW)	*km*	849	131	52	6	579	93
	Pipeline	1000mm diameter	*km*	7,104	4,696	1,124	789	8,262	5,628
		500 mm diameter	*km*	5,735	4,198	917	703	6,774	5,093
Hydrogen	Electrolyser	2020 (10 MW)	*MW*	10,008	9,675	88	72	5,746	5,456
		2030 (250 MW)	*MW*	7,901	7,638	70	57	4,536	4,307
		2050 (1000 MW)	*MW*	7,901	7,638	70	57	4,536	4,307
	Reconversion gas turbine (500 MW)		*MW*	154	23	7	1	111	16
Synthesis	DAC	Direct Air Capture	*t CO_2/a*	3.3	2.4	0.2	0.1	3.2	2.0
		CO_2 storage	*t CO_2/a*	0.023	0.006	0.002	0.001	0.025	0.007
	FT synthesis	2020 (90 MW)	*MW*	40,148	5,482	1,819	272	29,087	4,186
		2030 (493 MW)	*MW*	22,692	3,099	1,028	153	16,441	2,366
		2050 (1300 MW)	*MW*	17,892	2,443	810	121	12,963	1,865
	CH4 synthesis	2020 (20 MW)	*MW*	204	37	19	4	202	38
		2030 (180 MW)	*MW*	118	22	11	2	117	22
		2050 (500 MW)	*MW*	118	22	11	2	117	22
	MeOH synthesis	2020 (90 MW)	*MW*	45,027	6,149	2,040	305	32,622	4,694
		2030 (393 MW)	*MW*	27,659	3,777	1,253	187	20,039	2,884
		2050 (1000 MW)	*MW*	19,940	2,723	903	135	14,447	2,079
	DME synthesis	2020 (90 MW)	*MW*	62,653	8,556	2,838	424	45,392	6,532
		2030 (393 MW)	*MW*	38,369	5,239	1,738	259	27,798	4,000
		2050 (1000 MW)	*MW*	27,749	3,789	1,257	188	20,104	2,893
Storage	Methane	Cavern (500,000 m³)	*m³*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		LNG storage (110 m³)	*m³*	0.09	0.04	0.00	0.00	0.06	0.03
		LNG liquefaction	*MW*	104	17	4.8	0.8	75	12
	Household battery	2020 (40 kWh)	*MWh*	92	75	3.1	1.8	59	46
		2030 (50 kWh)	*MWh*	104	88	3.0	1.7	65	53
		2050 (70 kWh)	*MWh*	92	79	3.3	2.2	59	48
Charging / Fueling	Charging Points	AC charger 11 kW	*number*	1.4	1.2	0.2	0.2	1.3	1.0
		AC charger 44 kW	*number*	33	28	4.4	3.9	31	25
	Overhead line		*km*	7,373	3,345	595	200	5,989	2,475
	H_2 filling station	car pump	*number*	107	53	13	6	114	54
		truck pump	*number*	714	351	89	40	759	357

15.2.2 Specific environmental impacts: Vehicle production & disposal

Table 151: Specific GHG emissions of light-duty vehicle production (kg / vehicle).

Size	Fuel type	Status Quo			Balanced			All-In		
		2020	**2050a**	**2050b**	**2020**	**2050a**	**2050b**	**2020**	**2050a**	**2050b**
small	gasoline	4,818	1,774	822	5,355	2,124	905	7,911	3,704	1,242
	diesel	4,961	1,902	840	5,498	2,251	923	8,054	3,832	1,260
	CNG	5,457	2,004	876	5,873	2,310	950	8,376	3,872	1,282
	DME	4,961	1,902	840	5,498	2,251	923	8,054	3,832	1,260
	Methanol	4,818	1,774	822	5,355	2,124	905	7,911	3,704	1,242
	H2 ICE	6,412	2,385	967	6,617	2,608	1,020	9,043	4,139	1,345
	FCEV	7,959	4,263	1,365	6,933	3,349	1,155	9,409	4,899	1,485
	BEV	9,236	4,494	1,499	8,227	3,892	1,359	9,715	4,968	1,543
medium	gasoline	6,218	2,283	1,058	7,284	2,982	1,224	10,277	4,833	1,619
	diesel	6,517	2,550	1,096	7,583	3,248	1,262	10,576	5,100	1,657
	CNG	7,353	2,692	1,156	8,153	3,295	1,299	11,046	5,111	1,685
	DME	6,517	2,550	1,096	7,583	3,248	1,262	10,576	5,100	1,657
	Methanol	6,218	2,283	1,058	7,284	2,982	1,224	10,277	4,833	1,619
	H2 ICE	9,123	3,398	1,323	9,416	3,800	1,418	12,161	5,557	1,790
	FCEV	12,555	7,384	2,169	10,422	5,482	1,731	13,243	7,268	2,111
	BEV	14,756	7,622	2,363	12,702	6,397	2,075	13,515	7,200	2,155
large	gasoline	7,156	2,653	1,214	9,320	3,858	1,563	12,913	6,081	2,037
	diesel	8,242	3,253	1,383	9,758	4,250	1,619	13,352	6,472	2,092
	CNG	9,113	3,334	1,439	10,342	4,227	1,651	13,682	6,358	2,103
	DME	8,242	3,253	1,383	9,758	4,250	1,619	13,352	6,472	2,092
	Methanol	7,803	2,862	1,327	9,320	3,858	1,563	12,913	6,081	2,037
	H2 ICE	11,188	4,161	1,635	11,848	4,829	1,793	14,797	6,804	2,208
	FCEV	16,530	10,113	2,900	13,414	7,332	2,261	13,368	6,512	2,001
	BEV	17,834	9,239	2,856	15,355	7,761	2,507	15,870	8,403	2,524
SUV	gasoline	7,121	2,634	1,209	9,059	3,743	1,520	12,595	5,932	1,986
	diesel	8,018	3,158	1,346	9,471	4,112	1,572	13,008	6,300	2,038
	CNG	9,013	3,297	1,414	10,222	4,162	1,620	13,590	6,291	2,072
	DME	8,018	3,158	1,346	9,471	4,112	1,572	13,008	6,300	2,038
	Methanol	7,605	2,790	1,294	9,059	3,743	1,520	12,595	5,932	1,986
	H2 ICE	11,260	4,193	1,626	11,951	4,853	1,783	15,066	6,880	2,211
	FCEV	16,373	9,833	2,827	13,423	7,207	2,223	16,658	9,280	2,662
	BEV	20,462	10,810	3,257	16,963	8,726	2,760	16,986	9,166	2,712
LCV	gasoline	9,110	3,352	1,553	10,265	4,106	1,733	14,985	7,025	2,355
	diesel	9,422	3,630	1,592	10,577	4,384	1,772	15,297	7,304	2,395
	CNG	10,973	4,023	1,713	11,882	4,688	1,871	16,286	7,494	2,467
	DME	9,422	3,630	1,592	10,577	4,384	1,772	15,297	7,304	2,395
	Methanol	9,110	3,352	1,553	10,265	4,106	1,733	14,985	7,025	2,355
	H2 ICE	14,086	5,261	2,005	14,367	5,680	2,106	18,270	8,286	2,654
	FCEV	17,645	9,424	2,890	15,346	7,408	2,426	19,504	10,112	2,997
	BEV	32,030	17,174	5,068	24,983	12,980	4,057	22,690	12,277	3,636

Table 152: Other specific environmental impacts of light-duty vehicle production in 2020.

Size	Fuel type	Acidification 2020 (kg SO_2eq/veh.)			Eutrophication 2020 (kg PO_4eq/veh.)			PM formation 2020 (kg $PM_{2.5}$eq/veh.)		
		SQ	**Bal**	**All-In**	**SQ**	**Bal**	**All-In**	**SQ**	**Bal**	**All-In**
small	gasoline	35.1	42.1	58.9	3.2	3.7	4.7	28.6	33.8	45.0
	diesel	39.9	46.9	63.7	3.5	4.1	5.0	32.0	37.2	48.5
	CNG	37.3	43.9	60.5	3.6	4.1	5.0	30.4	35.3	46.3
	DME	39.9	46.9	63.7	3.5	4.1	5.0	32.0	37.2	48.5
	Methanol	35.1	42.1	58.9	3.2	3.7	4.7	28.6	33.8	45.0
	H2 ICE	40.9	46.7	63.0	4.2	4.5	5.4	33.2	37.4	48.3
	FCEV	68.4	68.1	84.6	5.9	5.8	6.7	52.2	52.0	63.0
	BEV	147.0	135.1	106.6	7.2	6.4	6.4	100.9	91.8	75.7
medium	gasoline	47.8	60.7	80.2	4.2	5.3	6.4	38.5	48.3	61.3
	diesel	57.9	70.8	90.3	4.9	6.0	7.1	45.7	55.5	68.5
	CNG	51.8	63.8	82.9	4.9	5.8	6.8	41.7	50.7	63.5
	DME	57.9	70.8	90.3	4.9	6.0	7.1	45.7	55.5	68.5
	Methanol	47.8	60.7	80.2	4.2	5.3	6.4	38.5	48.3	61.3
	H2 ICE	58.4	68.5	87.0	6.0	6.6	7.5	46.9	54.5	66.8
	FCEV	115.0	114.5	133.4	9.6	9.6	10.6	86.2	85.8	98.4
	BEV	266.0	240.1	168.8	12.1	10.3	9.5	179.3	159.8	118.1
large	gasoline	54.9	78.8	102.3	4.7	6.8	8.1	44.0	62.6	78.3
	diesel	76.2	93.6	117.1	6.4	7.9	9.2	59.8	73.1	88.9
	CNG	66.0	82.4	105.0	6.1	7.5	8.6	52.9	65.5	80.5
	DME	76.2	93.6	117.1	6.4	7.9	9.2	59.8	73.1	88.9
	Methanol	61.4	78.8	102.3	5.3	6.8	8.1	49.2	62.6	78.3
	H2 ICE	73.7	88.0	109.2	7.4	8.4	9.3	59.0	69.9	83.8
	FCEV	156.4	155.9	93.9	12.9	12.8	8.5	116.6	116.2	73.0
	BEV	315.2	282.2	186.3	14.6	12.5	11.1	213.3	188.9	131.9
SUV	gasoline	54.7	76.7	99.7	4.7	6.6	7.9	43.8	60.9	76.2
	diesel	73.5	90.7	113.6	6.2	7.6	8.9	57.7	70.8	86.2
	CNG	64.5	80.9	103.2	6.0	7.4	8.5	51.7	64.2	79.1
	DME	73.5	90.7	113.6	6.2	7.6	8.9	57.7	70.8	86.2
	Methanol	59.5	76.7	99.7	5.1	6.6	7.9	47.7	60.9	76.2
	H2 ICE	72.8	87.3	108.7	7.5	8.5	9.5	58.4	69.3	83.4
	FCEV	151.8	151.2	173.0	12.6	12.6	13.7	113.3	112.8	127.3
	BEV	390.4	338.8	220.7	17.0	14.0	12.2	261.0	223.8	153.7
LCV	gasoline	67.2	82.0	113.0	6.0	7.2	8.9	54.6	65.6	86.3
	diesel	77.8	92.6	123.5	6.8	8.0	9.7	62.1	73.2	93.9
	CNG	73.8	87.8	117.6	7.2	8.2	9.8	59.9	70.3	90.1
	DME	77.8	92.6	123.5	6.8	8.0	9.7	62.1	73.2	93.9
	Methanol	67.2	82.0	113.0	6.0	7.2	8.9	54.6	65.6	86.3
	H2 ICE	85.3	97.0	124.9	9.2	9.8	11.0	69.1	77.6	95.9
	FCEV	145.6	144.8	173.7	12.9	12.9	14.2	110.8	110.1	129.2
	BEV	671.2	555.9	316.9	26.8	20.7	16.2	442.2	361.2	217.4

Table 153: Other specific environmental impacts of light-duty vehicle production in 2050.

Size	Fuel type	**Acidification 2050** (kg SO_2eq/veh.)			**Eutrophication 2050** (kg PO_4eq/veh.)			**PM formation 2050** (kg $PM_{2.5}$eq/veh.)		
		SQ	**Bal**	**All-In**	**SQ**	**Bal**	**All-In**	**SQ**	**Bal**	**All-In**
small	gasoline	21.0	25.9	45.0	1.5	1.8	2.7	15.7	19.3	33.9
	diesel	25.7	30.7	49.7	1.8	2.2	3.1	19.0	22.7	37.3
	CNG	21.5	26.4	45.3	1.6	1.9	2.8	15.8	19.5	34.0
	DME	25.7	30.7	49.7	1.8	2.2	3.1	19.0	22.7	37.3
	Methanol	21.0	25.9	45.0	1.5	1.8	2.7	15.7	19.3	33.9
	H2 ICE	22.5	27.2	46.1	1.8	2.1	3.0	16.4	19.9	34.4
	FCEV	50.4	50.3	69.2	3.7	3.7	4.6	36.1	36.0	50.5
	BEV	111.1	104.4	85.9	3.9	3.4	3.9	71.7	66.4	58.6
medium	gasoline	29.7	38.6	60.7	2.0	2.7	3.8	21.9	28.7	45.6
	diesel	39.6	48.6	70.6	2.7	3.4	4.5	29.0	35.8	52.7
	CNG	30.6	39.3	61.3	2.2	2.9	3.9	22.2	28.9	45.9
	DME	39.6	48.6	70.6	2.7	3.4	4.5	29.0	35.8	52.7
	Methanol	29.7	38.6	60.7	2.0	2.7	3.8	21.9	28.7	45.6
	H2 ICE	32.5	40.7	62.5	2.6	3.2	4.2	23.3	29.7	46.6
	FCEV	89.6	89.3	111.2	6.6	6.5	7.6	63.7	63.5	80.3
	BEV	205.6	190.2	137.0	6.7	5.7	6.0	131.3	119.6	91.7
large	gasoline	35.9	50.5	77.1	2.3	3.6	4.9	26.2	37.6	58.0
	diesel	53.3	65.1	91.7	3.6	4.7	5.9	38.8	48.0	68.4
	CNG	39.7	51.3	77.7	2.7	3.8	5.0	28.8	37.9	58.3
	DME	53.3	65.1	91.7	3.6	4.7	5.9	38.8	48.0	68.4
	Methanol	38.7	50.5	77.1	2.5	3.6	4.9	28.5	37.6	58.0
	H2 ICE	42.0	53.0	79.0	3.2	4.1	5.3	30.1	38.9	59.0
	FCEV	124.7	124.4	67.8	9.1	9.1	5.0	88.6	88.4	52.0
	BEV	242.7	222.4	149.6	8.2	7.0	7.0	155.8	140.7	101.6
SUV	gasoline	35.3	49.2	75.3	2.3	3.5	4.7	25.8	36.6	56.6
	diesel	51.1	63.0	89.0	3.4	4.5	5.7	37.3	46.3	66.3
	CNG	38.5	50.1	76.0	2.7	3.7	4.9	27.9	36.9	56.9
	DME	51.1	63.0	89.0	3.4	4.5	5.7	37.3	46.3	66.3
	Methanol	37.4	49.2	75.3	2.4	3.5	4.7	27.5	36.6	56.6
	H2 ICE	41.0	52.1	77.7	3.2	4.1	5.2	29.3	38.0	57.8
	FCEV	119.6	119.3	145.0	8.8	8.7	9.9	84.8	84.6	104.4
	BEV	304.5	270.8	179.5	9.5	7.9	7.7	193.5	169.5	119.4
LCV	gasoline	40.6	51.0	86.1	2.8	3.6	5.3	30.2	38.0	64.8
	diesel	51.0	61.4	96.4	3.6	4.4	6.0	37.6	45.4	72.2
	CNG	42.0	52.3	87.1	3.2	3.9	5.5	30.8	38.5	65.2
	DME	51.0	61.4	96.4	3.6	4.4	6.0	37.6	45.4	72.2
	Methanol	40.6	51.0	86.1	2.8	3.6	5.3	30.2	38.0	64.8
	H2 ICE	45.5	55.1	89.3	3.9	4.5	6.0	32.7	40.0	66.4
	FCEV	106.1	105.8	140.2	8.0	8.0	9.5	75.4	75.2	101.7
	BEV	530.8	451.4	261.4	14.9	11.6	10.2	333.0	278.5	170.7

Table 154: Specific GHG emissions of heavy-duty vehicle production (kg / vehicle).

Size	Fuel type	Status Quo			Balanced			All-In		
		2020	2050a	2050b	2020	2050a	2050b	2020	2050a	2050b
3.5-7.5 t Rigid	diesel	11,377	3,885	1,722	12,623	4,811	1,903	12,398	4,779	1,855
	CNG	12,658	4,347	1,832	13,904	5,272	2,013	13,679	5,241	1,965
	DME	11,377	3,885	1,722	12,623	4,811	1,903	12,398	4,779	1,855
	Methanol	11,377	3,885	1,722	12,623	4,811	1,903	12,398	4,779	1,855
	H2 ICE	14,810	5,203	2,035	16,056	6,128	2,215	15,831	6,097	2,167
	FCEV	16,794	6,972	2,459	15,726	6,354	2,280	15,049	6,148	2,175
	BEV	27,907	13,798	4,254	23,908	11,500	3,685	20,861	10,399	3,268
7.5-16t Regional	diesel	17,501	5,977	2,943	20,158	7,939	3,330	19,733	7,883	3,238
	CNG	20,097	6,912	3,165	22,754	8,875	3,552	22,329	8,818	3,461
	DME	17,501	5,977	2,943	20,158	7,939	3,330	19,733	7,883	3,238
	Methanol	17,501	5,977	2,943	20,158	7,939	3,330	19,733	7,883	3,238
	H2 ICE	24,520	8,671	3,581	27,178	10,633	3,968	26,752	10,577	3,876
	FCEV	28,314	12,197	4,390	26,358	10,989	4,041	25,329	10,697	3,873
	BEV	49,298	25,114	7,808	41,719	20,765	6,728	35,941	18,680	5,936
16-40t Long-haul	diesel	44,444	14,716	8,382	49,025	18,382	9,010	47,586	18,177	8,705
	LNG	45,717	14,763	8,566	50,299	18,428	9,195	48,860	18,223	8,890
	DME	44,444	14,716	8,382	49,025	18,382	9,010	47,586	18,177	8,705
	Methanol	44,444	14,716	8,382	49,025	18,382	9,010	47,586	18,177	8,705
	H2 ICE	63,039	21,853	10,073	67,621	25,518	10,702	66,182	25,313	10,397
	FCEV	78,340	35,796	13,176	70,263	30,163	11,650	67,320	29,362	11,157
	CEV	67,956	29,646	11,895	61,437	26,315	10,894	56,260	24,672	10,108
40-60t Long-haul XL	diesel	58,156	19,331	11,124	64,113	24,127	11,938	62,192	23,856	11,530
	LNG	60,092	19,402	11,405	66,049	24,197	12,219	64,128	23,927	11,810
	DME	58,156	19,331	11,124	64,113	24,127	11,938	62,192	23,856	11,530
	Methanol	58,156	19,331	11,124	64,113	24,127	11,938	62,192	23,856	11,530
	H2 ICE	80,806	28,023	13,185	86,763	32,819	13,998	84,842	32,548	13,590
	FCEV	100,738	45,954	17,170	90,335	38,782	15,212	86,401	37,714	14,552
	CEV	89,048	38,942	15,740	80,391	34,527	14,410	73,514	32,348	13,363
City bus	diesel	18,400	6,058	2,928	20,261	7,245	3,150	20,230	7,234	3,146
	CNG	20,653	6,870	3,122	22,514	8,057	3,344	22,483	8,046	3,340
	DME	18,400	6,058	2,928	20,261	7,245	3,150	20,230	7,234	3,146
	Methanol	18,400	6,058	2,928	20,261	7,245	3,150	20,230	7,234	3,146
	H2 ICE	24,450	8,380	3,478	26,310	9,567	3,701	26,280	9,555	3,697
	FCEV	39,950	20,465	6,395	22,181	12,209	3,071	20,974	11,754	2,913
	BEV	46,086	22,611	7,172	38,884	18,219	6,095	34,195	16,450	5,479
Coach	diesel	46,743	14,740	8,240	48,421	15,647	8,288	48,153	15,546	8,253
	LNG	48,146	14,791	8,444	49,824	15,699	8,491	49,556	15,598	8,456
	DME	46,743	14,740	8,240	48,421	15,647	8,288	48,153	15,546	8,253
	Methanol	46,743	14,740	8,240	48,421	15,647	8,288	48,153	15,546	8,253
	H2 ICE	67,034	22,527	10,086	68,712	23,434	10,134	68,445	23,333	10,099
	FCEV	75,850	32,673	12,395	31,013	16,170	4,032	29,505	15,601	3,834
	CEV	70,596	29,418	11,828	62,044	24,010	10,386	57,924	22,456	9,845

Table 155: Other specific environmental impacts of heavy-duty vehicle production in 2020.

Size	Fuel type	Acidification 2050 (kg SO_2eq/veh.)			Eutrophication 2050 (kg PO_4eq/veh.)			PM formation 2050 (kg $PM_{2.5}$eq/veh.)		
		SQ	Bal	All-In	SQ	Bal	All-In	SQ	Bal	All-In
3.5-7.5 t Rigid	diesel	83.0	98.9	96.6	8.0	9.4	9.3	69.1	81.1	79.4
	CNG	87.5	103.5	101.2	8.8	10.2	10.1	72.8	84.8	83.0
	DME	83.0	98.9	96.6	8.0	9.4	9.3	69.1	81.1	79.4
	Methanol	83.0	98.9	96.6	8.0	9.4	9.3	69.1	81.1	79.4
	H2 ICE	95.5	111.4	109.1	10.2	11.6	11.4	79.1	91.1	89.4
	FCEV	153.9	145.9	119.9	11.8	11.1	10.6	116.3	109.9	94.1
	BEV	503.8	460.9	314.3	22.2	18.9	16.4	338.5	304.9	217.7
7.5-16t Regional	diesel	133.1	165.0	161.2	12.5	15.4	15.2	111.1	135.4	132.5
	CNG	142.3	174.1	170.4	14.1	17.0	16.8	118.5	142.9	139.9
	DME	133.1	165.0	161.2	12.5	15.4	15.2	111.1	135.4	132.5
	Methanol	133.1	165.0	161.2	12.5	15.4	15.2	111.1	135.4	132.5
	H2 ICE	158.7	190.5	186.8	16.9	19.8	19.6	131.5	155.9	152.9
	FCEV	249.2	237.9	202.0	20.1	19.2	18.4	190.5	181.3	159.4
	BEV	940.2	859.0	581.6	40.1	33.8	29.0	628.7	564.9	400.0
16-40t Long-haul	diesel	318.2	389.0	373.8	30.5	35.8	35.0	272.8	323.8	312.4
	LNG	325.2	395.9	380.8	31.2	36.5	35.7	282.3	333.3	321.9
	DME	318.2	389.0	373.8	30.5	35.8	35.0	272.8	323.8	312.4
	Methanol	318.2	389.0	373.8	30.5	35.8	35.0	272.8	323.8	312.4
	H2 ICE	386.0	456.7	441.5	42.3	47.6	46.8	327.0	377.9	366.6
	FCEV	719.6	688.7	592.3	55.8	53.2	51.1	544.5	519.0	459.8
	CEV	885.8	822.0	612.0	50.4	45.2	41.2	636.6	585.4	459.0
40-60t Long-haul XL	diesel	425.2	517.3	497.5	40.3	47.2	46.1	363.4	429.7	414.8
	LNG	435.8	527.9	508.1	41.3	48.2	47.1	377.8	444.1	429.2
	DME	425.2	517.3	497.5	40.3	47.2	46.1	363.4	429.7	414.8
	Methanol	425.2	517.3	497.5	40.3	47.2	46.1	363.4	429.7	414.8
	H2 ICE	507.8	599.8	580.0	54.6	61.5	60.4	429.3	495.6	480.7
	FCEV	937.2	895.9	767.4	71.9	68.4	65.6	708.8	674.8	595.9
	CEV	1,169.7	1,085.1	806.9	66.1	59.3	54.0	840.0	772.2	604.7
City bus	diesel	146.8	170.1	168.5	12.7	15.0	14.9	122.9	140.7	139.8
	CNG	154.8	178.0	176.5	14.1	16.4	16.4	129.3	147.1	146.2
	DME	146.8	170.1	168.5	12.7	15.0	14.9	122.9	140.7	139.8
	Methanol	146.8	170.1	168.5	12.7	15.0	14.9	122.9	140.7	139.8
	H2 ICE	168.9	192.1	190.6	16.5	18.8	18.8	140.5	158.3	157.4
	FCEV	439.1	343.9	282.6	29.5	21.0	20.0	320.2	236.0	199.7
	BEV	840.0	764.9	526.4	36.5	30.6	26.7	567.9	508.6	367.4
Coach	diesel	344.8	395.1	381.4	30.2	32.9	32.7	298.2	330.9	322.9
	LNG	352.4	402.7	389.1	31.0	33.7	33.5	308.6	341.4	333.3
	DME	344.8	395.1	381.4	30.2	32.9	32.7	298.2	330.9	322.9
	Methanol	344.8	395.1	381.4	30.2	32.9	32.7	298.2	330.9	322.9
	H2 ICE	418.7	469.0	455.4	43.1	45.8	45.6	357.2	390.0	381.9
	FCEV	689.7	419.4	342.7	52.0	27.4	26.1	532.0	289.2	243.8
	CEV	933.7	853.7	644.2	50.6	43.8	40.4	675.7	610.9	486.9

Table 156: Other specific environmental impacts of heavy-duty vehicle production in 2050.

Size	**Fuel type**	**Acidification 2050** (kg SO_2eq/veh.)			**Eutrophication 2050** (kg PO_4eq/veh.)			**PM formation 2050** (kg $PM_{2.5}$eq/veh.)		
		SQ	**Bal**	**All-In**	**SQ**	**Bal**	**All-In**	**SQ**	**Bal**	**All-In**
3.5-7.5 t Rigid	diesel	58.8	70.0	68.5	5.0	6.0	5.9	45.5	54.0	53.0
	CNG	59.8	71.0	69.5	5.2	6.2	6.2	45.8	54.4	53.4
	DME	58.8	70.0	68.5	5.0	6.0	5.9	45.5	54.0	53.0
	Methanol	58.8	70.0	68.5	5.0	6.0	5.9	45.5	54.0	53.0
	H2 ICE	62.2	73.4	71.9	5.7	6.7	6.7	47.1	55.7	54.7
	FCEV	107.7	103.6	82.7	6.7	6.3	6.2	76.0	72.5	60.0
	BEV	395.7	372.9	253.1	12.8	11.0	10.3	252.8	234.1	162.7
7.5-16t Regional	diesel	93.7	115.4	113.2	7.5	9.7	9.6	72.2	89.3	87.7
	CNG	95.7	117.5	115.2	8.0	10.2	10.1	73.0	90.1	88.5
	DME	93.7	115.4	113.2	7.5	9.7	9.6	72.2	89.3	87.7
	Methanol	93.7	115.4	113.2	7.5	9.7	9.6	72.2	89.3	87.7
	H2 ICE	100.6	122.4	120.1	9.0	11.2	11.1	75.6	92.7	91.2
	FCEV	171.3	165.6	136.9	11.3	10.9	10.6	122.0	117.2	100.0
	BEV	740.5	697.3	470.6	23.0	19.6	18.3	471.1	435.7	300.7
16-40t Long-haul	diesel	209.8	262.0	252.1	17.0	20.9	20.7	165.8	203.8	197.2
	LNG	210.4	262.5	252.6	17.0	21.0	20.8	166.5	204.5	197.9
	DME	209.8	262.0	252.1	17.0	20.9	20.7	165.8	203.8	197.2
	Methanol	209.8	262.0	252.1	17.0	20.9	20.7	165.8	203.8	197.2
	H2 ICE	228.1	280.3	270.4	21.0	24.9	24.7	174.9	212.9	206.3
	FCEV	512.8	497.4	420.8	32.0	30.8	30.2	360.3	347.3	301.1
	CEV	654.0	620.9	451.1	27.7	25.1	24.0	440.2	412.8	311.2
40-60t Long-haul XL	diesel	282.2	350.2	337.3	22.4	27.6	27.3	222.1	271.6	263.0
	LNG	283.1	351.0	338.2	22.5	27.7	27.4	223.1	272.6	264.0
	DME	282.2	350.2	337.3	22.4	27.6	27.3	222.1	271.6	263.0
	Methanol	282.2	350.2	337.3	22.4	27.6	27.3	222.1	271.6	263.0
	H2 ICE	304.6	372.5	359.7	27.3	32.5	32.2	233.1	282.6	274.1
	FCEV	667.9	647.4	545.2	41.1	39.4	38.7	469.2	451.8	390.2
	CEV	863.7	820.0	595.0	36.3	32.8	31.3	580.9	544.6	409.9
City bus	diesel	114.0	127.9	126.6	7.6	9.1	9.1	87.6	98.7	98.0
	CNG	115.8	129.7	128.4	8.0	9.6	9.6	88.3	99.4	98.6
	DME	114.0	127.9	126.6	7.6	9.1	9.1	87.6	98.7	98.0
	Methanol	114.0	127.9	126.6	7.6	9.1	9.1	87.6	98.7	98.0
	H2 ICE	120.0	133.9	132.6	8.9	10.4	10.4	90.6	101.7	100.9
	FCEV	349.6	285.1	234.8	18.9	14.7	14.5	240.7	187.5	157.6
	BEV	667.4	625.5	429.9	20.9	17.5	16.3	429.1	394.6	278.3
Coach	diesel	259.2	293.6	282.5	16.4	18.0	17.9	204.3	226.5	219.8
	LNG	259.8	294.2	283.1	16.4	18.0	18.0	205.0	227.2	220.5
	DME	259.2	293.6	282.5	16.4	18.0	17.9	204.3	226.5	219.8
	Methanol	259.2	293.6	282.5	16.4	18.0	17.9	204.3	226.5	219.8
	H2 ICE	279.2	313.6	302.5	20.7	22.3	22.3	214.2	236.3	229.7
	FCEV	521.2	333.1	270.2	29.4	17.6	17.3	372.7	217.3	179.9
	CEV	723.9	675.5	503.7	27.5	23.3	22.3	491.0	450.9	348.7

Table 157: Specific environmental impacts of light-duty vehicle disposal.

Size	Fuel type	Greenhouse gases (kg CO_2eq/veh.)			Acidification (kg SO_2eq/veh.)		Eutrophication (kg PO_4eq/veh.)		PM formation (kg $PM_{2.5}$eq/veh.)	
		2020	**2050**	**2050b**	**2020**	**2050**	**2020**	**2050**	**2020**	**2050**
small	gasoline	347	301	13	0.24	0.17	0.05	0.03	0.21	0.15
	diesel	347	301	13	0.24	0.17	0.05	0.03	0.21	0.15
	CNG	372	326	14	0.25	0.18	0.05	0.03	0.23	0.16
	DME	347	301	13	0.24	0.17	0.05	0.03	0.21	0.15
	Methanol	347	301	13	0.24	0.17	0.05	0.03	0.21	0.15
	H2 ICE	404	358	16	0.27	0.20	0.06	0.03	0.24	0.17
	FCEV	434	388	29	0.65	0.58	0.08	0.05	0.53	0.46
	BEV	504	347	29	2.23	1.77	0.19	0.11	1.66	1.23
medium	gasoline	432	377	16	0.31	0.22	0.06	0.03	0.27	0.19
	diesel	432	377	16	0.31	0.22	0.06	0.03	0.27	0.19
	CNG	474	418	18	0.33	0.24	0.07	0.04	0.29	0.21
	DME	432	377	16	0.31	0.22	0.06	0.03	0.27	0.19
	Methanol	432	377	16	0.31	0.22	0.06	0.03	0.27	0.19
	H2 ICE	529	474	21	0.35	0.27	0.07	0.04	0.31	0.23
	FCEV	607	552	48	1.15	1.07	0.12	0.08	0.92	0.84
	BEV	733	463	48	4.16	3.33	0.33	0.20	3.07	2.29
large	gasoline	532	466	20	0.37	0.27	0.08	0.04	0.32	0.23
	diesel	532	466	20	0.37	0.27	0.08	0.04	0.32	0.23
	CNG	581	515	22	0.39	0.29	0.08	0.04	0.35	0.25
	DME	532	466	20	0.37	0.27	0.08	0.04	0.32	0.23
	Methanol	532	466	20	0.37	0.27	0.08	0.04	0.32	0.23
	H2 ICE	648	582	25	0.41	0.31	0.09	0.05	0.38	0.28
	FCEV	766	700	66	1.59	1.49	0.15	0.11	1.27	1.17
	BEV	863	551	55	4.80	3.83	0.38	0.23	3.54	2.64
SUV	gasoline	522	456	20	0.37	0.27	0.08	0.04	0.33	0.23
	diesel	522	456	20	0.37	0.27	0.08	0.04	0.33	0.23
	CNG	577	512	22	0.40	0.30	0.08	0.04	0.35	0.26
	DME	522	456	20	0.37	0.27	0.08	0.04	0.33	0.23
	Methanol	522	456	20	0.37	0.27	0.08	0.04	0.33	0.23
	H2 ICE	653	588	26	0.43	0.33	0.09	0.05	0.39	0.29
	FCEV	765	699	64	1.54	1.44	0.15	0.11	1.23	1.13
	BEV	963	585	65	5.99	4.79	0.46	0.28	4.40	3.29
LCV	gasoline	651	564	25	0.46	0.33	0.10	0.05	0.41	0.28
	diesel	651	564	25	0.46	0.33	0.10	0.05	0.41	0.28
	CNG	728	642	28	0.50	0.36	0.10	0.05	0.44	0.32
	DME	651	564	25	0.46	0.33	0.10	0.05	0.41	0.28
	Methanol	651	564	25	0.46	0.33	0.10	0.05	0.41	0.28
	H2 ICE	834	748	33	0.54	0.41	0.11	0.06	0.49	0.37
	FCEV	912	826	62	1.38	1.24	0.16	0.11	1.12	1.00
	BEV	1,488	853	107	10.36	8.30	0.78	0.48	7.59	5.68

Table 158: Specific environmental impacts of heavy-duty vehicle disposal.

Size	Fuel type	Greenhouse gases (kg CO_2eq/veh.)			Acidification (kg SO_2eq/veh.)		Eutrophication (kg PO_4eq/veh.)		PM formation (kg $PM_{2.5}$eq/veh.)	
		2020	2020	2050	2020	2050	2020	2050	2020	2050
3.5-7.5 t Rigid	diesel	207	202	10	0.18	0.16	0.02	0.02	0.16	0.14
	CNG	269	264	13	0.21	0.19	0.03	0.03	0.19	0.17
	DME	207	202	10	0.18	0.16	0.02	0.02	0.16	0.14
	Methanol	207	202	10	0.18	0.16	0.02	0.02	0.16	0.14
	H2 ICE	358	353	17	0.25	0.23	0.04	0.03	0.23	0.21
	FCEV	355	277	24	1.54	1.26	0.12	0.08	1.15	0.90
	BEV	872	422	77	8.22	6.64	0.58	0.37	5.99	4.53
7.5-16t Regional	diesel	386	379	19	0.31	0.28	0.04	0.04	0.28	0.25
	CNG	511	503	25	0.36	0.34	0.05	0.05	0.34	0.31
	DME	386	379	19	0.31	0.28	0.04	0.04	0.28	0.25
	Methanol	386	379	19	0.31	0.28	0.04	0.04	0.28	0.25
	H2 ICE	693	686	34	0.44	0.42	0.07	0.06	0.42	0.40
	FCEV	706	600	52	2.45	2.07	0.19	0.14	1.86	1.52
	BEV	1,661	809	146	15.56	12.56	1.09	0.70	11.35	8.57
16-40t Long-haul	diesel	1,134	1,101	59	1.12	1.01	0.14	0.12	0.97	0.87
	LNG	1,134	1,101	59	1.12	1.01	0.14	0.12	0.97	0.87
	DME	1,134	1,101	59	1.12	1.01	0.14	0.12	0.97	0.87
	Methanol	1,134	1,101	59	1.12	1.01	0.14	0.12	0.97	0.87
	H2 ICE	1,948	1,915	99	1.48	1.36	0.20	0.19	1.35	1.25
	FCEV	2,303	2,019	188	7.68	6.68	0.59	0.46	5.88	4.96
	CEV	1,943	1,308	147	11.97	9.74	0.88	0.58	8.83	6.77
40-60t Long-haul XL	diesel	1,528	1,486	79	1.48	1.33	0.18	0.16	1.29	1.15
	LNG	1,528	1,486	79	1.48	1.33	0.18	0.16	1.29	1.15
	DME	1,528	1,486	79	1.48	1.33	0.18	0.16	1.29	1.15
	Methanol	1,528	1,486	79	1.48	1.33	0.18	0.16	1.29	1.15
	H2 ICE	2,520	2,478	128	1.91	1.77	0.26	0.24	1.75	1.61
	FCEV	2,983	2,604	242	10.07	8.74	0.78	0.60	7.70	6.47
	CEV	2,590	1,748	196	15.87	12.91	1.16	0.78	11.71	8.97
City bus	diesel	269	265	36	0.57	0.55	0.08	0.08	0.78	0.77
	CNG	377	373	42	0.61	0.60	0.09	0.08	0.84	0.82
	DME	269	265	36	0.57	0.55	0.08	0.08	0.78	0.77
	Methanol	269	265	36	0.57	0.55	0.08	0.08	0.78	0.77
	H2 ICE	534	529	49	0.68	0.67	0.10	0.10	0.91	0.89
	FCEV	1,001	811	132	5.59	4.93	0.42	0.33	4.53	3.91
	BEV	1,361	625	146	13.76	11.17	0.99	0.65	10.36	7.97
Coach	diesel	739	696	116	2.24	2.09	0.27	0.25	2.80	2.67
	LNG	739	696	116	2.24	2.09	0.27	0.25	2.80	2.67
	DME	739	696	116	2.24	2.09	0.27	0.25	2.80	2.67
	Methanol	739	696	116	2.24	2.09	0.27	0.25	2.80	2.67
	H2 ICE	1,627	1,585	159	2.63	2.48	0.34	0.32	3.22	3.08
	FCEV	1,731	1,494	226	7.56	6.73	0.64	0.53	6.80	6.03
	CEV	1,589	942	205	13.14	10.86	1.02	0.72	10.71	8.60

15.2.3 Specific material demand for vehicles and fuel supply chain infrastructure

Table 159: Specific material demand for light-duty vehicles I.

Size	Fuel type	Lithium (kg/vehicle)			Cobalt (kg/vehicle)			Nickel (kg/vehicle)		
		SQ	Bal	All-In	SQ	Bal	All-In	SQ	Bal	All-In
small	gasoline		0.1	0.6		0.1	0.0	1.4	2.2	2.0
	diesel		0.1	0.6		0.1	0.0	1.4	2.2	2.0
	CNG		0.1	0.6		0.1	0.0	1.4	2.2	2.0
	DME		0.1	0.6		0.1	0.0	1.4	2.2	2.0
	Methanol		0.1	0.6		0.1	0.0	1.4	2.2	2.0
	H2 ICE		0.1	0.6		0.1	0.0	4.3	4.5	4.1
	FCEV	0.1	0.1	0.6	0.2	0.1	0.0	4.1	4.1	3.7
	BEV	5.4	4.0	17.8	8.5	3.2	1.0	27.0	26.7	17.0
medium	gasoline		0.2	0.8		0.1	0.0	1.6	2.9	2.6
	diesel		0.2	0.8		0.1	0.0	1.6	2.9	2.6
	CNG		0.2	0.8		0.1	0.0	1.6	2.9	2.6
	DME		0.2	0.8		0.1	0.0	1.6	2.9	2.6
	Methanol		0.2	0.8		0.1	0.0	1.6	2.9	2.6
	H2 ICE		0.2	0.8		0.1	0.0	6.9	6.8	6.0
	FCEV	0.2	0.2	0.8	0.3	0.1	0.0	6.5	6.5	5.9
	BEV	10.5	7.7	33.3	16.6	6.1	1.9	51.7	50.5	30.8
large	gasoline		0.2	0.9		0.1	0.1	1.9	3.4	3.1
	diesel		0.2	0.9		0.1	0.1	1.9	3.4	3.1
	CNG		0.2	0.9		0.1	0.1	1.9	3.4	3.1
	DME		0.2	0.9		0.1	0.1	1.9	3.4	3.1
	Methanol		0.2	0.9		0.1	0.1	1.9	3.4	3.1
	H2 ICE		0.2	0.9		0.1	0.1	8.1	8.0	6.5
	FCEV	0.2	0.2	0.9	0.4	0.1	0.1	7.8	7.7	6.8
	BEV	12.2	8.8	33.3	19.4	7.0	1.9	60.4	58.2	31.4
SUV	gasoline		0.2	1.0		0.2	0.1	1.9	3.5	3.2
	diesel		0.2	1.0		0.2	0.1	1.9	3.5	3.2
	CNG		0.2	1.0		0.2	0.1	1.9	3.5	3.2
	DME		0.2	1.0		0.2	0.1	1.9	3.5	3.2
	Methanol		0.2	1.0		0.2	0.1	1.9	3.5	3.2
	H2 ICE		0.2	1.0		0.2	0.1	8.6	8.8	7.7
	FCEV	0.3	0.2	1.0	0.4	0.2	0.1	8.6	8.5	7.6
	BEV	15.9	11.1	45.4	25.2	8.8	2.6	77.8	72.9	41.8
LCV	gasoline		0.2	1.2		0.2	0.1	3.8	5.5	5.1
	diesel		0.2	1.2		0.2	0.1	3.8	5.5	5.1
	CNG		0.2	1.2		0.2	0.1	3.8	5.5	5.1
	DME		0.2	1.2		0.2	0.1	3.8	5.5	5.1
	Methanol		0.2	1.2		0.2	0.1	3.8	5.5	5.1
	H2 ICE		0.2	1.2		0.2	0.1	12.9	13.0	11.1
	FCEV	0.3	0.2	1.2	0.5	0.2	0.1	12.6	12.5	11.1
	BEV	28.9	19.4	71.9	46.0	15.4	4.2	141.6	127.2	66.5

Table 160: Specific material demand for light-duty vehicles II.

Size	**Fuel type**	**Copper** (kg/vehicle)			**Neodymium** (kg/vehicle)			**PGM** (g/vehicle)		
		SQ	**Bal**	**SQ**	**Bal**	**All-In**	**All-In**	**SQ**	**Bal**	**All-In**
small	gasoline	13	17	17		0.16	0.16	5	5	5
	diesel	13	18	17		0.16	0.16	7	7	7
	CNG	13	17	17		0.16	0.16	9	9	9
	DME	13	18	17		0.16	0.16	7	7	7
	Methanol	13	17	17		0.16	0.16	5	5	5
	H2 ICE	13	17	17		0.16	0.16	5	5	5
	FCEV	17	17	16	0.25	0.25	0.25	19	7	7
	BEV	62	50	28	0.25	0.25	0.25			
medium	gasoline	17	26	26		0.34	0.34	5	5	5
	diesel	18	27	26		0.34	0.34	7	7	7
	CNG	17	26	26		0.34	0.34	9	9	9
	DME	18	27	26		0.34	0.34	7	7	7
	Methanol	17	26	26		0.34	0.34	5	5	5
	H2 ICE	17	26	26		0.34	0.34	5	5	5
	FCEV	25	25	24	0.52	0.52	0.52	40	15	15
	BEV	113	89	46	0.52	0.52	0.52			
large	gasoline	22	35	34		0.50	0.50	5	5	5
	diesel	23	36	35		0.50	0.50	7	7	7
	CNG	22	35	34		0.50	0.50	9	9	9
	DME	23	36	35		0.50	0.50	7	7	7
	Methanol	22	35	34		0.50	0.50	5	5	5
	H2 ICE	22	35	34		0.50	0.50	5	5	5
	FCEV	33	33	32	0.76	0.76	0.76	58	22	25
	BEV	136	107	54	0.76	0.76	0.76			
SUV	gasoline	17	34	33		0.47	0.47	5	5	5
	diesel	23	35	34		0.47	0.47	7	7	7
	CNG	22	34	33		0.47	0.47	9	9	9
	DME	23	35	34		0.47	0.47	7	7	7
	Methanol	22	34	33		0.47	0.47	5	5	5
	H2 ICE	22	34	33		0.47	0.47	5	5	5
	FCEV	32	32	31	0.71	0.71	0.71	55	21	21
	BEV	166	126	61	0.71	0.71	0.71			
LCV	gasoline	34	44	43		0.36	0.36	5	5	5
	diesel	35	44	43		0.36	0.36	7	7	7
	CNG	34	44	43		0.36	0.36	9	9	9
	DME	35	44	43		0.36	0.36	7	7	7
	Methanol	34	44	43		0.36	0.36	5	5	5
	H2 ICE	34	44	43		0.36	0.36	5	5	5
	FCEV	43	42	41	0.54	0.54	0.54	41	16	16
	BEV	289	207	90	0.54	0.54	0.54			

Table 161: Specific material demand for heavy-duty vehicles I.

Size	Fuel type	Lithium (kg/vehicle)			Cobalt (kg/vehicle)			Nickel (kg/vehicle)		
		SQ	Bal	All-In	SQ	Bal	All-In	SQ	Bal	All-In
3.5-7.5 t Rigid	diesel		0.2	0.9		0.1	0.1	0.9	2.4	2.1
	CNG		0.2	0.9		0.1	0.1	0.9	2.4	2.1
	DME		0.2	0.9		0.1	0.1	0.9	2.4	2.1
	Methanol		0.2	0.9		0.1	0.1	0.9	2.4	2.1
	H2 ICE		0.2	0.9		0.1	0.1	0.9	2.4	2.1
	FCEV	3.7	2.7	14.4	5.8	2.2	0.8	18.0	18.0	13.2
	BEV	21.1	15.8	83.3	33.4	12.5	4.8	100.5	100.5	72.8
7.5-16t Regional	diesel		0.2	1.3		0.2	0.1	1.5	4.0	3.6
	CNG		0.2	1.3		0.2	0.1	1.5	4.0	3.6
	DME		0.2	1.3		0.2	0.1	1.5	4.0	3.6
	Methanol		0.2	1.3		0.2	0.1	1.5	4.0	3.6
	H2 ICE		0.2	1.3		0.2	0.1	1.5	4.0	3.6
	FCEV	5.0	3.7	19.7	7.9	3.0	1.1	25.1	25.1	18.6
	BEV	39.8	29.9	157.5	63.3	23.7	9.1	190.3	190.3	137.8
16-40t Long-haul	diesel		1.1	6.0		0.9	0.3	3.1	12.1	10.1
	LNG		1.1	6.0		0.9	0.3	25.9	34.8	32.8
	DME		1.1	6.0		0.9	0.3	3.1	12.1	10.1
	Methanol		1.1	6.0		0.9	0.3	3.1	12.1	10.1
	H2 ICE		1.1	6.0		0.9	0.3	3.1	12.1	10.1
	FCEV	13.3	10.0	52.5	21.1	7.9	3.0	67.1	67.1	49.5
	CEV	29.7	22.3	117.4	47.1	17.7	6.8	143.5	143.5	104.4
40-60t Long-haul XL	diesel		1.5	7.8		1.2	0.4	4.3	15.9	13.3
	LNG		1.5	7.8		1.2	0.4	38.9	50.5	47.9
	DME		1.5	7.8		1.2	0.4	4.3	15.9	13.3
	Methanol		1.5	7.8		1.2	0.4	4.3	15.9	13.3
	H2 ICE		1.5	7.8		1.2	0.4	4.3	15.9	13.3
	FCEV	17.7	13.3	70.1	28.1	10.6	4.1	89.3	89.3	65.9
	CEV	39.3	29.5	155.5	62.5	23.4	9.0	190.1	190.1	138.3
City bus	diesel		0.2	0.9		0.1	0.1	24.7	26.7	26.4
	CNG		0.2	0.9		0.1	0.1	24.7	26.7	26.4
	DME		0.2	0.9		0.1	0.1	24.7	3.2	26.4
	Methanol		0.2	0.9		0.1	0.1	24.7	26.7	26.4
	H2 ICE		0.2	0.9		0.1	0.1	24.7	26.7	26.4
	FCEV	8.9	6.6	35.0	14.1	5.3	2.0	67.7	67.7	56.0
	BEV	34.4	25.8	136.1	54.7	20.5	7.9	187.8	187.8	142.4
Coach	diesel		1.5	7.8		1.2	0.5	77.1	87.8	85.2
	LNG		1.5	7.8		1.2	0.5	102.1	112.8	110.2
	DME		1.5	7.8		1.2	0.5	77.1	87.8	85.2
	Methanol		1.5	7.8		1.2	0.5	77.1	87.8	85.2
	H2 ICE		1.5	7.8		1.2	0.5	77.1	87.8	85.2
	FCEV	11.1	8.3	43.8	17.6	6.6	2.5	130.5	130.5	115.9
	CEV	30.2	22.7	119.6	48.0	18.0	6.9	220.3	220.3	180.4

Table 162: Specific material demand for heavy-duty vehicles II.

Size	Fuel type	Copper (kg/vehicle)			Neodymium (kg/vehicle)			PGM (g/vehicle)		
		SQ	**Bal**	**SQ**	**Bal**	**All-In**	**All-In**	**SQ**	**Bal**	**All-In**
3.5-7.5 t Rigid	diesel	11	22	21		0.52	0.52	3	3	3
	CNG	11	22	21		0.52	0.52	3	3	3
	DME	11	22	21		0.52	0.52	3	3	3
	Methanol	11	22	21		0.52	0.52	3	3	3
	H2 ICE	11	22	21		0.52	0.52	3	3	3
	FCEV	52	44	30	0.52	0.52	0.52	4	2	2
	BEV	201	156	78	0.52	0.52	0.52			
7.5-16t Regional	diesel	22	44	43		1.14	1.14	5	5	5
	CNG	22	44	43		1.14	1.14	5	5	5
	DME	22	44	43		1.14	1.14	5	5	5
	Methanol	22	44	43		1.14	1.14	5	5	5
	H2 ICE	22	44	43		1.14	1.14	5	5	5
	FCEV	85	74	55	1.14	1.14	1.14	13	5	5
	BEV	384	298	150	1.14	1.14	1.14			
16-40t Long-haul	diesel	71	115	110		1.97	1.97	9	9	9
	LNG	71	115	110		1.97	1.97	9	9	9
	DME	71	115	110		1.97	1.97	9	9	9
	Methanol	71	115	110		1.97	1.97	9	9	9
	H2 ICE	71	115	110		1.97	1.97	9	9	9
	FCEV	220	191	142	1.97	1.97	1.97	86	33	33
	CEV	360	297	186	1.97	1.97	1.97			
40-60t Long-haul XL	diesel	96	153	146		2.59	2.59	12	12	12
	LNG	96	153	146		2.59	2.59	12	12	12
	DME	96	153	146		2.59	2.59	12	12	12
	Methanol	96	153	146		2.59	2.59	12	12	12
	H2 ICE	96	153	146		2.59	2.59	12	12	12
	FCEV	293	255	189	2.59	2.59	2.59	108	41	41
	CEV	478	394	248	2.59	2.59	2.59			
City bus	diesel	46	67	66		1.11	1.11	5	5	5
	CNG	46	67	66		1.11	1.11	5	5	5
	DME	46	21	66		1.11	1.11	5	5	5
	Methanol	46	67	66		1.11	1.11	5	5	5
	H2 ICE	46	67	66		1.11	1.11	5	5	5
	FCEV	142	123	90	1.11	1.11	1.11	77	30	30
	BEV	361	287	159	1.11	1.11	1.11			
Coach	diesel	149	189	181		1.54	1.54	7	7	7
	LNG	149	189	181		1.54	1.54	7	7	7
	DME	149	189	181		1.54	1.54	7	7	7
	Methanol	149	189	181		1.54	1.54	7	7	7
	H2 ICE	149	189	181		1.54	1.54	7	7	7
	FCEV	271	247	206	1.54	1.54	1.54	77	30	30
	CEV	435	370	258	1.54	1.54	1.54			

Table 163: Specific material demand for fuel supply chain infrastructure I.

Section	Category	Type	unit	Copper (kg/unit)	Nickel (kg/unit)	Silver (kg/unit)	Neodymium (kg/unit)
Power generation	PV standalone	5 MW	*MW*	6,867	1,239	95.7	0.0
	PV slanted roof	0.005 MW	*MW*	10,376	675	72.0	0.0
	Wind onshore	2020 (2.9 MW)	*MW*	4,314	2,569	4.9	125.9
		2030 (3.8 MW)	*MW*	4,590	2,733	5.2	134.0
		2050 (6 MW)	*MW*	5,370	3,197	6.1	156.7
	Wind offshore	2020 (4.15 MW)	*MW*	3,233	2,575	2.5	336.1
		2030 (8.5 MW)	*MW*	4,022	3,203	3.1	418.1
		2050 (15 MW)	*MW*	4,771	3,800	3.7	495.9
Transmission & Distribution	Lines/cables	Transmission line / sea cable	*km*	28,000			
		HV line	*km*	780			
		MV line	*km*	1,690			
		LV line	*km*	1,380			
	Transformers	HV-MV	*number*	7,150			
		MV-LV	*number*	600			
Hydrogen	Electrolyser	2020 (10 MW)	*MW*	4,049	4,440	0.2	0.0
		2030 (250 MW)	*MW*	3,197	3,505	0.2	0.0
		2050 (1000 MW)	*MW*	3,197	3,505	0.2	0.0
	H_2 seasonal storage		*m³*		0	0	0.0
Synthesis	DAC		*t CO2/a*	2	8	0.0	0.0
	CO_2 storage		*t CO2/a*		0	0	0.0
	FT synthesis	2020 (90 MW)	*MW*	62,353	18,003	102.8	0.1
		2030 (493 MW)	*MW*	35,243	10,176	58.1	0.0
		2050 (1300 MW)	*MW*	27,788	8,023	45.8	0.0
	CH4 synthesis	2020 (20 MW)	*MW*	196	52	0.0	0.0
		2030 (180 MW)	*MW*	113	30	0.0	0.0
		2050 (500 MW)	*MW*	113	30	0.0	0.0
	MeOH synthesis	2020 (90 MW)	*MW*	69,930	20,191	115.3	0.1
		2030 (393 MW)	*MW*	42,957	12,403	70.8	0.0
		2050 (1000 MW)	*MW*	30,969	8,942	51.1	0.0
	DME synthesis	2020 (90 MW)	*MW*	97,305	28,095	160.4	0.1
		2030 (393 MW)	*MW*	59,590	17,206	98.3	0.1
		2050 (1000 MW)	*MW*	43,097	12,444	71.1	0.0
Charging infrastructure	Charging Points	AC 11 kW	*number*	0			
		AC 44 kW	*number*	7			
	Overhead line	wire	*km*	4,240			
		other parts	*km*	3,426			
	H_2 filling station	car pump	*number*	14			
		truck pump	*number*	97			

Table 164: Specific material demand for fuel supply chain infrastructure II.

Section	Category	Type	unit	REE, others (kg/unit)	Lithium (g/unit)	Cobalt (g/unit)	Platinum (g/unit)
Power generation	PV standalone	5 MW	*MW*	0.0	0.4	18	8
	PV slanted roof	0.005 MW	*MW*	0.1	0.4	27	11
	Wind onshore	2020 (2.9 MW)	*MW*	297.4	0.5	9	4
		2030 (3.8 MW)	*MW*	316.3	0.5	10	5
		2050 (6 MW)	*MW*	370.1	0.6	12	5
	Wind offshore	2020 (4.15 MW)	*MW*	793.7	0.6	7	3
		2030 (8.5 MW)	*MW*	987.3	0.7	8	3
		2050 (15 MW)	*MW*	1,171.2	0.8	10	4
Hydrogen	Electrolyser	2020 (10 MW)	*MW*	0.0	0.1	1,630	158
		2030 (250 MW)	*MW*	0.0	0.1	1,287	125
		2050 (1000 MW)	*MW*	0.0	0.1	1,287	125
	H_2 seasonal storage		*m³*		0.0	0.0	0
Synthesis	DAC		*t CO_2/a*	0.0	0.0	0	0
	CO_2 storage		*t CO_2/a*		0.0	0.0	0
	FT synthesis	2020 (90 MW)	*MW*	0.1	2.2	315	75
		2030 (493 MW)	*MW*	0.1	1.2	178	43
		2050 (1300 MW)	*MW*	0.1	1.0	140	34
	CH4 synthesis	2020 (20 MW)	*MW*	0.0	0.0	7	0
		2030 (180 MW)	*MW*	0.0	0.0	4	0
		2050 (500 MW)	*MW*	0.0	0.0	4	0
	MeOH synthesis	2020 (90 MW)	*MW*	0.1	2.4	353	85
		2030 (393 MW)	*MW*	0.1	1.5	217	52
		2050 (1000 MW)	*MW*	0.1	1.1	157	37
	DME synthesis	2020 (90 MW)	*MW*	0.2	3.4	492	118
		2030 (393 MW)	*MW*	0.1	2.1	301	72
		2050 (1000 MW)	*MW*	0.1	1.5	218	52

15.2.4 Annual GHG emissions in the 100% scenarios

Table 165: Annual GHG emissions in the 100% scenarios (million tons CO_2 equivalents); 2030.

			Total	Contributions			Vehicle categories		
				Opera-tion	FSC in-frastruc-ture	Vehicle produc-tion	LDV	HDV	Non-road
Domestic	FT Fuel	Status Quo	1,370	1,041	205	124	744	481	145
		Balanced	1,268	938	185	145	722	431	115
		All-In	1,264	894	176	194	752	399	113
	Methane	Status Quo	1,314	974	204	136	735	466	113
		Balanced	1,238	905	180	153	719	420	99
		All-In	1,240	872	167	201	753	391	97
	DME	Status Quo	1,373	1,011	235	127	751	482	141
		Balanced	1,278	930	201	147	733	433	111
		All-In	1,281	898	188	196	769	403	110
	MeOH	Status Quo	1,350	1,008	220	123	736	471	142
		Balanced	1,259	926	190	143	721	426	112
		All-In	1,260	894	175	192	755	396	110
	H_2 Comb	Status Quo	1,285	976	149	159	737	447	100
		Balanced	1,208	906	130	172	717	404	86
		All-In	1,210	873	120	218	750	376	85
	FCEV	Status Quo	1,312	982	116	214	757	444	111
		Balanced	1,213	912	112	189	716	401	97
		All-In	1,215	879	104	232	746	373	95
	BEV	Status Quo	1,334	1,010	73	251	783	416	136
		Balanced	1,217	929	65	223	736	375	106
		All-In	1,196	897	60	240	743	349	105
International	FT Fuel	Status Quo	1,311	1,041	146	124	713	459	138
		Balanced	1,215	938	132	145	693	412	110
		All-In	1,214	894	125	194	725	381	108
	Methane	Status Quo	1,252	975	142	136	705	442	105
		Balanced	1,184	906	126	153	694	400	90
		All-In	1,191	873	117	201	730	372	89
	DME	Status Quo	1,310	1,011	172	127	720	456	133
		Balanced	1,223	930	147	147	708	411	105
		All-In	1,231	898	137	196	745	383	103
	MeOH	Status Quo	1,289	1,008	159	123	708	448	134
		Balanced	1,207	926	138	143	697	405	104
		All-In	1,212	894	126	192	732	377	103
	H_2 Comb	Status Quo	1,253	976	118	159	722	436	95
		Balanced	1,180	906	102	172	705	394	81
		All-In	1,185	873	94	218	738	367	80
	FCEV	Status Quo	1,288	982	91	214	749	434	105
		Balanced	1,190	912	88	189	707	392	91
		All-In	1,193	879	82	232	738	365	90
	BEV	Status Quo	1,318	1,010	56	251	777	411	129
		Balanced	1,203	929	51	223	731	371	101
		All-In	1,183	897	47	240	738	345	100

Table 166: Annual GHG emissions in the 100% scenarios (million tons CO_2 equivalents); 2050a.

			Total	Contributions			Vehicle categories		
				Opera-tion	FSC in-frastruc-ture	Vehicle produc-tion	LDV	HDV	Non-road
Domestic	FT Fuel	Status Quo	223	4	148	71	139	63	21
		Balanced	213	4	121	88	139	57	17
		All-In	241	4	109	129	173	52	17
	Methane	Status Quo	222	17	127	78	140	66	17
		Balanced	216	16	107	93	140	60	16
		All-In	245	16	96	133	172	56	16
	DME	Status Quo	225	5	147	74	140	64	21
		Balanced	214	5	119	90	139	58	17
		All-In	245	5	109	132	175	54	17
	MeOH	Status Quo	208	1	138	69	128	59	21
		Balanced	200	1	113	85	129	55	16
		All-In	228	1	101	126	162	50	16
	H_2 Comb	Status Quo	186	0	86	99	129	47	10
		Balanced	181	0	70	111	127	44	10
		All-In	212	0	62	149	160	41	10
	FCEV	Status Quo	254	0	63	191	190	52	11
		Balanced	209	0	61	148	152	45	11
		All-In	236	0	55	181	182	43	11
	BEV	Status Quo	273	1	60	212	210	37	26
		Balanced	231	1	54	176	176	33	22
		All-In	237	1	49	187	185	30	22
International	FT Fuel	Status Quo	194	4	120	71	124	53	17
		Balanced	190	4	98	88	127	49	14
		All-In	222	4	89	129	163	45	14
	Methane	Status Quo	203	19	107	78	130	59	15
		Balanced	201	17	91	93	132	55	14
		All-In	231	17	82	133	166	51	14
	DME	Status Quo	199	5	120	74	127	55	17
		Balanced	193	5	98	90	129	50	14
		All-In	226	5	90	132	166	47	14
	MeOH	Status Quo	183	1	114	69	115	51	17
		Balanced	180	1	94	85	119	48	13
		All-In	211	1	84	126	154	44	13
	H_2 Comb	Status Quo	170	0	71	99	120	42	8
		Balanced	169	0	58	111	121	40	8
		All-In	201	0	51	149	155	38	8
	FCEV	Status Quo	243	0	52	191	186	48	9
		Balanced	198	0	50	148	147	41	9
		All-In	226	0	45	181	178	39	9
	BEV	Status Quo	264	1	51	212	206	35	23
		Balanced	223	1	46	176	173	31	19
		All-In	230	1	42	187	183	28	19

Table 167: Annual GHG emissions in the 100% scenarios (million tons CO_2 equivalents); 2050b.

			Total	Contributions			Vehicle categories		
				Opera-tion	FSC in-frastruc-ture	Vehicle produc-tion	LDV	HDV	Non-road
Domestic	FT Fuel	Status Quo	72	4	39	29	46	20	6
		Balanced	69	4	32	34	46	18	5
		All-In	75	4	29	42	53	17	5
	Methane	Status Quo	82	17	33	32	49	26	7
		Balanced	79	16	28	35	49	24	7
		All-In	84	16	25	43	55	22	7
	DME	Status Quo	74	5	39	30	47	20	6
		Balanced	70	5	32	34	46	19	5
		All-In	76	5	29	43	54	17	5
	MeOH	Status Quo	67	1	36	29	42	19	6
		Balanced	64	1	30	33	42	17	5
		All-In	70	1	27	42	49	16	5
	H_2 Comb	Status Quo	59	0	23	36	41	15	3
		Balanced	57	0	19	39	41	14	3
		All-In	63	0	16	47	47	13	3
	FCEV	Status Quo	73	0	17	56	53	16	3
		Balanced	62	0	16	46	45	14	3
		All-In	67	0	14	52	51	13	3
	BEV	Status Quo	81	1	15	65	61	13	7
		Balanced	71	1	13	56	53	12	6
		All-In	69	1	12	56	53	11	6
International	FT Fuel	Status Quo	66	4	33	29	43	18	6
		Balanced	64	4	27	34	43	17	5
		All-In	70	4	24	42	51	15	5
	Methane	Status Quo	80	19	29	32	48	25	7
		Balanced	77	17	25	35	48	23	7
		All-In	82	17	22	43	54	22	6
	DME	Status Quo	68	5	33	30	44	19	6
		Balanced	66	5	27	34	44	17	5
		All-In	72	5	25	43	52	16	5
	MeOH	Status Quo	62	1	31	29	39	17	6
		Balanced	60	1	26	33	40	16	4
		All-In	66	1	23	42	47	15	4
	H_2 Comb	Status Quo	55	0	19	36	39	14	2
		Balanced	54	0	16	39	39	13	2
		All-In	61	0	14	47	46	12	2
	FCEV	Status Quo	70	0	14	56	52	15	3
		Balanced	59	0	13	46	44	13	3
		All-In	65	0	12	52	50	12	2
	BEV	Status Quo	79	1	13	65	61	12	6
		Balanced	69	1	12	56	53	11	5
		All-In	68	1	11	56	52	10	5

15.2.5 Cumulative GHG emissions in the 100% scenarios

Table 168: Cumulative GHG emissions in the 100% scenarios (million tons CO_2 equivalents); 2050a.

			Total	**Contributions**			**Vehicle categories**		
				Opera-tion	**FSC in-frastruc-ture**	**Vehicle produc-tion**	**LDV**	**HDV**	**Non-road**
Domestic	FT Fuel	Status Quo	29,966	20,041	6,470	3,455	16,770	10,043	3,153
		Balanced	27,916	18,545	5,409	3,962	16,112	9,159	2,645
		All-In	28,030	17,898	4,938	5,193	16,810	8,603	2,617
	Methane	Status Quo	28,784	19,525	5,506	3,753	16,641	9,677	2,467
		Balanced	27,399	18,517	4,702	4,180	16,194	8,912	2,294
		All-In	27,655	18,028	4,252	5,375	16,959	8,430	2,266
	DME	Status Quo	29,991	19,574	6,870	3,547	16,815	10,132	3,044
		Balanced	28,104	18,418	5,657	4,029	16,309	9,256	2,539
		All-In	28,424	17,949	5,214	5,260	17,156	8,752	2,516
	MeOH	Status Quo	29,321	19,598	6,307	3,416	16,353	9,835	3,133
		Balanced	27,600	18,439	5,263	3,898	15,928	9,061	2,611
		All-In	27,808	17,962	4,717	5,129	16,696	8,530	2,582
	H_2 Comb	Status Quo	27,475	18,924	4,123	4,428	16,265	9,140	2,069
		Balanced	26,107	17,934	3,436	4,737	15,755	8,444	1,909
		All-In	26,414	17,458	3,084	5,873	16,531	8,003	1,880
	FCEV	Status Quo	28,693	19,151	3,083	6,459	17,231	9,074	2,388
		Balanced	26,660	18,162	2,967	5,530	16,027	8,402	2,230
		All-In	26,940	17,685	2,711	6,544	16,761	7,973	2,206
	BEV	Status Quo	29,259	19,515	2,350	7,395	17,907	8,345	3,007
		Balanced	26,912	18,358	2,067	6,487	16,677	7,730	2,505
		All-In	26,603	17,890	1,877	6,836	16,777	7,334	2,492
International	FT Fuel	Status Quo	28,285	20,041	4,789	3,455	15,928	9,424	2,933
		Balanced	26,517	18,545	4,011	3,962	15,402	8,642	2,473
		All-In	26,757	17,898	3,665	5,193	16,167	8,143	2,447
	Methane	Status Quo	27,341	19,550	4,038	3,753	15,886	9,158	2,297
		Balanced	26,182	18,538	3,464	4,180	15,568	8,484	2,129
		All-In	26,565	18,047	3,143	5,375	16,409	8,052	2,103
	DME	Status Quo	28,319	19,574	5,198	3,547	16,021	9,481	2,817
		Balanced	26,732	18,418	4,285	4,029	15,657	8,716	2,359
		All-In	27,161	17,949	3,951	5,260	16,560	8,262	2,339
	MeOH	Status Quo	27,764	19,598	4,750	3,416	15,614	9,241	2,909
		Balanced	26,306	18,439	3,969	3,898	15,314	8,555	2,437
		All-In	26,650	17,962	3,559	5,129	16,158	8,081	2,411
	H_2 Comb	Status Quo	26,653	18,924	3,302	4,428	15,860	8,834	1,959
		Balanced	25,422	17,934	2,750	4,737	15,431	8,191	1,800
		All-In	25,799	17,458	2,468	5,873	16,248	7,777	1,774
	FCEV	Status Quo	28,087	19,151	2,477	6,459	16,997	8,822	2,269
		Balanced	26,076	18,162	2,384	5,530	15,797	8,168	2,111
		All-In	26,407	17,685	2,178	6,544	16,558	7,761	2,088
	BEV	Status Quo	28,794	19,515	1,885	7,395	17,757	8,227	2,810
		Balanced	26,515	18,358	1,670	6,487	16,537	7,624	2,354
		All-In	26,245	17,890	1,519	6,836	16,663	7,240	2,342

Table 169: Cumulative GHG emissions in the 100% scenarios (million tons CO_2 equivalents); 2050b.

			Total	Contributions			Vehicle categories		
				Operation	FSC infrastructure	Vehicle production	LDV	HDV	Non-road
Domestic	FT Fuel	Status Quo	28,995	20,041	5,769	3,185	16,174	9,765	3,055
		Balanced	27,017	18,545	4,843	3,629	15,536	8,913	2,568
		All-In	27,034	17,898	4,433	4,703	16,111	8,382	2,541
	Methane	Status Quo	27,908	19,525	4,938	3,445	16,079	9,422	2,407
		Balanced	26,563	18,517	4,227	3,820	15,643	8,684	2,236
		All-In	26,718	18,028	3,828	4,862	16,288	8,222	2,209
	DME	Status Quo	29,009	19,574	6,170	3,264	16,221	9,840	2,948
		Balanced	27,196	18,418	5,091	3,687	15,734	8,999	2,463
		All-In	27,406	17,949	4,696	4,760	16,449	8,516	2,441
	MeOH	Status Quo	28,412	19,598	5,661	3,152	15,803	9,566	3,042
		Balanced	26,748	18,439	4,734	3,575	15,389	8,817	2,542
		All-In	26,860	17,962	4,249	4,649	16,037	8,309	2,514
	H_2 Comb	Status Quo	26,652	18,924	3,703	4,026	15,703	8,927	2,023
		Balanced	25,327	17,934	3,094	4,298	15,217	8,248	1,862
		All-In	25,530	17,458	2,782	5,290	15,874	7,821	1,835
	FCEV	Status Quo	27,699	19,151	2,775	5,772	16,513	8,853	2,333
		Balanced	25,817	18,162	2,672	4,983	15,434	8,206	2,176
		All-In	25,998	17,685	2,444	5,869	16,056	7,790	2,152
	BEV	Status Quo	28,205	19,515	2,084	6,606	17,108	8,198	2,898
		Balanced	26,025	18,358	1,833	5,834	16,007	7,602	2,416
		All-In	25,696	17,890	1,665	6,141	16,076	7,216	2,403
International	FT Fuel	Status Quo	27,470	20,041	4,244	3,185	15,413	9,198	2,859
		Balanced	25,740	18,545	3,566	3,629	14,888	8,437	2,414
		All-In	25,867	17,898	3,266	4,703	15,522	7,956	2,389
	Methane	Status Quo	26,579	19,550	3,584	3,445	15,384	8,946	2,249
		Balanced	25,438	18,538	3,080	3,820	15,065	8,291	2,082
		All-In	25,709	18,047	2,799	4,862	15,778	7,874	2,057
	DME	Status Quo	27,482	19,574	4,643	3,264	15,498	9,241	2,743
		Balanced	25,939	18,418	3,835	3,687	15,138	8,500	2,301
		All-In	26,248	17,949	3,538	4,760	15,904	8,062	2,282
	MeOH	Status Quo	26,987	19,598	4,236	3,152	15,131	9,019	2,836
		Balanced	25,560	18,439	3,546	3,575	14,828	8,350	2,382
		All-In	25,794	17,962	3,184	4,649	15,544	7,894	2,356
	H_2 Comb	Status Quo	25,911	18,924	2,962	4,026	15,341	8,649	1,921
		Balanced	24,706	17,934	2,474	4,298	14,926	8,018	1,762
		All-In	24,972	17,458	2,224	5,290	15,619	7,616	1,737
	FCEV	Status Quo	27,151	19,151	2,228	5,772	16,303	8,624	2,225
		Balanced	25,290	18,162	2,145	4,983	15,229	7,994	2,067
		All-In	25,516	17,685	1,962	5,869	15,873	7,598	2,045
	BEV	Status Quo	27,789	19,515	1,668	6,606	16,976	8,093	2,720
		Balanced	25,670	18,358	1,478	5,834	15,883	7,507	2,280
		All-In	25,375	17,890	1,344	6,141	15,975	7,132	2,268

Table 170: Cumulative GHG emissions in the 100% scenarios – build-up of fuel supply chain infrastructure (million tons CO_2 equivalents); 2050a.

			PV	Wind	Electro-lysers	DAC	Fuel syn-thesis	Distri-bution	Char-ging	Other
Domestic	FT Fuel	Status Quo	3,663	1,201	186	714	686	0	0	20
		Balanced	3,056	1,006	154	593	584	0	0	17
		All-In	2,786	920	139	539	539	0	0	15
	Methane	Status Quo	3,316	1,097	162	550	6	329	22	24
		Balanced	2,799	928	136	463	5	329	22	20
		All-In	2,509	833	122	414	5	329	22	18
	DME	Status Quo	3,707	1,221	164	661	1,098	0	0	20
		Balanced	3,047	1,006	134	541	913	0	0	16
		All-In	2,808	928	123	498	842	0	0	15
	MeOH	Status Quo	3,432	1,132	157	709	860	0	0	18
		Balanced	2,858	945	130	590	726	0	0	15
		All-In	2,560	848	116	527	653	0	0	14
	H_2 Comb	Status Quo	2,925	964	152	17	18	10	21	15
		Balanced	2,430	803	126	17	18	8	21	12
		All-In	2,178	721	112	16	17	7	21	11
	FCEV	Status Quo	2,202	728	114	0	0	8	21	11
		Balanced	2,119	700	110	0	0	7	21	11
		All-In	1,934	640	100	0	0	7	21	10
	BEV	Status Quo	1,303	445	103	76	70	40	283	31
		Balanced	1,132	388	91	56	52	36	283	28
		All-In	1,007	345	80	56	52	30	283	24
International	FT Fuel	Status Quo	1,910	1,267	186	719	691	0	0	16
		Balanced	1,594	1,064	154	597	588	0	0	13
		All-In	1,454	974	140	543	542	0	0	12
	Methane	Status Quo	1,704	1,207	167	572	6	329	22	31
		Balanced	1,440	1,022	140	481	5	329	22	25
		All-In	1,291	918	125	430	5	329	22	22
	DME	Status Quo	1,934	1,302	165	670	1,113	0	0	15
		Balanced	1,590	1,073	135	548	926	0	0	13
		All-In	1,466	990	124	505	854	0	0	12
	MeOH	Status Quo	1,789	1,204	157	717	867	0	0	15
		Balanced	1,491	1,006	130	596	732	0	0	13
		All-In	1,336	903	116	533	659	0	0	12
	H_2 Comb	Status Quo	2,176	780	157	18	18	10	21	122
		Balanced	1,805	651	130	17	18	8	21	101
		All-In	1,616	585	116	16	17	7	21	90
	FCEV	Status Quo	1,654	583	118	0	0	8	21	95
		Balanced	1,591	561	113	0	0	7	21	91
		All-In	1,452	513	103	0	0	7	21	83
	BEV	Status Quo	840	361	114	76	71	36	283	103
		Balanced	739	310	102	56	52	33	283	95
		All-In	652	279	89	56	52	27	283	81

Table 171: Cumulative GHG emissions in the 100% scenarios – build-up of fuel supply chain infrastructure (million tons CO_2 equivalents); 2050b.

			PV	Wind	Electro-lysers	DAC	Fuel syn-thesis	Distri-bution	Char-ging	Other
Domestic	FT Fuel	Status Quo	3,319	1,021	167	609	635	0	0	18
		Balanced	2,784	857	139	506	542	0	0	15
		All-In	2,547	784	127	460	501	0	0	14
	Methane	Status Quo	3,039	935	148	469	6	298	20	22
		Balanced	2,573	792	125	395	5	298	20	19
		All-In	2,312	711	112	353	4	298	20	17
	DME	Status Quo	3,378	1,039	148	563	1,023	0	0	18
		Balanced	2,784	857	121	461	853	0	0	15
		All-In	2,569	790	112	425	787	0	0	14
	MeOH	Status Quo	3,132	964	142	605	802	0	0	17
		Balanced	2,616	805	118	503	678	0	0	14
		All-In	2,349	723	105	449	611	0	0	13
	H_2 Comb	Status Quo	2,670	821	138	15	17	9	19	14
		Balanced	2,225	685	115	15	16	8	19	11
		All-In	1,999	615	102	14	16	7	19	10
	FCEV	Status Quo	2,015	620	104	0	0	7	19	10
		Balanced	1,939	597	100	0	0	7	19	10
		All-In	1,773	546	91	0	0	6	19	9
	BEV	Status Quo	1,183	378	92	65	64	36	237	29
		Balanced	1,029	330	82	48	48	33	237	27
		All-In	918	294	72	48	47	27	237	23
International	FT Fuel	Status Quo	1,729	1,081	168	613	640	0	0	15
		Balanced	1,451	908	139	509	546	0	0	13
		All-In	1,328	832	127	463	505	0	0	12
	Methane	Status Quo	1,560	1,031	152	488	6	298	20	29
		Balanced	1,322	874	128	411	5	298	20	23
		All-In	1,189	785	114	367	5	298	20	21
	DME	Status Quo	1,760	1,111	149	571	1,037	0	0	14
		Balanced	1,452	917	122	467	865	0	0	12
		All-In	1,340	846	113	430	798	0	0	12
	MeOH	Status Quo	1,631	1,028	143	611	808	0	0	14
		Balanced	1,364	860	118	508	684	0	0	12
		All-In	1,224	772	106	454	616	0	0	11
	H_2 Comb	Status Quo	1,982	665	143	15	17	9	19	112
		Balanced	1,649	556	118	15	17	8	19	93
		All-In	1,480	500	106	14	16	7	19	83
	FCEV	Status Quo	1,510	497	107	0	0	7	19	87
		Balanced	1,453	478	103	0	0	7	19	84
		All-In	1,329	438	94	0	0	6	19	77
	BEV	Status Quo	762	308	102	65	65	32	237	96
		Balanced	671	264	91	48	48	30	237	89
		All-In	593	238	80	48	48	25	237	76

Table 172: Cumulative GHG emissions in the 100% scenarios – vehicle production and disposal (million tons CO_2 equivalents).

			Vehicle production							Dis-posal
			Small cars	Medium cars	Large cars	SUVs	LCV	Trucks	Buses	
2050a	FT Fuel	Status Quo	638	575	305	651	432	562	34	259
		Balanced	708	672	376	795	486	631	36	259
		All-In	1,035	937	515	1,093	698	620	36	259
	Methane	Status Quo	688	635	343	736	478	571	36	265
		Balanced	748	716	397	851	524	640	38	265
		All-In	1,071	975	530	1,139	727	630	38	265
	DME	Status Quo	650	593	326	691	434	562	34	259
		Balanced	721	690	388	819	487	631	36	259
		All-In	1,048	954	527	1,117	700	620	36	259
	MeOH	Status Quo	628	561	306	649	417	562	34	259
		Balanced	699	658	368	778	470	631	36	259
		All-In	1,026	923	507	1,076	683	620	36	259
	H_2 Comb	Status Quo	782	755	405	882	586	698	42	279
		Balanced	823	804	443	965	612	766	44	279
		All-In	1,138	1,054	565	1,238	798	756	44	279
	FCEV	Status Quo	1,071	1,184	689	1,470	813	880	62	290
		Balanced	930	981	560	1,205	703	820	41	290
		All-In	1,250	1,235	547	1,485	898	799	40	290
	BEV	Status Quo	1,166	1,285	682	1,687	1,387	843	65	280
		Balanced	1,059	1,135	605	1,443	1,113	796	57	280
		All-In	1,281	1,249	648	1,505	1,068	752	53	280
2050b	FT Fuel	Status Quo	589	531	281	602	399	526	31	225
		Balanced	651	616	344	728	445	586	33	225
		All-In	937	848	466	988	630	576	33	225
	Methane	Status Quo	634	584	315	677	439	535	33	229
		Balanced	686	655	363	777	479	594	35	229
		All-In	968	881	479	1,029	656	584	35	229
	DME	Status Quo	600	546	300	636	400	526	31	225
		Balanced	662	631	354	749	446	586	33	225
		All-In	947	863	476	1,009	631	576	33	225
	MeOH	Status Quo	581	520	283	601	385	526	31	225
		Balanced	643	605	337	713	432	586	33	225
		All-In	929	836	459	974	617	576	33	225
	H_2 Comb	Status Quo	715	689	369	803	533	641	38	238
		Balanced	752	732	403	877	555	700	40	238
		All-In	1,027	950	510	1,116	718	690	40	238
	FCEV	Status Quo	965	1,059	615	1,311	728	794	55	246
		Balanced	845	886	505	1,085	634	746	37	246
		All-In	1,124	1,108	495	1,330	804	727	36	246
	BEV	Status Quo	1,050	1,150	611	1,505	1,229	764	58	239
		Balanced	959	1,023	545	1,297	994	726	51	239
		All-In	1,153	1,122	583	1,352	956	688	48	239

15.2.6 Further environmental impacts

Table 173: Acidification potential in 2050 (million tons SO_2 equivalents).

			Total	Contributions		
				Operation	FSC infra-structure	Vehicle pro-duction
Domestic	FT Fuel	Status Quo	4.35	1.20	2.26	0.89
		Balanced	4.13	1.20	1.82	1.11
		All-In	4.42	1.20	1.62	1.60
	Methane	Status Quo	3.58	0.92	1.84	0.82
		Balanced	3.48	0.92	1.53	1.03
		All-In	3.79	0.92	1.36	1.51
	DME	Status Quo	4.32	1.17	2.16	0.99
		Balanced	4.12	1.17	1.74	1.21
		All-In	4.46	1.17	1.59	1.70
	MeOH	Status Quo	3.84	1.03	2.01	0.80
		Balanced	3.68	1.03	1.64	1.01
		All-In	3.98	1.03	1.45	1.50
	H_2 Comb	Status Quo	3.21	0.84	1.50	0.87
		Balanced	3.13	0.84	1.22	1.07
		All-In	3.46	0.84	1.07	1.55
	FCEV	Status Quo	5.44	0.00	1.10	4.34
		Balanced	3.26	0.00	1.06	2.21
		All-In	3.42	0.00	0.95	2.47
	BEV	Status Quo	7.01	0.39	1.03	5.59
		Balanced	6.35	0.39	0.91	5.05
		All-In	4.67	0.39	0.81	3.47
International	FT Fuel	Status Quo	3.98	1.20	1.89	0.89
		Balanced	3.84	1.20	1.52	1.11
		All-In	4.16	1.20	1.36	1.60
	Methane	Status Quo	3.32	0.92	1.58	0.82
		Balanced	3.27	0.92	1.32	1.03
		All-In	3.61	0.92	1.18	1.51
	DME	Status Quo	3.97	1.17	1.81	0.99
		Balanced	3.84	1.17	1.46	1.21
		All-In	4.21	1.17	1.34	1.70
	MeOH	Status Quo	3.52	1.03	1.69	0.80
		Balanced	3.43	1.03	1.38	1.01
		All-In	3.76	1.03	1.22	1.50
	H_2 Comb	Status Quo	3.03	0.84	1.33	0.87
		Balanced	2.98	0.84	1.07	1.07
		All-In	3.34	0.84	0.94	1.55
	FCEV	Status Quo	5.32	0.00	0.97	4.34
		Balanced	3.14	0.00	0.93	2.21
		All-In	3.31	0.00	0.84	2.47
	BEV	Status Quo	6.96	0.39	0.98	5.59
		Balanced	6.31	0.39	0.87	5.05
		All-In	4.64	0.39	0.77	3.47

Table 174: Eutrophication potential in 2050 (million tons PO_4 equivalents).

			Total	Contributions		
				Operation	FSC infra-structure	Vehicle pro-duction
Domestic	FT Fuel	Status Quo	0.41	0.24	0.11	0.06
		Balanced	0.41	0.24	0.09	0.08
		All-In	0.42	0.24	0.08	0.10
	Methane	Status Quo	0.33	0.17	0.10	0.06
		Balanced	0.33	0.17	0.08	0.08
		All-In	0.35	0.17	0.07	0.10
	DME	Status Quo	0.42	0.24	0.11	0.07
		Balanced	0.42	0.24	0.09	0.09
		All-In	0.43	0.24	0.08	0.11
	MeOH	Status Quo	0.35	0.19	0.10	0.06
		Balanced	0.35	0.19	0.08	0.07
		All-In	0.36	0.19	0.07	0.10
	H_2 Comb	Status Quo	0.30	0.16	0.07	0.07
		Balanced	0.30	0.16	0.06	0.09
		All-In	0.31	0.16	0.05	0.11
	FCEV	Status Quo	0.34	0.00	0.05	0.29
		Balanced	0.21	0.00	0.05	0.16
		All-In	0.21	0.00	0.04	0.17
	BEV	Status Quo	0.31	0.07	0.05	0.18
		Balanced	0.27	0.07	0.05	0.15
		All-In	0.27	0.07	0.04	0.15
International	FT Fuel	Status Quo	0.38	0.24	0.08	0.06
		Balanced	0.39	0.24	0.07	0.08
		All-In	0.40	0.24	0.06	0.10
	Methane	Status Quo	0.31	0.17	0.08	0.06
		Balanced	0.32	0.17	0.07	0.08
		All-In	0.33	0.17	0.06	0.10
	DME	Status Quo	0.39	0.24	0.08	0.07
		Balanced	0.40	0.24	0.07	0.09
		All-In	0.41	0.24	0.06	0.11
	MeOH	Status Quo	0.33	0.19	0.08	0.06
		Balanced	0.33	0.19	0.06	0.07
		All-In	0.35	0.19	0.06	0.10
	H_2 Comb	Status Quo	0.29	0.16	0.06	0.07
		Balanced	0.29	0.16	0.05	0.09
		All-In	0.31	0.16	0.04	0.11
	FCEV	Status Quo	0.33	0.00	0.04	0.29
		Balanced	0.20	0.00	0.04	0.16
		All-In	0.21	0.00	0.04	0.17
	BEV	Status Quo	0.30	0.07	0.04	0.18
		Balanced	0.27	0.07	0.04	0.15
		All-In	0.26	0.07	0.04	0.15

Table 175: PM formation potential in 2050 (million tons PO_4 equivalents).

			Total	Contributions		
				Operation	**FSC infra-structure**	**Vehicle pro-duction**
Domestic	FT Fuel	Status Quo	3.86	1.50	1.70	0.66
		Balanced	3.71	1.50	1.38	0.83
		All-In	3.93	1.50	1.23	1.21
	Methane	Status Quo	3.12	1.09	1.43	0.61
		Balanced	3.05	1.09	1.19	0.77
		All-In	3.29	1.09	1.06	1.14
	DME	Status Quo	3.89	1.51	1.65	0.74
		Balanced	3.74	1.51	1.33	0.90
		All-In	4.00	1.51	1.22	1.28
	MeOH	Status Quo	3.36	1.24	1.53	0.60
		Balanced	3.25	1.24	1.25	0.76
		All-In	3.48	1.24	1.11	1.13
	H_2 Comb	Status Quo	2.90	1.14	1.12	0.63
		Balanced	2.84	1.14	0.91	0.79
		All-In	3.11	1.14	0.80	1.16
	FCEV	Status Quo	3.95	0.11	0.82	3.02
		Balanced	2.46	0.11	0.79	1.56
		All-In	2.61	0.11	0.71	1.79
	BEV	Status Quo	4.93	0.60	0.76	3.57
		Balanced	4.45	0.60	0.67	3.18
		All-In	3.52	0.60	0.59	2.33
International	FT Fuel	Status Quo	3.55	1.50	1.39	0.66
		Balanced	3.46	1.50	1.13	0.83
		All-In	3.72	1.50	1.01	1.21
	Methane	Status Quo	2.90	1.09	1.21	0.61
		Balanced	2.87	1.09	1.02	0.77
		All-In	3.14	1.09	0.91	1.14
	DME	Status Quo	3.60	1.51	1.36	0.74
		Balanced	3.51	1.51	1.10	0.90
		All-In	3.79	1.51	1.01	1.28
	MeOH	Status Quo	3.10	1.24	1.26	0.60
		Balanced	3.03	1.24	1.04	0.76
		All-In	3.29	1.24	0.92	1.13
	H_2 Comb	Status Quo	2.75	1.14	0.97	0.63
		Balanced	2.72	1.14	0.79	0.79
		All-In	3.00	1.14	0.70	1.16
	FCEV	Status Quo	3.85	0.11	0.72	3.02
		Balanced	2.36	0.11	0.69	1.56
		All-In	2.52	0.11	0.62	1.79
	BEV	Status Quo	4.87	0.60	0.69	3.57
		Balanced	4.40	0.60	0.62	3.18
		All-In	3.47	0.60	0.55	2.33

Table 176: Land use for renewable power generation and DAC in 2050 (km²).

			EU27+UK			MENA + RoW			DAC	Total
			PV stand-alone	Wind onshore	Wind off-shore	PV stand-alone	Wind onshore	Wind off-shore		
2050a	FT Fuel	Status Quo	55,762	378	314				178	56,631
		Balanced	45,650	307	257				146	46,359
		All-In	41,144	274	231				131	41,781
	Methane	Status Quo	48,819	333	275				160	49,586
		Balanced	40,756	276	229				133	41,395
		All-In	36,229	244	204				118	36,796
	DME	Status Quo	55,438	380	312				163	56,293
		Balanced	45,109	308	254				132	45,803
		All-In	41,408	282	233				121	42,044
	MeOH	Status Quo	51,040	350	287				174	51,851
		Balanced	42,059	287	237				143	42,726
		All-In	37,419	254	211				127	38,012
	H_2 Comb	Status Quo	43,476	299	241				4	44,020
		Balanced	35,703	244	198				4	36,149
		All-In	31,750	216	176				4	32,146
	FCEV	Status Quo	32,450	222	183				0	32,855
		Balanced	31,188	213	176				0	31,577
		All-In	28,302	193	160				0	28,655
	BEV	Status Quo	16,084	140	114				19	16,358
		Balanced	13,705	121	99				14	13,939
		All-In	12,251	106	87				14	12,458
2050b	FT Fuel	Status Quo	16,799	129	86	12,410	601	90	179	30,294
		Balanced	13,762	104	70	10,167	489	74	147	24,814
		All-In	12,409	93	63	9,167	439	67	132	22,370
	Methane	Status Quo	14,550	115	74	10,774	576	81	167	26,337
		Balanced	12,158	95	55	9,002	479	67	139	21,996
		All-In	10,816	84	55	8,008	424	60	123	19,571
	DME	Status Quo	16,685	127	85	12,344	601	90	165	30,096
		Balanced	13,585	103	69	10,050	488	73	134	24,501
		All-In	12,473	94	63	9,228	447	67	123	22,495
	MeOH	Status Quo	15,366	118	78	11,347	555	83	176	27,723
		Balanced	12,670	97	65	9,356	457	68	145	22,857
		All-In	11,277	86	57	8,328	405	61	129	20,342
	H_2 Comb	Status Quo	12,961	100	65	19,655	208	100	4	33,095
		Balanced	10,626	82	54	16,114	171	82	4	27,134
		All-In	9,444	73	48	14,322	152	73	4	24,116
	FCEV	Status Quo	9,816	351	65	14,885	721	100	0	25,938
		Balanced	9,434	337	63	14,306	693	96	0	24,929
		All-In	8,561	305	57	12,983	627	87	0	22,621
	BEV	Status Quo	3,737	51	27	8,021	108	41	20	12,005
		Balanced	3,257	43	24	6,991	91	36	14	10,456
		All-In	2,861	38	21	6,141	82	36	14	9,193

15.2.7 Material demand in the scenarios

Table 177: Annual Li, Co & PGM demand for the EU27+UK transport sector in 100% domestic scenarios I.

			Lithium (thousand tons)	**Cobalt** (thousand tons)	**PGM** (tons)
2030	FT Fuel	Status Quo	0	1	123
		Balanced	4	3	122
		All-In	20	1	121
	Methane	Status Quo	0	1	165
		Balanced	4	3	163
		All-In	20	1	163
	DME	Status Quo	0	1	137
		Balanced	4	3	136
		All-In	20	1	135
	MeOH	Status Quo	0	0	109
		Balanced	4	3	107
		All-In	20	1	107
	H_2 Comb	Status Quo	0	0	107
		Balanced	4	3	106
		All-In	20	1	106
	FCEV	Status Quo	8	12	592
		Balanced	7	6	246
		All-In	36	2	249
	BEV	Status Quo	185	294	30
		Balanced	132	105	30
		All-In	549	32	30
2050	FT Fuel	Status Quo	0	0	145
		Balanced	4	3	142
		All-In	21	1	141
	Methane	Status Quo	0	0	203
		Balanced	4	3	201
		All-In	21	1	200
	DME	Status Quo	0	0	165
		Balanced	4	3	162
		All-In	21	1	161
	MeOH	Status Quo	0	0	122
		Balanced	4	3	120
		All-In	21	1	119
	H_2 Comb	Status Quo	0	0	120
		Balanced	4	3	118
		All-In	21	1	117
	FCEV	Status Quo	14	23	854
		Balanced	11	9	332
		All-In	56	3	337
	BEV	Status Quo	283	449	8
		Balanced	201	160	7
		All-In	840	49	6

Table 178: Annual raw material demand in 2050 for the EU27+UK transport sector in 100% scenarios I.

			Copper (thousand tons)		**Nickel** (thousand tons)		**Silver** (thousand tons)
			Vehicles	**FSC**	**Vehicles**	**FSC**	**FSC**
2050a	FT Fuel	Status Quo	446	3,198	46	1,897	16
		Balanced	669	2,609	78	1,560	13
		All-In	649	2,346	71	1,410	11
	Methane	Status Quo	454	1,716	61	1,283	11
		Balanced	664	1,419	93	1,071	9
		All-In	644	1,252	86	953	8
	DME	Status Quo	465	3,676	46	1,963	16
		Balanced	670	2,995	76	1,602	13
		All-In	654	2,745	71	1,472	12
	MeOH	Status Quo	454	3,162	46	1,839	15
		Balanced	663	2,607	78	1,521	12
		All-In	643	2,317	71	1,356	10
	H_2 Comb	Status Quo	454	1,499	156	728	10
		Balanced	663	1,222	164	598	8
		All-In	643	1,080	143	530	7
	FCEV	Status Quo	720	1,084	198	522	8
		Balanced	690	1,041	197	501	7
		All-In	637	939	170	453	7
	BEV	Status Quo	3,024	1,167	1,395	505	4
		Balanced	2,322	1,019	1,324	427	4
		All-In	1,176	913	781	382	4
2050b	FT Fuel	Status Quo	446	2,760	46	1,821	10
		Balanced	669	2,266	78	1,500	8
		All-In	649	2,046	71	1,358	7
	Methane	Status Quo	454	1,396	61	1,262	6
		Balanced	664	1,160	93	1,055	5
		All-In	644	1,027	86	939	5
	DME	Status Quo	465	3,284	46	1,903	10
		Balanced	670	2,684	76	1,555	8
		All-In	654	2,463	71	1,429	8
	MeOH	Status Quo	454	2,798	46	1,781	9
		Balanced	663	2,315	78	1,476	8
		All-In	643	2,062	71	1,316	7
	H_2 Comb	Status Quo	454	1,231	156	641	8
		Balanced	663	1,005	164	526	6
		All-In	643	888	143	466	6
	FCEV	Status Quo	720	888	198	456	6
		Balanced	690	852	197	438	6
		All-In	637	769	170	395	5
	BEV	Status Quo	3,024	1,298	1,395	478	3
		Balanced	2,322	1,147	1,324	403	3
		All-In	1,176	1,010	781	360	3

Table 179: Annual raw material demand in 2050 for the EU27+UK transport sector in 100% scenarios II.

			Silicon metal (thousand tons)		**Neodymium** (thousand tons)		**REE, others** (thousand tons)
			Vehicles	**FSC**	**Vehicles**	**FSC**	**FSC**
2050 Domestic	FT Fuel	Status Quo	0.0	279.1	0.0	41.6	98.4
		Balanced	0.1	220.3	8.3	34.8	82.2
		All-In	0.0	193.9	8.3	31.7	75.0
	Methane	Status Quo	0.0	224.5	0.0	37.8	89.2
		Balanced	0.1	183.0	8.3	31.9	75.4
		All-In	0.0	159.7	8.3	28.6	67.6
	DME	Status Quo	0.0	267.1	0.0	42.2	99.7
		Balanced	0.1	213.0	8.3	34.7	82.0
		All-In	0.0	193.9	8.3	32.0	75.6
	MeOH	Status Quo	0.0	243.2	0.0	39.1	92.3
		Balanced	0.1	196.1	8.3	32.6	76.9
		All-In	0.0	171.9	8.3	29.2	68.9
	H_2 Comb	Status Quo	0.0	207.7	0.0	33.3	78.7
		Balanced	0.1	166.5	8.3	27.7	65.4
		All-In	0.0	145.6	8.3	24.8	58.7
	FCEV	Status Quo	0.2	151.9	11.7	25.1	59.3
		Balanced	0.2	145.7	11.7	24.1	57.0
		All-In	0.1	130.6	11.7	22.1	52.1
	BEV	Status Quo	4.2	99.5	11.7	13.1	30.9
		Balanced	3.0	85.3	11.7	13.4	31.7
		All-In	1.0	74.3	9.8	11.9	28.1
205 Inter-national	FT Fuel	Status Quo	0.0	147.0	0.0	32.6	76.9
		Balanced	0.1	116.2	8.3	27.3	64.4
		All-In	0.0	102.3	8.3	24.9	58.8
	Methane	Status Quo	0.0	117.0	0.0	30.3	71.6
		Balanced	0.1	95.5	8.3	25.6	60.6
		All-In	0.0	83.5	8.3	23.0	54.3
	DME	Status Quo	0.0	140.9	0.0	33.2	78.5
		Balanced	0.1	112.4	8.3	27.4	64.6
		All-In	0.0	102.4	8.3	25.2	59.6
	MeOH	Status Quo	0.0	128.3	0.0	30.7	72.6
		Balanced	0.1	103.5	8.3	25.7	60.6
		All-In	0.0	90.8	8.3	23.0	54.3
	H_2 Comb	Status Quo	0.0	157.9	0.0	25.0	59.0
		Balanced	0.1	126.5	8.3	20.8	49.2
		All-In	0.0	110.6	8.3	18.7	44.1
	FCEV	Status Quo	0.2	116.6	11.7	18.8	44.5
		Balanced	0.2	111.9	11.7	18.1	42.8
		All-In	0.1	100.3	11.7	16.6	39.1
	BEV	Status Quo	4.2	63.8	11.7	9.2	21.7
		Balanced	3.0	55.3	11.7	9.4	22.2
		All-In	1.0	47.7	9.8	8.4	19.8

Table 180: Cumulative primary raw material demand 2021-2050 for the EU27+UK transport sector in 100% scenarios I.

			Lithium (thousand tons)	**Cobalt** (thousand tons)	**PGM** (thousand tons)
Domestic	FT Fuel	Status Quo	2	7	3.7
		Balanced	71	64	3.4
		All-In	369	27	3.4
	Methane	Status Quo	2	6	4.9
		Balanced	71	63	4.7
		All-In	369	27	4.6
	DME	Status Quo	2	6	4.3
		Balanced	71	63	3.8
		All-In	369	27	3.8
	MeOH	Status Quo	2	6	3.3
		Balanced	71	63	3.0
		All-In	369	27	2.9
	H_2 Comb	Status Quo	2	6	3.0
		Balanced	71	63	2.9
		All-In	369	26	2.9
	FCEV	Status Quo	193	323	18.1
		Balanced	148	129	7.6
		All-In	766	55	7.6
	BEV	Status Quo	4,882	8,178	0.6
		Balanced	3,487	2,990	0.6
		All-In	14,235	998	0.6
Cumulative primary raw material demand in international scenarios is almost identical as demand of these materials is dominated by vehicle production (>99% of total demand).					

Table 181: Cumulative primary raw material demand 2021-2050 for the EU27+UK transport sector in 100% scenarios II.

			Copper (million tons)	**Nickel** (million tons)	**Silver** (million tons)	**Neodymium** (million tons)	**REE, others** (million tons)	**Silicon metal** (million tons)
Domestic	FT Fuel	Status Quo	83	41	0.42	0.69	1.64	9.85
		Balanced	74	35	0.35	0.78	1.36	8.14
		All-In	68	32	0.31	0.73	1.23	7.38
	Methane	Status Quo	51	29	0.33	0.62	1.46	8.74
		Balanced	48	25	0.28	0.73	1.23	7.34
		All-In	44	23	0.24	0.67	1.10	6.55
	DME	Status Quo	97	43	0.44	0.70	1.65	9.88
		Balanced	84	36	0.36	0.78	1.35	8.08
		All-In	78	33	0.33	0.73	1.24	7.43
	MeOH	Status Quo	84	41	0.40	0.64	1.52	9.12
		Balanced	75	35	0.33	0.74	1.26	7.56
		All-In	68	31	0.29	0.68	1.13	6.74
	H_2 Comb	Status Quo	46	20	0.29	0.55	1.30	7.78
		Balanced	43	17	0.24	0.66	1.07	6.42
		All-In	39	15	0.21	0.61	0.96	5.73
	FCEV	Status Quo	40	16	0.22	0.68	0.97	5.83
		Balanced	39	15	0.21	0.69	0.94	5.61
		All-In	36	14	0.19	0.66	0.85	5.10
	BEV	Status Quo	81	32	0.13	0.53	0.60	3.71
		Balanced	65	26	0.12	0.52	0.52	3.21
		All-In	43	22	0.10	0.49	0.46	2.82
International	FT Fuel	Status Quo	71	39	0.25	0.55	1.30	5.15
		Balanced	65	33	0.21	0.66	1.08	4.26
		All-In	59	30	0.19	0.62	0.98	3.86
	Methane	Status Quo	42	28	0.18	0.51	1.20	4.50
		Balanced	40	25	0.15	0.63	1.01	3.78
		All-In	37	22	0.13	0.59	0.90	3.38
	DME	Status Quo	85	42	0.27	0.56	1.32	5.16
		Balanced	75	35	0.22	0.66	1.08	4.22
		All-In	70	32	0.20	0.63	1.00	3.89
	MeOH	Status Quo	74	39	0.24	0.52	1.22	4.76
		Balanced	67	34	0.20	0.64	1.01	3.95
		All-In	61	30	0.18	0.59	0.91	3.53
	H_2 Comb	Status Quo	39	18	0.22	0.41	0.96	5.80
		Balanced	38	15	0.18	0.54	0.80	4.79
		All-In	35	14	0.16	0.51	0.71	4.27
	FCEV	Status Quo	35	14	0.17	0.58	0.72	4.39
		Balanced	34	13	0.16	0.59	0.69	4.22
		All-In	31	13	0.14	0.56	0.63	3.84
	BEV	Status Quo	86	32	0.09	0.45	0.42	2.39
		Balanced	70	26	0.08	0.45	0.37	2.08
		All-In	47	21	0.07	0.43	0.33	1.80

15.3 Cost Assessment

15.3.1 Vehicle Costs

Table 182: BEV.

			Status Quo	Balanced	All-In
Passenger	Small	mio. EUR	382,156	409,779	420,300
	Medium	mio. EUR	493,139	512,745	507,930
	Large	mio. EUR	206,380	213,375	202,735
	SUV	mio. EUR	732,736	717,302	693,413
	LCV (N1)	mio. EUR	785,011	717,089	674,558
Heavy Duty Vehicles	Rigid (N2)	mio. EUR	23,796	25,571	25,571
	Regional Delivery (N3)	mio. EUR	32,051	33,803	33,803
	Long Haul (N3)	mio. EUR	166,155	200,137	200,624
	Super Long Haul (N3)	mio. EUR	37,077	45,583	45,697
Bus	Public Transport	mio. EUR	14,151	14,948	14,948
	Coaches	mio. EUR	5,457	6,415	6,415
Total		mio. EUR	**2,878,109**	**2,896,746**	**2,825,993**

Table 183: FCEV.

			Status Quo	Balanced	All-In
Passenger	Small	mio. EUR	384,999	417,416	439,636
	Medium	mio. EUR	490,289	523,832	539,252
	Large	mio. EUR	258,600	276,349	281,962
	SUV	mio. EUR	634,209	673,419	687,255
	LCV (N1)	mio. EUR	302,171	319,546	324,709
Heavy Duty Vehicles	Rigid (N2)	mio. EUR	3,004	4,778	4,778
	Regional Delivery (N3)	mio. EUR	4,730	6,482	6,482
	Long Haul (N3)	mio. EUR	161,177	195,155	195,642
	Super Long Haul (N3)	mio. EUR	37,253	45,758	45,873
Bus	Public Transport	mio. EUR	10,712	11,510	11,510
	Coaches	mio. EUR	4,059	5,017	3,609
Total		mio. EUR	**2,291,204**	**2,479,261**	**2,540,708**

Table 184: H2 Combustion.

			Status Quo	Balanced	All-In
Passenger	Small	mio. EUR	183,698	318,492	357,450
	Medium	mio. EUR	229,046	349,672	376,026
	Large	mio. EUR	102,325	169,884	178,421
	SUV	mio. EUR	272,811	433,314	456,573
	LCV (N1)	mio. EUR	163,224	238,161	246,637
Heavy Duty Vehicles	Rigid (N2)	mio. EUR	6,295	11,440	13,442
	Regional Delivery (N3)	mio. EUR	8,804	14,654	16,995
	Long Haul (N3)	mio. EUR	119,174	205,874	238,177
	Super Long Haul (N3)	mio. EUR	27,265	48,996	56,611
Bus	Public Transport	mio. EUR	5,333	8,655	11,740
	Coaches	mio. EUR	3,623	8,450	10,368
Total		mio. EUR	**1,121,598**	**1,807,592**	**1,962,440**

Table 185: FT Fuel.

			Status Quo	Balanced	All-In
Passenger	Small	mio. EUR	0	173,564	211,917
	Medium	mio. EUR	0	183,247	211,958
	Large	mio. EUR	0	97,948	111,640
	SUV	mio. EUR	0	219,270	248,717
	LCV (N1)	mio. EUR	0	111,129	125,550
Heavy Duty Vehicles	Rigid (N2)	mio. EUR	0	5,145	7,146
	Regional Delivery (N3)	mio. EUR	0	5,850	8,191
	Long Haul (N3)	mio. EUR	0	86,701	119,003
	Super Long Haul (N3)	mio. EUR	0	21,731	29,346
Bus	Public Transport	mio. EUR	0	3,322	6,408
	Coaches	mio. EUR	0	3,357	5,276
Total		mio. EUR	**0**	**911,264**	**1,085,151**

Table 186: Methane.

			Status Quo	Balanced	All-In
Passenger	Small	mio. EUR	15,920	174,127	216,780
	Medium	mio. EUR	9,000	183,006	214,215
	Large	mio. EUR	-9,969	83,593	97,706
	SUV	mio. EUR	9,446	220,620	251,803
	LCV (N1)	mio. EUR	-28,091	78,678	95,149
Heavy Duty Vehicles	Rigid (N2)	mio. EUR	1,445	6,590	8,591
	Regional Delivery (N3)	mio. EUR	2,020	7,870	10,211
	Long Haul (N3)	mio. EUR	27,043	113,744	146,046
	Super Long Haul (N3)	mio. EUR	6,167	27,898	35,513
Bus	Public Transport	mio. EUR	1,231	4,553	7,638
	Coaches	mio. EUR	3,839	7,342	9,362
Total		mio. EUR	**38,051**	**908,022**	**1,093,016**

Table 187: Methanol.

			Status Quo	Balanced	All-In
Passenger	Small	mio. EUR	-17,674	155,890	199,318
	Medium	mio. EUR	-26,741	156,506	188,722
	Large	mio. EUR	-28,579	69,369	84,599
	SUV	mio. EUR	-34,544	184,726	217,514
	LCV (N1)	mio. EUR	-60,389	50,740	68,783
Heavy Duty Vehicles	Rigid (N2)	mio. EUR	166	5,311	7,313
	Regional Delivery (N3)	mio. EUR	114	5,964	8,305
	Long Haul (N3)	mio. EUR	594	87,295	119,597
	Super Long Haul (N3)	mio. EUR	112	21,843	29,458
Bus	Public Transport	mio. EUR	79	3,401	6,487
	Coaches	mio. EUR	22	3,379	5,298
Total		mio. EUR	**-166,839**	**744,425**	**935,393**

Table 188: DME.

			Status Quo	Balanced	All-In
Passenger	Small	mio. EUR	41,875	214,503	246,327
	Medium	mio. EUR	51,017	232,654	256,799
	Large	mio. EUR	44,247	141,451	153,038
	SUV	mio. EUR	60,893	278,940	303,963
	LCV (N1)	mio. EUR	11,780	122,139	136,059
Heavy Duty Vehicles	Rigid (N2)	mio. EUR	211	5,356	7,357
	Regional Delivery (N3)	mio. EUR	297	7,982	9,771
	Long Haul (N3)	mio. EUR	4,062	90,763	123,065
	Super Long Haul (N3)	mio. EUR	930	22,661	30,276
Bus	Public Transport	mio. EUR	180	4,603	7,379
	Coaches	mio. EUR	173	3,530	5,448
Total		mio. EUR	**215,666**	**1,124,580**	**1,279,484**

15.3.2 Fuel Supply Chain Costs

Table 189: BEV Domestic.

		Status Quo	Balanced	All-In
Generation	billion EUR	826.66	761.99	650.20
Transmission (electricity)	billion EUR	167.42	154.04	130.56
Electrolyser	billion EUR	201.79	186.01	158.72
DAC	billion EUR	0.00	0.00	0.00
Synthesis	billion EUR	0.00	0.00	0.00
H2 Storage (Buffer)	billion EUR	151.88	142.02	124.96
Final Storage	billion EUR	0.00	0.00	0.00
Fuel Transmission	billion EUR	0.00	0.00	0.00
Fuel Distribution	billion EUR	60.24	55.34	46.62
Charging/Filling Station	billion EUR	559.43	559.43	559.43
International Transport	billion EUR	0.00	0.00	0.00
Total FSC Cost	billion EUR	1,967.42	1,858.82	1,670.48

Table 190: BEV International.

		Status Quo	Balanced	All-In
Generation	billion EUR	525.28	484.22	413.27
Transmission (electricity)	billion EUR	129.84	119.48	101.29
Electrolyser	billion EUR	120.09	110.70	94.45
DAC	billion EUR	0.00	0.00	0.00
Synthesis	billion EUR	0.00	0.00	0.00
H2 Storage (Buffer)	billion EUR	150.79	142.22	127.28
Final Storage	billion EUR	0.00	0.00	0.00
Fuel Transmission	billion EUR	0.00	0.00	0.00
Fuel Distribution	billion EUR	54.48	50.05	42.17
Charging/Filling Station	billion EUR	559.43	559.43	559.43
International Transport	billion EUR	884.83	814.32	690.75
Total FSC Cost	billion EUR	2,424.75	2,280.41	2,028.65

Table 191: FCEV Domestic.

		Status Quo	Balanced	All-In
Generation	billion EUR	1,466.92	1,399.87	1,256.01
Transmission (electricity)	billion EUR	86.29	82.29	73.43
Electrolyser	billion EUR	256.40	244.76	220.13
DAC	billion EUR	0.00	0.00	0.00
Synthesis	billion EUR	0.00	0.00	0.00
H2 Storage (Buffer)	billion EUR	42.15	42.16	42.39
Final Storage	billion EUR	0.00	0.00	0.00
Fuel Transmission	billion EUR	28.64	27.32	24.45
Fuel Distribution	billion EUR	40.93	39.05	34.96
Charging/Filling Station	billion EUR	148.16	148.16	148.16
Total FSC Cost	billion EUR	2,069.50	1,983.60	1,799.53

Table 192: FCEV International.

		Status Quo	Balanced	All-In
Generation	billion EUR	1,073.53	1,024.49	919.41
Transmission (electricity)	billion EUR	61.08	58.25	52.03
Electrolyser	billion EUR	265.43	253.37	227.88
DAC	billion EUR	0.00	0.00	0.00
Synthesis	billion EUR	0.00	0.00	0.00
H2 Storage (Buffer)	billion EUR	42.15	42.16	42.39
Final Storage	billion EUR	0.00	0.00	0.00
Fuel Transmission	billion EUR	28.64	27.32	24.45
Fuel Distribution	billion EUR	40.93	39.05	34.96
Charging/Filling Station	billion EUR	148.16	148.16	148.16
International Transport	billion EUR	0.05	0.05	0.04
Total FSC Cost	billion EUR	1,659.96	1,592.84	1,449.31

Table 193: H2 Combustion Domestic.

		Status Quo	Balanced	All-In
Generation	billion EUR	2,133.57	1,744.74	1,549.35
Transmission (electricity)	billion EUR	126.07	102.02	89.96
Electrolyser	billion EUR	372.20	305.77	272.35
DAC	billion EUR	0.00	0.00	0.00
Synthesis	billion EUR	0.00	0.00	0.00
H2 Storage (Buffer)	billion EUR	42.29	42.67	42.97
Final Storage	billion EUR	0.00	0.00	0.00
Fuel Transmission	billion EUR	41.73	33.97	30.08
Fuel Distribution	billion EUR	59.64	48.57	43.00
Charging/Filling Station	billion EUR	148.16	148.16	148.16
Total FSC Cost	billion EUR	2,923.66	2,425.89	2,175.87

Table 194: H2 Combustion International.

		Status Quo	Balanced	All-In
Generation	billion EUR	1,561.11	1,277.16	1,134.46
Transmission (electricity)	billion EUR	89.16	72.28	63.81
Electrolyser	billion EUR	385.30	316.53	281.94
DAC	billion EUR	0.00	0.00	0.00
Synthesis	billion EUR	0.00	0.00	0.00
H2 Storage (Buffer)	billion EUR	42.31	42.68	42.98
Final Storage	billion EUR	0.00	0.00	0.00
Fuel Transmission	billion EUR	42.25	34.39	30.45
Fuel Distribution	billion EUR	59.64	48.57	43.00
Charging/Filling Station	billion EUR	148.16	148.16	148.16
International Transport	billion EUR	0.07	0.06	0.05
Total FSC Cost	billion EUR	2,328.01	1,939.82	1,744.85

Table 195: FT Fuel Domestic.

		Status Quo	Balanced	All-In
Generation	billion EUR	2,595.07	2,225.31	2,030.23
Transmission (electricity)	billion EUR	155.00	130.36	117.45
Electrolyser	billion EUR	432.29	373.76	342.78
DAC	billion EUR	246.18	218.54	204.00
Synthesis	billion EUR	164.13	140.71	128.35
H2 Storage (Buffer)	billion EUR	61.27	62.37	63.20
Final Storage	billion EUR	0.00	0.00	0.00
Fuel Transmission	billion EUR	0.00	0.00	0.00
Fuel Distribution	billion EUR	0.00	0.00	0.00
Charging/Filling Station	billion EUR	1.54	1.54	1.54
Total FSC Cost	billion EUR	3,655.48	3,152.60	2,887.55

Table 196: FT Fuel International.

		Status Quo	Balanced	All-In
Generation	billion EUR	1,891.18	1,624.48	1,483.67
Transmission (electricity)	billion EUR	90.21	76.08	68.67
Electrolyser	billion EUR	442.87	383.02	351.33
DAC	billion EUR	252.90	224.47	209.52
Synthesis	billion EUR	168.73	144.66	131.96
H2 Storage (Buffer)	billion EUR	203.54	208.51	211.96
Final Storage	billion EUR	0.00	0.00	0.00
Fuel Transmission	billion EUR	0.00	0.00	0.00
Fuel Distribution	billion EUR	0.00	0.00	0.00
Charging/Filling Station	billion EUR	1.54	1.54	1.54
International Transport	billion EUR	0.00	0.00	0.00
Total FSC Cost	billion EUR	3,050.97	2,662.77	2,458.65

Table 197: Methane Domestic.

		Status Quo	Balanced	All-In
Generation	billion EUR	2,457.76	2,050.17	1,821.14
Transmission (electricity)	billion EUR	143.17	118.25	104.24
Electrolyser	billion EUR	404.63	338.88	301.94
DAC	billion EUR	202.94	174.76	159.02
Synthesis	billion EUR	127.53	106.84	95.48
H2 Storage (Buffer)	billion EUR	62.80	63.18	63.58
Final Storage	billion EUR	14.36	14.57	14.73
Fuel Transmission	billion EUR	8.03	6.65	5.88
Fuel Distribution	billion EUR	0.14	0.14	0.14
Charging/Filling Station	billion EUR	54.04	54.04	54.04
Total FSC Cost	billion EUR	3,475.42	2,927.47	2,620.18

Table 198: Methane International.

		Status Quo	Balanced	All-In
Generation	billion EUR	1,820.77	1,519.71	1,350.57
Transmission (electricity)	billion EUR	83.65	69.18	61.05
Electrolyser	billion EUR	422.11	353.43	314.85
DAC	billion EUR	215.11	185.08	168.29
Synthesis	billion EUR	140.38	117.56	105.00
H2 Storage (Buffer)	billion EUR	209.54	212.01	214.09
Final Storage	billion EUR	9.34	9.47	9.57
Fuel Transmission	billion EUR	5.13	4.25	3.75
Fuel Distribution	billion EUR	0.14	0.14	0.14
Charging/Filling Station	billion EUR	54.04	54.04	54.04
International Transport	billion EUR	43.63	38.10	35.02
Total FSC Cost	billion EUR	3,003.84	2,562.97	2,316.38

Table 199: MeOH Domestic.

		Status Quo	Balanced	All-In
Generation	billion EUR	2,431.81	2,064.47	1,831.70
Transmission (electricity)	billion EUR	142.92	120.30	106.01
Electrolyser	billion EUR	366.66	312.34	277.88
DAC	billion EUR	251.80	220.30	200.38
Synthesis	billion EUR	70.00	59.28	52.50
H2 Storage (Buffer)	billion EUR	61.88	62.19	62.51
Final Storage	billion EUR	0.00	0.00	0.00
Fuel Transmission	billion EUR	0.00	0.00	0.00
Fuel Distribution	billion EUR	0.00	0.00	0.00
Charging/Filling Station	billion EUR	0.84	0.84	0.84
Total FSC Cost	billion EUR	3,325.91	2,839.73	2,531.82

Table 200: MeOH International.

		Status Quo	Balanced	All-In
Generation	billion EUR	1,780.62	1,512.74	1,342.94
Transmission (electricity)	billion EUR	83.51	70.38	62.08
Electrolyser	billion EUR	377.34	321.48	286.03
DAC	billion EUR	258.88	226.43	205.90
Synthesis	billion EUR	72.18	61.13	54.13
H2 Storage (Buffer)	billion EUR	206.91	208.97	210.72
Final Storage	billion EUR	0.00	0.00	0.00
Fuel Transmission	billion EUR	0.00	0.00	0.00
Fuel Distribution	billion EUR	0.00	0.00	0.00
Charging/Filling Station	billion EUR	0.84	0.84	0.84
International Transport	billion EUR	0.00	0.00	0.00
Total FSC Cost	billion EUR	2,780.29	2,401.96	2,162.65

Table 201: DME Domestic.

		Status Quo	Balanced	All-In
Generation	billion EUR	2,656.59	2,213.51	2,027.92
Transmission (electricity)	billion EUR	156.25	129.03	117.67
Electrolyser	billion EUR	383.44	320.67	294.32
DAC	billion EUR	236.50	204.18	190.64
Synthesis	billion EUR	76.36	63.36	57.93
H2 Storage (Buffer)	billion EUR	62.02	62.30	62.49
Final Storage	billion EUR	0.00	0.00	0.00
Fuel Transmission	billion EUR	0.00	0.00	0.00
Fuel Distribution	billion EUR	0.00	0.00	0.00
Charging/Filling Station	billion EUR	5.96	5.96	5.96
Total FSC Cost	billion EUR	3,577.12	2,999.01	2,756.94

Table 202: DME International.

		Status Quo	Balanced	All-In
Generation	billion EUR	1,949.56	1,625.70	1,489.99
Transmission (electricity)	billion EUR	91.41	75.58	68.97
Electrolyser	billion EUR	395.51	330.81	303.65
DAC	billion EUR	244.57	211.07	197.04
Synthesis	billion EUR	79.09	65.62	60.00
H2 Storage (Buffer)	billion EUR	207.10	209.24	210.38
Final Storage	billion EUR	0.00	0.00	0.00
Fuel Transmission	billion EUR	0.00	0.00	0.00
Fuel Distribution	billion EUR	0.00	0.00	0.00
Charging/Filling Station	billion EUR	5.96	5.96	5.96
International Transport	billion EUR	6.87	5.69	5.20
Total FSC Cost	billion EUR	2,980.06	2,529.67	2,341.18

16 Annex II – Assumptions

16.1 Mobility demand assumptions

Table 203: Future development of mobility demand.

Transport activity			2020	2025	2030	2035	2040	2045	2050
Passenger		in Gpkm	5,255	5,457	5,676	5,849	6,003	6,156	6,279
Heavy Duty Vehicles		in Gtkm	2,109	2,277	2,446	2,564	2,672	2,763	2,835
Bus		in Gpkm	570	587	604	622	636	653	667
	Passenger	in Gpkm	591	644	693	739	788	833	878
	Freight	in Gtkm	482	533	580	619	662	695	724
Shipping		in Gtkm	389	411	432	449	467	480	492
Aviation		in Gpkm	693	776	860	944	1,031	1,104	1,177

[Source: (European Comission, 2016)].

Table 204: Annual mileage light duty vehicles.

Segment	Unit	Annual mileage
Small	*km/year*	12,377
Medium	*km/year*	15,168
Large	*km/year*	16,125
SUV	*km/year*	13,423
LCV (N1)	*km/year*	16,000

[Source: (NPM Arbeitsgruppe 2: Alternative Antriebe und Kraftstoffe für Nachhaltige Mobilität, 2019)].

Table 205: Annual mileage heavy duty vehicles.

Segment		Annual Mileage
Rigid (N2)	*km/year*	35,000
Regional Delivery (N3)	*km/year*	60,000
Long Haul (N3) [First Life]	*km/year*	116,000
Long Haul (N3) [Second Life]	*km/year*	60,000
Super Long Haul (N3) [First Life]	*km/year*	107,000
Super Long Haul (N3) [Second Life]	*km/year*	60,000
Public Transport	*km/year*	50,000
Coaches	*km/year*	52,000

[Source: (Schroten, et al., 2012), EU Regulation 2019-1242].

16.2 Fuel Demand Assumptions

Table 206: Specific fuel consumption of light-duty vehicles (kWh / 100km, WLTP "All season").

		gasoline	diesel	Methane	DME	MeOH	H_2 Comb	FCEV	BEV
Status Quo	Small	49.3	41.7	46.7	40.8	46.9	48.6	25.1	16.7
	Medium	52.2	48.9	49.8	48.2	49.7	53.2	28.6	19.6
	Large	60.3	55.4	57.4	54.6	57.4	62.0	32.7	22.8
	SUV	64.5	54.0	61.7	53.3	61.5	66.9	40.3	29.7
	LCV	81.2	78.3	81.7	80.9	80.8	91.1	64.1	54.2
Balanced	Small	40.0	33.8	37.9	33.0	38.2	38.5	25.1	16.5
	Medium	40.2	37.3	38.1	36.5	38.4	39.0	28.5	19.1
	Large	47.3	43.2	44.8	42.3	45.1	46.3	32.4	22.0
	SUV	53.6	44.8	51.0	44.0	51.1	53.0	39.9	27.8
	LCV	76.5	68.5	70.9	70.0	70.7	75.1	62.8	48.5
All-In	Small	36.0	31.8	34.0	31.0	34.3	34.6	22.6	14.0
	Medium	35.6	34.7	33.7	33.9	34.0	34.5	25.3	15.7
	Large	40.7	39.0	38.5	38.2	38.8	39.7	28.1	17.3
	SUV	46.0	40.3	43.7	39.6	43.8	45.3	34.4	21.5
	LCV	62.0	59.2	57.1	60.6	57.1	60.2	52.5	34.0

[Source: FVV Working Group].

Table 207: Specific fuel consumption of heavy-duty vehicles (kWh/km).

		diesel	Methane	DME	MeOH	H_2 Comb	FCEV	BEV
Status Quo	3.5-7.5t Rigid	1.33	1.50	1.33	1.43	1.45	0.91	0.62
	7.5-16t Regional	2.04	2.28	2.05	2.18	2.20	1.66	0.94
	40t Long-haul	3.14	3.43	3.15	3.32	3.38	2.94	1.61
	60t Long-haul XL	4.09	4.46	4.11	4.32	4.41	3.83	2.10
	City bus	2.83	3.18	2.84	3.02	3.07	2.21	1.28
	Coach	4.14	4.58	4.16	4.45	4.51	3.01	1.65
Balanced	3.5-7.5t Rigid	1.10	1.23	1.10	1.17	1.19	0.84	0.52
	7.5-16t Regional	1.72	1.87	1.72	1.79	1.84	1.52	0.82
	40t Long-haul	2.63	2.83	2.62	2.74	2.81	2.68	1.42
	60t Long-haul XL	3.39	3.63	3.37	3.52	3.62	3.47	1.83
	City bus	2.38	2.60	2.37	2.47	2.55	2.04	1.11
	Coach	3.59	3.91	3.59	3.80	3.91	2.77	1.47
All-In	3.5-7.5t Rigid	1.02	1.12	1.02	1.07	1.09	0.75	0.45
	7.5-16t Regional	1.62	1.71	1.62	1.64	1.71	1.39	0.76
	40t Long-haul	2.31	2.50	2.36	2.42	2.50	2.43	1.30
	60t Long-haul XL	2.97	3.22	3.02	3.11	3.21	3.13	1.68
	City bus	2.23	2.37	2.22	2.25	2.37	1.88	1.01
	Coach	3.32	3.57	3.32	3.46	3.61	2.55	1.37

[Source: FVV Working Group].

16.3 Main technical specifications for road vehicles

All configurations and technical specifications of road vehicles were defined in the project-specific focus groups by the participating FVV members.

Table 208: Main technical specifications for light-duty vehicles I.

Size	Fuel type	Power (kW)			Empty weight (kg)			Light weighting effects (kg), *only All-In*	
		ICE	Electric*	Fuel cell	SQ	Bal	All-In	Steel reduction	Aluminium additional weight
small	gasoline	44	29		980	1,080	884	588	392
	diesel	44	29		1,030	1,130	934	588	392
	CNG	44	29		988	1,081	882	588	392
	DME	44	29		1,035	1,128	930	588	392
	Methanol	44	29		980	1,080	884	588	392
	H2 ICE	44	29		1,096	1,137	932	588	392
	FCEV	-	44	44	1,186	1,167	962	588	392
	BEV	-	44		1,399	1,315	1,015	588	392
medium	gasoline	92	61		1,280	1,380	1,124	768	512
	diesel	92	61		1,363	1,463	1,207	768	512
	CNG	92	61		1,317	1,402	1,140	768	512
	DME	92	61		1,401	1,485	1,225	768	512
	Methanol	92	61		1,280	1,380	1,124	768	512
	H2 ICE	92	61		1,516	1,497	1,224	768	512
	FCEV	-	92	92	1,639	1,603	1,329	768	512
	BEV	-	92		2,049	1,879	1,413	768	512

large	gasoline	135	90		1,615	1,715	1,392	969	646
	diesel	135	90		1,725	1,825	1,502	969	646
	CNG	135	90		1,663	1,746	1,414	969	646
	DME	135	90		1,773	1,855	1,526	969	646
	Methanol	135	90		1,615	1,715	1,392	969	646
	H2 ICE	135	90		1,896	1,859	1,512	969	646
	FCEV	-	135	135	1,647	2,038	1,689	969	646
	BEV	-	135		2,537	2,330	1,752	969	646
SUV	gasoline	127	85		1,572	1,672	1,358	943	629
	diesel	127	85		1,650	1,750	1,436	943	629
	CNG	127	85		1,626	1,711	1,387	943	629
	DME	127	85		1,696	1,782	1,462	943	629
	Methanol	127	85		1,572	1,672	1,358	943	629
	H2 ICE	127	85		1,877	1,841	1,498	943	629
	FCEV	-	127	127	2,061	2,009	1,666	943	629
	BEV	-	127		2,699	2,423	1,780	943	629
LCV	gasoline	96	64		1,979	2,079	1,683	1,187	792
	diesel	96	64		1,858	1,958	1,563	1,187	792
	CNG	96	64		1,939	2,024	1,611	1,187	792
	DME	96	64		2,064	2,148	1,740	1,187	792
	Methanol	96	64		1,858	1,958	1,563	1,187	792
	H2 ICE	96	64		2,286	2,211	1,760	1,187	792
	FCEV	-	96	96	2,467	2,382	1,969	1,187	792
	BEV	-	96		3,851	3,264	2,232	1,187	792

** for ICE powertrains only Balanced and All-In.*

Table 209: Main technical specifications for light-duty vehicles II.

Size	**Fuel type**	**Net (usable) battery capacity (kWh)***			**Gross (installed) battery capacity (kWh)***			**Tank capacity (kg)**		
		SQ	**Bal**	**All-In**	**SQ**	**Bal**	**All-In**	**SQ**	**Bal**	**All-In**
small	gasoline		0.9	0.9		1.3	1.3			
	diesel		0.9	0.9		1.3	1.3			
	CNG		0.9	0.9		1.3	1.3	10.1	8.2	7.3
	DME		0.9	0.9		1.3	1.3			
	Methanol		0.9	0.9		1.3	1.3			
	H2 ICE		0.9	0.9		1.3	1.3	4.4	3.5	3.1
	FCEV	0.9	0.9	0.9	1.3	1.3	1.3	2.3	2.3	2.0
	BEV	44.0	43.5	36.9	48.4	47.8	40.6			
medium	gasoline		1.3	1.3		1.9	1.9			
	diesel		1.3	1.3		1.9	1.9			
	CNG		1.3	1.3		1.9	1.9	17.9	13.7	12.1
	DME		1.3	1.3		1.9	1.9			
	Methanol		1.3	1.3		1.9	1.9			
	H2 ICE		1.3	1.3		1.9	1.9	8.0	5.9	5.2
	FCEV	1.3	1.3	1.3	1.9	1.9	1.9	4.3	4.3	3.8
	BEV	86.0	83.8	69.1	94.6	92.2	76.0	-		
large	gasoline		1.4	1.4		2.0	2.0			
	diesel		1.4	1.4		2.0	2.0			
	CNG		1.4	1.4		2.0	2.0	20.7	16.1	12.1
	DME		1.4	1.4		2.0	2.0			
	Methanol		1.4	1.4		2.0	2.0			
	H2 ICE		1.4	1.4		2.0	2.0	9.3	7.0	4.2
	FCEV	1.4	1.4	1.4	2.0	2.0	2.0	4.9	4.9	3.8
	BEV	100.1	96.4	69.1	110.1	106.0	76.0	-		
SUV	gasoline		1.6	1.6		2.3	2.3			
	diesel		1.6	1.6		2.3	2.3			
	CNG		1.6	1.6		2.3	2.3	22.2	18.4	15.7
	DME		1.6	1.6		2.3	2.3			
	Methanol		1.6	1.6		2.3	2.3			
	H2 ICE		1.6	1.6		2.3	2.3	10.0	8.0	6.8
	FCEV	1.6	1.6	1.6	2.3	2.3	2.3	6.1	6.0	5.2
	BEV	130.4	121.8	94.3	143.5	134.0	103.7	-		
LCV	gasoline		1.8	1.8		2.6	2.6			
	diesel		1.8	1.8		2.6	2.6			
	CNG		1.8	1.8		2.6	2.6	29.4	25.5	20.5
	DME		1.8	1.8		2.6	2.6			
	Methanol		1.8	1.8		2.6	2.6			
	H2 ICE		1.8	1.8		2.6	2.6	13.7	11.3	9.0
	FCEV	1.8	1.8	1.8	2.6	2.6	2.6	9.6	9.4	7.9
	BEV	237.7	212.8	149.2	261.5	234.1	164.1	-		

** Operation range of battery-electric vehicles has been defined in the focus group: all small vehicles have a real driving range of 300km, all other size classes of 500km. Installed battery capacity is for BEV 10% higher and for FCEV and hybridised ICEs 46% higher then net usable battery capacity.*

Table 210: Main technical specifications for heavy-duty vehicles I.

Size	Fuel type	Power (kW)			Empty weight (kg)			Weight reduction (kg)	
		ICE	Electric*	Fuel cell	SQ	Bal	All-In	Bal	All-In
3.5-7.5 t Rigid	diesel	107	85		2,509	2,419	2,239	90	180
	CNG	107	85		2,563	2,473	2,293	90	180
	DME	107	85		2,514	2,424	2,244	90	180
	Methanol	107	85		2,514	2,424	2,244	90	180
	H2 ICE	107	85		2,758	2,668	2,488	90	180
	FCEV	-	85	10	3,095	2,950	2,598	90	180
	BEV	-	85		4,094	3,370	2,873	90	180
7.5-16t Regional	diesel	175	185		4,900	4,670	4,440	230	460
	CNG	175	185		5,001	4,771	4,541	230	460
	DME	175	185		4,887	4,657	4,427	230	460
	Methanol	175	185		4,887	4,657	4,427	230	460
	H2 ICE	175	185		5,355	5,125	4,895	230	460
	FCEV	-	185	31	5,680	5,375	5,088	230	460
	BEV	-	185		7,899	6,469	5,639	230	460
16-40t Long-haul	diesel	325	320		15,729	15,179	14,629	550	1,100
	LNG	325	320		15,404	14,854	14,304	550	1,100
	DME	325	320		15,341	14,791	14,241	550	1,100
	Methanol	325	320		15,341	14,791	14,241	550	1,100
	H2 ICE	325	320		16,362	15,812	15,262	550	1,100
	FCEV	-	320	200	17,080	16,330	16,274	550	1,100
	CEV	-	320		17,963	15,179	15,523	550	1,100
40-60t Long-haul XL	diesel	455	420		21,129	20,479	19,829	650	1,300
	LNG	455	420		21,063	20,413	19,763	650	1,300
	DME	455	420		20,821	20,171	19,521	650	1,300
	Methanol	455	420		20,997	20,347	19,697	650	1,300
	H2 ICE	455	420		22,065	21,415	20,765	650	1,300
	FCEV	-	420	250	22,966	22,049	21,563	650	1,300
	CEV	-	420		24,089	22,255	21,013	650	1,300
City bus	diesel	175	180		4,670	4,520	4,370	150	300
	CNG	175	180		4,709	4,559	4,409	150	300
	DME	175	180		4,628	4,478	4,328	150	300
	Methanol	175	180		4,628	4,478	4,328	150	300
	H2 ICE	175	180		5,024	4,874	4,724	150	300
	FCEV	-	180	180	5,708	5,425	5,400	150	300
	BEV	-	180		7,261	6,074	5,406	150	300
Coach	diesel	250	250		14,800	14,400	14,000	400	800
	LNG	250	250		14,896	14,896	14,896	400	800
	DME	250	250		14,787	14,787	14,787	400	800
	Methanol	250	250		15,007	15,007	15,007	400	800
	H2 ICE	250	250		15,936	15,936	15,936	400	800
	FCEV	-	250	180	16,231	15,665	15,345	400	800
	CEV	-	250		17,076	15,765	14,910	400	800

** for ICE powertrains only Balanced and All-In.*

Table 211: Main technical specifications for heavy-duty vehicles II.

Size	Fuel type	Tank capacity	Gross (installed) battery capacity (kWh)*
3.5-7.5 t Rigid	diesel	57 l	2.1
	CNG	20.2 kg	2.1
	DME	61 l	2.1
	Methanol	81 l	2.1
	H2 ICE	9.4 kg	2.1
	FCEV	5.1 kg	33.0
	BEV	-	190.2
7.5-16t Regional	diesel	98 l	3.0
	CNG	41 kg	3.0
	DME	124 l	3.0
	Methanol	180 l	3.0
	H2 ICE	19.3 kg	3.0
	FCEV	12.3 kg	45.0
	BEV	-	359.8
16-40t Long-haul	diesel	275 l	13.7
	LNG	324 l	13.7
	DME	329 l	13.7
	Methanol	893 l	13.7
	H2 ICE	51.1 kg	13.7
	FCEV	37.5 kg	120.0
	CEV	-	268.1
40-60t Long-haul XL	diesel	337 l	17.7
	LNG	492 l	17.7
	DME	401 l	17.7
	Methanol	889 l	17.7
	H2 ICE	62.2 kg	17.7
	FCEV	45.7 kg	160.0
	CEV	-	355.2
City bus	diesel	106 l	2.0
	CNG	35.6 kg	2.0
	DME	107 l	2.0
	Methanol	210 l	2.0
	H2 ICE	16.6 kg	2.0
	FCEV	14.1 kg	80.0
	BEV	-	310.9
Coach	diesel	255 l	17.8
	LNG	356 l	17.8
	DME	359 l	17.8
	Methanol	480 l	17.8
	H2 ICE	55.8 kg	17.8
	FCEV	31.8 kg	100.0
	CEV	-	273.1

**Operation range of electric vehicles has been defined in the focus group: The battery-electric range for the 3.5-7.5 t rigid truck is 230 km; for the 7.5-12 t truck 299 km and for the city bus 280 km under real driving conditions. All catenary-electric vehicles (CEV) (trucks above 16t as well as the coach) have a battery-electric range of 120 km.*

16.4 Vehicle Costs

Table 212: Vehicle Costs.

		Status Quo			Balanced		All-In
Classification	**Type**	**2020**	**2030**	**2050**	**2030**	**2050**	**2050**
Passenger cars (Small)	BEV	€ 19,892	€16,988	€14,084	€16,888	€14,017	€14,564
	FCEV	€18,916	€16,723	€14,965	€ 16,718	€14,961	€16,117
	ICEV CNG	€9,886	€10,192	€10,555	€12,704	€12,157	€14,376
	ICEV gasoline	€9,130	€ 9,587	€9,587	€12,213	€11,765	€14,024
	ICEV Methanol	€9,310	€9,767	€9,767	€12,393	€11,945	€14,204
	ICEV DME	€10,174	€10,755	€10,738	€13,364	€12,901	€14,557
	ICEV H2 combustion	€13,624	€13,207	€12,550	€15,106	€14,137	€16,164
	ICEV diesel	€10,059	€10,663	€10,663	€13,290	€12,841	€14,500
Passenger cars (Medium)	BEV	€36,119	€30,445	€24,770	€30,022	€24,488	€24,125
	FCEV	€33,948	€29,738	€26,417	€29,716	€26,399	€27,561
	ICEV CNG	€17,170	€17,693	€17,478	€21,445	€20,633	€22,984
	ICEV gasoline	€15,826	€ 16,618	€16,618	€20,622	€19,974	€22,401
	ICEV Methanol	€16,006	€16,798	€16,798	€ 20,802	€ 20,154	€22,581
	ICEV DME	€17,663	€18,664	€18,630	€22,624	€21,951	€23,770
	ICEV H2 combustion	€23,922	€23,120	€21,923	€25,425	€23,898	€25,884
	ICEV diesel	€17,437	€18,483	€ 8,483	€22,488	€21,840	€23,667
Passenger cars (Large)	BEV	€56,410	€49,537	€42,932	€48,801	€42,441	€40,615
	FCEV	€57,643	€51,731	€47,321	€51,699	€47,295	€48,259
	ICEV CNG	€35,068	€36,433	€36,185	€41,014	€40,122	€42,545
	ICEV gasoline	€33,517	€35,193	€35,193	€40,045	€39,347	€41,962
	ICEV Methanol	€33,697	€35,373	€35,373	€40,225	€39,527	€42,142
	ICEV DME	€37,183	€39,348	€39,310	€44,154	€43,427	€45,416
	ICEV H2 combustion	€42,925	€42,746	€41,352	€45,719	€43,979	€45,445
	ICEV diesel	€36,928	€39,143	€39,143	€43,996	€43,298	€45,313
Passenger cars (SUV)	BEV	€51,091	€42,484	€33,877	€40,786	€32,745	€30,858
	FCEV	€44,684	€38,946	€34,441	€38,893	€34,398	€35,491
	ICEV CNG	€21,865	€22,542	€22,275	€27,332	€26,314	€28,778
	ICEV gasoline	€20,199	€21,209	€21,209	€26,231	€25,433	€28,024
	ICEV Methanol	€20,379	€21,389	€21,389	€26,411	€25,613	€28,204
	ICEV DME	€22,504	€23,789	€23,752	€28,776	€27,948	€29,925
	ICEV H2 combustion	€30,349	€29,356	€27,850	€32,705	€30,715	€32,553
	ICEV diesel	€22,255	€23,590	€23,590	€28,612	€27,814	€29,805
Passenger cars (LCV)	BEV	€85,434	€69,744	€54,055	€64,812	€50,767	€44,282
	FCEV	€50,098	€44,461	€40,006	€44,306	€39,879	€40,667
	ICEV CNG	€27,416	€28,235	€27,882	€32,820	€31,616	€34,128
	ICEV gasoline	€25,210	€26,471	€26,471	€31,288	€30,391	€33,142
	ICEV Methanol	€25,390	€26,651	€26,651	€31,468	€30,571	€33,322
	ICEV DME	€28,445	€30,053	€29,997	€34,830	€33,884	€36,006
	ICEV H2 combustion	€38,988	€37,521	€35,470	€40,418	€37,830	€39,123
	ICEV diesel	€28,067	€29,751	€29,751	€34,568	€33,671	€35,822

		Status Quo			Balanced		All-In
Classification	**Type**	**2020**	**2030**	**2050**	**2030**	**2050**	**2050**
Rigid (N2)	BEV	€67,785	€56,071	€44,659	€56,071	€44,659	€44,659
	FCEV	€34,500	€31,105	€28,086	€31,105	€28,086	€28,086
	ICEV CNG	€27,636	€28,756	€28,425	€32,864	€32,043	€38,023
	ICEV gasoline	€23,010	€24,161	€24,161	€28,269	€27,778	€27,778
	ICEV Methanol	€25,747	€27,281	€27,281	€31,389	€30,899	€36,879
	ICEV DME	€25,867	€27,341	€27,297	€31,449	€30,914	€36,895
	ICEV H2 combustion	€34,336	€34,357	€32,844	€38,465	€36,462	€42,442
	ICEV diesel	€25,567	€27,101	€27,101	€31,209	€30,719	€36,699
Regional Delivery (N2/N3)	BEV	€140,398	€118,313	€96,723	€118,313	€96,723	€96,723
	FCEV	€77,046	€70,965	€65,608	€70,965	€65,608	€65,608
	ICEV CNG	€63,080	€65,775	€65,104	€72,995	€71,609	€83,008
	ICEV gasoline	€53,000	€55,649	€55,649	€62,870	€62,154	€62,154
	ICEV Methanol	€59,068	€62,602	€62,602	€69,822	€69,107	€80,505
	ICEV DME	€59,502	€62,913	€62,822	€73,486	€72,009	€80,725
	ICEV H2 combustion	€76,690	€77,130	€74,037	€84,350	€80,542	€91,941
	ICEV diesel	€58,888	€62,422	€62,422	€69,642	€68,927	€80,325
Long Haul (N3)	BEV	€192,980	€153,613	€132,743	€153,613	€132,743	€132,743
	FCEV	€172,111	€152,100	€134,479	€152,100	€134,479	€134,479
	ICEV CNG	€103,330	€106,690	€104,943	€124,895	€119,868	€145,042
	ICEV gasoline	€83,168	€87,327	€87,327	€105,531	€102,251	€102,251
	ICEV Methanol	€92,589	€98,134	€98,134	€116,338	€113,058	€138,232
	ICEV DME	€94,040	€99,259	€99,016	€117,463	€113,941	€139,115
	ICEV H2 combustion	€139,370	€136,721	€128,527	€154,925	€143,452	€168,626
	ICEV diesel	€92,409	€97,954	€97,954	€116,158	€112,878	€138,052
Super Long Haul (N3)	BEV	€209,680	€164,719	€138,626	€164,719	€138,626	€138,626
	FCEV	€190,416	€164,854	€142,418	€164,854	€142,418	€142,418
	ICEV CNG	€105,661	€108,555	€106,435	€132,798	€126,441	€158,016
	ICEV gasoline	€83,168	€87,327	€87,327	€111,570	€107,333	€107,333
	ICEV Methanol	€92,589	€98,134	€98,134	€122,377	€118,140	€149,715
	ICEV DME	€94,396	€99,543	€99,248	€123,786	€119,254	€150,829
	ICEV H2 combustion	€149,583	€145,148	€135,167	€169,391	€155,174	€186,749
	ICEV diesel	€92,409	€97,954	€97,954	€122,197	€117,960	€149,535
Public Transport	BEV	€329,310	€310,162	€291,510	€310,162	€291,510	€291,510
	FCEV	€313,430	€300,577	€289,543	€300,577	€289,543	€289,543
	ICEV CNG	€263,311	€278,164	€277,582	€284,564	€283,499	€306,799
	ICEV gasoline	€233,706	€245,391	€245,391	€251,791	€251,309	€251,309
	ICEV Methanol	€259,853	€275,433	€275,433	€281,834	€281,351	€304,651
	ICEV DME	€260,203	€275,678	€275,599	€284,988	€283,845	€304,816
	ICEV H2 combustion	€275,032	€287,947	€285,281	€294,347	€291,199	€314,498
	ICEV diesel	€259,673	€275,253	€275,253	€281,654	€281,171	€304,471
Coaches	BEV	€422,745	€383,289	€362,119	€383,289	€362,119	€362,119
	FCEV	€388,982	€371,875	€356,800	€371,875	€356,800	€324,957
	ICEV CNG	€330,463	€347,163	€345,238	€368,988	€362,820	€406,206
	ICEV gasoline	€286,589	€300,918	€300,918	€322,743	€318,500	€318,500
	ICEV Methanol	€318,612	€337,718	€337,718	€359,543	€355,300	€398,686
	ICEV DME	€320,211	€338,961	€338,697	€360,786	€356,279	€399,665
	ICEV H2 combustion	€369,664	€379,829	€337,658	€401,654	€388,470	€431,856
	ICEV diesel	€318,432	€337,538	€337,538	€359,363	€355,120	€398,506

16.5 Fuel Supply Chain – technical characteristics

16.5.1 General

Table 213: Generation.

Parameter	Year	Capacity in MW	Lifetime in years	Source
Capacity Wind Offshore per unit	2020	4.15	25	Syseet Data
Capacity Wind Offshore per unit	2030	8.5	25	Syseet Data
Capacity Wind Offshore per unit	2050	15	25	Syseet Data
Capacity Wind Onshore per unit	2020	2.9	20	Syseet Data
Capacity Wind Onshore per unit	2030	3.8	20	Syseet Data
Capacity Wind Onshore per unit	2050	6	20	Syseet Data
Capacity PV Standalone per unit	2020	5	30	Syseet Data
Capacity PV Standalone per unit	2030	5	30	Syseet Data
Capacity PV Standalone per unit	2050	5	30	Syseet Data
Capacity PV Slanted Roof per unit	2020	0.005	30	Syseet Data
Capacity PV Slanted Roof per unit	2030	0.005	30	Syseet Data
Capacity PV Slanted Roof per unit	2050	0.005	30	Syseet Data

Table 214: Offshore Transmission.

Parameter	Year	Unit	Value	Source
Losses due to converter stations	2020-2050	%	1.5%	(Institut für Energieversorgung und Hochspannungstechnik, kein Datum)
Losses due to HVDC cable	2020-2050	%	2%	(Council of European Regulators, 2017)
Voltage of HVDC cable	2020	kV	320	Frontier calculations based on existing and planned platforms in Northern Sea
Voltage of HVDC cable	2030	kV	525	Frontier calculations based on existing and planned platforms in Northern Sea
Voltage of HVDC cable	2050	kV	525	Frontier calculations based on existing and planned platforms in Northern Sea
Average cable capacity per converter platform	2020	kV	900	Frontier calculations based on existing and planned platforms in Northern Sea
Average cable capacity per converter platform	2030	kV	2000	Frontier calculations based on existing and planned platforms in Northern Sea
Average cable capacity per converter platform	2050	kV	2000	Frontier calculations based on existing and planned platforms in Northern Sea
Average distance (converter to coast)	2020	km/platform	106	Frontier calculations based on existing and planned platforms in Northern Sea
Average distance (converter to coast)	2030	km/platform	158	Frontier calculations based on existing and planned platforms in Northern Sea
Average distance (converter to coast)	2050	km/platform	200	(Myhr, et al., 2014)

Table 215: Electrolysis.

Parameter	Year	Unit	Value	Source
Efficiency	2020	kWh(H2)/kWh(el)	0.64	FVV Working Group, (Liebich, et al., 2019)
Efficiency	2030	kWh(H2)/kWh(el)	0.69	FVV Working Group, (Liebich, et al., 2019)
Efficiency	2050	kWh(H2)/kWh(el)	0.71	FVV Working Group, (Liebich, et al., 2019)
Capacity Electrolyser per unit	2020	MW (el)	10	(FCH, 2021)
Capacity Electrolyser per unit	2030	MW (el)	250	FVV Working Group
Capacity Electrolyser per unit	2050	MW (el)	1000	FVV Working Group

Table 216: Hydrogen Storage.

Parameter	Year	Unit	Value	Source
Capacity Hydrogen Pressure Storage per unit	2020	kg (H2)	1000	(NPROXX, kein Datum)
Capacity Hydrogen Pressure Storage per unit	2030	kg (H2)	1000	(NPROXX, kein Datum)
Capacity Hydrogen Pressure Storage per unit	2050	kg (H2)	1000	(NPROXX, kein Datum)
Energy demand for H2 Pressure Storage	2020-2050	kWh (el)/kg(H2)	1.9	(Linde, 2020)
Losses due to H2 Pressure Storage	2030	%	0.10%	(Petitpas, 2018)
Capacity of a typical Cavern Storage – Volume	2020	m³	500,000	(DLR, 2014)
Capacity of a typical Cavern Storage – Volume	2030	Mio. m³	500	(DLR, 2014)
Capacity of a typical Cavern Storage – Volume	2050	Mio. m³	500	(DLR, 2014)
Losses of cavern stage due to compression	2020	%	2%	(International Energy Agency, 2019)

Table 217: Hydrogen Pipelines for Hydrogen Storage.

Parameter	Year	Unit	Value	Source
Capacity of line	2020-2050	GW	7	(Wang, et al., 2020)
Additional energy demand for compression	2020-2050	%	0.77%	(Hänggi, et al., 2019)
Average compressor size	2020-2050	MW/unit	260	(Wang, et al., 2020)

Table 218: Direct Air Capturing.

Parameter	Year	Unit	Value	Source
Electricity Demand	2020	kWh(el)/kg CO2	2.2	(Liebich, et al., 2019), (Fasihi, et al., 2019)
Electricity Demand	2030	kWh(el)/kg CO2	1.5	(Viehbahn, et al., 2018)
Electricity Demand	2050	kWh(el)/kg CO2	1.39	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
Thermal Demand	2020	kWh(therm)/kg CO2	0.5	(Viehbahn, et al., 2018)
Thermal Demand	2030	kWh(therm)/kg CO2	0.4	(Viehbahn, et al., 2018), (Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
Thermal Demand	2050	kWh(therm)/kg CO2	0.28	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
Capacity per module	2020-2050	tCo2/mod-ule	0.135	Climeworks

Table 219: CO2 Storage.

Parameter	Year	Unit	Value	Source
Capacity of a typical unit	2020-2050	tCO2/unit	12,310	(Business, Energy and Industrial Strategy Department, 2018)

Table 220: Standard approach for fuel stations.

Parameter	Year	Unit	Value	Source
Pumps per fuel station (passenger ve-hicles)	2020-2050	Units	8	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
Pumps per fuel station (trucks)	2020-2050	units	4	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
Total pumps required in 100% scenario (passenger vehicles)	2020-2050	Units	717,939	Upscale for Euroean size based on (Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
Total pumps required in 100% scenario (trucks)	2020-2050	units	479,684	Upscale for Euroean size based on (Forschungsvereinigung Verbrennungskraftmaschinen, 2018)

Table 221: Import via Shipping.

Parameter	Year	Unit	Value	Source
Average Distance per ship (RoW – e.g. Patagonia)	2020-2050	Km	15,000	Assumption based on average distance from Patagonia to Rotterdam and South Europe (Sea-Distances, 2021)
Average Distance per ship (MENA)	2020-2050	km	2,500	Assumption based on average distance from North African Coast to Rotterdam and from North Africa to South Europe (Sea-Distances, 2021)
Average Speed	2020-2050	Km/h	30	(World Ocean Review, 2021)

16.5.2 BEV specific

Table 222: Transmission Grid.

Parameter	Year	Unit	Value	Source
HVDC Cable	2020-2050	GW	2	(ENTSOE, kein Datum)
AC Overhead	2020-2050	GW	2	(ENTSOE, kein Datum)

Table 223: Distribution Grid.

Parameter	Year	Unit	Value	Source
High Voltage 110 kV	2020-2050	GW	0.66	Frontier Economics based on technical parameters
Medium Voltage 25-60 kV	2020-2050	GW	0.22	Frontier Economics based on technical parameters
Low Voltage 400V	2020-2050	GW	0.02	Frontier Economics based on technical parameters

Table 224: Lifetimes of Charger.

Parameter	Year	Unit	Value	Source
Lifetime Private Charger per unit	2020-2050	Years	17	FVV Working Group
Lifetime Truck Charger per unit	2020-2050	Years	10	(DREWAG, kein Datum)
Lifetime Semi Public Charger per unit	2020-2050	Years	10	(DREWAG, kein Datum)
Lifetime Fast Charger per unit	2020-2050	Years	10	(DREWAG, kein Datum)

Table 225: Overhead grid for catenary trucks and coaches.

Countries	EUROSTAT Motorway In km	EUROSTAT E-Road In km	TEN-T comprehensive in km	Value considered in km
Austria	1,743	2,250	1,735	2,250
Belgium	1,763	0	948	1,763
Bulgaria	757	2,981	#N/A	2,981
Croatia	1,310	2,255	#N/A	2,255
Cyprus	257	0	#N/A	257
Czechia	1,252	2,636	#N/A	2,636
Denmark	1,329	945	1,556	1,556
Estonia	154	995	1,350	1,350
Finland	926	4,348	5,220	5,220
France	11,671	13,218	#N/A	13,218
Germany (until 1990 former territory of the FRG)	13,141	0	10,700	13,141
Greece	0	0	4,816	4,816
Hungary	1,982	2,359	1,450	2,359
Ireland	916	0	2,163	2,163
Italy	6,943	0	8,715	8,715
Latvia	0	202	#N/A	202
Lithuania	324	1,650	1,652	1,652
Luxembourg	165	0	90	165
Malta	0	0	#N/A	200*
Netherlands	2,758	0	1,886	2,758
Poland	1,637	5,818	7,622	7,622
Portugal	3,065	2,254	#N/A	3,065
Romania	823	6,269	#N/A	6,269
Slovakia	482	1,537	686	1,537
Slovenia	769	725	594	769
Spain	15,585	0	12,198	15,585
Sweden	2,132	6,755	6,417	6,755
United Kingdom	3,838	3,792	6,989	6,989
Total roads to be electrified in 2050	75,722	60,989	76,787	118,248

[Source: Based on EUROSTAT and TEN-T (https://www.cedr.eu/download/Publications/2018/TEN-T-Performance-report-2017.pdf). As for Malta no values are available the following source was taken (https://peritmarkjohn.com/the-maltese-road-network/). Note: Following a conservative approach, the maximum value of the three different sources has been taken into account].

Table 226: Re-conversion from Hydrogen to Electricity.

Parameter	Year	Unit	Value	Source
Efficiency	2020	kWh(H2)/kWh(el)	0.45	(Geitmann, 2016)
Efficiency	2030	kWh(H2)/kWh(el)	0.475	(Geitmann, 2016)
Efficiency	2050	kWh(H2)/kWh(el)	0.50	(Geitmann, 2016)
Capacity	2020-2050	MW (el)	500	(Simoes, et al., 2013)

Table 227: Import cable.

Parameter	Year	Unit	Value	Source
Average distance per line	2020-2050	km	1,500	Average Distance from MENA to Europe

16.5.3 H2 specific

Table 228: Distribution stage including compression.

Parameter	Year	Unit	Value	Source
Capacity per Hydrogen truck	2020	kg(H2)	900	(ADAC & Ludwig-Bölkow-Stiftung , 2019)
Capacity per Hydrogen truck	2030	kg(H2)	900	(ADAC & Ludwig-Bölkow-Stiftung , 2019)
Capacity per Hydrogen truck	2050	kg(H2)	1100	FVV Working Group
Energy demand for compression	2020-2050	kWh/kg	1.9	(Linde, 2020)
Capacity per hour per unit	2020-2050	kg(H2)/hour	56	(Linde, 2020)

Table 229: Import Pipeline.

Parameter	Year	Unit	Value	Source
Average distance per line	2020-2050	km	1,500	Average Distance from MENA to Europe
Average Capacity of line	2020-2050	GW	13	(Wang, et al., 2020
Compressor	2020-2050	MW(el)/1000km	260	(Wang, et al., 2020

16.5.4 FT Fuel specific

Table 230: FT Synthesis.

Parameter	Year	Unit	Value	Source
Capacity FT Synthesis per unit	2020	MW (FT Fuel)	90	(Liebich, et al., 2019)
Capacity FT Synthesis per unit	2030	MW (FT Fuel)	493.3	Linearly interpolated
Capacity FT Synthesis per unit	2050	MW (FT Fuel)	1300	FVV Working Group

16.5.5 CH4 specific

Table 231: Methanisation.

Parameter	Year	Unit	Value	Source
Capacity Methanisation per unit	2020	MW (CH4)	20	FVV Working Group
Capacity Methanisation per unit	2030	MW (CH4)	80	FVV Working Group
Capacity Methanisation per unit	2050	MW (CH4)	500	FVV Working Group

Table 232: Methane Central Storage.

Parameter	Year	Unit	Value	Source
Average capacity of a Cavern	2020-2050	mio m³	500	(Deutsches Zentrum für Luft-und Raumfahrt, 2015)
Storage losses (incl. compression)	2020-2050	%	2%	(International Energy Agency, 2019)

Table 233: Liquefaction for LNG.

Parameter	Year	Unit	Value	Source
Capacity per liquefaction unit	2020-2050	t/a	100,000	FVV Working Group (small scale liquefaction plant)
Full load hours	2020-2050	h	8000	FVV Working Group
Additional energy demand (incl. gas turbine demand)	2020	kWh(CH4)/kWh(LNG)	0.07	FVV Working Group
Additional energy demand (incl. gas turbine demand)	2030	kWh(CH4)/kWh(LNG)	0.06	FVV Working Group
Additional energy demand (incl. gas turbine demand)	2050	kWh(CH4)/kWh(LNG)	0.05	FVV Working Group

Table 234: Methane Losses.

Parameter	Year	Unit	Value	Source
Losses incl. compression for distribution	2020-2050	%	0.2%	(ConocoPhillips, 2015)
Daily storage losses incl. compression for LNG Storage	2020-2050	%/day	0.05%	(GIIGNL - International Group of Liquefied Natural Gas Importers, 2015)

16.5.6 MeOH specific

Table 235: MeOH Synthesis.

Parameter	Year	Unit	Value	Source
Capacity Methanol Synthesis Unit size	2020	MW (MeOH)	90	(Liebich, et al., 2019)
Capacity Methanol Synthesis Unit size	2030	MW (MeOH)	393.3	Linearly interpolated
Capacity Methanol Synthesis Unit size	2050	MW (MeOH)	1000	FVV Working Group

16.5.7 DME specific

Table 236: DME Synthesis.

Parameter	Year	Unit	Value	Source
Capacity DME Synthesis Unit size	2020	MW (DME)	90	FVV Working Group
Capacity DME Synthesis Unit size	2030	MW (DME)	393.3	FVV Working Group
Capacity DME Synthesis Unit size	2050	MW (DME)	1000	FVV Working Group

Table 237: Liquefaction of DME.

Parameter	Year	Unit	Value	Source
Additional energy demand to liquify	2020-2050	%	0.78%	(LBST, 2013)
Capacity	2020-2050	t(DME)	100,000	Analogue to LNG

16.6 Fuel Supply Chain Costs

16.6.1 Investment Costs

16.6.1.1 General

Table 238: Investment Cost Generation – Domestic.

Parameter	Year	Unit	Value	Source
Wind Offshore	2020	EUR/kW(el)	3,300	(Erichsen, et al., 2019)
Wind floating Offshore	2020	EUR/kW(el)	3,450	(Beiter, et al., 2020)
Wind Onshore	2020	EUR/kW(el)	1,450	(Erichsen, et al., 2019)
PV Standalone	2020	EUR/kW(el)	1,000	(Erichsen, et al., 2019)
PV slanted	2020	EUR/kW(el)	1,500	(Erichsen, et al., 2019)
Wind Offshore	2030	EUR/kW(el)	2,600	(Erichsen, et al., 2019)
Wind floating Offshore	2030	EUR/kW(el)	2,718	(Beiter, et al., 2020)
Wind Onshore	2030	EUR/kW(el)	1,200	(Erichsen, et al., 2019)
PV Standalone	2030	EUR/kW(el)	675	(Erichsen, et al., 2019)
PV slanted	2030	EUR/kW(el)	1,000	(Erichsen, et al., 2019)
Wind Offshore	2050	EUR/kW(el)	2,150	(Erichsen, et al., 2019)
Wind floating Offshore	2050	EUR/kW(el)	2,248	(Beiter, et al., 2020)
Wind Onshore	2050	EUR/kW(el)	1,100	(Erichsen, et al., 2019)
PV Standalone	2050	EUR/kW(el)	500	(Erichsen, et al., 2019)
PV slanted	2050	EUR/kW(el)	750	(Erichsen, et al., 2019)

Table 239: Investment Cost Generation – International.

Parameter	Year	Unit	Value	Source
Wind Offshore	2020	EUR/kW(el)	2,800	(Agora Verkehrswende, Agora Energiewende und Frontier Economics, 2018)
Wind Onshore	2020	EUR/kW(el)	1,526	(Agora Verkehrswende, Agora Energiewende und Frontier Economics, 2018)
PV Stanalone	2020	EUR/kW(el)	908	(Agora Verkehrswende, Agora Energiewende und Frontier Economics, 2018)
PV slanted	2020	EUR/kW(el)	1,500	Analogue to domestic
Wind Offshore	2030	EUR/kW(el)	2,200	(Agora Verkehrswende, Agora Energiewende und Frontier Economics, 2018)
Wind Onshore	2030	EUR/kW(el)	1,260	(Agora Verkehrswende, Agora Energiewende und Frontier Economics, 2018)
PV Stanalone	2030	EUR/kW(el)	718	(Agora Verkehrswende, Agora Energiewende und Frontier Economics, 2018)
PV slanted	2030	EUR/kW(el)	1,000	Analogue to domestic
Wind Offshore	2050	EUR/kW(el)	1,600	(Agora Verkehrswende, Agora Energiewende und Frontier Economics, 2018)
Wind Onshore	2050	EUR/kW(el)	1,078	(Agora Verkehrswende, Agora Energiewende und Frontier Economics, 2018)
PV Stanalone	2050	EUR/kW(el)	486	(Agora Verkehrswende, Agora Energiewende und Frontier Economics, 2018)
PV slanted	2050	EUR/kW(el)	750	Analogue to domestic

Table 240: Investment cost for Electrolysis.

Parameter	Year	Unit	Value	Source
Electrolysis	2020	EUR/kW(el)	700	(Vos, et al., 2020)
Electrolysis	2030	EUR/kW(el)	400.	Linearly Interpolated
Electrolysis	2050	EUR/kW(el)	250	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)

Table 241: Investment cost for DAC.

Parameter	Year	Unit	Value	Source
Direct Air Capturing	2020	EUR/t (CO2)	730	(Fasihi, et al., 2019)
Direct Air Capturing	2030	EUR/t (CO2)	338	(Fasihi, et al., 2019)
Direct Air Capturing	2050	EUR/t (CO2)	199	(Fasihi, et al., 2019)

Table 242: Investment cost for H2 Storage.

Parameter	Unit	Value	Source
Cavern Storage - retrofit	EUR/m³	90.00	(Erichsen, et al., 2019)
Pressure Storage	EUR/m³	11,979	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)

Table 243: Investment Cost Hydrogen pipelines for Storage.

Parameter	Year	Unit	Value	Source
Hydrogen Pipeline (new built)	2020	Mio. EUR/km	1.21	(International Energy Agency, 2019)
Hydrogen Pipeline (new built)	2030	Mio. EUR/km	1.21	(International Energy Agency, 2019)
Hydrogen Pipeline (new built)	2050	Mio. EUR/km	1.21	(International Energy Agency, 2019)
Hydrogen Compressor per unit/MW (new built)	2020	EUR/MW	3,400,000	(Wang, et al., 2020) (average, medium scenario)
Hydrogen Compressor per unit/MW (new built)	2030	EUR/MW	3,400,000	(Wang, et al., 2020) (average, medium scenario)
Hydrogen Compressor per unit/MW (new built)	2050	EUR/MW	3,400,000	(Wang, et al., 2020) (average, medium scenario)

Table 244: Investment Cost for CO2 Storage.

Parameter	Unit	Value	Source
CO2 Storage	EUR/ t CO2	903	(elementenergy, 2018)

16.6.1.2 BEV specific

Table 245: Investment cost for transmission grid.

Parameter	Year	Unit	Value	Source
AC Overhead Line	2020	EUR/km	2,200,000	Frontier Economics based on (Übertragungsnetzbetreiber , 2019)
AC Overhead Line	2030	EUR/km	2,200,000	Frontier Economics based on (Übertragungsnetzbetreiber , 2019)
AC Overhead Line	2050	EUR/km	2,200,000	Frontier Economics based on (Übertragungsnetzbetreiber , 2019)
HVDC Overhead Line	2020	EUR/km	2,000,000	Frontier Economics based on (Übertragungsnetzbetreiber , 2019)
HVDC Overhead Line	2030	EUR/km	2,000,000	Frontier Economics based on (Übertragungsnetzbetreiber , 2019)
HVDC Overhead Line	2050	EUR/km	2,000,000	Frontier Economics based on (Übertragungsnetzbetreiber , 2019)
HVDC Underground Cable	2020	EUR/km	6,000,000	Frontier Economics based on (Übertragungsnetzbetreiber , 2019)
HVDC Underground Cable	2030	EUR/km	6,000,000	Frontier Economics based on (Übertragungsnetzbetreiber , 2019)
HVDC Underground Cable	2050	EUR/km	6,000,000	Frontier Economics based on (Übertragungsnetzbetreiber , 2019)

Table 246: Investment cost for converter offshore platform.

Parameter	Unit	Value	Source
Converter Offshore platform	EUR/unit	160,000,000	(Flament, et al., 2015)

Table 247: Investment cost for import cable for electricity.

Parameter	Year	Unit	Value	Source
Line (2GW)	2020	EUR/km	6,000,000	Frontier Economics based on (Übertragungsnetzbetreiber , 2019)
Line (2GW)	2030	EUR/km	6,000,000	Frontier Economics based on (Übertragungsnetzbetreiber , 2019)
Line (2GW)	2050	EUR/km	6,000,000	Frontier Economics based on (Übertragungsnetzbetreiber , 2019)

Table 248: Investment cost for Hydrogen gas turbine.

Parameter	Year	Unit	Value	Source
Hydrogen Turbine	2020	EUR/ kW(el)	675	(Goldman Sachs, 2020)
Hydrogen Turbine	2030	EUR/ kW(el)	610	(Goldman Sachs, 2020), assuming 1% price decrease p.a.
Hydrogen Turbine	2050	EUR/ kW(el)	499	(Goldman Sachs, 2020), assuming 1% price decrease p.a.

Table 249: Investment cost for power storage in batteries.

Parameter	Year	Unit	Value	Source
LI Battery	2020	EUR/MWh	650,000	(Erichsen, et al., 2019)
LI Battery	2030	EUR/MWh	250,000	(Erichsen, et al., 2019)
LI Battery	2050	EUR/MWh	150,000	(Erichsen, et al., 2019)

Table 250: Investment cost for electricity distribution.

Parameter	Year	Unit	Value	Source
HS	2020	EUR/km	60,000	(Deutsche Energie-Agentur, 2012)
HS	2030	EUR/km	60,000	(Deutsche Energie-Agentur, 2012)
HS	2050	EUR/km	60,000	(Deutsche Energie-Agentur, 2012)
MS	2020	EUR/km	110,000	(Deutsche Energie-Agentur, 2012)
MS	2030	EUR/km	110,000	(Deutsche Energie-Agentur, 2012)
MS	2050	EUR/km	110,000	(Deutsche Energie-Agentur, 2012)
NS	2020	EUR/km	80,000	(Deutsche Energie-Agentur, 2012)
NS	2030	EUR/km	80,000	(Deutsche Energie-Agentur, 2012)
NS	2050	EUR/km	80,000	(Deutsche Energie-Agentur, 2012)

Table 251: Investment cost for electricity distribution – transformers.

Parameter	Unit	Value	Source
Transformer HV-MV	EUR/unit	3,000,000	(Deutsche Energie-Agentur, 2012)
Transformer MV-NV	EUR/unit	35,000	(Deutsche Energie-Agentur, 2012)

Table 252: Investment cost for charger.

Parameter	Year	Unit	Value	Source
Charging Point (11kW)	2020	EUR	1,056	(Nicholas, 2019)
Charging Point (11kW)	2030	EUR	1,056	(Nicholas, 2019)
Charging Point (11kW)	2050	EUR	1,056	(Nicholas, 2019)
Charging Point (44kW)	2020	EUR	8,000	(The Mobility House, 2020)
Charging Point (44kW)	2030	EUR	8,000	(The Mobility House, 2020)
Charging Point (44kW)	2050	EUR	8000	(The Mobility House, 2020)
Charging Point (150kW)	2020	EUR	65,000	(Transport & Environment, 2020)
Charging Point (150kW)	2030	EUR	65,000	(Transport & Environment, 2020)
Charging Point (150kW)	2050	EUR	65,000	(Transport & Environment, 2020)

Table 253: Investment cost for catenary grid.

Parameter	Year	Unit	Value	Source
Catenary Grid	2020	mio EUR/km	3	(Den Boer, et al., 2013)
Catenary Grid	2030	mio EUR/km	2.3	(Den Boer, et al., 2013)
Catenary Grid	2050	mio EUR/km	2	(Den Boer, et al., 2013)

16.6.1.3 Hydrogen specific

Table 254: Investment Cost Hydrogen Transmission Pipelines.

Parameter	Year	Unit	Value	Source
Hydrogen Pipeline (new built)	2020	Mio EUR/km	2.75	(Wang, et al., 2020) (average, medium scenario)
Hydrogen Pipeline (new built)	2030	Mio EUR/km	2.75	(Wang, et al., 2020) (average, medium scenario)
Hydrogen Pipeline (new built)	2050	Mio EUR/km	2.75	(Wang, et al., 2020) (average, medium scenario)
Hydrogen Pipeline (retrofit)	2020	Mio EUR/km	0.50	(Wang, et al., 2020) (average, medium scenario)
Hydrogen Pipeline (retrofit)	2030	Mio EUR/km	0.50	(Wang, et al., 2020)
Hydrogen Pipeline (retrofit)	2050	Mio EUR/km	0.50	(Wang, et al., 2020)
Hydrogen Pipeline Compressor	2020	EUR/MW	3,400,000	(Wang, et al., 2020) (average, medium scenario)
Hydrogen Pipeline Compressor	2030	EUR/MW	3,400,000	(Wang, et al., 2020) (average, medium scenario)
Hydrogen Pipeline Compressor	2050	EUR/MW	3,400,000	(Wang, et al., 2020) (average, medium scenario)

Table 255: Investment Cost for H2 compressors for truck distribution.

Parameter	Year	Unit	Value	Source
Investment Cost Compressor	2020	EUR/kg	14.15	Assumption - analogue to compressors for pipelines
Investment Cost Compressor	2030	EUR/kg	14.15	Assumption - analogue to compressors for pipelines
Investment Cost Compressor	2050	EUR/kg	14.15	Assumption - analogue to compressors for pipelines

Table 256: Investment Cost H2 Fuel Station.

Parameter	Year	Unit	Value	Source
H2 Station (Cars)	2020	EUR/pump	412,500	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
H2 Station (Cars)	2030	EUR/pump	412,500	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
H2 Station (Cars)	2050	EUR/pump	412,500	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
H2 Station (Trucks)	2020	EUR/pump	412,500	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
H2 Station (Trucks)	2030	EUR/pump	412,500	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
H2 Station (Trucks)	2050	EUR/pump	412,500	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)

16.6.1.4 FT Fuel specific

Table 257: Investment Cost FT Synthesis.

Parameter	Year	Unit	Value	Source
Synthesis Unit	2020	EUR/kW (FT Fuel)	850	(Agora Verkehrswende, Agora Energiewende und Frontier Economics, 2018)
Synthesis Unit	2030	EUR/kW (FT Fuel)	652	(Schemme, 2020)
Synthesis Unit	2050	EUR/kW (FT Fuel)	434	(International Energy Agency, 2019)

Table 258: Investment Cost FT Fuel Stations.

Parameter	Year	Unit	Value	Source
FT Station	2020	EUR/pump	2500	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
FT Station	2030	EUR/pump	2500	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
FT Station	2050	EUR/pump	2500	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)

16.6.1.5 Methane specific

Table 259: Investment Cost Methane Synthesis.

Parameter	Year	Unit	Value	Source
Methanation Unit	2020	EUR/kW (Methane)	579	(Zauner, et al., 2019)
Methanation Unit	2030	EUR/kW (Methane)	220	(Zauner, et al., 2019)
Methanation Unit	2050	EUR/kW (Methane)	105	(Zauner, et al., 2019)

Table 260: Investment Cost Methane Transmission.

Parameter	Year	Unit	Value	Source
Methane Pipeline	2020	EUR/km	2,360,000	Proposal Frontier Economics: compliantly commented and agreed in 1:1s with FVV Working Group Members
Methane Pipeline	2030	EUR/km	2,360,000	Proposal Frontier Economics: compliantly commented and agreed in 1:1s with FVV Working Group Members
Methane Pipeline	2050	EUR/km	2,360,000	Proposal Frontier Economics: compliantly commented and agreed in 1:1s with FVV Working Group Members
Compressor	2020	EUR/MW	3,120,000	Focus Group, (Cerbe et. al., 2017), (Klocke et. al. 2017), (FNB Gas 2017), (FNB Gas 2019), (FNB Gas)
Compressor	2030	EUR/MW	3,120,000	Focus Group, (Cerbe et. al., 2017), (Klocke et. al. 2017), (FNB Gas 2017), (FNB Gas 2019), (FNB Gas)
Compressor	2050	EUR/MW	3,120,000	Focus Group, (Cerbe et. al., 2017), (Klocke et. al. 2017), (FNB Gas 2017), (FNB Gas 2019), (FNB Gas)

Table 261: Investment Cost International Transport.

Parameter	Year	Unit	Value	Source
Methane Liquefaction	2020	ct/kW	435	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
Methane Liquefaction	2030	ct/kW	435	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
Methane Liquefaction	2050	ct/kW	435	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
Shipping LNG	2020	EUR/m³	970	(Kamalinejad, et al., 2016)
Shipping LNG	2030	EUR/m³	970	(Kamalinejad, et al., 2016)
Shipping LNG	2050	EUR/m³	970	(Kamalinejad, et al., 2016)
International Methane Pipeline	2020	EUR/km	4,500,000	(Sahm, 2017)
International Methane Pipeline	2030	EUR/km	4,500,000	(Sahm, 2017)
International Methane Pipeline	2050	EUR/km	4,500,000	(Sahm, 2017)
LNG Storage	2020	EUR/m³	2,000	(TRACTEBEL ENGINEERING S.A., 2015)
LNG Storage	2030	EUR/m³	2,000	(TRACTEBEL ENGINEERING S.A., 2015)
LNG Storage	2050	EUR/m³	2,000	(TRACTEBEL ENGINEERING S.A., 2015)

Table 262: Investment Cost Methane Distribution.

Parameter	Year	Unit	Value	Source
Methane Pipeline	2020	EUR/km	800,000	Proposal Frontier Economics: compliantly commented and agreed in 1:1s with FVV Working Group Members
Methane Pipeline	2030	EUR/km	800,000	Proposal Frontier Economics: compliantly commented and agreed in 1:1s with FVV Working Group Members
Methane Pipeline	2050	EUR/km	800,000	Proposal Frontier Economics: compliantly commented and agreed in 1:1s with FVV Working Group Members

Table 263: Investment Cost for LNG and CNG fuel pumps.

Parameter	Year	Unit	Value	Source
CNG Station (full investment)	2020	EUR/pump	130,000	(Smith & Gonzales, 2014)
CNG Station (full investment)	2030	EUR/pump	110,000	(Drive Natural Gas Initiative, 2013)
CNG Station (full investment)	2050	EUR/pump	110,000	(Drive Natural Gas Initiative, 2013)
LNG Station (full investment)	2020	EUR/pump	382,000	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
LNG Station (full investment)	2030	EUR/pump	382,000	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
LNG Station (full investment)	2050	EUR/pump	382,000	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)

16.6.1.6 Methanol specific

Table 264: Investment Costs for Methanol Synthesis.

Parameter	Year	Unit	Value	Source
Methanol Synthesis Unit	2020	EUR/kW(fuel)	300	(Vos, et al., 2020)
Methanol Synthesis Unit	2030	EUR/kW(fuel)	253	Linearly interpolated
Methanol Synthesis Unit	2050	EUR/kW(fuel)	230	(Schemme, 2020)

Table 265: Investment Costs for Methanol Fuel Stations.

Parameter	Year	Unit	Value	Source
Methanol Station - Car (retrofit)	2020	EUR/pump	2,250	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
Methanol Station - Car (retrofit)	2030	EUR/pump	2,250	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
Methanol Station - Car (retrofit)	2050	EUR/pump	2,250	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
Methanol Station - Truck (retrofit)	2020	EUR/pump	3,000	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
Methanol Station - Truck (retrofit)	2030	EUR/pump	3,000	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
Methanol Station - Truck (retrofit)	2050	EUR/pump	3,000	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)

16.6.1.7 DME specific

Table 266: Investment Costs for DME Synthesis.

Parameter	Year	Unit	Value	Source
DME Synthesis Unit	2020	EUR/ kW(DME)	291	(Schemme, 2020)
DME Synthesis Unit	2030	EUR/ kW(DME)	291	(Schemme, 2020)
DME Synthesis Unit	2050	EUR/ kW(DME)	291	(Schemme, 2020)

Table 267: Investment Cost for DME liquefaction.

Parameter	Year	Unit	Value	Source
DME Liquefaction	2020	EUR/MW	87,000	Assumption 1/5 of costs for LNG
DME Liquefaction	2030	EUR/MW	87,000	Assumption 1/5 of costs for LNG
DME Liquefaction	2050	EUR/MW	87,000	Assumption 1/5 of costs for LNG

Table 268: Investment Cost for DME fuel stations.

Parameter	Year	Unit	Value	Source
Investment Cost DME Station - Car	2020	EUR/pump	17,000	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
Investment Cost DME Station - Car	2030	EUR/pump	17,000	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
Investment Cost DME Station - Car	2050	EUR/pump	17,000	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
Investment Cost DME Station - Truck	2020	EUR/pump	13,750	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
Investment Cost DME Station - Truck	2030	EUR/pump	13,750	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
Investment Cost DME Station - Truck	2050	EUR/pump	13,750	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)

16.6.2 O&M Cost

16.6.2.1 General

Table 269: O&M Generation – Domestic.

Parameter	Year	Unit	Value	Source
Wind Offshore	2020	%invest/a	3.50%	(Erichsen, et al., 2019)
Wind Onshore	2020	%invest/a	3.30%	(Erichsen, et al., 2019)
PV Standalone	2020	%invest/a	1.50%	(Erichsen, et al., 2019)
PV slanted	2020	%invest/a	1.50%	(Erichsen, et al., 2019)
Wind Offshore	2030	%invest/a	3.50%	(Erichsen, et al., 2019)
Wind Onshore	2030	%invest/a	3.30%	(Erichsen, et al., 2019)
PV Standalone	2030	%invest/a	1.50%	(Erichsen, et al., 2019)
PV slanted	2030	%invest/a	1.50%	(Erichsen, et al., 2019)
Wind Offshore	2050	%invest/a	3.50%	(Erichsen, et al., 2019)
Wind Onshore	2050	%invest/a	3.30%	(Erichsen, et al., 2019)
PV Standalone	2050	%invest/a	1.50%	(Erichsen, et al., 2019)
PV slanted	2050	%invest/a	1.50%	(Erichsen, et al., 2019)

Table 270: O&M Cost Generation – International.

Parameter	Year	Unit	Value	Source
Wind Offshore	2020	%invest/a	3.20%	(Agora Verkehrswende, Agora Energiewende und Frontier Economics, 2018)
Wind Onshore	2020	%invest/a	2.50%	(Agora Verkehrswende, Agora Energiewende und Frontier Economics, 2018)
PV Stanalone	2020	%invest/a	1.50%	(Agora Verkehrswende, Agora Energiewende und Frontier Economics, 2018)
PV slanted	2020	%invest/a	1.50%	Analogue to PV Standalone
Wind Offshore	2030	%invest/a	3.20%	(Agora Verkehrswende, Agora Energiewende und Frontier Economics, 2018)
Wind Onshore	2030	%invest/a	2.50%	(Agora Verkehrswende, Agora Energiewende und Frontier Economics, 2018)
PV Stanalone	2030	%invest/a	1.50%	(Agora Verkehrswende, Agora Energiewende und Frontier Economics, 2018)
PV slanted	2030	%invest/a	1.50%	Analogue to PV Standalone
Wind Offshore	2050	%invest/a	3.20%	(Agora Verkehrswende, Agora Energiewende und Frontier Economics, 2018)
Wind Onshore	2050	%invest/a	2.50%	(Agora Verkehrswende, Agora Energiewende und Frontier Economics, 2018)
PV Stanalone	2050	%invest/a	1.50%	(Agora Verkehrswende, Agora Energiewende und Frontier Economics, 2018)
PV slanted	2050	%invest/a	1.50%	Analogue to PV Standalone

Table 271: O&M Cost Offshore converter platform.

Parameter	Unit	Value	Source
Converter Offshore platform	%invest/a	2.5%	http://www.northseagrid.info/sites/default/files/NorthSeaGrid_Final_Report_Annexes.pdf (Flament, et al., 2015)

Table 272: O&M Cost Electrolysis.

Parameter	Year	Unit	Value	Source
Electrolysis	2020	%invest/a	2.00%	(Vos, et al., 2020)
Electrolysis	2030	%invest/a	2.00%	(Vos, et al., 2020)
Electrolysis	2050	%invest/a	2.00%	(Vos, et al., 2020)

Table 273: O&M Cost DAC.

Parameter	Year	Unit	Value	Source
Direct Air Capturing	2020	%invest/a	4%	(Fasihi, et al., 2019)
Direct Air Capturing	2030	%invest/a	4%	(Fasihi, et al., 2019)
Direct Air Capturing	2050	%invest/a	4%	(Fasihi, et al., 2019)

Table 274: O&M Cost for H2 Storage.

Parameter	Unit	Value	Source
Cavern Storage - retrofit	%invest/a	2.50%	(Erichsen, et al., 2019)
Pressure Storage	%invest/a	5.00%	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)

Table 275: O&M Cost for hydrogen distribution pipelines (for storage).

Parameter	Year	Unit	Value	Source
Hydrogen Pipeline (new built)	2020	% invest/a	1%	(Wang, et al., 2020)
Hydrogen Pipeline (new built)	2030	% invest/a	1%	(Wang, et al., 2020)
Hydrogen Pipeline (new built)	2050	% invest/a	1%	(Wang, et al., 2020)
Hydrogen Compressor	2020	% invest/a	1%	(Wang, et al., 2020) (average, medium scenario)
Hydrogen Compressor	2030	% invest/a	1%	(Wang, et al., 2020) (average, medium scenario)
Hydrogen Compressor	2050	% invest/a	1%	(Wang, et al., 2020) (average, medium scenario)

Table 276 - O&M Cost for CO2 Storage.

Parameter	Unit	Value	Source
CO2 Storage	%invest/a	5.00%	(elementenergy, 2018)

16.6.2.2 BEV specific

Table 277: O&M Cost Transmission Grid.

Parameter	Year	Unit	Value	Source
AC Overhead Line	2020	EUR/km/year	2,300	(Seidl & Heuke, 2014)
AC Overhead Line	2030	EUR/km/year	2,300	(Seidl & Heuke, 2014)
AC Overhead Line	2050	EUR/km/year	2,300	(Seidl & Heuke, 2014)
HVDC Overhead Line	2020	EUR/km/year	20,000	(Seidl & Heuke, 2014)
HVDC Overhead Line	2030	EUR/km/year	20,000	(Seidl & Heuke, 2014)
HVDC Overhead Line	2050	EUR/km/year	20,000	(Seidl & Heuke, 2014)
HVDC Underground Cable	2020	EUR/km/year	920	(Seidl & Heuke, 2014)
HVDC Underground Cable	2030	EUR/km/year	920	(Seidl & Heuke, 2014)
HVDC Underground Cable	2050	EUR/km/year	920	(Seidl & Heuke, 2014)

Table 278: O&M Cost International electricity import.

Parameter	Year	Unit	Value	Source
Line (2GW)	2020	%invest/a	2.00%	(Vos, et al., 2020)
Line (2GW)	2030	%invest/a	2.00%	(Vos, et al., 2020)
Line (2GW)	2050	%invest/a	2.00%	(Vos, et al., 2020)

Table 279: O&M Cost H2 Reconversion.

Parameter	Year	Unit	Value	Source
Hydrogen Turbine	2020	%invest/a	2%	Proposal Frontier Economics: compliantly commented and agreed in 1:1s with FVV Working Group Members
Hydrogen Turbine	2030	%invest/a	2%	Proposal Frontier Economics: compliantly commented and agreed in 1:1s with FVV Working Group Members
Hydrogen Turbine	2050	%invest/a	2%	Proposal Frontier Economics: compliantly commented and agreed in 1:1s with FVV Working Group Members

Table 280: O&M Cost Electricity Storage.

Parameter	Year	Unit	Value	Source
LI Battery	2020	EUR/MWh	1.40%	(Erichsen, et al., 2019)
LI Battery	2030	EUR/MWh	1.40%	(Erichsen, et al., 2019)
LI Battery	2050	EUR/MWh	1.30%	(Erichsen, et al., 2019)

Table 281: O&M Cost Electricity distribution.

Parameter	Year	Unit	Value	Source
HS	2020	EUR/km/a	600	Proposal Frontier Economics: compliantly commented and agreed in 1:1s with FVV Working Group Members
HS	2030	EUR/km/a	600	Proposal Frontier Economics: compliantly commented and agreed in 1:1s with FVV Working Group Members
HS	2050	EUR/km/a	600	Proposal Frontier Economics: compliantly commented and agreed in 1:1s with FVV Working Group Members
MS	2020	EUR/km/a	1,100	Proposal Frontier Economics: compliantly commented and agreed in 1:1s with FVV Working Group Members
MS	2030	EUR/km/a	1,100	Proposal Frontier Economics: compliantly commented and agreed in 1:1s with FVV Working Group Members
MS	2050	EUR/km/a	1,100	Proposal Frontier Economics: compliantly commented and agreed in 1:1s with FVV Working Group Members
NS	2020	EUR/km/a	800	Proposal Frontier Economics: compliantly commented and agreed in 1:1s with FVV Working Group Members
NS	2030	EUR/km/a	800	Proposal Frontier Economics: compliantly commented and agreed in 1:1s with FVV Working Group Members
NS	2050	EUR/km/a	800	Proposal Frontier Economics: compliantly commented and agreed in 1:1s with FVV Working Group Members
Transformer HV-MV		EUR/unit/a	30,000	Proposal Frontier Economics: compliantly commented and agreed in 1:1s with FVV Working Group Members
Transformer MV-NV		EUR/unit/a	350	Proposal Frontier Economics: compliantly commented and agreed in 1:1s with FVV Working Group Members

Table 282: O&M cost Charger.

Parameter	Year	Unit	Value	Source
Charging Point (11kW)	2020	EUR/a	50	(Spirit Energy)
Charging Point (11kW)	2030	EUR/a	47	(Spirit Energy)
Charging Point (11kW)	2050	EUR/a	45	(Spirit Energy)
Charging Point (44kW)	2020	EUR/a	1400	(Chen, et al., 2020)
Charging Point (44kW)	2030	EUR/a	1400	(Chen, et al., 2020)
Charging Point (44kW)	2050	EUR/a	1400	(Chen, et al., 2020)
Charging Point (150kW)	2020	EUR/a	5600	(Chen, et al., 2020)
Charging Point (150kW)	2030	EUR/a	5600	(Chen, et al., 2020)
Charging Point (150kW)	2050	EUR/a	5600	(Chen, et al., 2020)

Table 283: O&M Cost catenary grid for trucks and coaches.

Parameter	Year	Unit	Value	Source
Catenary Grid	2020	mio EUR/km	2%	(Den Boer, et al., 2013)
Catenary Grid	2030	mio EUR/km	2%	(Den Boer, et al., 2013)
Catenary Grid	2050	mio EUR/km	2%	(Den Boer, et al., 2013)

16.6.2.3 Hydrogen specific

Table 284: O&M cost H2 Transmission Pipelines including compression.

Parameter	Year	Unit	Value	Source
Hydrogen Pipeline	2020	% invest/a	1%	(Wang, et al., 2020) (average, medium scenario)
Hydrogen Pipeline	2030	% invest/a	1%	(Wang, et al., 2020) (average, medium scenario)
Hydrogen Pipeline	2050	% invest/a	1%	(Wang, et al., 2020) (average, medium scenario)
Compressor	2020	% invest/a	1%	Assumption - analogue to compressors for pipelines
Compressor	2030	% invest/a	1%	Assumption - analogue to compressors for pipelines
Compressor	2050	% invest/a	1%	Assumption - analogue to compressors for pipelines

Table 285: O&M Cost H2 compressors for truck distribution.

Parameter	Year	Unit	Value	Source
Compressor	2020	% invest/a	1 %	Assumption - analogue to compressors for pipelines
Compressor	2030	% invest/a	1%	Assumption - analogue to compressors for pipelines
Compressor	2050	% invest/a	1%	Assumption - analogue to compressors for pipelines

Table 286: O&M cost for H2 fuel station.

Parameter	Year	Unit	Value	Source
H2 Station (Cars)	2020	EUR/pump	412,500	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
H2 Station (Cars)	2030	EUR/pump	412,500	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
H2 Station (Cars)	2050	EUR/pump	412,500	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
H2 Station (Trucks)	2020	EUR/pump	412,500	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
H2 Station (Trucks)	2030	EUR/pump	412,500	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
H2 Station (Trucks)	2050	EUR/pump	412,500	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)

16.6.2.4 FT Fuel specific

Table 287: O&M cost FT synthesis.

Parameter	Year	Unit	Value	Source
Synthesis Unit	2020	EUR/kW (FT Fuel)	4%	(Runge, et al., 2019)
Synthesis Unit	2030	EUR/kW (FT Fuel)	4%	(Runge, et al., 2019)
Synthesis Unit	2050	EUR/kW (FT Fuel)	4%	(Runge, et al., 2019)

Table 288: O&M cost FT fuel stations.

Parameter	Year	Unit	Value	Source
FT Station	2020	% of retrofit-ting costs/a	5%	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
FT Station	2030	% of retrofit-ting costs/a	5%	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
FT Station	2050	% of retrofit-ting costs/a	5%	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)

16.6.2.5 Methane specific

Table 289: O&M Cost Methanisation.

Parameter	Year	Unit	Value	Source
Methanation Unit	2020	% of invest-ment/a	2.5%	(Agora Verkehrswende, Agora Energiewende und Frontier Economics, 2018)
Methanation Unit	2030	% of invest-ment/a	2.5%	(Agora Verkehrswende, Agora Energiewende und Frontier Economics, 2018)
Methanation Unit	2050	% of invest-ment/a	2.5%	(Agora Verkehrswende, Agora Energiewende und Frontier Economics, 2018)

Table 290: O&M Cost Transmission Methane Pipeline.

Parameter	Year	Unit	Value	Source
Methane Pipeline	2020	EUR/km/a	5,000	Proposal Frontier Economics: compliantly commented and agreed in 1:1s with FVV Working Group Members
Methane Pipeline	2030	EUR/km/a	5,000	Proposal Frontier Economics: compliantly commented and agreed in 1:1s with FVV Working Group Members
Methane Pipeline	2050	EUR/km/a	5,000	Proposal Frontier Economics: compliantly commented and agreed in 1:1s with FVV Working Group Members
Compressor	2020	EUR/MW/a	200	Proposal Frontier Economics: compliantly commented and agreed in 1:1s with FVV Working Group Members
Compressor	2030	EUR/MW/a	200	Proposal Frontier Economics: compliantly commented and agreed in 1:1s with FVV Working Group Members
Compressor	2050	EUR/MW/a	200	Proposal Frontier Economics: compliantly commented and agreed in 1:1s with FVV Working Group Members

Table 291: O&M International Transport.

Parameter	Year	Unit	Value	Source
Methane Liquefaction	2020	% of investment/a	4%	Proposal Frontier Economics: compliantly commented and agreed in 1:1s with FVV Working Group Members
Methane Liquefaction	2030	% of investment/a	4%	Proposal Frontier Economics: compliantly commented and agreed in 1:1s with FVV Working Group Members
Methane Liquefaction	2050	% of investment/a	4%	Proposal Frontier Economics: compliantly commented and agreed in 1:1s with FVV Working Group Members
International Methane Pipeline	2020	% of investment/a	0.21%	Assumption: analogue to Hydrogen pipeline
International Methane Pipeline	2030	% of investment/a	0.21%	Assumption: analogue to Hydrogen pipeline
International Methane Pipeline	2050	% of investment/a	0.21%	Assumption: analogue to Hydrogen pipeline
LNG Storage	2020	% of investment/a	3%	Proposal Frontier Economics: compliantly commented and agreed in 1:1s with FVV Working Group Members
LNG Storage	2030	% of investment/a	3%	Proposal Frontier Economics: compliantly commented and agreed in 1:1s with FVV Working Group Members
LNG Storage	2050	% of investment/a	3%	Proposal Frontier Economics: compliantly commented and agreed in 1:1s with FVV Working Group Members

Table 292: O&M Cost Distribution Methane Pipelines.

Parameter	Year	Unit	Value	Source
Methane Pipeline	2020	% of investment/a	0.4%	Proposal Frontier Economics: compliantly commented and agreed in 1:1s with FVV Working Group Members
Methane Pipeline	2030	% of investment/a	0.4%	Proposal Frontier Economics: compliantly commented and agreed in 1:1s with FVV Working Group Members
Methane Pipeline	2050	% of investment/a	0.4%	Proposal Frontier Economics: compliantly commented and agreed in 1:1s with FVV Working Group Members

Table 293: O&M Cost CNG and LNG Fuel stations.

Parameter	Year	Unit	Value	Source
CNG Station (full investment)	2020	% of investment/a	5%	(Smith & Gonzales, 2014)
CNG Station (full investment)	2030	% of investment/a	5%	(Drive Natural Gas Initiative, 2013)
CNG Station (full investment)	2050	% of investment/a	5%	(Drive Natural Gas Initiative, 2013)
LNG Station (full investment)	2020	% of investment/a	5%	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
LNG Station (full investment)	2030	% of investment/a	5%	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
LNG Station (full investment)	2050	% of investment/a	5%	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)

16.6.2.6 Methanol specific

Table 294: O&M Cost Methanol synthesis.

Parameter	Year	Unit	Value	Source
Methanol Synthesis Unit	2020	% of investment/a	4%	(Runge, et al., 2019)
Methanol Synthesis Unit	2030	% of investment/a	4%	(Runge, et al., 2019)
Methanol Synthesis Unit	2050	% of investment/a	4%	(Runge, et al., 2019)

Table 295: O&M cost Methanol fuel stations.

Parameter	Year	Unit	Value	Source
Methanol Station - Car (retrofit)	2020	% of retrofitting costs/a	5%	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
Methanol Station - Car (retrofit)	2030	% of retrofitting costs/a	5%	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
Methanol Station - Car (retrofit)	2050	% of retrofitting costs/a	5%	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
Methanol Station - Truck (retrofit)	2020	% of retrofitting costs/a	5%	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
Methanol Station - Truck (retrofit)	2030	% of retrofitting costs/a	5%	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
Methanol Station - Truck (retrofit)	2050	% of retrofitting costs/a	5%	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)

16.6.2.7 DME specific

Table 296: O&M cost DME synthesis.

Parameter	Year	Unit	Value	Source
DME Synthesis Unit	2020	% of investment /a	4%	Assumed to be analogue to FT
DME Synthesis Unit	2030	% of investment /a	4%	Assumed to be analogue to FT
DME Synthesis Unit	2050	% of investment /a	4%	Assumed to be analogue to FT

Table 297: O&M cost DME liquefaction.

Parameter	Year	Unit	Value	Source
DME Liquefaction	2020	% of investment /a	4%	Assumed to be similar to Synthesis
DME Liquefaction	2030	% of investment /a	4%	Assumed to be similar to Synthesis
DME Liquefaction	2050	% of investment /a	4%	Assumed to be similar to Synthesis

Table 298: O&M cost DME fuel station.

Parameter	Year	Unit	Value	Source
Investment Cost DME Station - Car	2020	% of retrofit-ting costs/a	5%	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
Investment Cost DME Station - Car	2030	% of retrofit-ting costs/a	5%	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
Investment Cost DME Station - Car	2050	% of retrofit-ting costs/a	5%	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
Investment Cost DME Station - Truck	2020	% of retrofit-ting costs/a	5%	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
Investment Cost DME Station - Truck	2030	% of retrofit-ting costs/a	5%	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)
Investment Cost DME Station - Truck	2050	% of retrofit-ting costs/a	5%	(Forschungsvereinigung Verbrennungskraftmaschinen, 2018)

16.7 Profiles of raw materials

16.7.1 Lithium

Production: Lithium production in 2019 reached 86,000 tonnes metal content. During last decades, production increased significantly driven by increasing demand for batteries in different appliances. Compared to 1994, the first year covered by extraction statistics of USGS, lithium mining skyrocketed by +1310 %. Main producer is Australia, followed by Chile and China. (USGS, 2021a) Extraction and production of lithium metal are linked to several environmental impacts. On global average, 47 t $CO_{2\text{-eq}}$ are linked to each produced tonne of lithium (ecoinvent, 2020). Particularly brine-based production can lead to severe local impacts on water availability. Technologies are further developed with solvent extraction and ion-exchanger in order to lower water evaporation; but the overall effects of technological improvement on environmental impacts are not yet convincing. (BGR, 2020a)
Global reserves of lithium are estimated at 21 million tonnes metal content (USGS 2021a). Knowledge on reserves increased in recent decades remarkably. Highest reserves are found in brine-based sources in South America, particularly in Chile with 9.2 million tonnes, followed by Australia with mineral deposits of 4.7 million tonnes (USGS, 2021a).
Global resources are estimated at 86 million tonnes metal content (USGS, 2021a). Highest resources can be found in the Andes, particularly in Bolivia (21 million tonnes), Argentina (19.3 million tonnes) and Chile (9.6 million tonnes). Further sources are identified in the ocean, Yang et al. (2018) quantified the lithium resources in the oceans at 230 billion tonnes.
Use: Predominant global use of lithium are batteries (71 %) due to its excellent electrical conductivity and electrochemical potentials. Lithium is furthermore used in ceramic and glass industry (14 %), as lubricating greases (4 %), for casting and polymer production (each 2 %) and air treatment (1 %) and other uses (6 %). The consumption of lithium for batteries has increased significantly because rechargeable batteries are used increasingly for portable electronic devices, in electric tools and vehicles, and in grid storage applications. (European Commission, 2020b; USGS, 2021a) Lithium is considered a critical raw material for lithium-ion batteries in the mobility and energy storage sector, and thus an essential raw material for the implementation of the EU long-term strategy for a climate-neutral economy by 2050. (European Commission, 2020a)
Prices: Lithium prices have been increasing until 2018, dropping thereafter and increasing again since 2021, reflecting a volatile demand and non-flexible supply, which was overestimated in recent years. Demand decreased due to Corona pandemic, but has recovered strongly since the end of 2020. Prices rose up to around 13,800 US$/t for battery grade lithium carbonate in May 2021 (European Commission, 2020b; Roskill, 2021; USGS, 2021a).
Recycling: Recycling of lithium is existent, but not yet relevant. Except batteries, the majority of end-uses of lithium is dissipative and thus not or hardly available for recycling. Recycling of lithium-ion batteries started in few specialized companies at industrial scale. However, recycling processes of Li-ion batteries predominantly focus on higher-price metals. EC reports that at least 85 % of lithium can be recovered by combining mechanical processing with subsequent hydrometallurgical processing. (European Commission, 2020a)
Substitution: Several substitution options are available although performance is lower compared to lithium, e.g. with respect to resistance against temperature. For example, calcium, magnesium, mercury or zinc can be used as anode materials in batteries. Recharchable sodium batteries are developed but electricity storage performance is still limited (Ung Choi et al. 2020, DW 2020). Calcium or aluminium soaps can substitute lithium in greases; sodic or potassic fluxes can be used in ceramics and glass manufacture instead of lithium and lanthanum or gallium can be used in electronics. (European Commission, 2020b; USGS, 2021a)

16.7.2 Cobalt

Production: Production of cobalt in 2019 reached 144,000 tonnes metal content, four times the production amount in 2000. With 70 % of global mine production in 2019, DR Congo continues to be the global leading source of cobalt. (USGS, 2021d)

Except for artisan mines in DR Congo and Madagascar, most cobalt is mined as a by-product of copper or nickel. As a result, environmental impacts of cobalt extraction and mining is closely linked to those of the respective main products. The water demand for the extraction and mining of Australian nickel-cobalt ore sulphide deposits, for instance, is between 1,100-1,400 litres of water per tonne of ore. CO_2 emissions for the mining and processing of cobalt-bearing sulphide ores range between 20-170 kg CO_2/tonne ore. For laterite ores, emissions are higher due to the higher energy intensity of the processing, ranging between 360 - 620 kg CO_2/tonne ore. (BGR, 2021a)

Reserves have been increasing stepwise to 7.1 million tonnes in 2020. (USGS, 2021d)

Global cobalt resources are estimated at 25 million tonnes. Further cobalt resources are manganese nodules and crusts on the floor of oceans (approximately 120 million tonnes). (USGS, 2021d)

Use: Cobalt is used in several applications mainly due to its high energy density, heat resistance and hardness. Globally, half of cobalt (46 %) was used in rechargeable batteries in 2017. Other end uses are superalloys (17 %), carbides, diamond tools and other alloys (14 %), catalysts (7 %), ceramics and pigments (5 %), magnets (5 %), and others (6 %). (Marscheider-Weidemann et al., 2021)

China is the world's leading refiner and consumer of cobalt, with more than 80 % of its consumption being used by the rechargeable battery industry. In the U.S. superalloys are the most important use sector for cobalt (43 %), whereas in Europe superalloys roughly account for 36 % of cobalt end use. (European Commission, 2020a) (USGS, 2021d)

In the last decade, the global shares of end uses of cobalt were rather constant in most sectors. However, cobalt used for batteries doubled in the last ten years (from 37.5 to 66 million tonnes in 2020). Marscheider-Weidemann et al. (2021) expects that cobalt content in Li-ion batteries will decrease in the next decades.

Prices: Prices of cobalt are rather volatile, which is, amongst other, due to concerns over the supply and demand balance, but also by the prevailing political situation of the principal producer. A price peak was reached in 2018 (37 $/tonne), directly leading to an increase in artisanal mining of cobalt in DR Congo. (European Commission, 2020a)

Recycling: Up to date there exist several recycling activities; i.e. of superalloys with recycling rates of approx. 90 %. Technically, secondary cobalt supply can also be more anticipated from hard metals, magnets and catalysts. For pigments, recycling is not feasible due to dissipative losses. Especially in the batteries sector (EV), the recycling potential is significant (easy to collect). Yet, large-scale recycling is estimated to only be effectively accomplished beyond 2025. Cobalt prices affect recycling activities. According to UNEP, the fraction of secondary (scrap) metal in the total input to metal production range between 25 – 50 %. (European Commission, 2020a; UNEP, 2011)

Substitution: Depending on the application, substitution for cobalt results in a loss in product performance or an increase in cost. Potential commercially available cobalt-free substitutes use iron (e.g. in batteries, superalloys, hard metals, magnets, pigments and catalysts). Instead of substituting cobalt completely, a reduction of cobalt content in EV batteries with higher nickel and manganese content is considered a way forward to moderate performance losses. Substitution of cobalt in pigments is straightforward and can be substituted with cerium, acetate, iron, lead, manganese, or vanadium without loss in performance. (CMR InnoNET, 2015)

16.7.3 Platinum group metals (PGM)

Production: In 2019, platinum production reached 186 tonnes metal content; palladium production reached 227 tonnes, thus, in total 413 tonnes (metal content) of Palladium and Platinum were produced (USGS, 2021h). Primary production of total PGM including iridium, rhodium and ruthenium was 447 tonnes in 2017 (European Commission, 2020a). According to statista (2021), production in 2018 of total PGM was 470 metric tonnes. During last decades, production of platinum and palladium increased rather steadily, with some fluctuations. Compared to 1994, platinum mining increased by +45 %, while production of palladium increased by factor 2.3. Main producer of platinum is South Africa (72 %). For palladium, main producers are Russia (43 %), South Africa (36 %) and Canada (8 %). (USGS 2021)

PGM mining is energy, capital and labour-intensive. With approximately 72 %, power consumption during mining and ore beneficiation causes the major environmental impact (CO_2 emissions) of the production of PGM, among others, due to low ore grades. On average, one gram of produced platinum [palladium] is linked to 33 [25] kilograms CO_2 -emissions and a primary energy demand of 387 [304] MJ. Smelting and refining of PGMs cause 27 % of the environmental impacts, while only 1 % of impacts is attributed to recycling, which is mainly due to much higher PGM concentrations in recycled products. (European Commission, 2020a)

Global reserves of PGM only slightly increased and are currently estimated at 69,000 tonnes; more than 90 % of PGM reserves are located in South Africa (USGS, 2021c). JRC estimates global reserves at a lower extend with only 17,000 tonnes (European Commission, 2020a).

PGM resources are estimated at 100,000 tonnes (PGM content); in the last decades no new resources were identified. The largest reserves are in the Bushveld Complex in South Africa. (European Commission, 2020a; USGS, 2021c)

Uses: The automotive industry is the main consumer of PGMs due to their catalytic properties. Given stricter emission standards, PGMs are mainly used in catalytic converters to decrease emissions from motor vehicles (60 % of end use globally in 2018). Jewellery accounts for 12 % in 2018. PGMs are also used in catalysts for bulk-chemical production and petroleum refining (9 %). A wide range of PGM alloy compositions is used in low-voltage and low-energy contacts, thick- and thin-film circuits, thermocouples and furnace components and electrodes. Electronic applications (such as in computer hard disks, hybridised integrated circuits, and multilayer ceramic capacitors) account for 7%, laboratory equipment for 6 %, dental and medical devices and glass manufacturing for 3% each. The demand in most sectors remained stable since 2015, however, the demand of PGM as part of catalytic converter has increased by 46 %, the demand in the jewellery sector, in contrast, has dropped sharply by -36 %. (USGS, 2021c; h)

Platinum and palladium (as well as iridium and ruthenium) are considered important materials for the transition to a climate economy. They are used in hydrogen technologies and fuel cells for energy generation and storage in transport and stationary applications. (European Commission, 2020a)

Prices: PGM prices are relatively high and often volatile due to limited availability in nature and little flexibility for rapid changes in demand. Given the high prices (e.g. 1,300 €/troy oz. in May 2019 for palladium), secondary PGM supply from recycling is important. (European Commission, 2020a; LPPM, 2019)

Recycling: From an ecological perspective, PGM from secondary production has lower environmental impacts compared to the primary production, which is due to the much higher concentration of PGM in end-of-life products compared to the relatively low ore grades (European Commission, 2020a; Hagelüken, 2012; IPA, 2015).

Due to their characteristics and durability in use, generally, PGMs are highly recyclable (UNEP, 2011). Recovery rates for platinum and palladium of over 95 % are technically attainable.

In 2020, about 102 tonnes of palladium and platinum was recovered from new and old scrap worldwide. The most important recycling flows are fed by spent automotive exhaust catalysts and spent chemical catalysts. In the United States, about 57 tonnes were recovered from automobile catalytic converters in 2020. Likewise, automotive catalysts represent the main source of secondary material in the EU. Secondary palladium and platinum approximately comprise 28 % of global production. Recycling activities jumped up in 2012. (USGS, 2021h)

Substitution: There are no effective substitution options for PGM providing the same performances. For some industrial end uses, one PGM can substitute for another, but with losses in efficiency. Palladium has been substituted for platinum in gasoline-engine catalytic converters because of the historically lower price for palladium relative to that of platinum. About 25 % of palladium can be substituted for platinum in diesel catalytic converters; the proportion can be as much as 50 % in some applications. (European Commission, 2020a)

16.7.4 Copper

Production: Primary copper production in 2019 reached 20.4 million tonnes metal content. Following iron and aluminium, copper is the third largest metal used by humans. During last decades, production increased steadily. Compared to 1994, copper mining doubled (+119 %). Main producer is Chile, followed by Peru and China. (USGS, 2021i)

On average, one tonne of refined copper is associated with 3.3 m² land occupation, 74 m³ water, 570 tonnes of excavation materials, 2.6 t CO_2 and 2 kg SO_2. Particularly the water requirements can lead to local conflicts. Modern technologies such as filter appliances can reduce emissions to air significantly. (BGR, 2020b)

Global reserves: Knowledge on reserves increased in recent decades to 870 million tonnes reflecting growing demand. Highest reserves are found in Chile, Peru and Australia with mineral deposits of 200, 92 and 88 million tonnes, respectively. (USGS, 2021i)

Global resources are estimated at 2.1 billion tonnes discovered or identified and further 3.5 billion tonnes undiscovered metal content (ICSG - International Copper Study Group, 2020; USGS, 2021i). For undiscovered resources, the existence is only postulated, comprising deposits that are separate from discovered resources. Highest identified resources can be found in South and North America (39 and 23 % of identified copper resources). (ICSG - International Copper Study Group, 2020)

Use: Copper is an outstanding conductor of electricity and heat, it has high corrosion resistant properties, durability, machinability and good ability to be cast with high precision. Hence, it is used in electrical appliances, electronics and communication, as well as in industrial machinery and equipment. Copper plays an indispensable role in the transformation towards a de-fossilised world. In 2019, copper was used globally in equipment (31 %), building and construction (28 %), infrastructure (16 %), transport (13 %) and in industries (12 %). (ICSG - International Copper Study Group, 2020)

Prices: Over the last century, real price and production costs of copper have dropped to one third, amongst other, due to falling energy prices. However, since the turn of the millennium, prices increased again with China’s demand as a major driver (Barrera, 2020; USGS, 2021b). Currently, the price for one tonne of copper is around 9.230 US$ at the London Metal Exchange (LME - London Metal Exchange, 2021).

Recycling: Recycling of copper is well established. Copper is not degrading or losing chemical or physical properties due to recycling. ICSG (2020) estimates that around 32 % of global copper production is from secondary copper, comprising end-of-life scrap, new scrap (closed loops in production) and metal-bearing residues.

Substitution: Copper can be substituted by aluminium in several of its uses, e.g. automobile radiators, cooling and refrigeration tube, electrical equipment, and power cables. Titanium and steel can be used in heat exchangers and optical fibre substitutes can substitute copper in telecommunication applications. Furthermore, plastics can be used in drainpipe, plumbing fixtures, and water pipe instead of copper. (USGS, 2021i)

16.7.5 Nickel

Production: Production of nickel in 2019 [2020 estimate] reached 2.61 [2.5] million tonnes metal content, doubling the production amount from the year 2000. (USGS, 2021f) In general, two classes of primary nickel products; class I and II nickel vary according to their nickel content[1]. (Metals Hub, 2021) The production of class I and II nickel are linked to very different greenhouse gas emissions: for the production of 1 kg of class I nickel approximately 13 kg CO2-eq are emitted, whereas for 1 kg of ferronickel (class II nickel), derived from lateritic ore, 45 kg CO2-eq emissions are caused. Especially in hydrometallurgical processing of nickel (usually for low nickel ore contents), leaching operations pose a latent risk to the aquatic environment due to possible leaks of alkalis and acids. (BGR, 2021c)
[1] Class I contains products with a nickel content of more than 99 wt % (e.g. cathodes, pellets, briquettes, rondelles). Class II contains products with a nickel content of less than 99 wt % (e.g. ferronickel, nickel pig iron) (Metals Hub 2021)
Reserves have been increasing continuously to approximately 94 million tonnes. (USGS, 2021f)
Global cobalt resources were for a long time estimated at 130 million tonnes, just recently increasing to 300 million tonnes (2020) with about 60 % in laterites and 40 % in sulfide deposits. Further nickel resources also are found in manganese crusts and nodules on the ocean floor. One third of global nickel mine production in 2019 took place in Indonesia. (USGS, 2021f)
Use: Nickel is used in several applications due to its formability, weldability, ductility and corrosion resistance. Globally, the leading uses for primary nickel are stainless and alloy steels (47 %), 42 % of nickel is used for non-ferrous alloys and superalloys to increase corrosion and heat resistance of capacitors or seawater pipes. The end use in electroplating accounts for 7 %, and 4 % comprise several applications. (USGS, 2021f) According to the Nickel Institute approximately 16 % of nickel is used in the transport sector, and 3-5 % of nickel is used for production of batteries. (Dominish et al., 2021; European Commission, 2020b) In 2016 approx. 39 % of Li-ion batteries contained nickel (Nickel Institute, 2018). In batteries for electric vehicles, depending on the Li-ion type, batteries contain 33 % or 80 % of nickel (Nickel Institute, 2018). The demand of nickel for batteries is expected to increase mainly due to a growing market for electric vehicles and the use of nickel as hydroxide or intermetallic compound in batteries. Roskill forecasts that globally the share of nickel used in batteries will grow from roughly below 5 % of the total nickel consumption to 15–20 % (European Commission 2020b; c, also Marscheider-Weidemann et al., 2021). Due to its use in renewable energy technologies (e.g. solar panels), fuel cells (for coating the bipolar plates, in the composition of stainless steel or as anode) and batteries (e.g. Li-ion batteries, medical devices and cordless power tools), nickel is considered a key raw material for the decarbonization of the EU (European Commission, 2020b)
Prices: Prices of nickel are rather volatile, a peak was reached in 2007 (38 $/ton), currently the price per tonne is around 14 $. (USGS, 2021j) Nickel is thus, cheaper compared to Lithium, but much more expensive than cobalt. (Windisch-Kern et al., 2021)
Recycling: According to the Nickel Institute, Nickel can be recycled without loss of quality and used as secondary raw material in many of its applications. Secondary nickel is used to supplement newly mined ores (Nickel Institute, 2018). The share of secondary nickel in total global production is approximately 34 % (UNEP, 2011). According to the latest Study of DERA for nickel, the share of secondary nickel in total global nickel demand has been around 30-35 % in recent years (Szurlies et al., 2021). For the US and EU a share of 43 % and 45 % of secondary nickel in nickel consumption is reported (Nickel Institute, 2016). It is estimated that approximately 68 % of nickel from end-of life consumer products is recycled and another 15 % enters the carbon steel loop (Nickel Institute, n.d.). However, these recycling rates are dominated by the high recycling rates of stainless steel, nickel and copper based alloys. It is very unlikely that secondary nickel from stainless steel and alloys recycling will be used for (li-ion) battery production. Currently, nickel recycling from batteries exists but is not yet relevant; battery recycling is rather designed to recycle cobalt and lithium. Yet, it is technologically possible to recover nickel at a rate of 95 % from batteries. (Dominish et al., 2021)
Substitution: In the stainless steel industry high-grade class I nickel can be substituted by low-grade class II nickel. Nickel in metal products (e.g. plates, tubes, beams) can be substituted by other steel alloy materials such as titanium, chromium, manganese and cobalt (Markaana Karhu et al., 2019). Yet, the substitutes tend to have a higher cost or imply a loss in performance. In batteries as end-use, for instance, there is even a reverse tendency of substituting amounts of cobalt by nickel. (European Commission, 2020c)

16.7.6 Silver

Production: Production of silver in 2019 [2020] reached 26,500 tonnes [estimated 25,000 tonnes] metal content, approximately 40 % more compared to 2000 (USGS, 2021k). Global trend of mined silver production is falling because of a decline in grades at main silver mines, a lower silver output from copper mines and loss due to disruption at some major producers (The Silver Institute, 2020). Silver is primarily extracted as a by-product from lead-zinc mines, copper mines and gold mines (USGS, 2021k). Mexico, Peru and China remain the three countries with the largest amount of silver production (USGS, 2021k).

Silver production is linked to a global warming potential of 196 kg CO_2-eq. per kg silver mainly due to the high cumulative energy demand of 3280 MJ-eq/kg. For silver, the purification stage contributes more to overall environmental impacts than subsequent refining (Nuss / Eckelman, 2014). Worldwide, about 3,000 metric tonnes of silver are released into the environment each year, with tailings and landfills accounting for nearly three-quarters of the total amount (Eckelman / Graedel, 2007).

Reserves are fluctuating and currently reach about 560,000 tonnes in 2019. Compared to 1995, reserves have doubled in the last decades. (USGS, 2021k)

Silver resources are estimated at 796,700 tonnes in 2019. Resources increased by approximately +54 % in the last decades (compared to 1995). (The Silver Institute, 2020)

Uses: Silver is a precious metal and used in several applications due to its malleability, heat and electricity conductivity (DERA, 2016). In 2020, the global (estimated) uses of silver were electrical and electronics (29 %), coins and bars (26 %), industrial uses (17 %), jewellery (16 %), brazing alloys (5 %) and silverware (5 %) (Newman / Webb, 2020). Over 60 million ounces of silver are used annually in motor vehicles (The Silver Institute, 2021). Silver is used in light-weight, high-capacity batteries that employ silver oxide or silver zinc alloys (European Commission, 2020c; Marscheider-Weidemann et al., 2016). With regard to renewable energy systems, silver is used in solar PV panels as a conductive paste on front and back side of the crystalline solar cells (European Commission, 2020b).

Prices: Prices of silver were highest in 2011 and have since been decreasing. The estimated average silver price in 2020 was $20.00 per troy ounce (USGS, 2021k).

Recycling: The share of secondary silver in total refined silver is approximately 15 % in 2014. Material flows of silver scrap have declined compared to 2010/11. (European Commission, 2020c)

Recycling rates vary strongly among different applications; e.g. silver losses in electric and electronic parts in vehicles occur in collection, shredding and metallurgical recovery operations, resulting in a recycling rate of 0-5 %. Especially in the case of electronics, recovery rates in modern metallurgical plants can approach 100 % of the silver contained, if the printed circuit boards are properly collected and pre-treated. (European Commission, 2020c).

Substitutes exist for silver in various applications: In electrical and electronics, silver is considered the best electrical conductor. However, copper, aluminium and other precious metals in many electrical and electronic uses can replace silver. Yet, silver wire is usually reserved for more sensitive systems and specialty electronics where high conductivity over a small distance is prioritized. (European Commission, 2020c)

Silver in coins, silverware and jewellery can in principle be substituted by other metals (e.g. gold or platinum), depending on price and quality requirements. Substitution of silver from brazing alloys and solders with other metals such as tin is possible, however implies a loss in physical and chemical performance (European Commission, 2020c; Marscheider-Weidemann et al., 2016)

16.7.7 Rare earth elements (including Neodymium)

Production: Global production of Rare Earths (RE) accounted for approximately 220,000 tonnes REO (Rare-earth oxide) in 2019 (estimates for 2020 reach 240,000 tonnes), without neodymium (Nd) and dysprosium (Dy) global production reached roughly 188,000 tonnes in 2019 (USGS, 2021g). The production of neodymium and dysprosium accounts for 30,687 and 1,397, respectively, tonnes in 2019 (European Commission, 2020a). RE metals only occur and can only be mined together. Most of the rare earths are found rather frequently in the earth's crust, but they are not often enriched in economically mineable amounts (DERA, 2016). With a market share of over 80 %, China dominates worldwide production of rare earths (Schüler-Zhou, 2018). In 2019 rare earth mine production in China was 132,000 tonnes REO (Rare Earth Oxide), followed by the United States (28,000 tonnes REO), Burundi (25,000 tonnes REO) and Australia (20,000 tonnes REO) (USGS, 2021g). The majority of rare earth production is dominated by lanthanum and cerium, but most of the demand for rare earths is for neodymium or dysprosium (Jowitt et al., 2018). On average, rare earth elements have a global warming potential of 30 t CO2 or 37 t CO2-eqv. per tonne REO, depending on specific rare earth elements, production sites and processing. The extraction of rare earths can have a high specific land occupation. On the one hand, this is due to the low REO content (<0.2 wt. %) in combination with inefficient mining methods for ion adsorption clays, and on the other hand due to the preferential extraction in opencast mines. (BGR, 2021b)
Reserves are 120 million tonnes REO and resources are estimated at approximately 478 million tonnes REO (Zhou et al., 2017). Largest resources are identified in China, Brazil, Vietnam, Russia, India, Australia, USA, Tanzania, Canada, South Africa, Malaysia and Greenland (JRC, 2020). USGS identified resources for the United States to include 2.7 million tonnes and more than 15 million tonnes in Canada (USGS, 2021g).
Uses: In 2019, rare earth elements were used as follows: magnets (29 %), catalysts (21 %), polishing (13 %), metallurgy (8 %), glass (8 %), batteries (7 %), ceramics (4 %), phosphor (1 %), pigments (0.4 %) and others (9 %) (European Commission, 2020a). Consumption in the EU differs in that automotive catalysts make up the largest share (27 %) of total consumption (European Commission, 2020a). Domestic consumption of rare earth elements in the US is dominated by catalysts too (75 %) (USGS, 2021g). Rare earths are essential in the production of high-tech, low-carbon goods such as electric vehicles, wind turbines, batteries and energy efficient light bulbs. Furthermore, they are important in the defence sector (European Commission, 2020a). Neodymium, praseodymium, dysprosium, samarium, gadolinium and cerium are used in permanent magnets for electricity generators and electric motors; permanent magnets containing rare earth elements represent 29 % (41,046 tonnes of REO) of total rare earth elements global demand in 2019 (ibid.). Magnets are the leading application of rare earth elements demand since 2015; used in permanent magnet synchronous motors (ibid.). According to JRC, the supply risk of the rare earths in permanent magnets generators for wind turbines is one of the most concerning feature of wind industry related to raw materials (European Commission, 2020b). The majority of hybrid and electric vehicles uses synchronous motors with NdFeB magnets because they are the strongest magnets. NdFeB magnets contain several rare earth elements such as neodymium, praseodymium and dysprosium (European Commission, 2020b).
Prices: Prices are volatile. Trends show a 12-fold increase in 2010-2011 triggered by decreasing export quotas from China and “geopolitical tension in a period of high demand for permanent magnets, driven by the expected growth of the renewable energy and electric vehicles markets” ((European Commission, 2020a); (DERA, n.d.)). Prices have since fallen and remained relatively low, although China’s intervention in illegal mining is expected to reduce overcapacity and additional environmental protection measures could lead to an increase in prices on the world market (Schüler-Zhou, 2018).
Recycling: According to Jowitt et al. (2018) only around 1 % of the rare earth elements are recycled from end-products, with the rest deporting to waste and being removed from the materials cycle. Dysprosium has an end-of life recycling input rate (EOL-RIR) of 0 %, while recycling of Neodymium amounts to 1 %. The highest EOL-RIR are for europium (38 %), yttrium (31 %), praseodymium (10 %) and terbium (estimates reach from 6 % - 28 %) in descending order (European Commission, 2018b, 2020a).
Substitution: Most rare earth applications lack material substitutes with comparable cost and technical performance (European Commission, 2020a); they are often less effective (USGS, 2021g). For magnets rare earth elements can be substituted with terbium and gadolinium or applying other alternative technologies such as ferrite or SmCo magnets (European Commission, 2020a).

16.7.8 Silicon metal

Production: According to USGS production quantities of silicon metal in 2019 reached 8.4 million tonnes; this amount comprises the silicon content of both, ferrosilicon and silicon metal (USGS, 2021l). According to Boubault (2019) approximately 3 million tonnes of metallurgical silicon are produced annually, with China clearly dominating the production (70 %). According to the same author, China dominates the production of ferrosilicon, which estimated at 8 million tonnes annually (Bell, 2019; Boubault, 2019). Compared to ferrosilicon, metallurgical grade silicon has a purity of greater than 99 percent and is mostly extracted from extremely high-purity quartz due to their high silica content[1] (European Commission, 2020a). Silicon metal production is energy intensive; thus, the environmental impacts (e.g. CO2 emissions) depend strongly on the energy source, which for instance in China is mostly coal. In Europe, historically most silicon production plants are located close to hydropower plants. Silicon is not classified as hazardous. (European Commission, 2020a)
[1] In this analysis, only silicon metal is analysed. As silicon (in form of silicon minerals) is the second most abundant element in the earth crust, a variety of products can be produced depending on the silicon source (and grade). Glass, for instance, is an important industrial product which is amongst others used for the production of PV panels, yet glass is produced from silicia sand which is essentially made up of broken down quartz crystals. Of such quartz crystals, only extremely high-purity quartz is used to produce metallurgical grade silicon. (European Commission, 2020c) The material demand of silicon for glass components for PV power plants (which is around 46.6 t/MW according to Carrara et al. (2020)) is thus, not considered in this study.
Reserves and resources: There are no quantitative estimates of reserves of silicon metal worldwide. The Minerals4EU project records data on several silicon reserves and resources with varying silicon grades (e.g. quartz sand, quartzite, silicia sand, glass sand, foundry sand) for some European countries (European Commission, 2020c). However, the listed quantities are not reflecting the silicon metal content nor do they indicate whether the different grades are suitable for the production of silicon metal, which is produced from high purity quartz. Therefore, the estimates are not accurate enough to be used as a proxy in this study. USGS (2021h) estimated that the world resources in the producing countries China, United States, Brazil and Norway are sufficient to supply world demand of silicon metal for many decades
Uses: The major uses of silicon metal are in metallurgy mostly for aluminium alloys (41 %). Aluminium manufacturers use silicon metal to improve its castability, hardness and strength (Boubault, 2019). The demand of lighter and more economical material has triggered a growth in silicon metal consumption by aluminium manufacturers. (Boubault, 2019; Ferroglobe, 2020) 35 % of global silicon metal is used in the chemical industry for silicon compounds (Boubault, 2019). Silicon compounds are the raw material for a large and growing number of industrial and consumer products such as silicon rubber parts, insulating materials, sealants, adhesives, lubricants, food additives, coatings, polishes and cosmetics. (European Commission, 2020a; Ferroglobe, 2020) Almost a fifth (18 %) of silicon metal is used in photovoltaic solar cells and electronic semiconductors (e.g. silicon wafers). In 2019, roughly 95 % of the global PV technology produced was silicon-based technology (Si-wafers) (Fraunhofer ISE, 2021). 6 % of silicon metals is used for other purposes (e.g. microelectronics). (European Commission, 2020a) The consumption of silicon metal is on a rising trend, which is partly due to the increasing demand for silicones, solar cells and aluminium alloys. Li-ion batteries containing silicon are also being actively developed due to their high storage capacities. (Boubault, 2019)
Recycling: Currently, the end-of life recycling rate of silicon metal is close to zero. Silicon-containing alloys can be recycled, but without element separation (no functional recycling). New silicon metal waste and cutting sludge can be recycled during production. Recycling of electronic products and photovoltaic panels is theoretically possible, but hardly profitable due to the small quantities in the products and the difficulty of separating silicon parts from other components. Some companies are developing solutions to recycle high-purity silicon or polysilicon in the form of scrap or sludge. (Boubault, 2019)
Substitution: Silicon metal as a material is not substitutable in most of its applications. However, technical (rather than material) alternatives exist in solar and electronic applications, e.g. CdTe and CIGS photovoltaic thin films or germanium–wafers in micro-electronic applications. Yet, these alternatives sometimes have significant toxicities, e.g. cadmium in CdTe photovoltaic cells. (Boubault, 2019; European Commission, 2020a)

17 Appendix

17.1 Bibliography – Frontier

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